Application of flow variability analysis to identify impacts of agricultural land-use change on the River Axe, southwest England

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

ABSTRACT

Flow variability analysis based on the annual number and duration of pulses above flow thresholds has been used to identify potential impacts of agricultural land-use change on the River Axe catchment (288.5 km^2). The analysis shows significant trend and step changes in runoff response which coincide both with changes in land use and management and with changes in rainfall amount and intensity. The effects of climatic variability are taken into account by regression analysis; residuals from regression continue to show a trend which is ascribed to land-use change. Seasonal analysis indicates that the winter season has the greatest change in runoff response but little change in rainfall. In contrast, the summer season shows little change in runoff response but altered rainfall frequency. The success of flow variability methods in identifying trends and the sources of trends in the runoff response on the Axe catchment indicates the potential of the methods for more general application for the development of flood risk management policies based on land-use and management.

Key words | flood risk management, flow variability, land management, land use, runoff trends, soil structure

D. Climent-Soler
I. P. Holman
Natural Resources Department,
Cranfield University,
Cranfield MK43 0AL,
UK

D. R. Archer (corresponding author)
JBA Consulting Engineers and Scientists,
South Barn,
Broughton Hall,
Skipton, North Yorkshire BD23 3AE,
UK

D. R. Archer (corresponding author)
Present address: 2 Welburn Close, Ovingham,
Northumberland NE42 6BD,
UK
Tel.: +44 1661 834063
E-mail: david.archer@jbaconsulting.co.uk

INTRODUCTION

Three prominent reports commissioned by the UK government have recently highlighted the potential impact of land use and management on the hydrological regime. Following widespread flooding in Britain in autumn 2000, the Institution of Civil Engineers Presidential Commission Report *Learning to Live with Rivers* (Fleming *et al.* 2001) recommended a catchment-wide approach to flood risk management, including further study on the link between land use and flooding. Such studies were seen as capable of generating policy changes that could lead to significant reduction in flood risk. The *Foresight Report* (Evans *et al.* 2004) noted that 'there is a growing perception that changes in land-use and land management have a significant effect on flood risk'. *Making Space for Water* (Defra 2004), published following a consultation exercise, noted that 'Most consultees considered rural land management

practices (such as cultivation practice and woodland creation) to be capable of ameliorating run-off and reducing the incidence of flooding on a local scale' and 'We will be giving priority to further research into the role rural land management techniques might play in managing flood risk at catchment level'.

There is strong scientific evidence to support anthropogenic influence on river flood response at the local scale. O'Connell *et al.* (2004) pointed to evidence that changes in rural landscapes and agricultural systems in the UK, driven by national and EU agricultural policies, had the potential to alter soil structure. This in turn can influence saturated hydraulic conductivity and reduce soil water storage capacity (Hollis 2005), and infiltration rates (Holman *et al.* 2003), leading to greater generation of stormwater runoff (Tollan 2002), including localised 'muddy floods'

(Boardman *et al.* 2003). However, despite the evidence of increased plot and field-scale runoff generation, there is little direct evidence of how these changes affect the surface stream network and the hydrological and flood response of the river at a catchment scale greater than $10\,\text{km}^2$ (O'Connell *et al.* 2007).

The overriding influence of climatic variability makes it difficult to identify trends in flood magnitude associated with either climate or land-use change. This is true whether dealing with national methods of flood frequency estimation (Institute of Hydrology 1999), the search for significantly changing trends in flood frequency nationally (Robson 2002) or comparing flood frequency on paired research catchments with different land use (Kirby *et al.* 1991).

The preferred alternative is to develop appropriate physical models of the runoff process in which land-use changes can be incorporated. However, Wheater (2002) indicated that data and models were inadequate to represent rural land-use change and called for the development of new modelling approaches to represent those impacts. Critically he suggested a major step forward is required in the ability of hydrological models to assimilate physical process information at the scale of field observation, and to represent the associated effects at catchment scale. O'Connell *et al.* (2007) outlined some of the limitations of existing models and suggested an approach through multi-scale catchment experimentation such as outlined by Mayes *et al.* (2006).

The need to test more sophisticated methods for searching for evidence of the impacts of land use and management change on flood runoff generation in hydrological datasets has recently been addressed through the Department of Environment Food and Rural Affairs (Defra) Project FD2120 (Beven *et al.* 2007). The project applied new modelling techniques to nine catchments in which significant change in land use or management had been identified, including the Axe catchment, the subject of analysis in this paper. Comparative results are discussed below.

Quite different techniques for identifying the impact of land use were developed by Archer (2000) who examined changes in flow variability or flashiness between different time periods in terms of numbers and durations of pulses over a wide range of flow thresholds. Archer & Newson (2002) and Archer (2003) compared

drainage and afforestation effects in the Coalburn ($1.5\,\text{km}^2$) and Irthing ($335\,\text{km}^2$) catchments. Archer (2007) compared the paired experimental catchments on the Wye ($10.5\,\text{km}^2$) and Severn ($8.7\,\text{km}^2$) 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. In the case of the Coalburn catchment the effect of climate variation from year to year was accounted for by means of a linear regression between annual numbers and durations of pulses and annual measured rainfall, then looking at trends in the residuals. In the case of the paired moorland and forest catchments at Plynlimon, the annual differences between pulse numbers and durations in the two catchments were analysed as a way of controlling for the effects of climate.

The analysis is carried forward in this paper by further developing and applying the method to flow data from the Axe catchment in southwest England.

A second but related method, based on the rates of rise and fall in the flow hydrograph, was applied to the Plynlimon catchments and demonstrated distinct differences between the forested and moorland catchments. This method has also been modified for application to the Axe catchment and results are described in a parallel paper (Archer *et al.* submitted). Links between results of the two methods are discussed below.

THE STUDY CATCHMENT

The Axe (Figure 1), situated in southwest England, rises on the Somerset and Blackdown Hills and drains to Lyme Bay and the English Channel at Seaton. The highest point of the catchment is at 315 m OD in the headwaters of the River Yarty in the northwest of the catchment. The catchment area to Whitford is $288.5\,\text{km}^2$.

