Changes in discharge rise and fall rates applied to impact assessment of catchment land use

D. R. Archer, D. Climent-Soler and I. P. Holman

ABSTRACT

Despite substantial evidence that land use and management can enhance flood runoff at a local scale, evidence of increased flood risk based on peak discharges is lacking in catchments greater than 10 km^2. This analysis is instead based on assessing changes in short-term rates of change in discharge. The influence of land use is demonstrated first on the small Coalburn catchment where changes in rates of rise are closely related to drainage and afforestation. For the larger Axe catchment (288 km^2), changes in rates of rise are investigated by comparing annual maximum and peaks over a threshold flows for different periods, by comparing rates of rise associated with given daily rainfall and by adapting the method of flow variability analysis for use of rates of change rather than flow itself. All these methods demonstrate significant changes in river flow dynamics which seem to be in parallel with land use changes even when the influence of climate variability from year to year has been taken into account. Rates of change in discharge appear to respond to land use changes and thus provide a potential basis for application to land use management policies.

Key words | flood risk management, land management, land use change, rates of change in flow, soil structure

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INTRODUCTION

Recent extreme and widespread flooding incidents in northern Europe and in particular in the UK during Easter 1998, autumn 2000 and summer 2007 have raised public awareness and governmental concern about flood risk. Given the associated loss of life, personal deprivation and economic costs, the question of whether the traditional approach to flood risk management, through the provision of structural defences to vulnerable locations, is inadequate is being asked (Vinet 2008). As an alternative, the potential for impacts to be mitigated at source is being considered, with the prime strategies in rural catchments being the application of land use and land management changes (Wheater 2002; Evans *et al.* 2004; Camorani *et al.* 2005; Evrard *et al.* 2007).

O'Connell *et al.* (2007) noted that there is substantial evidence that modern land management practices have enhanced surface runoff generation at the local scale and therefore that frequency of flooding can be reduced by appropriate land management practices (Martyn *et al.* 2000; Evans & Boardman 2003). In their review of the extensive literature on the analysis of flooding trends and modelling the impact of changes in land use and management, they found 'an almost complete lack of evidence that local scale effects aggregate causing impacts at larger scales downstream'. Moreover, they concluded that current rainfall–runoff models are unsuitable for use in operational assessment of land use management on flooding. They also recommended a research programme to test more sophisticated methods to search for evidence of the impacts of land use and management change on flood runoff generation in hydrological datasets.

Further study was conducted under Defra FD2120 project (Beven *et al.* 2007) to address the identifiability of hydrological changes as a result of land use and

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management in rural catchments. New modelling techniques were applied to historical datasets, to look for impacts of land use and management change on flood generation in catchments where substantial changes in land use and management had occurred over the period of the hydrometric record. Only two of the nine catchments investigated (including the Axe catchment which is one of the subjects of this study) showed limited evidence of hydrological trends which might be related to land use change. The analysis confirmed the difficulty of using models to identify the impacts of changes in land use and land management on hydrological responses at the catchment scale in the face of uncertainties in the hydrological data and the variability and change in climate variables.

A further recent study commissioned by the Environment Agency for England and Wales on catchment-scale land use planning (Halcrow 2008) also concluded that the combined effects of land management on flood risk are difficult to determine. This is because they are the collective result of many local-scale effects which are hard to quantify and are also dependent on individual physical catchment characteristics. Changing land management practices may not therefore provide significant observable benefits in terms of reducing the peak flows of extreme floods.

Each of these UK studies concluded that the lack of evidence does not necessarily equate to the lack of effect, only that the available models and procedures to validate them are not yet good enough to detect effects.

It is ultimately the risk of extreme levels and discharges which is of concern for flood risk management and hence for policy application. However, peak flows may be seriously affected by variability in rainfall time and spatial distribution and by soil moisture variability. It may therefore be more difficult to detect land use change signals in peak flow data than in other characteristics of the flood hydrograph. Two different aspects of hydrograph response for identifying the impact of land use were developed by Archer (2000, 2003 and 2007) and Archer & Newson (2002).

Changes in flow variability or flashiness in terms of numbers and durations of pulses

A pulse is an event characterized by two crossings, first upward and later downward, of a particular discharge threshold. The analysis consists of counting the annual or seasonal number of pulses in each period for each threshold and calculating their aggregated and mean duration. Archer & Newson (2002) and Archer (2003) compared drainage and afforestation effects in the Coalburn (1.5 km^2) and Irthing (335 km^2). Archer (2007) compared the paired experimental catchment on the Wye (10.5 km^2) and Severn (8.7 km^2) catchments at Plynlimon. Results from these analyses show how the numbers and duration of pulses change over time in parallel with land use change, suggesting a causal relationship. The analysis is carried forward in a parallel paper by developing the method further in the Axe catchment in southwest England (Climent-Soler *et al.* 2009).

Changes in rates of short-term rise and fall in the flow hydrograph

In the analysis of the paired Plynlimon catchments, Archer (2007) demonstrated distinct differences between the forested and moorland catchments; the moorland catchment has more rapid rates of change over the greater part of the flow range. This difference in rate of change is despite the fact that no significant difference was found between the catchments in flood frequency based on peak flows (Kirby *et al.* 1992). However, given the absence of a pre-afforestation flow record, the differences between the catchments could conceivably have originated from pre-afforestation differences in the natural catchment, which have survived through the change in land use.

It was therefore considered necessary to test the usefulness of rate-of-change characteristics of the hydrograph in assessing the impacts of land use change. Analysis has been applied to two quite different catchments: the small forested Coalburn catchment (1.5 km^2) in northwest England and the agricultural Axe catchment (288.5 km^2) in southwest England (Figure 1).

