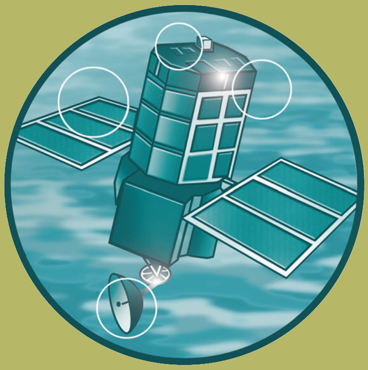
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

FD2120: Analysis of historical data sets to look for impacts of land use management change on flood generation

R&D Technical Report FD2120/TR



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FD2120: Analysis of historical data sets to look for impacts of land use and management change on flood generation

R&D Technical Report FD2120/TR

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Author(s):
Keith Beven, Peter Young, Renata Romanowicz, Lancaster University
Enda O’Connell, John Ewen, Greg O’Donnell, University of Newcastle
Ian Homan, Helena Posthumus, Joe Morris, John Hollis, Cranfield University
Steve Rose, Rob Lamb, Dave Archer, JBA Consultants

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Publishing organisation
Department for Environment, Food and Rural Affairs
Flood Management Division,
Ergon House,
Horseferry Road
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Tel: 020 7238 3000 Fax: 020 7238 6187
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Executive Summary

The purpose of this study was to provide an analysis of historical data sets to ascertain whether any impacts of land use and management change on flood generation could be identified. This report presents the results of the study. Data on the nature of change in agricultural land use and management are reviewed. These data were then used to choose catchments for which change had been developed and for which hourly hydrological data were available over several decades. The change identification methodologies used were Dynamic Harmonic Regression (DHR) methods to examine longer term trends in monthly rainfalls and flows and Data Based Mechanistic (DBM) models, with a State Dependent Parameter (SPD) nonlinear filtering of rainfall inputs to examine changes in storm responses using the shorter periods of available hourly data.

In general, variability between years and inconsistencies in the rainfall and flow data appear to dominate any tendency to changes over time or with hydrological conditions. In the DHR analyses, only monthly flows could be shown to exhibit any significant trend and then only for 2 of the 9 catchments prioritised for study, the Axe and the (nearby) Isle. In the DBM analysis of modelled hydrograph characteristics most catchments showed no clear changes over time. Where tendencies for change in hydrograph characteristics with time are evident, they are masked by year to year variability. There was some tendency to reflect the hydrological conditions as represented by maximum flow in a period. This suggests that the modelling strategy has not captured all of the information content of the data.

A method was developed to test the analysis methodology by imposing changes to runoff generation in a consistent way by modifying the measured data series, retaining the natural variability and inconsistencies in the datasets in the modifications. Data for two catchments were modified in this way. In both cases, it proved difficult to identify the changes relative to year to year variability in response. This may be a result of real variability, uncertainty induced by data inconsistencies, and uncertainty induced by the statistical assumptions of the analysis not being met.

The most promising method of change identification in the catchment dynamics was found to be to analyse groups of “similar” events classified by antecedent condition and peak flows. This analysis was applied to the Axe catchment only, but revealed some consistent changes in the DBM model parameters for some of the classes, including an apparent change in response in the pre-1980 period.

The policy implications of the results are considered with the following recommendations:

1. Both climate variability, particularly rainfall variability, and land use and management affect changes in flood runoff. Changes in discharge should not be analysed without consideration of changes in catchment rainfall inputs.
2. The preliminary study of catchment responses within different event classifications was the most promising form of analysis developed during this project. Different classification schemes should be investigated to check the nature of changes, including a more complete uncertainty analysis. Careful quality control of existing datasets is necessary in carrying out such analyses.

The method should also be tested against modified data sets produced by the Juke methodology.

3. Adequate information about past land management changes and soil conditions is not readily available but will need to be collected and made available in future for different land use categories if improved understanding of the links between runoff and land management is to be gained and used at catchment scales.
4. The results of this project show that there will be a real difficulty of estimating the benefits of such measures in respect of any reduction of flood risk. Further monitoring of studies aimed at reducing runoff should be carried out to evaluate the effectiveness of different types of measure at the local level in the context of farm environment schemes
5. The difficulty in identifying consistent change given the limitations of the available data means that land management measures cannot be relied on as alternatives to more proven flood risk management options.
6. The difficulty in identifying consistent change given the limitations of the available data does not mean that change is not happening and should not be taken to imply a policy of doing nothing. Contextually relevant management practice guidelines (linked to land use, soil type, antecedent condition) should be developed and monitored to deliver multiple benefits including reduced runoff generation and local flood risk.

Further science needs

There are in addition implications for science in the results of the study. While points 4 and 5 effectively rule out for the moment reliance on land management measures as an alternative to more proven flood risk management options, there are indications that there may be some impacts hidden in climate variability and uncertain data.

It is noted for instance that the failure to identify impacts may be in part a result of the limitations of the data available for both rainfall and discharges. It is also noted that there were changes in catchment dynamics for different classes of events in the Axe catchment. This appears to show quite different trends in response for different classes of events, with an increase in the speed of the fast responses in one class, and a decrease in two other classes.

It is therefore concluded that while reliable assessment is not possible at this time, there is a strong case for continuing with the present research projects on land use and runoff experimentation and modelling in FRMRC2, in the NERC FREE programme and in project SC060092 (Multiscale Experimentation, Monitoring and Analysis of long-term land use changes and flood risk). By careful measurement and analysis, these promise to increase our understanding and allow progress towards providing improved predictive tools to assess sensitive locations, sensitive types of flood events, and robust FRM options in the future. These projects do, however, cover only a limited range of land management classes and there is a need to identify suitable sites for catchment scale studies of the impacts of changes in arable management practices.

CONTENTS

1. INTRODUCTION AND BACKGROUND TO THE PROJECT

The purpose of this project was to identify the hydrological changes resulting from changes in land use and management in rural catchments. The need for such a project was originally suggested by the previous FD2114 review of the impacts of rural land use on floods and flooding (O'Connell et al., 2004a,b). The relevant conclusions of the FD2114 review may be summarised as follows:

- The last 50 years have seen a significant intensification of agriculture, with anecdotal evidence that this has had an effect on flood peaks
- There is evidence from small scale manipulation experiments that land use/management has a significant effect on runoff at local scales
- There is very limited evidence that effects of land use/management can be distinguished at catchment scales in the face of climate variability
- There is evidence that surface runoff can be reduced by local land management, but effects on flood peaks may depend on spatial and temporal integration to catchment scales
- It is not possible (at least yet) to rely on rainfall-runoff modelling to predict impacts of land use/management changes

In recommending a research programme in this area, FD2114 noted that there was a 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 data sets. The objectives of this project (FD2120), as set out in the tender documents, were:

- To develop methods for analysing rainfall-runoff and land data to quantify flooding effects caused by historic changes in rural land use and management practices
- To assemble data sets
- To apply analysis methods to these catchments
- To distinguish effects of land use and land management from changes in downstream flood plain & channel management, other catchment changes and climatic variability
- To set out limitations of methods
- To recommend how results could be used to support policy decisions

These have been incorporated into four Work Packages (WPs). WP1 assessed the evidence for land use change, selected catchments for analysis, and assembled the historical data sets for analysis; WP2 developed and applied methods of time series and system dynamics analysis for identification of change; WP3 developed methods of testing the change detection methodology; while WP4 considered how the outcomes of the analysis might support policy decisions for Flood Risk Management.

As noted in the review of FD2114, past studies have found it difficult to identify the impacts of rural land use and management on flood peaks. Robinson (1990) reviewed a number of studies of change at the catchment scale and presents a number of studies of catchment data (Ray, Catchwater, Llanbrynmaier) using an approach based on deriving the unit hydrograph for different periods in the available records. Robinson demonstrates changes (increases in the peak) in the unit hydrograph with increasing drainage, using the Flood Studies Report methodology to separate the storm runoff for individual storms. It is not clear whether the magnitude of the changes was greater than the limits of uncertainty of the analysis. At larger scales, a similar unit hydrograph analysis of the response of the River Severn was used by Gilman (2002).