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, and more permeable silty soils in the upper reaches (Findlay *et al.* 1984).
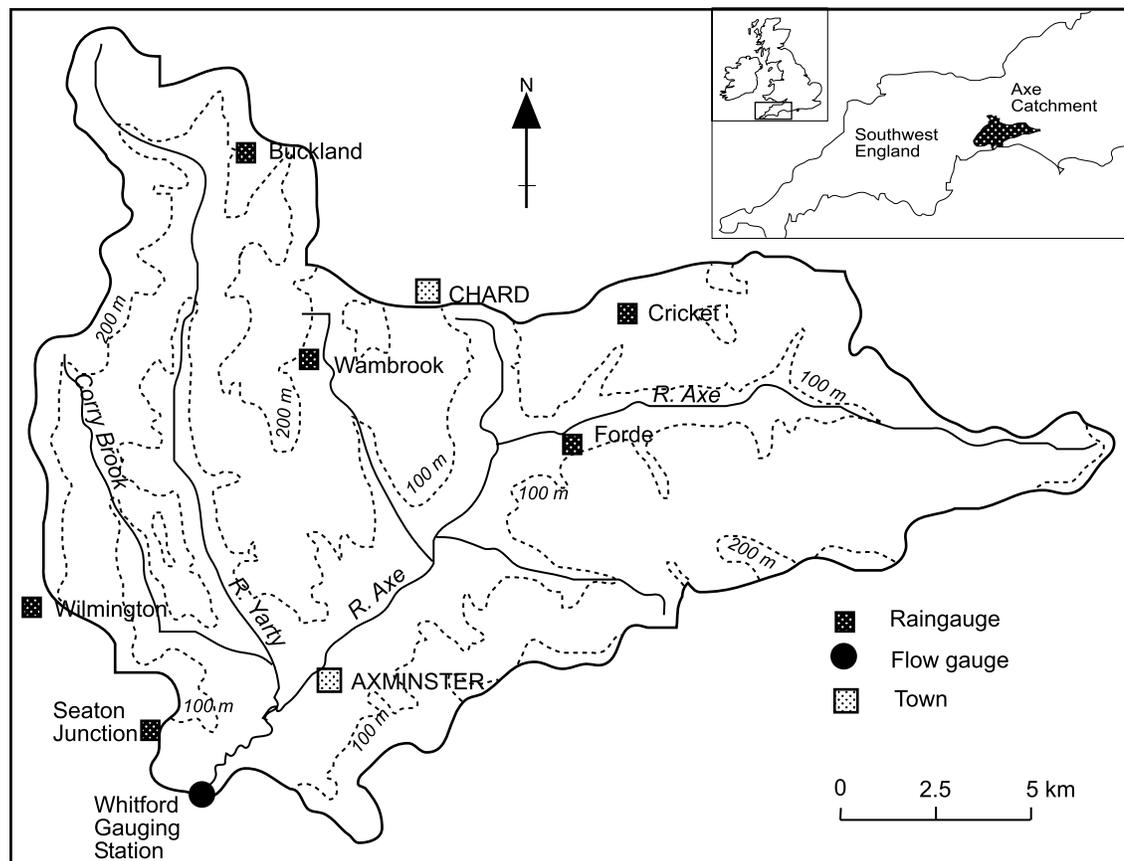
Figure 1 │ The Axe catchment to the Whitford gauging station.

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, with the wettest period of the year on average being over the months of October–February. The mean daily flow at the Whitford gauging station (045004) is $5.11\,\mathrm{m^3\,s^{-1}}$ and a relatively high Base Flow Index (BFI) of 0.495 reflects the significant contribution of groundwater to maintaining river flows during dry weather (Boorman *et al.* 1995).

The climatic influence on runoff was considered through catchment precipitation. Daily rainfall totals were obtained from the British Atmospheric Data Centre database for a network of stations within and in the vicinity of the catchment. Data gaps were filled with data from the closest adjoining stations. Six stations (Figure 1) were selected to calculate daily average catchment rainfall by the Thiessen polygon method (Thiessen 1911) for the period of the streamflow record.

Hydrological data

Hourly flow data from the Whitford gauging station were available from 1966 to 1980, and 15 min interval data thereafter to 2002. The analysis was carried out hourly to provide a common record for the full data period (1966–2002).

Land use and land-use change

Land use in the catchment is predominantly agricultural, 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 present.

Changes in agricultural land use and management with the potential to enhance farm runoff generation (Holman *et al.* 2003) were identified for the Axe catchment for the period 1966–2004. Information on changes in land cover, crops and stock densities were evaluated from the Defra June Agricultural Census data (http://edina.ac.uk/agcensus), although livestock data were only available until 2003. Data were obtained at the 5 km × 5 km grid level, except for the cattle and pig density at 2 km × 2 km resolution. Existing technical reports (Environment Agency 2004, 2005) complemented the latter source of data.

Autumn-sown (Sibbesen *et al.* 1994; Boardman *et al.* 2003) and late-harvested cropping systems (Speirs & Frost 1985; Arvidsson 2001) were identified as critical runoff enhancement factors within the catchment. The percentages of land cover of maize, sugar beet and potatoes (late-harvested crops) were aggregated on a total catchment basis from 1969–2004 and their evolution studied. The same procedure was applied to wheat, winter barley and oilseed rape (autumn-sown crops) cultivated areas.

Similarly, the total number and density of sheep, cattle and pigs was obtained separately on a catchment basis. Sheep and cattle densities were calculated under the assumption that they grazed the managed grassland, whose total area was also variable throughout the period of record. Total numbers of livestock were weighted in order to obtain number of livestock units (LU) per hectare. In accordance with Defra (2001), one sheep equals 0.15 LU and cattle are either 0.6 LU (between 6 months and 2 years old) or 1 LU (older cattle). However, incongruity in the census datasets with respect to cattle ages for each year led to the adoption of an average figure of 0.8 for all cattle included in the study (Sullivan *et al.* 2004). The final LU density was calculated excluding pigs, due to the lack of information about their rearing patterns (indoors or outdoors).