CATCHMENT DESCRIPTION

Coalburn catchment

The Coalburn catchment is a rolling upland catchment, a headwater tributary of the River Irthing and of the River Eden with an area of 1.5 km^2 (Figure 1). It varies in

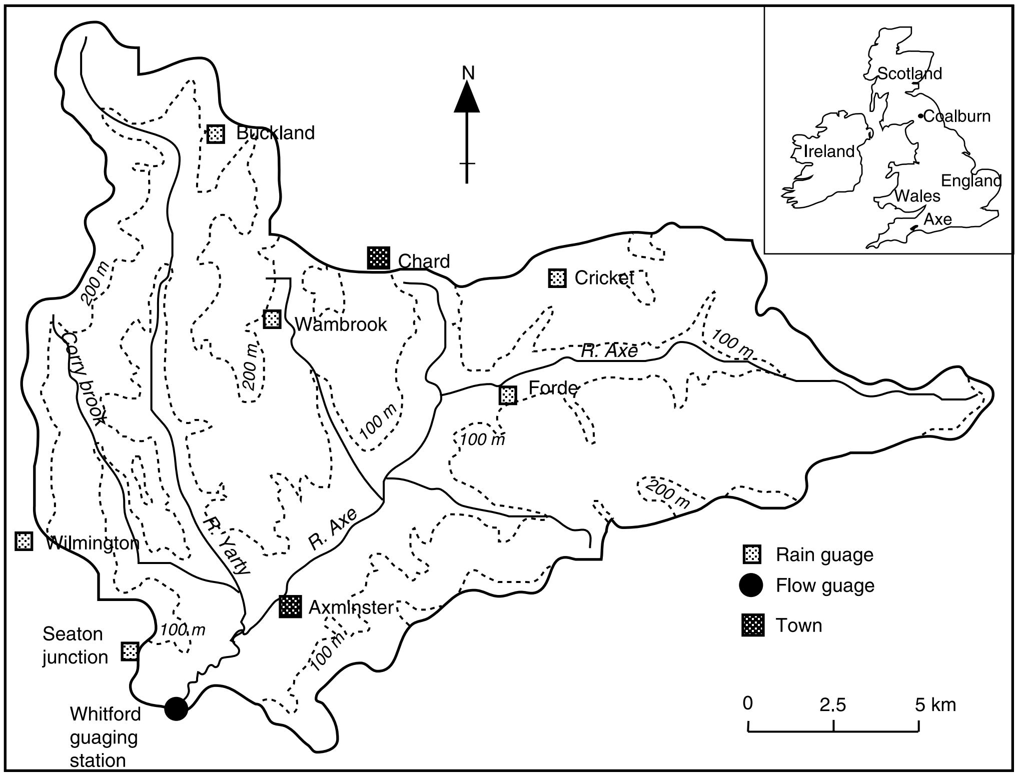

Figure 1 | The Axe catchment to Whitford gauging station with inset location of Axe and Coalburn catchments.

altitude from 270 to 330 m OD. Mean annual rainfall is 1,277 mm. 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} which was 60 times greater than the original stream network. Ninety percent of the catchment was planted, predominantly with Sitka spruce (*Picea sitchensis*), in spring 1973. Trees typically reached a height of 1 m in 1978 and 7–12 m in 1996, by which time some 60% of the catchment had reached canopy closure (Robinson *et al.* 1998). The forest is due for felling in 2016.

Axe catchment

The Axe catchment to Whitford gauging station (288.5 km^2) (Figure 1) rises on the Somerset and Blackdown Hills and drains to Lyme Bay and the English Channel. The highest point of the catchment is at 315 m OD. The catchment is underlain by Cretaceous Greensand and Chalk in the upper catchment and by Triassic and Jurassic calcareous clays and Mudstones in the middle and lower reaches. This difference in geology is reflected in the soils, which are predominantly slowly permeable loams and silts, prone to seasonal waterlogging in the middle and lower reaches. More permeable silty soils are present in the upper reaches (Findlay *et al.* 1984).

The average annual rainfall in the catchment ranges from less than 800 mm in the coastal areas to over 1,000 mm in the upper catchment. The wettest period of the year is, on average, during the months of October to February. The mean daily flow at Whitford gauging station is 5.11 $\mathrm{m}^3\,\mathrm{s}^{-1}$.

Agricultural land use predominates, accounting for approximately 93% of the catchment area. The catchment is dominated by intensive dairy farming and maize crops, although other livestock (such as sheep and pigs) and arable farming (such as wheat and barley) are also present. Autumn-sown (Boardman *et al.* 2003) and late-harvested cropping systems (Speirs & Frost 1985) were identified as critical runoff enhancement factors within the catchment. Between 1966 and 2002, the areas of critical crops in the Axe catchment exhibited notable changes. Autumn-sown crops represented 2.3% of the catchment in 1979, increasing progressively to their largest value in 1996 (9.4%) and falling thereafter. Late-harvested crops represented less than 0.6% of the catchment area until the late 1980s, when the area rose steadily to reach more than 4.5% at the end of 2004. The steepest increases, between 1988 and 1996, were mainly due to an increase in maize cultivation. Further details are given in Climent-Soler *et al.* (2009).

With respect to livestock activities, statistics show a progressive increase in sheep numbers since the early 1980s reaching the highest values during the 1990s. Cattle numbers, however, remained relatively stable. Average farm stocking densities show a clear tendency upwards, driven not only by the growth in sheep numbers but also by the reduction in managed grass in favour of arable land (EA 2004)

ANALYSIS: COALBURN CATCHMENT

Land use change has been sufficiently widespread and the catchment size sufficiently small to provide clear evidence of effects on flood response (Robinson 1986; Robinson *et al.* 1998). Peak flows increased by 20% and the time to peak of the unit hydrograph decreased in the first five years after planting, when response was dominated by the artificial drainage network. However, peak flows declined thereafter as the forest matured. Using flow variability analysis, Archer & Newson (2002) demonstrated that the hydrological response is dominated by the drainage network for approximately 12 years after planting and the runoff is more flashy than the initial moorland cover. After that period, the forest assumes a greater role in the runoff response which becomes much less flashy. By 1999, annual flood pulse numbers had reduced by nearly 40% below those experienced under the moorland cover. Average pulse duration had increased by more than 20% over most of the flow range.

Analysis for this study is intended not only to establish whether different stages in drainage and forest growth are reflected in rates of rise and fall in discharge, but also whether rates of change provide a better index of land use change than peak flows.

Methodology

Archer & Newson (2002) divided the record period into four time blocks with respect to land use as follows:

1. 1967–1972: pre drainage;
2. 1974–1982: immediate post drainage and planting;
3. 1983–1990: intermediate period;
4. 1992–1999: approaching/reaching canopy closure.

These time blocks have also been used for this study with the addition of a further block from 2000 to 2006. The flow records for these intervals are too short for comparative flood frequency analysis, so median annual and summer (April to September) peak flow maxima and rates of one-hour rise and fall have been determined for each period and compared (Table 1).

Significance of a linear trend in peak flow and rates of change in flow is tested by bootstrap sampling with 1000 resamples (Kundzewicz & Robson 2004) for the period of forest growth (1974–2006) following the step change of drainage in 1972. As a means of assessing the possible impact of changing rainfall on peak flows and rates of change, linear trend analysis is also applied to annual and seasonal daily rainfall maxima.