Hiscock et al. (2001) examined the hydrological records of the Wensum (536 km^2), Bure (313 km^2) and Nar 152 km^2) catchments in East Anglia in relation to documented changes in land use over the period 1930-1992. Calibrating a rainfall-runoff model for the Wensum for the period 1964-1974, they looked for trend in the residuals from observed discharges in the post-1974 period. Again, no uncertainty in either model predictions or discharge observations was taken into account but they found no obvious trends in time.

A number of other studies have appeared since the FD2114 review. Ward et al. (2007) by coupling a climate model and a hydrological model in a study of the 33000 km^2 Meuse catchment have suggested that over time scales of several thousand years land use change has dominated climate variability, with increasing runoff and decreasing flood peak return periods. However, they did not attempt to simulate the effects of land use change in the 20th Century, and although both mean runoff and flood frequency were increasing in that period, this was due to increased precipitation predicted by the climate model. As the authors note, the model components required for such a study are necessarily uncertain. An analysis of the historical data for the Meuse by Tu (2006) did not find any identifiable changes in flood frequency during the 20th Century.

In the UK, Howorth and Manning (2004) examined trends in flow duration curves and water quality for the Kird (67 km^2) and Lod (52 km^2) catchments on the Weald in Southern England in relation to land use in the period since 1970. They used a combination of t-tests and principle components analysis (PCA) to demonstrate that there were significant differences between the decadal flow duration curves and that the changes in Q5, Q50 and Q95 were related to changes in the area of arable and other land uses, but negatively related to rainfall. These results should be interpreted with some care. It is not clear that the assumptions of the t-test are met in comparing non-Gaussian flow duration curves while PCA looks for purely linear interactions between variables.

A more interesting technique is that developed by Archer (2003, 2007) who looks at changes in the numbers and durations of pulses over different flow thresholds between different time periods. His papers have compared afforestation effects in the Coalburn (1.5 km^2) and Irthing (335 km^2); and in the paired catchment experiments on the Wye (10.5 km^2) and Severn (8.7 km^2) catchments at Plynlimon. These analyses shows how the numbers of peaks changes over time. This might not only be a result of land use change, of course. In the first study Archer (2003) attempts to condition for climate variability by means of a linear regression between annual numbers asnd durations of peaks and annual measured rainfall, then looking at trends in the residuals. This may not take adequate account of the effect of changing rainfall characteristics on flood peaks. In the case of the paired catchment experiment at Plynlimon, the differences between pulses and durations in the two catchments are analysed as a way of controlling for the effects of climate. Both seasonal and annual trends are then examined, with the greatest effects being found during the summer season (the forested Severn catchment being less flashy than the grassland Wye, though there is some indication that the Severn might have been flashier than the Wye in pre-forestation conditions). Archer (2007) notes, however, that recent trends in rainfall and the lower probability of snow events in recent years might also have had an effect on the differences between the catchments.

This type of analysis has also been applied to one of the catchments chosen for use in this project by Climent i Soler (2007). He looked at numbers and durations of pulses, and the speed of rise and fall of the hydrograph, above different thresholds, for hourly flow data the River Axe catchment (438 km^2) in Devon and Somerset from 1965-2003. He also used residuals from a regression analysis to try and condition for the effects of climate, but extended the method of Archer (2003) to include a number of different rainfall-derived variables in simple linear and multiple (2 variable) regressions. Annual and seasonal analyses were performed. The conclusions were that the residual peaks and durations, and rates of rise and fall, all showed trends over the period. A peak discharge frequency analysis also suggested change, though it is noted that this does not take account of the changes in rainfall characteristics during the period. The observed increases in mean rainfall and in the number of days with heavier rainfalls would be expected to result in changes in flood frequencies quite independent of any land use management effects.

In the Axe therefore, there would appear to be no doubt that there have been changes in the hydrological regime (see Sections 4.3-4.5). The question is how far this can be due to change and variability in climate and how far it can be assigned to change in land use. In terms of these peak flow and rate of change of flow analyses, any inferences that can be made about this separation of effects is linked to how far linear regression analysis based on annual and seasonal totals can account for the effects of climate change and variability that affects runoff generation and peak flow at much shorter time scales and in a nonlinear way.

There may also be other reasons for this difficulty in identifying the impacts of change at the catchment scale (O'Connell et al., 2007). These include the uncertainty in estimates of inputs to a catchment; the nonlinear impacts of changing catchment inputs over time on stream discharges; the uncertainty in measurements of discharge outputs; the uncertainty in characterising land use / management patterns in space and time; and the fact that significant impacts at small scale may not necessarily have significant impact at catchment scales. It is also apparent from these past studies that changes might be more apparent under some hydrological conditions than others. Such factors also make it difficult to simulate the impacts of different types of change directly.

It should be noted that this project and report are not concerned with the direct simulation of the effects of land use change and management on stream discharges. Rainfall-runoff modelling for predicting land use management impacts on flooding is in its infancy, and cannot yet be used for operational evaluation of the likely impacts of land use change (O'Connell et al., 2004a, 2007). The development of robust models and modelling techniques is essential to underpin the planning and policy making process, allowing the evaluation of different scenarios and the assessing the effectiveness of mitigation measures. However, before proceeding to prediction, it is first necessary to examine whether the effects can be identified. Direct simulation was never intended to be part of this study, but a methodology for modifying the observed hydrology to reflect spatial distributed change was developed with a view to testing the methods of analysis employed in this study (see Section 4).

The final section in this report considers the implications of the results of the analyses for policy.

2. CHOICE OF CATCHMENTS FOR ANALYSIS

2.1 Introduction

Hydrological research associated with land use change has tended to focus on changes that are either permanent, or long term, such as urbanisation (Cheng & Wang, 2002; Reed, 1999), land drainage (Robinson,1990; Skaggs et al., 1994; Harris et al., 1993) and forestry (e.g. Robinson, 1998; Whitehead & Robinson, 1993), whilst land management research in this area has tended to concentrate on erosion monitoring (e.g. Chambers & Garwood, 2000; Boardman, 1995), erosion control (e.g. Martin, 1999; Fullen, 1998) and phosphorus losses (e.g. Hooda et al., 2000; McDowell et al., 2000). Studies have shown that the impact of soil structural degradation on in-field runoff is significant (e.g. Martyn et al., 2000; O'Connell et al., 2004a). However, the impact of this soil degradation on river flow response is less clear. Prior to FD2120, little data has been collated (see O'Connell et al., 2004a) for agricultural cropping and land management effects on flooding.

Unlike urbanisation, forestry and land drainage, soil structural degradation associated with specific agricultural management practices will be spatially and temporally variable (Holman et al., 2002 and 2003). The chronology of soil surface changes associated with a land management regime, even for a single field, will change within a season (Imeson & Kwaad, 1990), and from season to season (Burt & Slattery, 1996). Such intra-annual and inter-annual changes in soil structure and infiltration capacity make the identification of any short-term effects of soil structural degradation on river flows difficult. They will not occur in the same parts of a catchment at the same time each year nor necessarily generate a consistent increase in runoff, but will depend on the interactions between weather, tillage system, crop type and management on the runoff mechanisms (Burt & Slattery, 1996).

Since the 1960s, agriculture in the UK has become more intensive, resulting in many changes to the rural landscape. The pre-war landscape with small fields, hedgerows and natural meandering rivers, was transformed into a post-war landscape with larger fields, compacted soils due to machinery, land drains and aligned rivers and channels (O'Connell et al., 2004a). The major drivers of the changes in agriculture over the past 5 decades have been changing agricultural policies, the influence of markets, prices and subsidies, rural demographics and changes in field machinery systems and operations. These drivers of change are reviewed in Appendix 1.

Work Package 1 of FD2120 was intended to shortlist catchments which have had a significant likelihood of experiencing land-use induced changes to their hydrological response as a consequence of these drivers. These catchments therefore provide the test bed for the modelling within WP2. The criteria which were agreed at the first project meeting for identifying these catchments were:

- Catchments where agricultural land use and management impacts on soil structural conditions are likely to be greatest;
- Catchments with long-term, high resolution (hourly) digital flow datasets;
- Catchments with high resolution rainfall data (Tipping bucket).