Between 1969 and 2004, the areas of critical crops in the Axe catchment exhibited notable changes (Figure 2(a)). Data for autumn-sown crops are available from 1979, when this crop system represented 2.3% of the catchment. Since then their area increased to their largest value in 1996 (9.4%) and decreased 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, with the steepest increases being between 1988 and 1996, mainly because of an increase in forage maize cultivation.
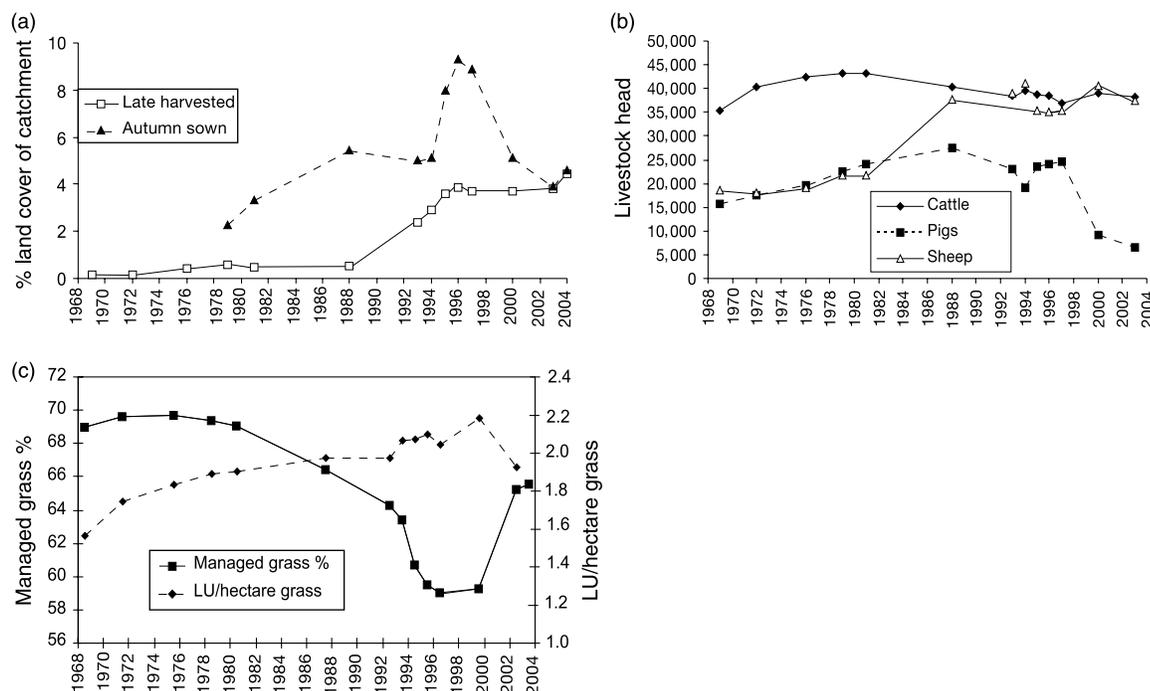

Figure 2 | Land-use changes in the Axe catchment (1969–2004). (a) Critical crops, (b) livestock numbers, (c) livestock units density and managed grassland.

With respect to livestock activities (Figure 2(b)), statistics show a progressive increase in sheep numbers since the early 1980s reaching the highest values during the 1990s, whereas cattle numbers remained relatively stable. Pig numbers have also varied, but remain low in comparison to sheep and cattle. In terms of average farm stocking densities (excluding pigs), there has been a clear tendency upwards (Figure 2(c)) driven not only by the growth in sheep numbers but also by the reduction in managed grass in favour of arable land (Environment Agency 2004). In 1969 the average density on managed grass was $1.56\,LU\,ha^{-1}$ and it increased steadily up to $2.18\,LU\,ha^{-1}$ in 2000 (about a 40% increase). A trend towards a less uniform distribution of stock (represented by the number of grid cells within the catchment at different stocking densities) can be identified for sheep and cattle (Figure 3). In particular, the last 15 years present a greater disparity of farm stock densities and localised high densities rather than a regular spread.

Further qualitative data were obtained by interview with catchment stakeholders during February 2007 to identify the main changes in land management practices which have the potential to enhance runoff generation. This included assessing the use of larger machinery, changes in drainage systems and the timing of grazing, harvesting and sowing.

Stakeholders agreed that intensification in farm activities had occurred within the catchment, especially during the last 15 years, driven by the economy of scale. The increase in farm stock densities had been one of the most important consequences in the dairy sector, from 80 cows per farm in 1995 to 180 cows per farm (Richard Smith, Environment Agency, personal communication).

Interviewees also recognised the common practice of extending the in-field grazing period for stock into the wet soil seasons because of new paddock grazing systems and because of limited slurry storage facilities. Additionally, farmers within the area increasingly rely, especially for harvesting and fertilization, on contractors who show less flexibility about field operations in wet soil conditions. The removal of hedges due to the amalgamation of fields and the reduction of riparian vegetation for extending farm limits (Environment Agency 2004) were also identified as issues by the stakeholders, as well as the increase in arable soils and the use of plastic in fields to protect and speed early crop development.

METHODOLOGY

An analysis of the variations in the river flow dynamics was undertaken using methods described in Archer (2000) but supported by improved techniques, described below, to allow for the effect of climate variability. The analysis of flow variability is based on the frequency and duration of 'pulses' above selected levels of flow over the time series. A pulse is an event characterised by two crossings, upward first and downward later, of a particular discharge threshold (Figure 4). The flow thresholds for defining pulses were specific multiples of the median discharge (M) for the Axe catchment of $2.82\,m^3\,s^{-1}$, calculated over the whole period (1966–2002). The multiples ranged from the median discharge $(M = 2.82\,m^3\,s^{-1})$ to 30 times the median discharge $(30 \times median$ or $30M = 84.6\,m^3\,s^{-1})$ and are reported as $M–2M–3M–4M–5M–6M–7M–8M–10M–15M–20M–30M$, so that the entire spectrum of flow was
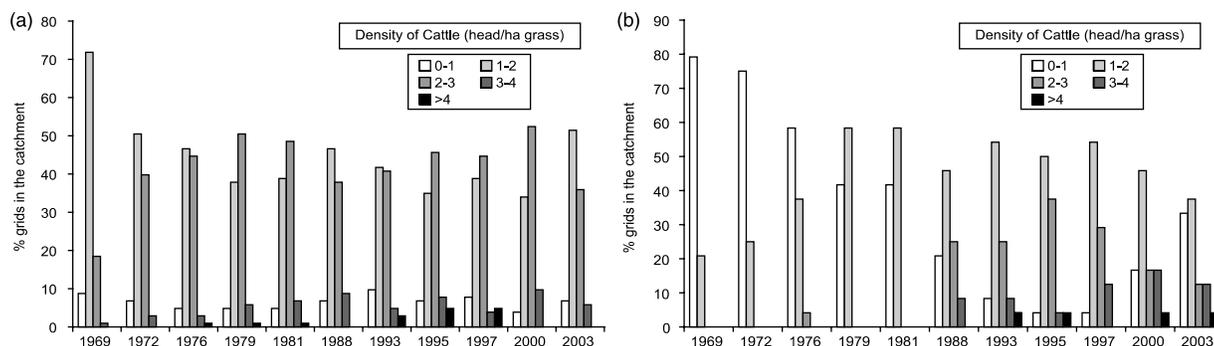