Results

Table 1 suggests little change in annual maximum peak flows; there is little evidence of trend from 1974 to 2006 (significance of linear trend (Sig.) 48.2%). However, it is noted that, with few exceptions, the annual maximum peak flow occurs in winter. When the period from April to September is considered separately, Table 1 suggests a distinct increase from the natural catchment to the post-drainage period and then a steady reduction with forest growth. Linear trend from 1974 to 2006 is significant (Sig. 96.1%).

Although annual peak flows show no clear trend, annual maximum rates of rise and fall demonstrate patterns similar to April to September peak flow with

Table 1 | Comparison of median maximum discharge and median maximum rate of rise and fall in discharge for consecutive land use periods: (a) annual and (b) April to September

Period	Median maximum flow ($m^3 s^{-1}$)	Median maximum 1 hr rise ($m^3 s^{-1} h^{-1}$)	Median maximum 1 hr fall ($m^3 s^{-1} h^{-1}$)
(a) annual			
67–99	1.83	0.86	−0.49
67–72	1.94	0.74	−0.40
74–82	1.89	1.12	−0.66
83–90	1.73	0.86	−0.46
92–99	1.64	0.63	−0.34
00–06	1.81	0.70	−0.34
(b) April–September			
67–99	1.14	0.48	−0.26
67–72	1.16	0.39	−0.26
74–82	1.46	0.84	−0.46
83–90	1.14	0.61	−0.33
92–99	0.88	0.28	−0.16
00–06	0.57	0.21	−0.08

highest rates from 1974 to 1982 (Table 1), decreasing through the following 25 years. Linear trends from 1974 to 2006 are significant: 97.9% and 98.4% for annual rates of rise and fall, respectively. The contrast between periods is even more clearly demonstrated for rates of rise and fall from April to September with rates in the most recent period less than one-quarter of the rate during the post-drainage period (Table 1). Linear trends from 1974 to 2006 are highly significant: 99.3% and 99.9% for rise and fall, respectively.

Although generally downwards, the trend in maximum daily rainfall is not significant for either annual (Sig. 72%) or April–September rainfall (Sig 78%).

It is therefore concluded that land use is the principal influence on the changes in observed flow change rates over the period, and that rate of change in flow provides a better index of land use change than peak flow.

ANALYSIS: AXE CATCHMENT

Given the larger catchment size, the smaller proportion and piecemeal development of land use change on the Axe catchment, it was anticipated that impact on hydrological response would be less marked and more difficult to identify. Analysis for the Axe was therefore more comprehensive and progressively more sophisticated than for the Coalburn to take account of differing impact with season, with magnitude of rainfall and over a wider range of flow.

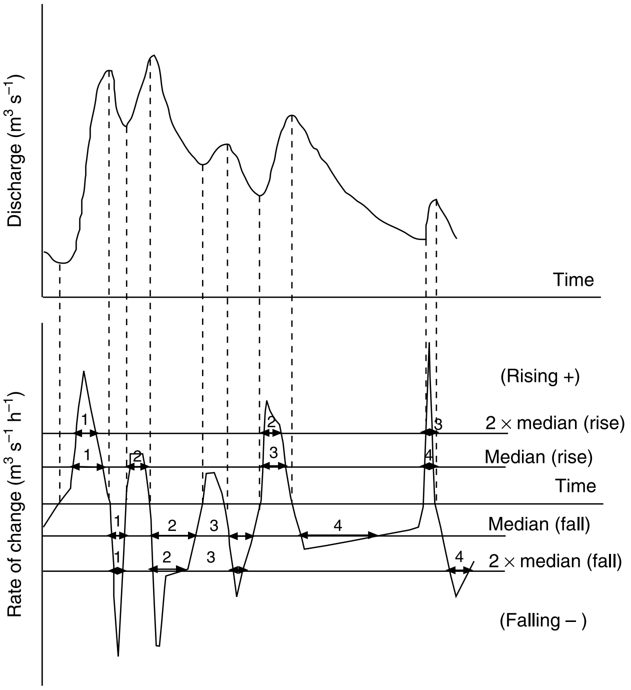

Figure 2 | Definition diagram for pulse numbers and pulse duration for rates of change.

Table 2 | Median annual rates of change in discharge ($m^3 s^{-1} h^{-1}$) for different sub-periods in the Axe catchment

Period	Median annual maximum rise	Median annual maximum fall	Landuse change
1966–2002	20.0	9.7	–
1966–1977	13.3	7.9	Little agricultural change
1978–1990	20.0	8.6	Increasing autumn sown cereals and livestock intensity
1991–2002	25.8	11.1	Increasing late harvested crops, autumn sown cereals and livestock intensity

Methodology

An hourly rate-of-change time series was derived (as the derivative function of the discharge with respect to time, i.e. the steepness of the hydrograph for each time) from the hourly flow record for Whitford gauging station from 1966 to 2002. Statistics of rise and fall were compiled by water year (October to September) as follows.

1. As for the Coalburn, median annual maximum rates of change were calculated. The 37 water years were then divided into three time periods: 1966–1977, 1978–1990 and 1991–2002, representing progressively intensifying changes in agricultural land use and management.
2. To allow for a wider spread of flood flows, the *peaks-over-threshold* (POT) approach was also applied. The rate-of-change threshold was iteratively determined to give an average number of 5 peak exceedances per water year. In order to ensure the required independence of the occurrences, the USWRC (1976) hydrological independence criterion was adopted. Two data subsets for 1966–1984 and 1985–2002 were fitted to a Generalized Pareto Distribution (GPD) (Coles 2001) and relationships between rate of change and return period were obtained for comparison.
3. The method of flow variability analysis described in Archer (2000) and Archer & Newson (2002) was adapted for use of rates of change in flow rather than flow itself. This allows the full flow hydrograph to be inspected. The original method is based on the frequency and duration of pulses above selected levels of flow, established as multiples of the median flow, over the time series. A pulse is an event characterized by two crossings, upward first and downward later, of a particular discharge threshold. The analysis consists of counting the number of pulses in each water year or season for each threshold, calculating their aggregated and mean duration and studying their variation in the period of study. Figure 2 shows the transformation of the method from the flow data series to the rate of change data series.