There have been 7 stages in identifying catchments for the subsequent modelling:

1. Identification of the agronomic factors that are likely to give rise to the greatest hydrological impacts;
2. Distribution of potentially vulnerable cropping/stock systems;
3. Distribution of soil types which are potentially vulnerable to soil structural degradation
4. Identification of a long-list of catchments with a combination of critical crops, significant land use/cropping changes, vulnerable soils and flow gauges within the HiFlows dataset;
5. Short-list of catchments which have the best/most suitable hydrological (river flow and rainfall) data and, where possible, quantitative data on soil structural conditions;
6. Screening of preferred catchments, according to feedback received from local Environment Agency staff regarding streamflow data quality;
7. Analysis of additional catchments proposed by Stakeholders at the workshop on 28th November, 2006.

2.2 Identification of agronomic factors

A range of cropping and stock management systems in UK agriculture have the potential to significantly modify soil hydrology (e.g. Boardman, 1991; Boardman, 1995; Boardman et al., 1996; Chambers & Garwood, 2000), by impacting upon soil structural conditions. Initial work has therefore focussed on identifying the factors that are likely to give rise to the greatest impacts and the data sources and methods that will enable changes in these factors to be quantified. The main factors that are likely to give rise to significant impacts are:

- Land Drainage practices (Robinson, 1990) that alter the natural soil water regime.
    - Such practices affect forest systems; arable systems and grassland systems on slowly permeable seasonally waterlogged soils and soils seasonally waterlogged by rising groundwater.
- Practices which keep bare soil surfaces on inherently weakly structured sandy and silty soils that are susceptible to crusting and compaction.
    - Such practices apply to autumn sown crops (Kwaad, 1994); late-harvested crops (Maize, sugar beet); orchards; winter vegetables.
- Practices which require access to land when the soil hydrological cycle is at or approaching its wettest period cause compaction (Earl, 1997), especially on soils with impeded drainage.
    - Such practices apply to autumn sown crops; late-harvested crops such as maize and sugar beet (Arvidsson, 2001); livestock rearing, especially sheep (Vallentine, 1990); winter vegetables (Harrod, 1994).
- The trends for heavier farm machinery, particularly since the middle of the 20th century (Imeson et al., 2004), associated with e.g. sugar beet harvesting (Poodt et al., 2003); a shift to precision chopping of silage or large bale

machines (Appendix 1). According to Alakukku et al. (2003), soil compaction by machinery will depend on:

- type of machine, especially wheel load and size of the tyre contact area with soil;
- size of the area affected by the machine in the field;
- number of passes which causes cumulative effect of stresses;
- period of use of the machine, in relation to the soil wetness.

All of the above aspects within grassland and arable agricultural areas were incorporated in the catchment selection process, either explicitly (e.g. crops which are associated with potentially detrimental practices) or implicitly (e.g. crops which require heavy machinery, or soils which require land drainage for intensive arable or grassland use).

2.3 Distribution of potentially vulnerable cropping/stock systems

Although the types of management practices and machinery used are important in determining compaction and soil structural damage (Le Bas et al., 2004), details of these are generally very scarce. Therefore based on the above factors the following list of potentially vulnerable cropping/stock systems has been identified, since the type of crop will determine the type of operations and the periods when they are performed, and also the depth of cultivation (Chamen et al., 2003):

- Late harvested arable crops e.g. maize; sugar beet, maincrop potatoes
- Autumn sown arable crops e.g. winter wheat, winter barley and winter oilseed rape;
- Managed grassland (primarily under sheep);
- Orchards;
- Winter harvested vegetables e.g. winter cabbages, brussel sprouts, parsnips, winter cauliflowers;
- Early potatoes and bulb flowers.

Data on land use change for England has been collated from the EDINA data service at Edinburgh University. EDINA is a Joint Information Systems Committee (JISC) funded national data centre, which offers the UK tertiary education and research community networked access to a library of data, information and research resources. The data is based on the Agricultural Census, which is conducted in June each year by the Department for Environment, Food and Rural Affairs (DEFRA), and formerly the Ministry of Agriculture, Fisheries and Food. Each farmer declares the agricultural activity on their land via a postal questionnaire. The respective government departments collect the over 150 items of data and publish information relating to farm holdings for recognised geographies, for which Edinburgh University Data Library has developed algorithms which convert this data for recognised geographies into grid square estimates. Although the data are collected each year, data are only available from EDINA for selected years (Table 2.1) between 1969 and 2004.

Table 2.1 Years with agricultural census data available from EDINA

		Year within decade									
		0	1	2	3	4	5	6	7	8	9
Decade	1960's										■
	1970's			■				■			■
	1980's		■							■	
	1990's				■	■	■	■	■		
	2000's	■			■	■					

The 5km x 5km gridded data has been used. However, the regular changes to the questions (and classes) within annual questionnaire, have made the derivation of consistent time series of cropping/land use data problematic:

- Autumn sown arable crops (Autumn sown wheat, barley and oilseed rape)
    - There is no subdivision of autumn and spring sown wheat but it has been assumed that autumn sown wheat is dominant. Oilseed rape was only sub-divided in the data into autumn and spring sown in 1996 and 1997. However, as there was a consistent relationship between the proportions of autumn sown to total oilseed rape in the grid squares in both years, these proportions have been used to estimate winter oilseed rape in the pre-1996 and post-1997 data. Finally, there was no subdivision of winter and spring barley before 1979 and no relationship could be found between autumn sown to total barley in later years.
    - A time series of Autumn sown arable crops was therefore derived based on combined data for 1979-2004 on wheat, winter barley and estimated autumn oilseed rape
- Late Harvested arable crops (Maize, Sugar beet and maincrop potatoes):
    - Maize was not included in the questionnaire in 1969, and so it has been assumed that it was not grown. Since 1988, there has been no subdivision in the data between early and maincrop potatoes
    - A time series of Late Harvested arable crops was therefore derived based on combined data for 1969 – 2004 on maize, Sugar beet and Total Potatoes (early and maincrop).
- Grass
    - The classification of permanent and temporary grassland changes throughout the data period. However, it was possible to derive a time series of permanent and temporary (< 5 years) grassland for the period 1969-2004
- Sheep
    - Between 1993-97, the only data on sheep related to ‘Breeding ewes’, ‘two teeth ewes’ and ‘lambs’. Therefore, a time series of Sheep numbers was derived based on combined data for the period 1969-2004 on breeding ewes, two teeth ewes and lambs
- Fruit
    - There was no data on any forms of fruit from 1993-97 inclusive, and little consistent sub-division of fruit categories.

    - A time series of Fruit was therefore derived for 1969-88 and 2000-04 for 'Total Orchards and soft fruit'
- Winter-harvested vegetables
    - Due to the paucity of detailed vegetable data since 1988, this cropping group was not analysed
- Early potatoes and bulb flowers
    - Due to the paucity of detailed data on both these crops, this cropping group was not analysed (although, due to data restrictions, early potatoes are included within the late harvested arable crops) potatoes) so that areas with significant early potato production (e.g. in south west England) would appear in that crop class.

For each unified dataset, the time series for each grid square were individually analysed (Figures 2.1 to 2.5) for the following:

a) Hectarage or headage data for 2004 data to identify areas of significant current production,
b) Standard deviation of the time series, to identify areas with temporally variable production. The standard deviation was used, rather than a Coefficient of Variation, to avoid the data being normalised by area.
c) Indicative trend within the time series as given by the linear regression slope. This was intended to identify areas in which the variation in annual area or headage have given an apparent trend of increasing (or decreasing) production. However, because of the variable behaviour of land use change in the grid squares, this simple analysis does not imply that there is an actual linear trend in the data.