Figure 3 │ Relative number of grids bearing specific stock densities for (a) sheep and (b) cattle in the Axe catchment (1969–2003).
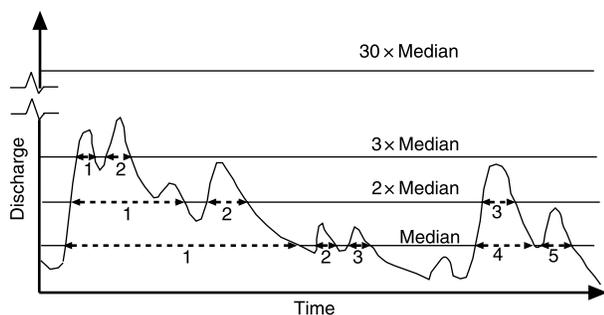
Figure 4 | Schematic definition diagram for pulse numbers and pulse duration (Archer 2000).

evaluated. The median annual maximum flow is $103.4 \, \mathrm{m^3 \, s^{-1}}$ ($37M$) and the maximum recorded peak discharge between 1964 and 2006 was $251.8 \, \mathrm{m^3 \, s^{-1}}$.

The analysis consists of counting the number of pulses in each water year or season for each threshold, then calculating their aggregated and mean pulse duration to create annual and seasonal time series for the period of record. Incomplete pulses at the beginning and the end of each water year or season are omitted.

For the annual analysis, the time series was divided into water years (from 1 October to 30 September). The seasonal analysis was initially based on four three-month periods (Oct–Dec, Jan–Mar, Apr–Jun, Jul–Sep). However, the fact that the initial results did not show relevant differences between inter-equinox seasons within a water year (autumn vs winter and spring vs summer) led to a division of the water year into two seasons: a wetter season (October–March), characterised as having the soil at field capacity most of the time and having most of the annual rainfall, and a drier season (April–September), with lower soil moisture content and the greatest evapotranspiration rates.

An important component of any changes detected in the pulse analysis could arise from the effect of weather conditions during a particular time interval. In order to remove this effect, Archer (2000, 2003, 2004) and Archer & Newson (2002) carried out regression analysis between annual numbers and duration of pulses and a series of variables based on annual or daily rainfall. They found that the total annual catchment rainfall gave the best linear correlation with pulse number and duration. The regression relationship was then employed to compute an 'expected'

number and duration of pulses for a given set of climatic values. Then the residual number and duration of pulses within the observed dataset, which might be related to land use/management practices, were calculated and time variability patterns studied.

Although the foundations of the method were preserved, a range of other measures of rainfall, in addition to annual rainfall total, were tested to allow for effects of variation in climate from year to year. For both annual and seasonal studies, simple and multiple (two variable) regression analyses were performed for each multiple of the median and a set of annual or seasonal precipitation-linked parameters (Table 1) with the potential to influence the pulse variability. A comparative examination for determining the combination of variables that presented the most appropriate regression relationship was performed.

RESULTS

The study of agricultural land use and management practices within the Axe catchment suggested that the last 10–15 years of the record constituted a critical period in terms of changes with potential to affect runoff generation. This was the period with highest stock densities and areas of critical crops and an intensification of practices likely to enhance surface runoff and rate of response. The flow analysis was therefore divided into the sub-periods shown in Table 2 in order to study possible step changes in river flow dynamics.

Time series of the number of pulses and of their duration above each threshold were constructed in order to assess both trend and step changes. The annual number of pulses over each threshold was found to have statistically significant positive trends for the range of high thresholds (Table 3(a)). A more acute trend was found in the pulse duration time series (Tables 3(b, c)). High correlations and statistical significances correspond to a wider range of thresholds in the duration case. For example, pulse number and duration time series for $10M$ and $15M$ are represented in Figure 5(a, b).

Inspection of Figure 5(a, b) suggests that this trend is chiefly due to a statistically significant increase in the number of pulses during the 1990s.

Table 1 | Variables used in the regression analysis for removing climate variability effect

Variable	Expression	Rationale
Total rainfall	$\sum_{T} p_i$	Main driver for river flow responses
Total rainfall squared	$(\sum_{T} p_i)^2$	Reflects the nonlinear relationship, between flow variability and rainfall, in the runoff generation process
Addition of daily precipitation squared	$\sum_{T} p_i^2$	
Number days with rainfall totals	$(\sum_{T} i)\|p_i >$ threshold	Since event-based records are not available, the frequency of "wet days" for different thresholds can be an indicator of rainfall intensity (Orr & Carling 2006)
$>1\,\mathrm{mm}$		
$>5\,\mathrm{mm}$		
$>10\,\mathrm{mm}$		
$>15\,\mathrm{mm}$		
$>20\,\mathrm{mm}$		
Daily rainfall standard deviation	$S = \sum_{T} \frac{\sqrt{(p_i - \overline{p_T})^2}}{n}$	May account for intra-period dispersion between magnitudes of daily rainfall episodes, which may potentially affect flow variability
Antecedent precipitation	$\sum_{T-1} p_i$	The "wetness" of the antecedent period affects the soil moisture at which the study period starts influencing the potential runoff generation for the period of study.

T = period of study; i = day; p_i = rainfall total for the i; n = number of days in T.