Table 3 | Thresholds of 60 min rate of rise and fall in discharge ($m^3 s^{-1} h^{-1}$) and the average number of over threshold occurrences per year for each sub-period

	Threshold ($m^3 s^{-1} h^{-1}$)	Annual average number of exceedances 1966–2002	1966–1984	1985–2002
Rate of rise 60 min	5.90	5.00	4.47	5.55
Rate of fall 60 min	3.56	5.00	4.47	5.55

The median values of the rate of rise and rate of fall in 60 min were used to derive a series of multiples of the median thresholds to cover the range of occurrence of the 'rate of rise' or 'rate of fall'. The number and average duration of pulses was calculated for each threshold and each water year. The average duration of 'rate of rise'

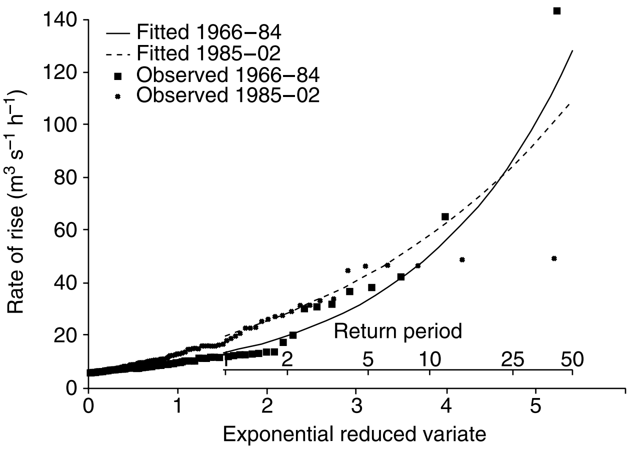

Figure 3 | Relationship between return period and maximum rate of rise in discharge in 60 min for different sub-periods.

Table 4 | Linear and Spearman correlation coefficients (r) for trend in annual pulse time series for rates of change in 60 min

Threshold	0.5M	M	2M	3M	4M	6M	8M	10M	15M	20M	30M	40M	60M	80M	100M	150M	200M	300M
(a1) Pulse number rate of rise 60 min ($M = 0.043\,m^3\,s^{-1}\,h^{-1}$)																		
Linear r	**0.468**	0.252	0.242	0.205	0.196	0.263	*0.277*	*0.318*	0.266	*0.289*	**0.337**	**0.380**	**0.434**	**0.496**	**0.537**	**0.430**	**0.518**	**0.611**
Spearman r	**0.359**	0.152	0.228	0.170	0.141	0.204	0.168	0.224	0.182	0.174	0.246	0.257	*0.314*	**0.430**	**0.474**	**0.353**	**0.477**	**0.576**
(a2) Pulse number rate of fall 60 min ($M = 0.050\,m^3\,s^{-1}\,h^{-1}$)																		
Linear r	**0.355**	0.273	**0.348**	**0.394**	**0.409**	**0.502**	**0.528**	**0.561**	**0.587**	**0.553**	**0.447**	**0.436**	**0.484**	**0.583**	**0.569**	**0.399**	*0.279*	−0.009
Spearman r	0.248	0.173	0.258	*0.289*	**0.333**	**0.436**	**0.437**	**0.452**	**0.502**	**0.472**	**0.354**	**0.393**	**0.422**	**0.560**	**0.492**	**0.396**	0.211	−0.170
(b1) Pulse duration rate of rise 60 min ($M = 0.043\,m^3\,s^{-1}\,h^{-1}$)																		
Linear r	0.223	0.136	0.171	0.159	0.178	0.212	0.251	***0.278***	***0.321***	**0.373**	**0.402**	**0.432**	**0.481**	**0.537**	**0.539**	**0.593**	**0.579**	**0.551**
Spearman r	0.202	0.092	0.124	0.102	0.143	0.158	0.172	0.196	0.225	0.252	0.266	**0.325**	**0.411**	**0.468**	**0.475**	**0.585**	**0.553**	**0.524**
(b2) Pulse duration rate of fall 60 min ($M = 0.050\,m^3\,s^{-1}\,h^{-1}$)																		
Linear r	−0.005	0.064	0.214	*0.297*	**0.380**	**0.458**	**0.500**	**0.502**	**0.498**	**0.480**	**0.472**	**0.512**	**0.538**	**0.553**	**0.494**	0.248	0.161	−0.020
Spearman r	−0.013	0.051	0.139	0.210	*0.286*	**0.353**	**0.378**	**0.381**	**0.415**	**0.384**	**0.385**	**0.443**	**0.487**	**0.499**	**0.382**	0.237	0.135	−0.163

Figures in bold come from regressions where P^2 is a statistically significant variable at 95% level; italic figures at the 90% level.

pulses can be viewed as the length of time over which the river discharge is uninterruptedly increasing at a rate above a certain threshold.

Variations in climate and weather conditions also affect flood response and these were taken into account using the methodology described by Archer (2000, 2003 and 2004) and Archer & Newson (2002) and developed by Climent-Soler (2007). Six stations (Figure 1) were employed to calculate daily average catchment rainfall by the Thiessen polygons method for the period of the streamflow record. Regression analysis between annual number and duration of pulses and the simple and squared total annual catchment rainfall (P and P^2) were conducted. The regression relationships were employed to compute an expected number and duration of pulses above each threshold for a given set of climatic values. The residual number and duration of pulses within the observed dataset, which might be related to land use/management practices, were then calculated and time variability patterns studied.

4. For evaluating whether changes in agricultural land use and management raised the maximum rate of rise for specific individual rainfall episodes, a comparison between maximum rates of rise in discharge within a day and the associated rainfall total in that day for the two sets of water years was carried out. Days were categorized into 27 groups based upon defined ranges of rainfall totals (e.g. between 3 and 4 mm). Daily maximum rates of rise in each group were analyzed by comparing the median, average and highest maximum daily rates between the two subsets of data (1966–1984 and 1985–2002).

Results

Annual maxima

Median annual maximum rates of change in discharge calculated and compared between three periods (Table 2) show that median values for both rise and fall have increased over time, reaching the maximum in the last sub-period 1991–2002.