Key areas of change that are evident in Figures 2.1 – 2.5 are:

- Autumn sown arable crops:
    - generally increasing trend suggested in area to the east of the Pennines / north of The Wash;
    - no clear trend elsewhere, although apparent pockets of increased production in Norfolk/Suffolk border and Kent
- Late harvested arable crops:
    - A decreasing trend is suggested in the East, with exception of Norfolk and Yorkshire wolds;
    - Little change through central England;
    - Increasing trend suggested in Western England, though limited in Cornwall, consistent with the westwards expansion of maize production
- Managed grassland:
    - Little change in East
    - Decreasing trend through central England and North East;
    - Increasing trend in North West and South West
- Sheep:
    - Little change in most areas in East, though significant reduction in numbers in Kent and Lincolnshire/North Yorkshire
    - Decreasing trend through central England;
    - Increasing trend in North West, Pennines and South West
- Fruit:
    - Generally decreasing trend in most areas

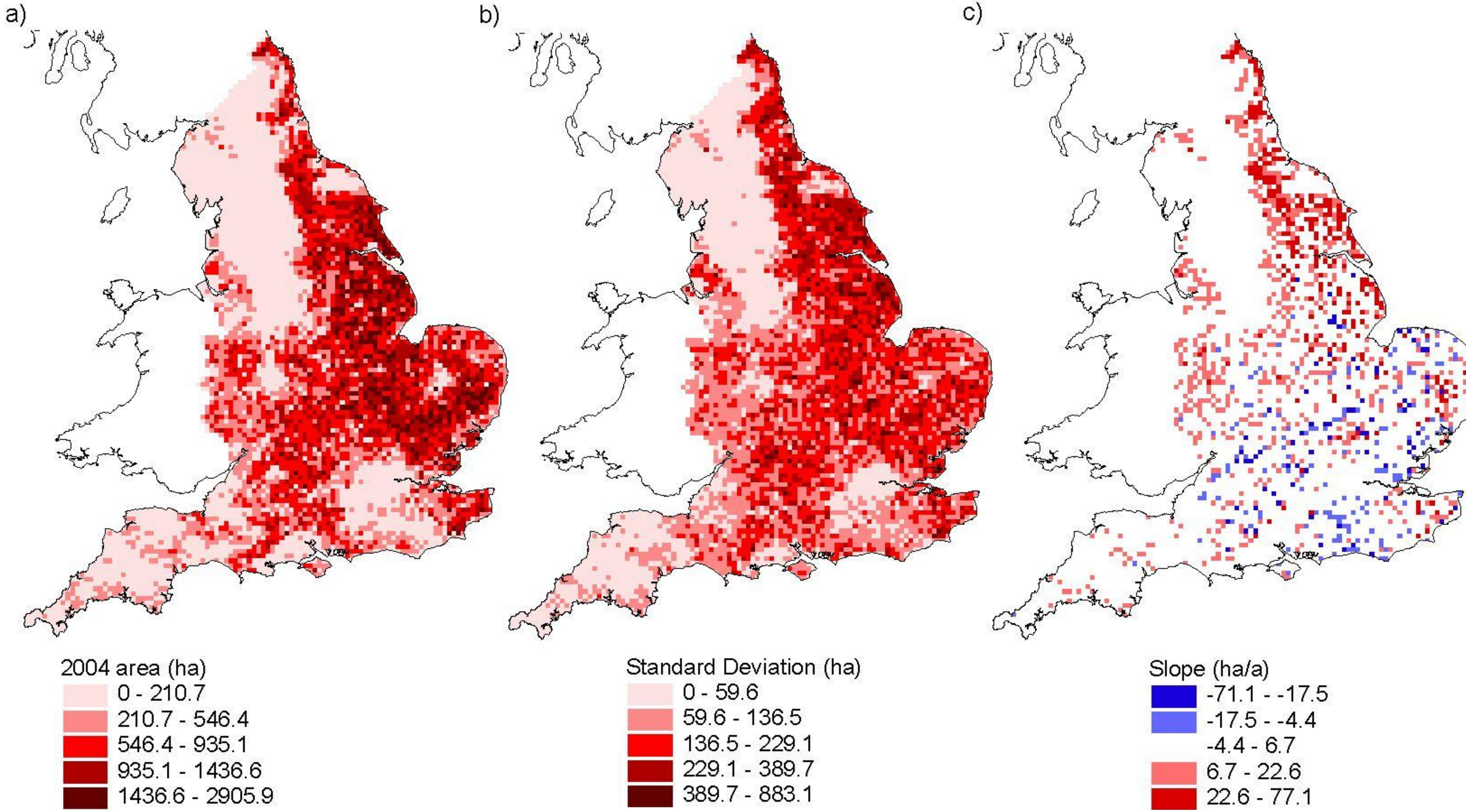

Figure 2.1 Analysis of autumn sown arable crops (wheat, barley and winter oilseed rape) between 1979-2004 in England

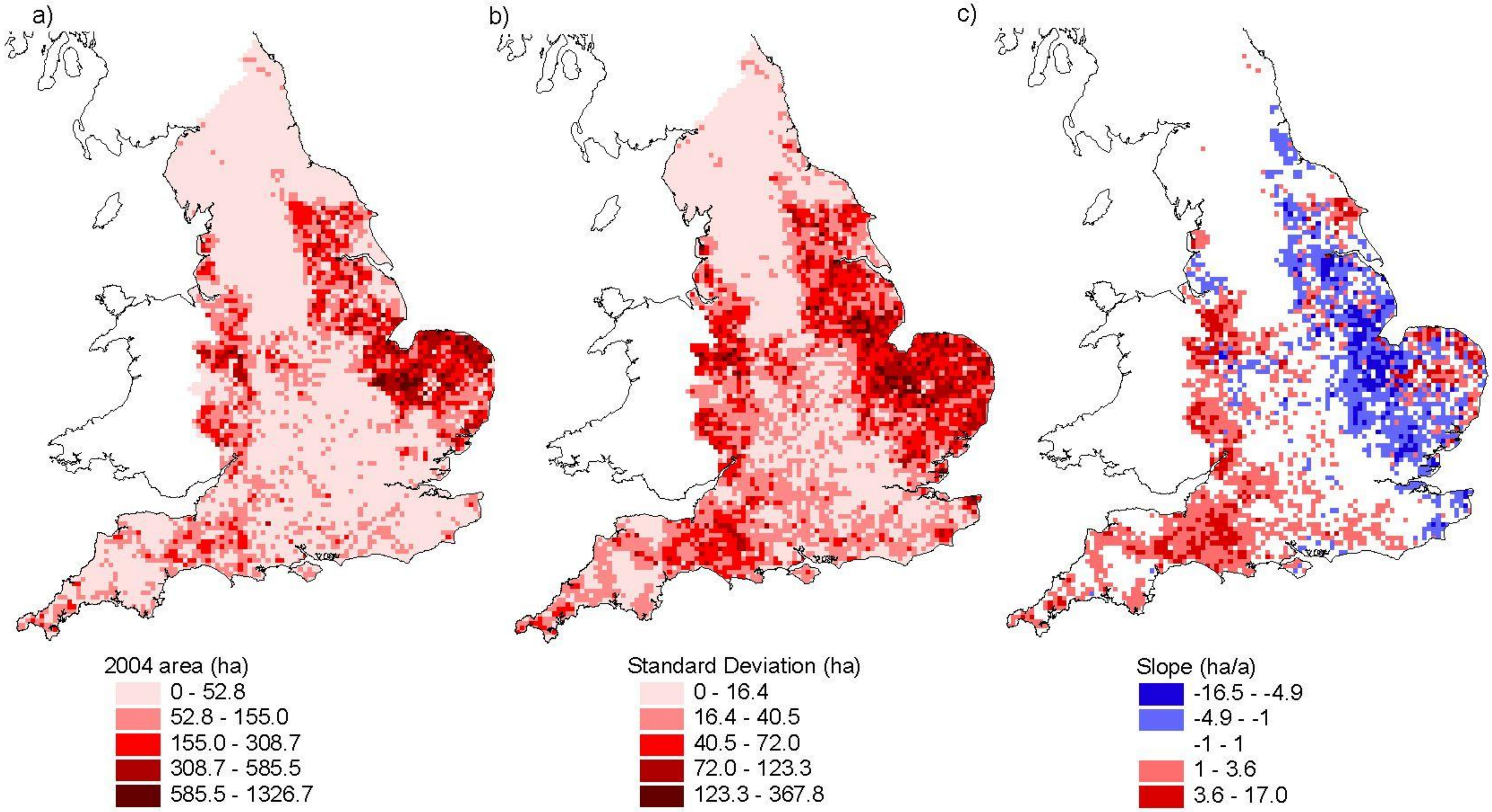

Figure 2.2 Analysis of late harvested crop (maize, sugar beet and potatoes) between 1969-2004 in England