The next step in the analysis attempted to separate the influence of climatic variability and land-use change. Among the several precipitation-linked parameters used for the regression analysis in order to remove the effect of climate variability, those shown in Table 4 provided the best adjustment in terms of both R^2 and statistical significance of the variables employed. The fact that P^2 is a common variable in the best models in the three cases (annual, wet and dry season) might be connected to the nonlinear relationship in the runoff generation process, i.e. the fact that runoff–rainfall ratios become higher as rainfall increases and as soil moisture during the period rises (Maidment 1993). For the wet season the precipitation during the previous dry season $(P - 1)$ is significant in the regression model together with P^2. This may be because a wet summer leads to an earlier field capacity recovery which might increase the runoff generation potential for the following wet season, whereas the dry season might not be

Table 2 | Sub-division of the record for studying step changes in flow dynamics in the River Axe

Initial period	Intermediate period	Last period
1966–1977 (12 water years)	1978–1990 (13 water years)	1991–2002 (12 water years)

so influenced by the previous wet season rainfall. The residuals of the mean duration of pulses' analysis showed weak trend relationships.

The residuals confirmed the annual trends detected in pulse number, but only for thresholds above $10M$ (Table 5(a) and Figure 6(a)). The statistical analysis of the difference between sub-periods verified the increase in pulse number for high thresholds during the 1990s (Table 6(a) and Figure 6(b)). Stronger confirmations were given by the residuals of the total duration of pulses; the same trends and step changes were detected for all the thresholds above $5M$ (Table 5(b), Figure 6(c), Table 6(b) and Figure 6(d)).

The analysis carried out on a seasonal basis showed that similar significant changes to those detected in the annual case were identifiable in the wetter season (October to March). Statistically significant increases in number and duration of pulses in the 1990s for medium-high thresholds (of greater than $7M$ for the residual wet season pulse numbers and $4M$ or greater for residual pulse duration) were found in trend analysis. Residuals analysis confirmed those changes as illustrated in Figure 7(a) for residual pulse numbers and Figure 7(b) for residual pulse duration.

In the case of the drier season (April to September) consistent increases in the number and duration of pulses

Table 3 | Product moment linear and Spearman correlation coefficients (r) for annual pulse series against time

Threshold	M	2M	3M	4M	5M	6M	7M	8M	10M	15M	20M	30M
(a) Pulse number												
Linear r	−0.22	0.15	0.22	0.20	0.22	*0.34*	0.36	0.37	0.41	0.55	0.61	0.51
Spearman r	−0.17	0.12	0.09	0.15	0.18	0.26	*0.29*	*0.27*	0.31	0.52	0.58	0.42
(b) Pulse duration												
Linear r	0.19	0.24	*0.28*	0.37	0.44	0.47	0.49	0.50	0.55	0.63	0.64	0.46
Spearman r	0.20	0.19	0.23	*0.30*	0.34	0.39	0.42	0.42	0.46	0.57	0.56	0.42
(c) Mean pulse duration												
Linear r	0.29	0.09	0.14	0.33	0.44	0.40	0.39	0.35	0.36	0.37	*0.30*	0.21
Spearman r	0.30	0.08	0.12	0.32	0.40	0.41	0.40	0.38	0.40	0.42	0.33	0.21

Figures in the body of the table in bold are statistically significant at 95% level, and in italics at 90% level.

were found for a central range of thresholds before removing the effect of climate variability. However, the analysis of the residuals showed no such consistent patterns in statistically significant step changes between sub-periods as illustrated in Figure 7(c, d). The trend in the raw data appears to be primarily driven by a 17.5% statistically significant increase in drier season rainfall for the period 1991–2002 compared with the previous years of record. In contrast, October to March rainfall totals did not experience significant changes over the period of record.

DISCUSSION

The application of flow variability analysis to the River Axe demonstrates clearly that there have been significant changes in flow dynamics both in terms of pulse numbers and duration during the period of analysis from 1966 to 2002. Variability is principally influenced by year-to-year variability in rainfall as shown by the significant correlation between pulse numbers and duration and measures of annual and seasonal rainfall in Table 4. The trend is chiefly due to the significant increases during the 1990s; subdivision of the record into three 12- or 13-year periods indicates a common response during the period 1966–90 but a step change to the period from 1991–2002. This later period coincides with the period of greatest changes in land use and farm management that have the potential to influence runoff response at the catchment scale (Figures 2 and 3).

Trends and step changes in annual data continue to be demonstrated for pulse numbers and for pulse duration (Figures 6 and 7 and Table 5) after the effects of climatic variability have been taken into account (Table 4).
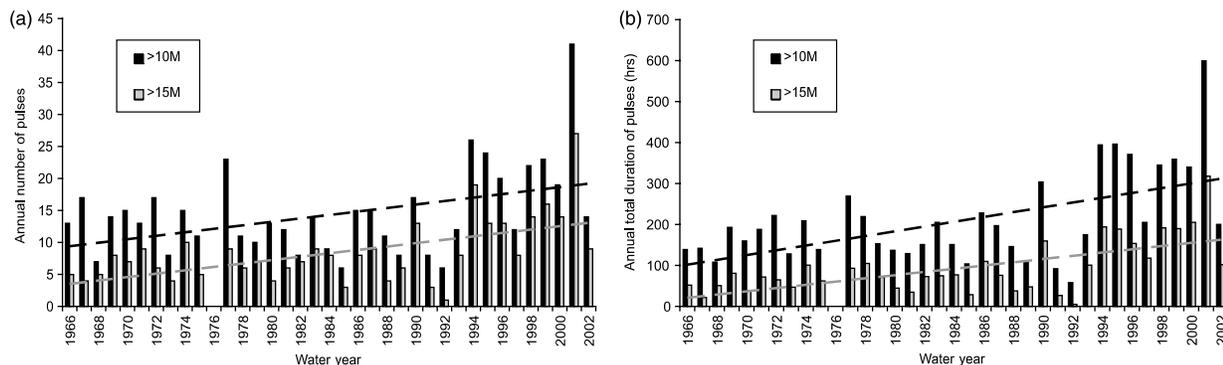

Figure 5 | (a) Time series of (left) annual number of pulses above thresholds of 10M (10 times the median flow) and 15M. (b) Annual total duration of pulses above thresholds of 10M and 15M.