This analysis already shows correspondence between timing of land use and hydrological change, but further

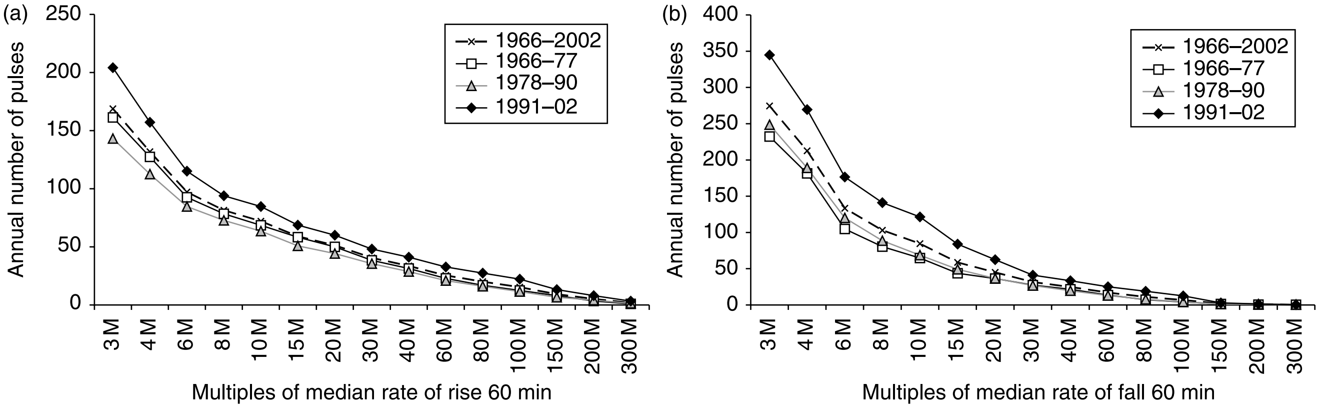

Figure 4 | Annual number of pulses for rate of (a) rise and (b) fall in 60 min for the range of thresholds and sub-periods.

analysis is required to clarify comparative impacts of climate, weather and range of flow.

Peaks over threshold analysis

Peaks over threshold frequency analysis was applied to the two periods 1966–1984 and 1985–2002, and relationships between rates of change and return period were calculated and plotted. The USWRC (1976) hydrological independence criterion required that the time separation (θ) between consecutive events for analysis is:

$$\theta > 5\,\text{days} + \log(\text{square miles of catchment area})$$
$$= 9.7\,\text{days (for the Axe)}.$$

The examination of the flow hydrographs together with the low base flow index of the catchment (<0.5) suggested that the accepted time separation for the Axe is conservative.

Table 3 presents the densities of over-threshold occurrences of rates of rise and fall for each sub-period, indicating a greater number of over-threshold occurrences in the later period coinciding with more intense agricultural use. Figure 3 shows the results of frequency analysis for the rate of rise for 60 min time interval with fitted lines using the Generalized Pareto Distribution (GPD). The plot suggests little difference between the periods for frequently occurring events (>2 per year). However, over much of the range of discharge and return period, rates of rise are greater during the later period. Values for the first sub-period become greater for high-return periods (those for which statistical inference becomes weak) mainly because their relationship is affected by two exceptional events in November 1965 and July 1968. A similar pattern of comparative behaviour between the two periods was observed for rates of fall (not shown).

It is acknowledged that climate and particularly rainfall variability between sub-periods is not considered in the peaks over threshold analysis. Attempts at accounting for rainfall variability are made in the following analysis.

Flow variability analysis

The median values of the rate of rise and rate of fall in 60 min were 0.043 and 0.050 $\mathrm{m^3\,s^{-1}\,h^{-1}}$, respectively. Eighteen multiples of the median (M) as 0.5M-M-2M-3M-4M-6M-8M-10M-15M-20M-30M-40M-60M-80M-100M-150M-200M-300M were used as thresholds to cover the range of occurrence of the rate of rise or rate of fall.

Time series of the number of pulses and duration above each threshold were constructed for rates of rise and fall in 60 min in order to assess trend and step changes. The annual number of pulses over each threshold in all the cases was found to present a general positive long-term trend for the period of record, but was only significant for higher thresholds and more marked for rates of fall than for rates of rise (Table 4a). Analogous, but more marked changes were also found in the pulse duration time series

Table 5 | Adjusted coefficient of determination (R^2) for the adopted regression models used for removing the climate variability effect for annual rate of change time series

Threshold	**0.5M**	**M**	**2M**	**3M**	**4M**	**6M**	**8M**	**10M**	**15M**	**20M**	**30M**	**40M**	**60M**	**80M**	**100M**	**150M**	**200M**	**300M**
(a) Rate of rise 60ºmin. Used variable: mean annual catchment rainfall squared (P^2)																		
Pulse number	0.371	**0.473**	**0.452**	**0.432**	**0.476**	**0.607**	**0.723**	**0.761**	**0.727**	**0.688**	**0.650**	**0.724**	**0.676**	**0.641**	**0.560**	**0.449**	**0.421**	0.274
Total duration	0.531	**0.632**	**0.690**	**0.740**	**0.791**	**0.850**	**0.862**	**0.855**	**0.842**	**0.809**	**0.773**	**0.754**	**0.690**	**0.619**	**0.580**	**0.451**	**0.394**	**0.323**
(b) Rate of fall 60ºmin. Used variable: mean annual catchment rainfall squared (P^2)																		
Pulse number	**0.481**	**0.611**	**0.568**	**0.530**	**0.534**	**0.507**	**0.544**	**0.548**	**0.519**	**0.524**	**0.702**	**0.567**	**0.507**	**0.412**	**0.343**	**0.280**	**0.153**	0.066
Total duration	**0.646**	**0.709**	**0.800**	**0.837**	**0.846**	**0.825**	**0.792**	**0.783**	**0.733**	**0.719**	**0.649**	**0.541**	**0.467**	**0.395**	**0.354**	**0.234**	**0.184**	0.046

Figures in bold come from regressions where P^2 is a statistically significant variable at 95% level.

(Table 4b). The manifestation of this trend is chiefly due to a significant increase in the number of pulses during the 1990 s compared to the earlier time periods (Figure 4).

Differences in the average annual number and duration of pulses between sub-periods using the Student's *t* statistic were not statistically significant between the two first sub-periods (1966–1977 and 1978–1990) but were between 1991–2002 and both earlier periods.

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 pulse numbers and duration and measures of catchment rainfall. Different variables based on daily and annual rainfall were tested in regression analysis with annual and seasonal pulse numbers and duration (Climent-Soler *et al.* 2009). It was concluded that annual rainfall squared (P^2) gave the most effective relationship for flow rates of change as for flow. Coefficients of determination (R^2) for the adopted regression models used for removing the climate variability effect for annual rate of change time series are shown in Table 5. Total duration adjustments were notably better than for number of pulses.