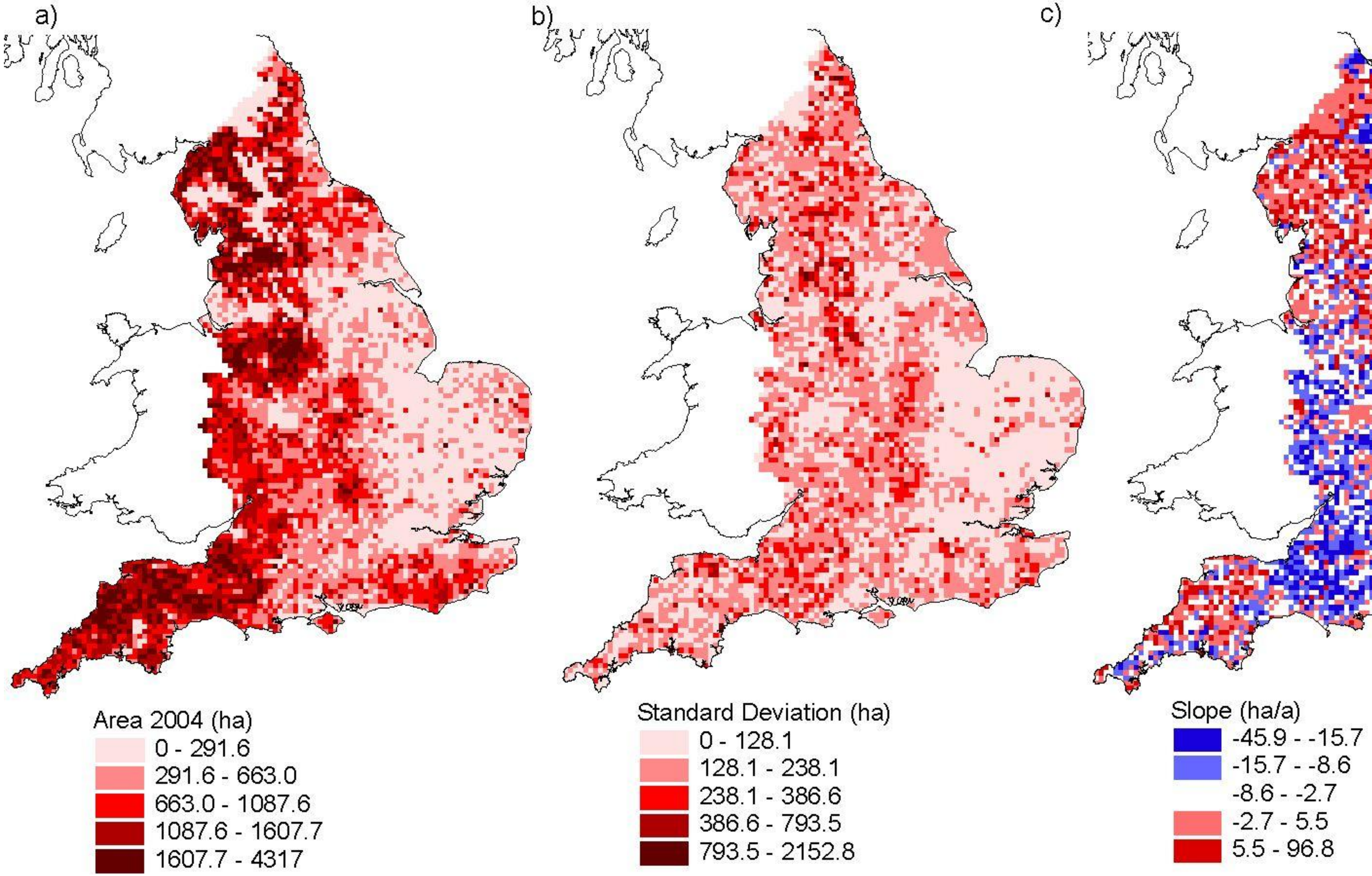

Figure 2.3 Analysis of managed grassland between 1969-2004 in England

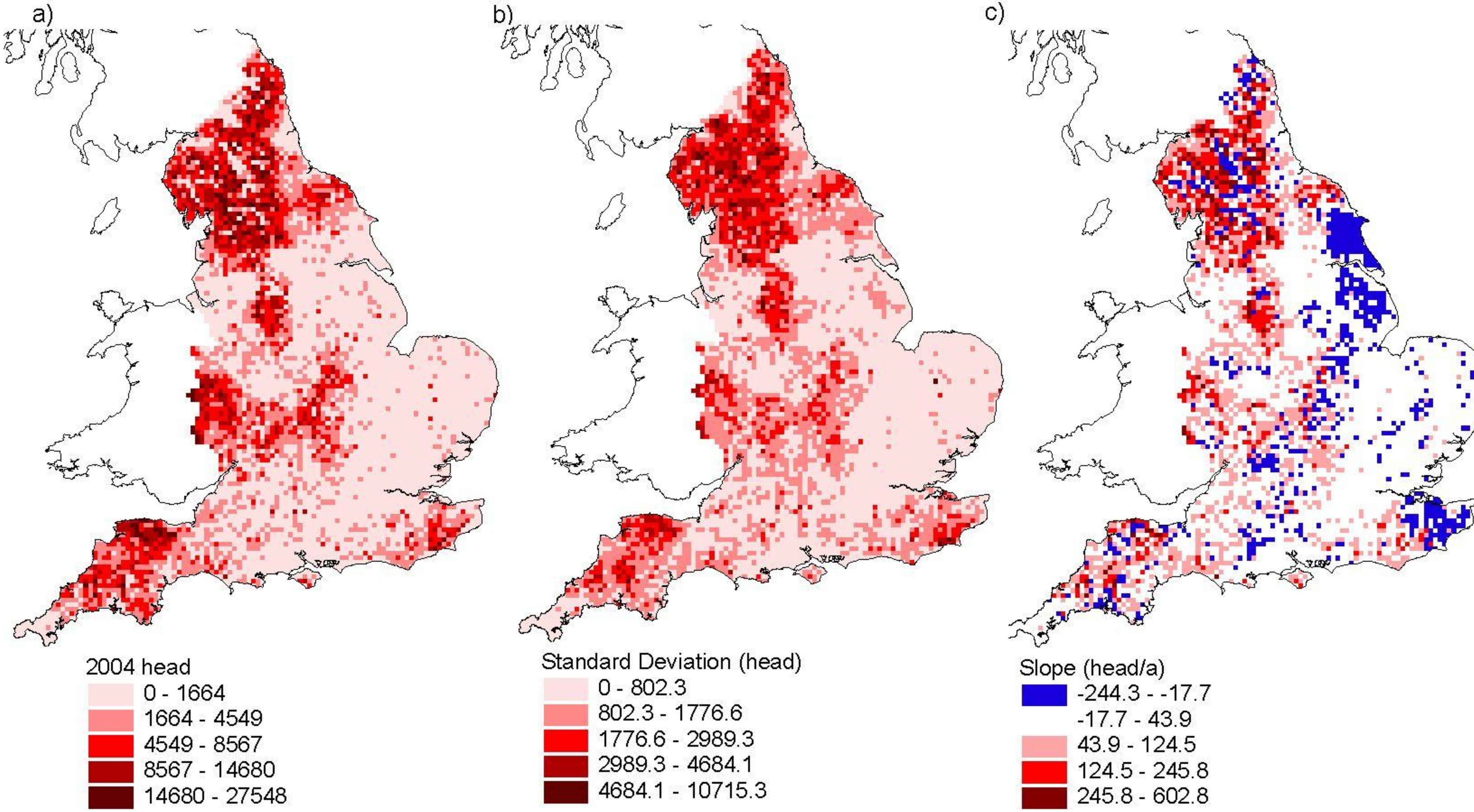

Figure 2.4 Analysis of sheep numbers between 1969-2004 in England

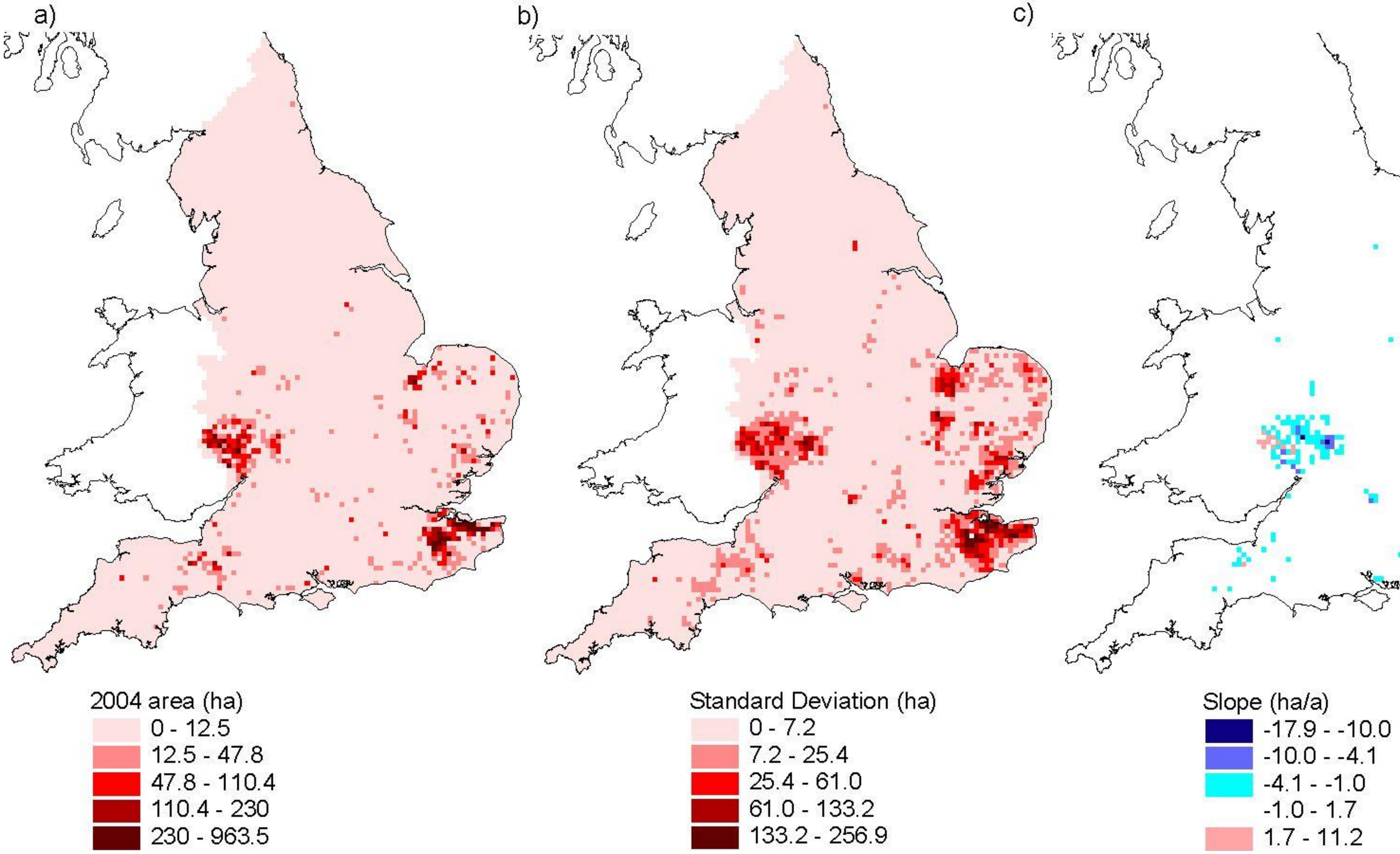

Figure 2.5 Analysis of fruit (orchard and soft fruit) between 1969-88 and 2000-04 in England

2.4 Distribution of soil types which are potentially vulnerable to soil structural degradation

The speed with which water reaches the river network is strongly influenced by the nature and condition of the underlying soil (Boorman et al., 1995; U.S. Soil Conservation Service, 1986), which might be affected by soil structural degradation. The susceptibility of a soil to structural degradation associated with land management practices is strongly influenced by natural soil physical properties, in particular texture and inherent water regime. For example, soils with a large clay content have lower bearing strength when wet and are therefore more susceptible to compaction and damage during trafficking and cultivation than soils with a small clay content. Conversely soils with high silt content and low clay content are more prone to capping (or crusting) at the surface associated with the breakdown of soil aggregates (Holman et al., 2003).

However, information about soil mechanical properties, on which to assess sensitivity to compaction, is scarce, and it is thus necessary to make indirect assessments using more readily available data and soil properties. In the absence of an appropriate model and sufficient information about soil mechanical properties, an assessment has been made based on expert knowledge of soil properties, such as soil texture, organic matter content, structure, bulk density, etc. which are available in the soil survey. The expert judgement has been based on the quantitative evidence of soil structural problems collected by soil surveyors from Cranfield University in a range of catchments throughout England. These include:

- 11 catchments in Cornwall, Devon, Somerset and Hampshire (surveyed during 2002 – 06);
- 2 catchments in the south east -the Uck and Bourne, surveyed in 2000/01 (Holman et al., 2002, 2003) and 02/03, together with the work of John Boardman in the South Downs.