Table 4 │ Adjusted coefficient of determination (R^2) for the adopted regression models used for removing the climate variability effect

Threshold	M	2M	3M	4M	5M	6M	7M	8M	10M	15M	20M	30M
(a) Annual												
Variable used: mean annual catchment rainfall squared (P^2)												
Pulse number	−0.03	**0.13**	**0.45**	**0.74**	**0.75**	**0.80**	**0.76**	**0.76**	**0.73**	0.52	0.44	0.29
Total duration	**0.18**	**0.79**	**0.80**	**0.81**	**0.78**	**0.75**	**0.73**	**0.70**	**0.61**	0.48	0.38	0.31
Mean duration	0.03	**0.38**	**0.26**	**0.25**	**0.28**	**0.27**	**0.16**	**0.11**	**0.08**	**0.17**	**0.10**	0.06
(b) Wet season												
Variables used: Mean seasonal catchment rainfall squared (P^2); mean catchment rainfall in the previous season ($P-1$)												
Pulse number	0.29	0.15	**0.55**	0.73	**0.76**	**0.84**	**0.88**	**0.89**	**0.86**	**0.71**	**0.54**	**0.43**
Total duration	0.32	0.90	**0.95**	**0.93**	**0.91**	**0.90**	**0.87**	**0.84**	**0.77**	**0.65**	**0.53**	**0.50**
Mean duration	0.26	**0.58**	0.28	0.32	0.31	0.30	0.07	0.05	0.01	0.09	0.04	0.16
(c) Dry season												
Variables used: mean seasonal catchment rainfall (P); mean seasonal catchment rainfall squared (P^2)												
Pulse number	**0.16**	**0.49**	**0.59**	0.66	0.72	**0.79**	**0.79**	0.77	**0.78**	**0.70**	**0.69**	**0.64**
Total duration	0.29	0.54	0.62	**0.78**	**0.81**	**0.83**	**0.81**	**0.79**	**0.77**	**0.71**	**0.72**	**0.63**
Mean duration	0.18	0.16	0.20	0.29	0.25	0.33	0.34	0.30	0.31	0.49	**0.57**	0.31

Figures in bold come from regressions where all variables used (P^2, $P-1$ and/or P) are statistically significant at 95% level. In the others, at least one of the variables used in each case is not statistically significant at 95%.

The detected residual increase in the number and duration of pulses for discharges becomes more evident as the threshold rises but is imperceptible for low thresholds. The differences between the early and later periods also remain in the residuals as shown by the *T*-Student statistic for differences between the periods (Table 6), strengthening the proposition that these detected changes were land-use driven.

The changing response on the Axe also appears different from that which was identified for the upland Coalburn (Archer 2000; Archer & Newson 2002) and Plynlimon catchments (Archer 2007). In the Coalburn catchment a period of increased pulse frequency associated with pre-afforestation drainage coincided with little change in total pulse duration but a marked decrease in average pulse duration. This was followed by a period of maturing forest growth with a steady decrease in pulse numbers and increase in average pulse duration. Similar differences in response characteristics were noted between the forested

Table 5 │ Correlation coefficients (*r*) for annual residual pulse series against time

Threshold	M	2M	3M	4M	5M	6M	7M	8M	10M	15M	20M	30M
(a) Pulse number												
Linear *r*	0.03	0.03	0.03	−0.10	−0.06	0.19	0.23	0.25	**0.31**	**0.50**	**0.56**	**0.56**
Spearman *r*	−0.19	−0.02	0.02	−0.09	0.00	0.28	0.30	0.23	*0.29*	**0.52**	**0.57**	**0.38**
(b) Pulse duration												
Linear *r*	0.07	−0.04	0.05	0.26	**0.41**	**0.45**	**0.47**	**0.48**	**0.52**	**0.60**	**0.60**	**0.36**
Spearman *r*	−0.01	−0.01	0.14	0.22	**0.39**	**0.44**	**0.44**	**0.46**	**0.48**	**0.60**	**0.60**	**0.30**

Figures in the body of the table in bold are statistically significant at 95% level, and in italics at 90% level.
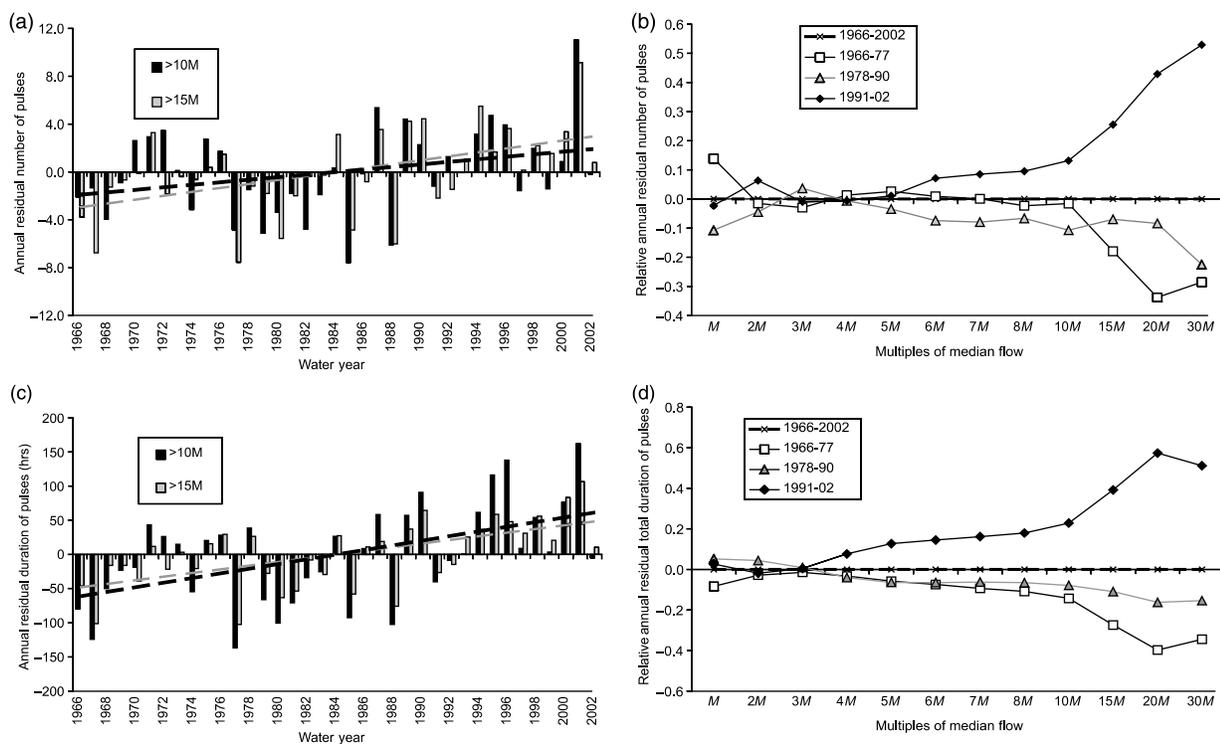
Figure 6 | Time series of (a) annual residual pulse number and (c) annual residual pulse duration above thresholds of 10*M*–15*M*, and relative annual residual (b) number of pulses and (d) duration of pulses for the range of thresholds and sub-periods. (Note: "Relative" means that average residuals have been normalized by the total number or duration of pulses (depending on the case) for each threshold for a better scaling and understanding of the magnitude of the changes).