For each year and rate of change in flow threshold, the expected number and duration of pulses was calculated from catchment rainfall. This expected number was then subtracted from the observed value to give a residual with zero mean for the full period. Trend analysis of each of the residual time series was then carried out and the range of thresholds over which residual pulses and durations were calculated is shown in Table 6. Statistical differences between the three flow periods were also tested for step changes.

Trends in the residual number and duration of pulses were statistically significant for thresholds between 80M and 300M for rate of rise (Table 6). Examples for trend in residuals at 80M and 100M for (a) number and (b) duration are shown in Figure 5. The range of thresholds over which change was detectable was wider for rates of fall and they included relatively low thresholds (Table 6). For both rise and fall, the study of step changes showed that trend detection was mostly due to increases in the 1990s.

Table 6 | Range of rate-of-change (rise or fall) thresholds both for trend and step changes with statistically significant changes in residuals

	Rate of rise 60 min		**Rate of fall 60 min**	
	Range of thresholds		**Range of thresholds**	
Annual	**Trend**	**Step**	**Trend**	**Step**
Residual pulse number	80M–300M, *150M*	60M–200M, *150M*	8M–100M, *150M*	8M–150M
Residual pulse duration	40M–300M, *30M*	30M–300M	4M–100M	4M–150M

Figures in italics are statistically significant at 90% level; the others at 95%.

Daily rainfall and rates of rise

Median, maximum and average maximum rate of rise for a 60 min time interval in a day and its associated daily rainfall total are shown in Table 7. The sub-period 1985–2002 had consistently greater rate-of-rise values for days with catchment rainfall totals in the range 10–30 mm and many of the differences in averages were statistically significant. The association seems to vanish when reaching high values of daily rainfall (approximately >30 mm), although the reducing number of days with such high rainfall totals makes comparison difficult at that level. Differences for lower rainfalls were randomly distributed and also lack statistical significance.

DISCUSSION

The study of the river rates of change time series has demonstrated that significant changes in river flow dynamics which seem to be in parallel with land use changes occurred in the Axe. Table 8 summarizes the key outcomes from the analysis.

All these analyses, based on rates of change in flow, show increased rates for the period from 1985 to 2002 and particularly from 1991. The key question is whether the changes can be attributed to land use and management or whether some or all of the change could result from changes in climate, which are not accounted for in the methods of accounting for rainfall variability.

Analysis of rainfall patterns throughout the period of record showed changes with potential to bias the interpretation of the river flow analysis and increase climate-driven hydrological disturbance. In particular, the period 1991–2002 presented statistically significant differences ($p < 0.05$) with respect to the previous 25 years of the record. Average annual rainfall in the catchment increased by 9.5%. The number of days with more than 20 mm of total rainfall increased by 25%, again mainly due to a rise during 1991–2002. In the case of the extreme rate-of-change using annual maxima and POT series, analysis could certainly be influenced by both land use change and climate variability

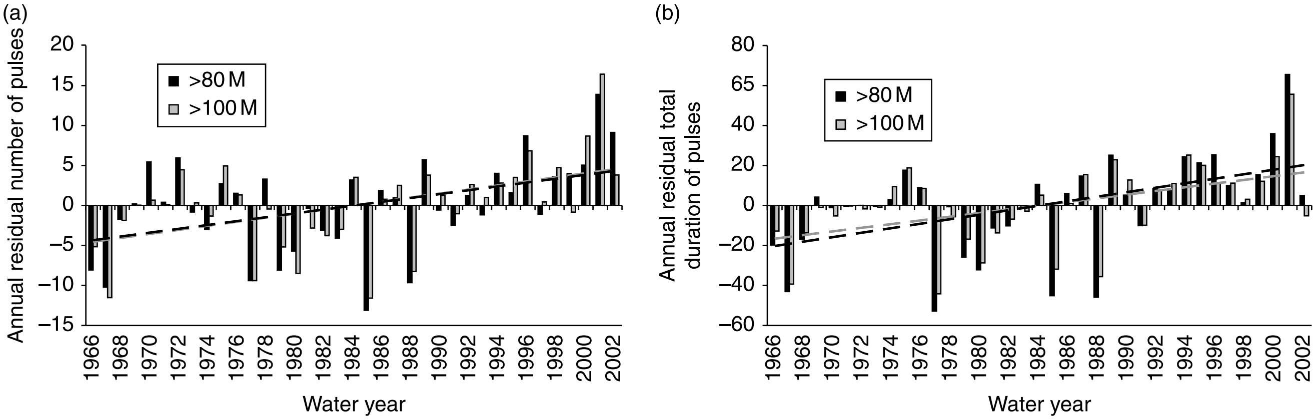

Figure 5 | Time series of annual residual (a) number and (b) duration of pulses for a rate of rise in 60 min above thresholds of 80M and 100M (where M refers to the median rate of rise in 60 min).

Table 7 | Comparison between median, maximum and average maximum daily rate of rise in 60 min for different ranges of total daily rainfalls and sub-periods

	Median		**Maximum**		**Average**	
Daily P (mm)	**1966–1984**	**1985–2002**	**1966–1984**	**1985–2002**	**1966–1984**	**1985–2002**
1–2	0.07	0.06	10.09	9.74	0.25	0.23
2–3	0.10	0.11	10.15	18.80	0.34	0.43
3–4	0.14	0.14	11.03	20.66	0.45	0.57
4–5	0.24	0.20	37.05	11.75	0.80	0.62
5–6	0.37	0.30	7.21	6.15	0.76	0.73
6–7	0.51	0.38	7.01	5.42	0.95	0.89
7–8	0.61	0.87	12.29	22.87	0.99	**1.76**
8–9	0.77	0.88	12.34	11.00	1.39	1.48
9–10	0.89	0.88	19.83	5.86	1.58	1.43
10–11	1.36	1.77	12.49	15.48	1.92	*2.59*
11–12	1.47	1.56	13.44	15.04	2.17	2.40
12–13	1.13	2.34	7.55	13.75	1.66	**2.80**
13–14	2.79	3.43	10.74	29.12	3.16	**4.25**
14–15	2.29	3.86	7.34	44.58	2.38	**4.60**
15–16	2.34	3.04	9.48	27.62	2.87	**4.10**
16–17	3.28	4.21	9.16	10.48	3.62	**4.65**
17–18	2.80	3.69	9.87	26.15	3.62	4.55
18–19	3.11	3.17	11.77	16.78	4.35	4.80
19–20	4.02	6.59	9.01	14.66	4.35	**6.77**
20–21	3.49	6.42	13.93	12.37	4.78	6.15
21–23	5.07	6.40	11.52	16.03	4.98	**6.14**
23–25	4.60	6.99	12.64	16.19	5.16	**7.93**
25–27	5.70	7.88	12.98	19.76	5.90	**7.93**
27–30	6.71	5.95	31.05	27.03	7.20	7.87
30–40	6.63	9.58	64.98	46.48	10.91	12.36
40–50	3.73	33.39	224.15	49.30	30.57	29.03
> 50	6.26	25.50	30.32	48.71	13.46	26.50

The largest value in each comparison is highlighted. Averages showing statistically significant difference at 95% or 90% confidence level (t-values) are shown in bold or italics, respectively.

since it did not incorporate techniques to make allowance for the effect of climate variability.