- the Severn catchment (surveyed in 2000/01- Holman et al., 2002, 2003), and the Pont Bren catchment (2005).
- The Yorkshire Ouse (surveyed in 2000/01- Holman et al., 2002, 2003).
- The Wensum in Norfolk (Feb 2006).

Three broad soil groups have been identified as particularly vulnerable to compaction and slaking, based upon the following rules:

- Free draining silty soils
  - Texture - uniformly silty, light silty, medium silty, light silty over loamy and medium silty over clayey;
  - Hydrological behaviour - HOST classes 1-6 (no impermeable or seasonally waterlogged layers within 100 cm and groundwater or aquifer normally present at >2m depth) or HOST class 7 within non-alluvial soils.
- Free draining sandy loam soils
  - Texture - uniformly light loamy or light loamy over gravel;
  - Topsoil constraint– sand content > 50%;

    - Hydrological behaviour - HOST classes 1-6 (no impermeable or seasonally waterlogged layers within 100 cm and groundwater or aquifer normally present at >2m depth) or HOST class 7 within non-alluvial soils.
- Slowly permeable, seasonally wet non-calcareous loamy and clayey soils
    - Texture - uniformly medium loamy, clayey, medium loamy over clayey;
    - Topsoil constraint– sand <50%, clay <30% and arable pH < 7.5;
    - Hydrological behaviour - HOST classes 24 and 25 (seasonally waterlogged within 40cm associated with slowly permeable or soft impermeable substrate hydrogeology).

The distribution of these soils (Figure 2.6) which are vulnerable to soil structural degradation associated with agricultural land management has been derived using the Spatial Environmental Information System for Modelling the Impact of Chemicals (SEISMIC) scenario mapping tool developed by the National Soil Resources Institute at Cranfield University. This incorporates a 5km gridded version of the 1:250,000 scale National Soil Map of England and Wales (Ragg et al., 1984).

2.4.1 Identification of long-list of catchments

Catchments with a combination of critical crops, significant land use/cropping changes and vulnerable soils were been identified from the datasets described above. These were restricted to a long-list based on the presence of a gauging station within the HiFlows UK database. Figure 2.7 shows the distribution of catchments, which contain 50 HiFlows gauging stations, which are uniformly distributed throughout England.