and moorland catchments in the Plynlimon experiment. In contrast, the increasing pulse numbers in the 1991–2002 period on the Axe catchment was accompanied by an increase both in total and average pulse duration. The combination of increased numbers and increased average pulse duration is particularly surprising for a land-use effect

where more rapid transmission might have been expected as a consequence of reduced capacity for soil moisture storage.

However, it is also noted that significant changes in rainfall patterns also occurred from the earlier to the later period 1991–2002. Average annual rainfall was 9.5% higher

Table 6 | *T*-Student statistic for differences in residual pulse (a) number and (b) duration between sub-periods

Threshold	M	2M	3M	4M	5M	6M	7M	8M	10M	15M	20M	30M
(a) Residual number of pulses												
1966–77 vs. 78–90	0.08	0.39	0.22	0.38	0.19	0.10	0.17	0.30	0.18	0.25	0.15	0.43
1978–90 vs. 91–02	0.23	0.11	0.31	0.50	0.20	**0.00**	**0.03**	**0.05**	**0.02**	**0.03**	**0.01**	**0.03**
1966–77 vs. 91–02	0.17	0.24	0.42	0.38	0.42	0.15	0.14	*0.08*	**0.05**	**0.00**	**0.00**	**0.02**
1966–90 vs. 91–02	0.39	0.13	0.43	0.43	0.37	**0.01**	**0.04**	**0.04**	**0.02**	**0.00**	**0.00**	**0.01**
(b) Residual duration of pulses												
1966–77 vs. 78–90	0.13	0.11	0.34	0.46	0.47	0.46	0.37	0.33	0.30	0.19	0.18	0.30
1978–90 vs. 91–02	0.34	0.14	0.48	*0.06*	**0.01**	**0.02**	**0.02**	**0.02**	**0.01**	**0.00**	**0.00**	*0.06*
1966–77 vs. 91–02	0.18	0.44	0.40	*0.08*	**0.01**	**0.01**	**0.01**	**0.01**	**0.00**	**0.00**	**0.00**	**0.03**
1966–90 vs. 91–02	0.29	0.31	0.46	**0.05**	**0.01**	**0.01**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**

Bold and italicised values highlight statistically significance differences at 95% and 90% level, respectively.
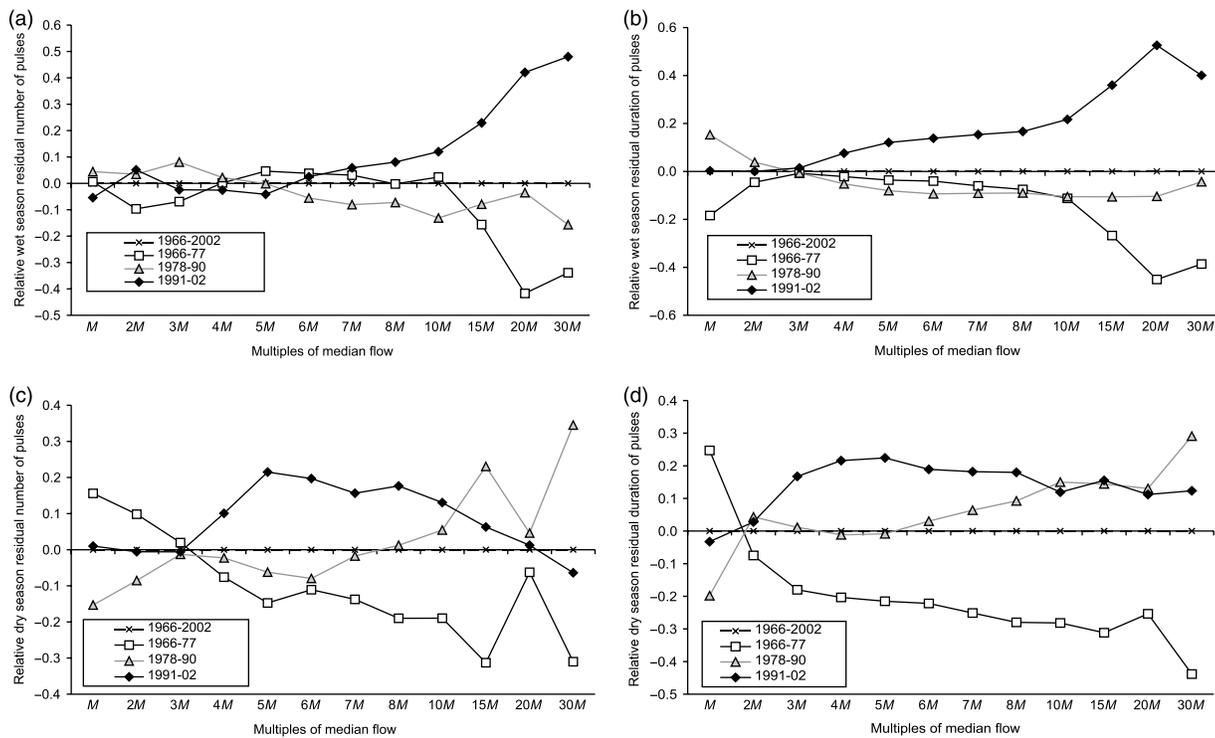
Figure 7 | Relative wet season residual (a) number and (b) duration of pulses, and relative dry season residual (c) number and (d) duration of pulses for the range of thresholds and sub-periods.

than during the previous 25 years whilst there was an increase in rainfall intensity in the same period (number of days with more than 20 mm rainfall increased by 25%). Given the parallel change in rainfall amount and land-use change and the different kinds of response from the Coalburn and Plynlimon catchments, it is conceivable that the period differences in runoff response have been generated by some aspect of climate change not detected by the regression analysis. The comparative effects of land use and climate therefore require closer inspection.