The strong influence of climate on annual rate of rise pulse numbers and duration is shown by the high coefficients of determination between annual pulse numbers and duration and a measure of annual rainfall (P^2) (Table 5). Nevertheless, when effects of climate variability were removed, significant trend still remained, strengthening the possibility that these detected changes were land-use driven. The increase in hydrological disturbance emerged during the 1990 s, when agricultural activities reached their highest level. Possibly the most significant evidence for the influence of land use is the observation that while significant changes in rainfall frequency and amount have been confined to the spring/summer season, the principal change in the number and frequency of flow pulses (as opposed to rate of change pulses) occurs during the autumn/winter period (Climent-Soler *et al.* 2009). This analysis accounted for the possible effect of the antecedent wetness conditions by including the precipitation of the previous seasons as a regression variable in the study of the pulse residuals. The main change occurred in the April–September rainfall

Table 8 | Main outcomes from the river flow dynamics analysis of River Axe

	Significant changes in river flow dynamics detected for the period of intense agricultural activities (1985–2002)	Allow for climate variability
Extreme values (annual and seasonal maximum rates of change)	Higher median annual and seasonal maximum rates of change	NO
Extreme values (POT)	Higher annual maximum rates of change over the greater range of return periods	
	Higher frequency of over-thresholds episodes	NO
Pulse method for rates-of-change in discharge	Increase in pulse numbers for relatively high thresholds, increase frequency of high rates of change (1991–2002)	
	Larger relative increase in duration of pulses for medium-high thresholds (1991–2002)	YES
Rates of rise associated with daily rainfall totals	Consistent higher rates of rise in days with total catchment rainfall >10 mm, but no clear changes for days with more than 30 mm	YES

when there was a 17.5% statistically significant increase in average rainfall in the period 1991–2002 compared with the previous years of record. Autumn/winter rainfall totals, by contrast, did not experience significant changes over the period of record.

The study of maximum rates of rise associated with daily rainfall total also allows for climate effects when comparing days with similar total rainfall. However, it does not take into account possible differences in rainfall intensities and antecedent soil moisture conditions, and further work will be directed towards incorporating these factors. However, changes detected were consistent with those from the pulse analysis for which climate variability effects were removed. This suggests that although the magnitude of the changes could be smaller, a significant agriculturally induced effect may still exist.

The detected changes using the pulse method are imperceptible for low thresholds but become more evident as the threshold rises. Similarly, the results from the study of maximum rate of rise associated with rainfall totals would support this idea, since significant differences only occurred in days with rainfall totals higher than ~10 mm whose associated rates of rise are of the order of those from which changes started to be detectable in the pulse analysis. This suggests that the impact of the agricultural-driven enhanced field runoff generation only significantly alters the hydrological response of the river above a certain level of rainfall. Lower amounts and intensities of rainfall may well be absorbed by soil and landscape storage irrespective of land use and management.

The study also provided evidence that effects of land use on increases in rates of change in flow deteriorate for extreme events. The POT analysis of extremes (Figure 3) suggests that very rapid rates of change in flow occur in extreme events irrespective of land use. The highest observed rates of change occurred in the early part of the record in November 1965 and July 1968. This would support the idea that land use effects would be of secondary importance compared to natural climatic variability in such events (O'Connell *et al.* 2004). In the most extreme events, widespread overland flow is generated irrespective of land use.

It is concluded that the exacerbation of the river response is likely to be partially due to the increase in farm surface runoff contribution to river flow, arising mainly from surface compaction, loss of structure and exposure of bare surfaces. Agricultural-induced enhancement of the degree of connectivity between field runoff and receiving watercourses (such as tramlines or removal of hedges) may also have played a role in reducing the time taken by water to reach the river course. The likely increase in overland flow due to agricultural activities in the late 1980 s and the 1990 s seems to have produced a rise in the frequency and duration of high rates of change in flow. Results suggest that, within certain levels of rainfall, the hydrological response of the river to rainfall events became faster in parallel with intensification of agricultural activities.

Increased rates of change in flow at the catchment scale imply greater and more rapid surface runoff. Rate of change analysis therefore makes the connection between the catchment scale and the field scale, where land use influences have been directly observed e.g. with respect to reduced soil water storage capacity (Hollis 2005) and infiltration rates (Holman *et al.* 2003) and greater generation of stormwater runoff (Tollan 2002). Even in the absence of a trend in peak flows, enhanced surface runoff associated with increased rates of change may help to generate higher sediment loads and muddy floods observed by Boardman *et al.* (2003).

CONCLUSIONS

The question of whether land use changes are reflected in rates of rise and fall in discharge, and also whether rates of change provide a better index of land use change than peak flows, was asked. The small Coalburn catchment provides clear positive answers to both these questions. While median annual maximum discharges show no significant change over the record period, there are significant trends in the rate of rise and rate of fall statistics which correspond to stages of catchment drainage and forest growth. Corresponding trends in annual maximum daily rainfall over the period of maturing forest are not significant.

Given the larger catchment size and the piecemeal nature of agricultural land use changes on the Axe catchment, more elaborate applications of rate of change statistics were applied. These also demonstrate significant changes in river flow dynamics which seem to be in parallel with land use changes. Methods have been developed to account for the influence of climate variability from year to year. The residual variations in hydrological response still show changes in rate of change statistics in parallel with intensification of agricultural activities. However, the clearest evidence of change appears over moderate rather than extreme floods, with significant evidence for change mainly in events arising from rainfall of 10–30 mm per day.

The principal policy interest in land use impacts on flood flows is with respect to the mitigation of extreme discharges and levels. Although trends in peak discharges resulting from such changes have not been found, the discovery that rates of change in discharge respond more readily to land use changes (although also affected by climate and weather) provides a potential basis for land use management policies to be established within the context of an integrated catchment approach.