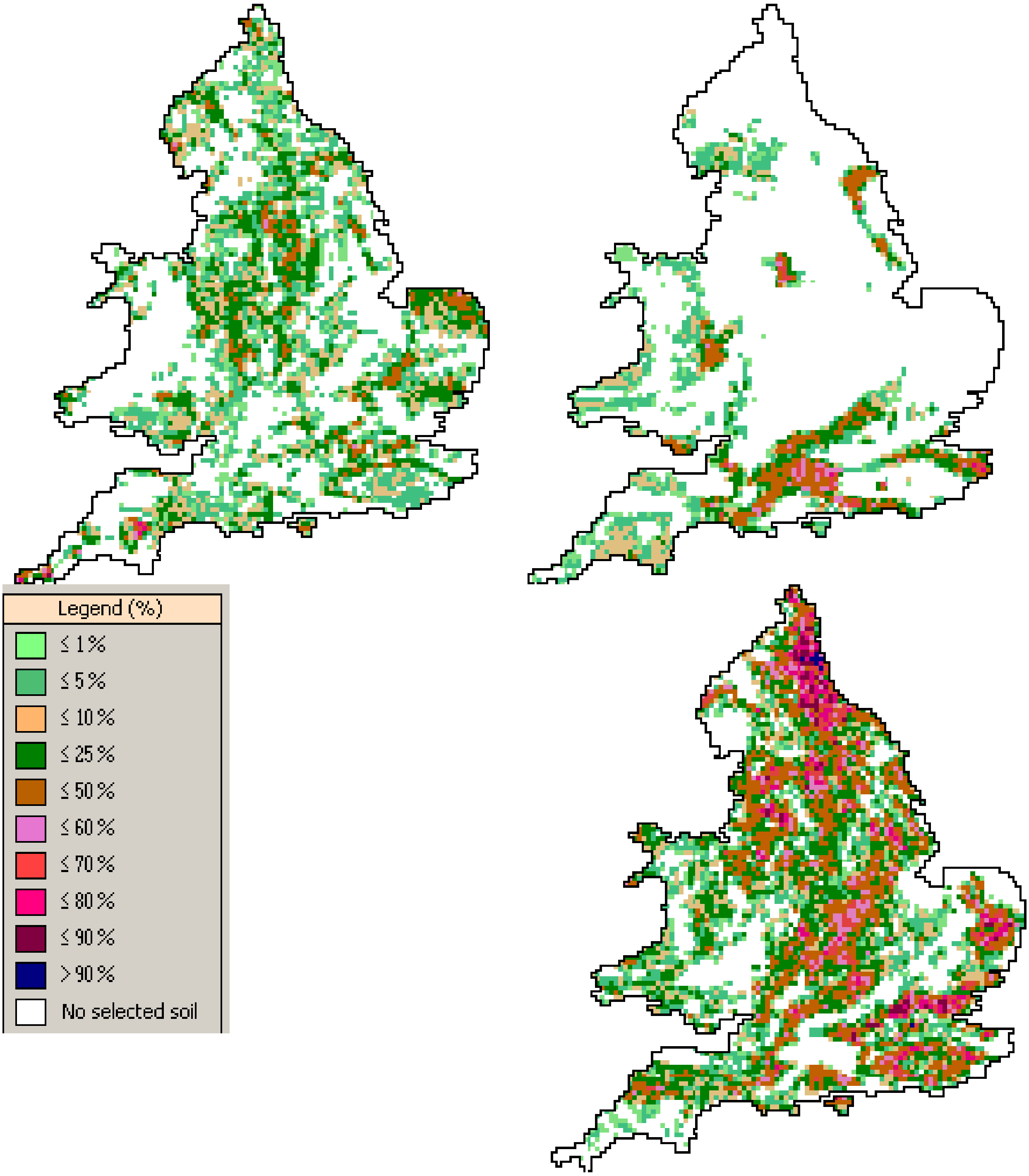

Figure 2.6 Distribution of soil types which are particularly vulnerable to soil structural degradation: (top left) free draining sandy loam, (top right) free draining silty soils and (lower right) slowly permeable, seasonally waterlogged, non-calcareous, loamy and clayey soils

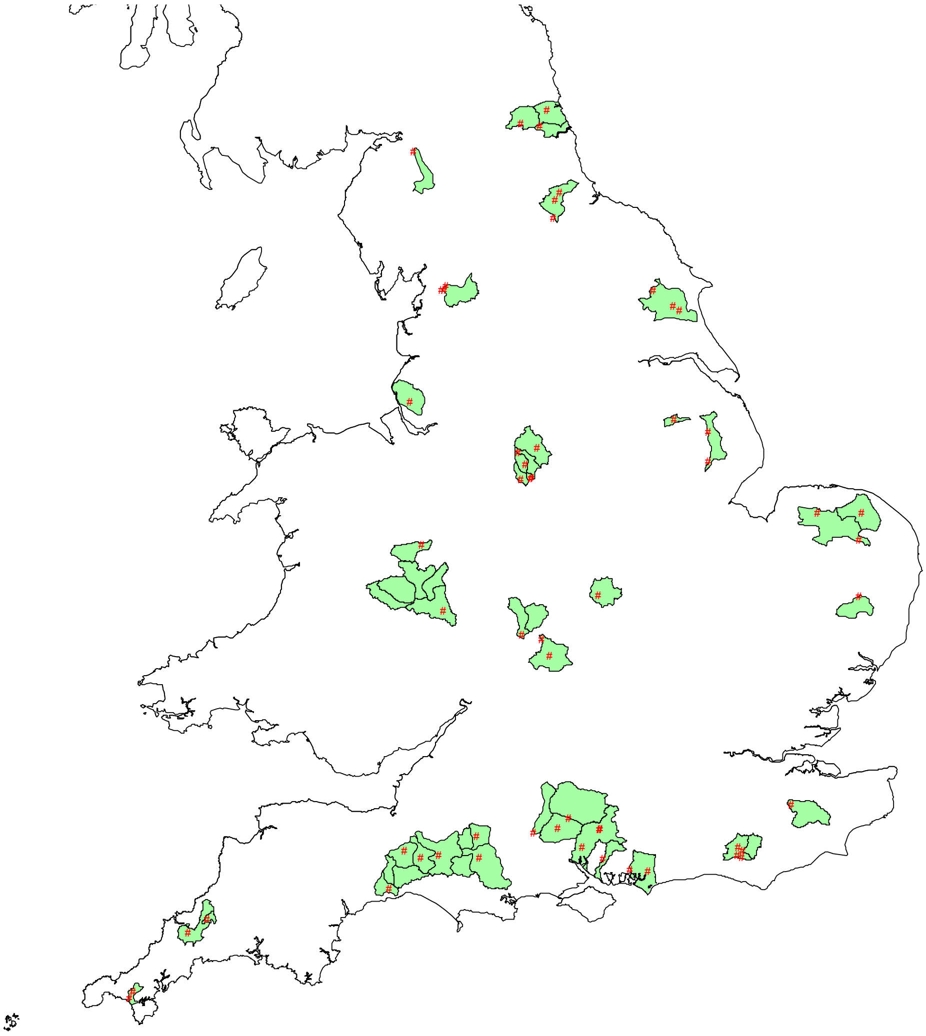

Figure 2.7 Distribution of long-list of vulnerable catchments. HiFlowsUK gauging stations are indicated by red dots

2.5 Identification of short-list of catchments

This project requires the identification, extraction and use of the best quality flow datasets from gauging stations with long digital records (pre-dating 1980).

2.5.1 Ensuring flow data quality

All of the flow station datasets utililised within this project have been extracted from the HiFlow-UK database, which underwent a rigorous data quality process. This data quality work undertaken as part of the HiFlows-UK development work is described in Spencer et al. (2004). An extract from this paper is reproduced here:

“Ensuring data quality has been challenging. The challenges arose from a number of factors, including the many gauging stations, the number of different offices and their different data archiving systems, the several different sources of data (including the FEH dataset itself, digital, written, and microfiche), the complexities of some rating histories, and the often limited information about

past events, particularly before the start of digital records. A frequent source of uncertainty was how some stations really behave at the highest flows, especially where they have been designed and operated primarily for the measurement of low flows. The data quality procedures have been carried out at two stages. Firstly, by setting up clear and consistent data quality procedures for the data capture phase, and secondly by subsequent review.