There is certainly field evidence that significant changes in agricultural land-use and management practices with the potential to degrade soil structure occurred during the period of record. These changes were likely to have reduced soil water storage capacity and infiltration rates, leading to an enhancement of farm-scale runoff generation. A soil survey in the Axe catchment by Palmer (2004) noted that farm soils showed high structural degradation levels, confirming that the soil degradation potential of land-use change in the last 15–20 years has actually translated into field effects. This is likely to have increased the probability

of overland flow production able to contribute to channel flow. The rise in sediment content experienced during the last 15 years in the River Axe (Environment Agency 2004) provides a further sign of increased farm runoff and soil structural degradation. However, these changes do not in themselves prove that changes in hydrological response at the catchment scale are driven by land-use change. Further inspection of the climatological and hydrological evidence is necessary.

Evidence in favour of a land-use explanation is found in the seasonal analysis. Whereas the increase in rainfall from 1991–2002 was mainly concentrated in the spring–summer period, changes in runoff response were least marked during this period. Average rainfall for this season showed a 17.5% statistically significant increase for 1991–2002 compared with the previous years of record. In contrast, the main runoff response changes occurred during the autumn–winter period when there were no significant changes either in rainfall amount or intensity. Furthermore, rainfall changes during the preceding season were accounted for in the regression analysis between wet season

rainfall and climate. This contrast suggests the possibility that land-use effects are most notable when soils are at or approaching field capacity, farm activities are carried out in a wetter environment and fields left exposed following winter sowing. During the spring–summer period the increase in soil vegetation development and cover (Angers & Caron 1998), the lower soil moisture content during the development of agricultural activities and the lower seasonal rainfall amount may play a role in limiting land-use effects. This seasonal distinction may also indicate intra-annual changes in soil structure (Burt & Slattery 1996).

In parallel with the analysis of pulse frequency and duration, annual maximum rates of change in flow in the Axe were analysed (Archer *et al.* submitted). This analysis was based on the observation of significant differences in rates of change between the forested and moorland experimental catchments at Plynlimon (Archer 2007). For the Axe catchment, maximum rates of rise and fall over 1 and 2 h periods were again greatest from 1991–2002 but the change in response appears to commence by the mid-1980s, before the observed shift in summer rainfall. In common with the pulse analysis, the most marked seasonal changes are during the autumn–winter period, with less marked change during the drier spring–summer period. This analysis again adds support to changes in land use as the principal source of the observed changes in runoff response.

The Axe catchment was one of nine catchments investigated for impacts of land-use change using new modelling techniques as part of Defra Project FD2120 (Beven *et al.* 2007). Two types of methods for the identification of change, based directly on the analysis of the historic data, were applied. The first applied dynamic harmonic regression (Young *et al.* 1999), which searches for trends and changes in amplitude of frequency components in a catchment discharge series, allows non-stationary changes in the characteristics of the time series to be identified together with estimates of uncertainty in the modelled components. The second methodology used the Data-based Mechanistic (DBM) modelling approach of Young (2001) which is concerned with identifying change in the dynamic response of the catchment. In most of the nine catchments no clear changes were identified over time. For the Axe catchment, a trend related to land use was not clearly identified but there appeared to be nonlinearities in the response that the model did not totally capture, indicating possible land-use influences.

The linkage between land-use changes in the catchment and changes in runoff response identified using flow variability analysis must also be considered indicative rather than definitive. However, the method offers the distinct advantage that only daily rainfall data are required, whereas the models described above need high quality sub-daily discharge and rainfall data. There is thus the opportunity to apply the method to a wider range of land-use-affected catchments affected by land use or management change. Replicability would ultimately provide a means of further supporting the causal link between land use and runoff response.

Whilst this analysis does not address the changes in flood risk *per se*, the observed changes in flow variability appear likely to reflect an increased risk of flooding affecting land and property. Furthermore, the increase in frequency and duration of high flow episodes may increase the chances of bank collapse even more closely than the peak magnitudes of the events involved (Orr & Carling 2006). Evidence of increasing bank erosion rates in the Axe during the last decade (Environment Agency 2004) support the detected changes in the river flow dynamics. Bank erosion provides a source of sediment for the river that may reduce channel capacity (Murgatroyd & Ternan 1983) and contribute to a further increase in the incidence of flooding.

CONCLUSIONS

Flow variability as described by statistics of pulse frequency and duration is strongly influenced by the climate of the current year. Attempts to screen the effect of climate using multiple regression analysis result in residuals which show a time trend, with the greatest pulse frequency and duration during the latest period 1991–2002. This period corresponds to both the most intensive agricultural change and also a period of higher summer rainfall. Whilst an undetected influence of changing rainfall patterns cannot be ruled out, the seasonal distribution of hydrological change strongly suggests that the changing pattern of (residual) runoff response is driven by land-use change.

It is therefore concluded that the hydrological changes in river flow response observed during the late 1980s and the 1990s in the River Axe have the potential to increase flood risk at the catchment scale. Observed trends are greatest at higher flow levels up to 30 times the median flow and above the level of the median annual flood. Increased pulse frequency and duration could also have a significant geomorphological effect through increased bank erosion, channel deposition and reduced channel capacity which could contribute to increased flood incidence.

There is a reasonable basis to interpret variations in flow dynamics in the River Axe as partially caused by an enhancement in field runoff generation arising from agricultural intensification during the late 1980s and 1990s. Good farming practices which reduce the impact of agricultural activities on soil structure (e.g. Evans & Boardman 2003), and are thus locally sustainable, are also likely to mitigate runoff generation both at a local and a catchment scale. This synergy provides an opportunity for integrating actions within the wider framework of current agricultural policies (Posthumus *et al.* 2008), in particular through the linking of agri-environmental payments with practices aiming to mitigate or control farm runoff.

The success of flow variability methods in identifying trends and the sources of trends in runoff response on the Axe catchment indicates the potential of the methods for more general application as a basis for the development of flood risk management policies based on land use and management. However, with respect to the Axe the linkage must still be considered indicative rather than definitive; replication on other land-use-affected catchments affected by land-use change will confirm the linkage.

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