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REFERENCES

Archer, D. R. 2000 Indices of flow variability and their use in identifying the impact of land use changes. *Proceedings of Seventh National Hydrology Symposium*, British Hydrological Society, Sept 2000, pp. 2.67–2.74.

Archer, D. R. 2003 Scale effects on the hydrological impact of upland afforestation and drainage using indices of flow variability: the River Irthing, England. *Hydrol. Earth Syst. Sci.* **7**(3), 325–338.

Archer, D. R. 2004 New hydrological insights from the analysis of flow variability on the impact of land use change and river regulation. In *Hydrology: Science and Practice for the 21st Century*, (Vol. 2). British Hydrological Society, London, pp. 1–9.

Archer, D. R. 2007 The use of flow variability analysis to assess the impact of land use change on the paired Plynlimon catchments, mid-Wales. *J. Hydrol.* **347**, 487–496.

Archer, D. R. & Newson, M. D. 2002 The use of indices of flow variability in assessing the hydrological and instream habitat impacts of upland afforestation and drainage. *J. Hydrol.* **268**, 244–258.

Beven, K., Young, P., Romanowicz, R., O'Connell, E., Ewen, J., O'Donnell, G., Holman, I., Morris, J., Hollis, J., Rose, S., Lamb, R. & Archer, D. 2007 *FD2120: Analysis of historical data sets to look for impacts of land use and management change on flood generation.* Final Report, Defra, London.

Boardman, J., Evans, R. & Ford, J. 2003 Muddy floods on the South Downs southern England: problem and responses. *Environ. Sci. Policy* **6**, 69–83.

Camorani, G., Castellarin, A. & Brath, A. 2005 Effects of land-use changes on the hydrologic response of reclamation systems. *Phys. Chem. Earth* **30**, 561–574.

Climent-Soler, D. 2007 *Investigation of the effects of agriculture on river hydrological response in the Axe catchment, Devon, and the implications for flood risk*. Unpublished MSc in Water Management Thesis, Cranfield University.

Climent-Soler, D., Holman, I. & Archer, D. R. 2009 Application of flow variability analysis to identify impacts of agricultural land use change on the River Axe, southwest England. *Hydrol. Res.* **40**(4), 380–393.

Coles, S. 2001 *An Introduction to Statistical Modelling of Extreme Values*. Springer-Verlag, London.

Environment Agency 2004 Catchment fluvial geomorphological audit of the Axe catchment: detailed geomorphological survey (Report B). http://bb.cranfield.ac.uk

Evans, R. & Boardman, J. 2003 Curtailment of muddy floods in the Sompton, South Downs, West Sussex, southern England. *Soil Use Manage.* **19**, 223–231.

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A. J., Sayers, P. & Thorne, C. 2004 *Foresight Future Flooding*. Office of Science and Technology, London.

Evrard, O., Bielders, C. L., Vandaele, K. & van Wesemael, B. 2007 Spatial and temporal variation of muddy floods in central Belgium, off-site impacts and potential control measures. *Catena* **70**, 443–454.

Findlay, D. C., Colborne, G. J. N., Cope, D. W., Harrod, T. R., Hogan, D. V. & Staines, S. J. 1984 Soils and their use in South West England. *Bulletin No. 14*. Soil Survey of England and Wales, Harpenden, UK.

Halcrow Group Limited 2008 Delivery of Making Space for Water: Project HA6: The role of land use and land management in delivering flood risk management, Environment Agency.

Hollis, J. 2005 Is there any link between soil compaction and flooding? A review of the evidence. *Proceedings of Land-use and Water Series Integrating Water and Soil Strategies: Translating Research into Action*. CIWEM, October 2005, London, pp. 21–22.

Holman, I. P., Hollis, J. M., Bramley, M. E. & Thompson, T. R. E. 2003 The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales. *Hydrol. Earth Syst. Sci.* **7**(5), 754–765.

Kirby, C., Newson, M. D. & Gilman, K. 1992 *Plynlimon Research: The First Two Decades*. Institute of Hydrology Report, 109, Wallingford, UK.

Kundzewicz, Z. W. & Robson, A. J. 2004 Change detection in hydrological records–a review of methodology. *Hydrol. Sci. J.* **49**(1), 7–19.

Martyn, T. M., Donaldson, G., Clements, R. O. & Lindsay, J. 2000 Soil erosion control in maize stubbles. *Proceedings of Sixth Research Conference, British Grassland Society*, Aberdeen, UK, pp. 29–30.

O'Connell, P. E., Beven, K. J., Carney, J. N., Clements, R. O., Ewen, J., Fowler, H., Harris, G. L., Hollis, J., Morris, J., O'Donnell, G. M., Packman, J. C., Parkin, A., Quinn, P. F., Rose, S. C. & Shepherd, M. 2004 *Review of Impacts of Rural Land Use and Management on Flood Generation*. Impact Study Report, Defra/Environment Agency R&D Technical Report (FD2114), London.

O'Connell, P. E., Ewen, J., O'Donnell, G. & Quinn, P. 2007 Is there a link between agricultural land-use management and flooding? *Hydrol. Earth Syst. Sci.* **11**(1), 96–107.

Robinson, M. 1986 Changes in catchment runoff following drainage and afforestation. *J. Hydrol.* **175**, 71–84.

Robinson, M., Moore, R. E., Nisbet, N. R. & Blackie, J. R. 1998 *From Moorland to Forest: The Coalburn Catchment Experiment*. IH Report No 133, Institute of Hydrology Wallingford, UK.

Speirs, R. B. & Frost, C. A. 1985 The increasing incidence of accelerated soil water erosion on arable land in the east of Scotland. *Res. Dev. Agric.* **2**, 161–168.

Tollan, A. 2002 Land use change and floods: what do we need most research or management? *Water Sci. Technol.* **45**(8), 183–190.

USWRC 1976 Guidelines for determining flood flow frequency. United States Water Resources Council, Bull.17, Hydrol. Comm. Washington, DC, p. 73.

Vinet, F. 2008 From hazard reduction to integrated risk management: toward adaptive flood prevention in Europe. In Proverbs, D., Brebbia, C. A. & Penning-Rowsell, E. (eds) *Flood Recovery, Innovation and Response I. Transactions in Ecology and the Environment*, (Vol. 118). WIT Press, Southampton UK, pp. 113–122.

Wheater, H. S. 2002 Progress in and prospects for fluvial food modelling. *Phil. Trans. R. Soc. Lond.* **360**, 1409–1431.

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