Consistent data quality procedures were established for the data capture phase by JBA preparing a database for the Consultants capturing the data to complete, and this also provided tools to visualise and check the data, including:

- *Comparison of rating relationships with flow gaugings*
- *Checking changes in ratings against the history of physical changes*
- *Time series graphs of the AMAX and POT series*
- *Trend analysis*
- *Comparing the HiFlows-UK data with that in the FEH dataset*
- *Comparing peak flows with other stations on the same river*
- *Visually examining the flow hydrographs for the largest digitally available 5 peaks*

The data collected and ratings applied were reviewed and approved by gauging authority staff. The Consultants then prepared a summary report. All this work was done under the Consultants' own quality systems (including review and approval) before supply to the project.

The next, and very important stage, was a further review of the initial data and information. This was done by releasing the database to selected Consultants and then by making a complete pilot website available for external review. This gave users an opportunity to contribute their knowledge. The project received over 500 "station-person" comments, all which were followed up. In addition, JBA and project staff have carried out further extensive reviews of the data and consultations with hydrometric staff."

The Hydrometric Register and Statistics 1996-2000 (CEH/BGS, 2003) and the HiFlows-UK database were used by JBA to assess the data quality of the records within the 'long-list' of catchments provided. There was also the supplementary requirement that each target catchment should have at least one tipping bucket raingauge within the catchment boundary with a reasonable length of record. The availability of additional tipping bucket raingauge records, together with long term storage raingauge records, from locations around the study catchments have provided extra information to WP2 on the rainfall-runoff characteristics.

HiFlows-UK provides flood peak data and flow gauging station information, at around 1000 river flow gauging stations throughout the UK. The data from these stations is intended for use with the statistical flood estimation methods set out in the Flood Estimation Handbook (FEH). The data in HiFlows-UK originates from the hydrometric data archives held by the Environment Agency for England and Wales, the Scottish Environment Protection Agency (SEPA) for

Scotland and the Rivers Agency for Northern Ireland. Additional data and background information were also supplied by the National River Flow Archive, held at CEH Wallingford, and the University of Dundee. All the stations on the HiFlows-UK database were deemed to have good quality sub-daily flow records. JBA Consulting were involved in the development of the HiFlows-UK database and the analysis of the data quality for the gauging stations. Further details on the data assessment are given in Appendix 2.

An interrogation of the HiFlows-UK database, together with discussions with some Environment Agency hydrometric staff, has provided statistics on the length of the sub-daily digital flow record for each of the target catchments, together with information on the incidence and duration of missing records. For many of the gauging stations there will also be non-digital records (e.g. paper chart, microfiche) for a period that precedes the digital record. However, considerable effort and resources would be needed to locate, collate and digitise these records, which were outside the scope of the project.

The most suitable flow gauging stations, in terms of satisfying the general modelling requirements, were identified (Figure 2.8). Details are given in the Table 2.2 overleaf. They are:

Blyth @ Hartford Bridge	Teme @ Tenbury	Axe @ Whitford
Bain @ Fulsby	Alt @ Kirkby	De Lank @ De Lank
Stour @ Alscot Park	Petteril @ Harraby Green	Camel @ Denby
Wye @ Ashford	Ancholme @ Toft Newton	Arrow @ Broom New
Dove @ Izaak Walton	Yeo @ Pen Mill	
Manifold @ Ilam	Isle @ Ashford Mill	

In terms of regional coverage, these stations are Anglian (2), North West (2), North East (1), South West (5) and Midlands (6)

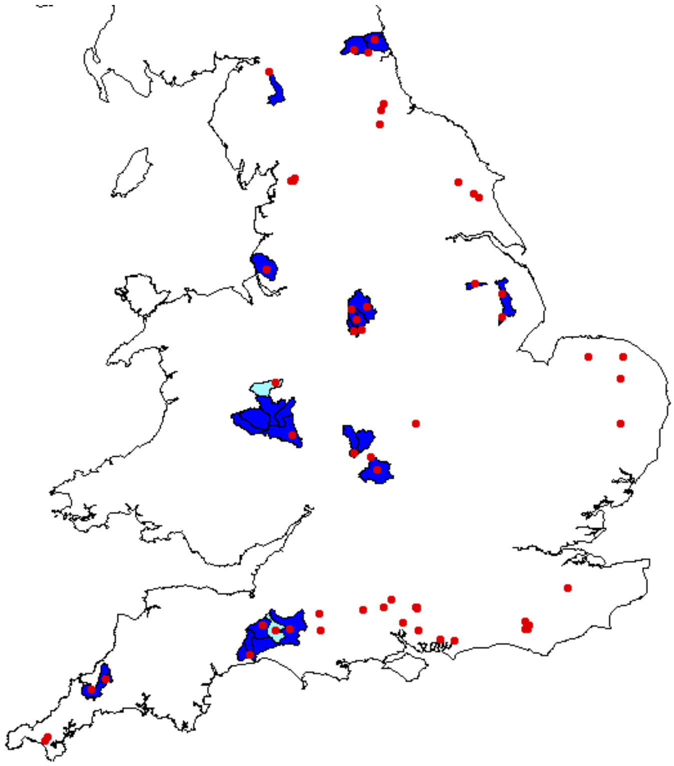

Figure 2.8 Shortlisted catchments (dark blue have at least one tipping bucket raingauge, pale blue catchments contain no TBR)

2.5.2 Ensuring rainfall data quality

Data from recording gauges (also known as tipping bucket raingauges) and daily storage gauges were needed for WP2. Ideally, 2-4 raingauges (for both recording and storage gauges) were required for each of the study catchments for analytical purposes. Typically, the recording raingauge datasets only go back in time to the 1980s or early 1990s. In contrast, daily read storage gauges often go back to the 1960s or early 1970s and therefore provide a much longer continuous record for analysis and comparison with the daily record (when the records coincide).

JBA Consulting hold a copy of the Environment Agency raingauge dataset up to 2003, which was developed as a supplementary component to the HiFlows-UK database. This database was interrogated to find suitable raingauges for each study catchment.

In some cases it was not possible to locate the specific number of raingauges of the required record length within the actual study catchment boundary. In these instances raingauges were located in the geographical proximity of the study catchment. The chosen raingauges are described in the Table 2.2 below.

Table 2.2 Identification of most suitable flow gauging stations, in terms of satisfying the general modelling requirements

■ Catchments with most suitable flow record (since before 1980) AND at least one tipping bucket raingauge in catchment
░ Catchments with most suitable flow record (since before 1980) BUT no tipping bucket raingauge in catchment

Catchment	EA Region	Gauging station number	Catchment area (sq km)	Station start	Digital data period	Number of missing flow data periods 0-10 days	Number of missing flow data periods 11-31 days	Number of missing flow data periods 32-100 days	Number of missing flow data periods >100 days	Max. missing flow record period (days) if >100 days	Number of tipping bucket raingauges in
Pont	NE	22801	48	1999	99-03	2	0	0	0		1
Blyth	NE	22006	269	1960	63-03	0	1	0	0		1
Ouseburn	NE	23018	9	1973	83-03	6	11	4	1	1194	1-2*
Skerne	NE	25020	147	1972	82-03	71	0	1	0		0
Skerne	NE	25021	70	1973	82-03	66	0	2	0		0
Gypsey Race	NE	26802	16	1998	98-03	280	0	0	0		1
Water Forlornes	NE	26803	32	1970	98-03	134	4	4	0		2
West Beck	NE	26009	228	1988	88-03	13	0	0	0		2
Bain	A	30011	63	1966	79-03	0	3	1	1	942	4
Bain	A	30003	197	1960	79-03	6	1	0	0		7
Bure	A	34003	165	1959	79-03	6	10	2	1	537	0
Beult	S	40005	277	1958	68-03	13	15	6	1	127	4
Itchen	S	42010	360	1958	81-02	0	0	0	0		3
Anton	S	42012	185	1956	81-03	1	0	0	0		2-3
Wallop Brook	S	42005	54	1955	86-03	4	6	8	2	221	1
Stour	SW	43009	523	1970	92-03	0	0	0	0		4-5
Stour	M	54106	185	1972	86-03	14	2	0	0		3
Stour	M	54010	316	1958	74-03	13	2	1	1	273	4
Avon	M	54102	110	1951	74-03	8	0	0	1	729	1
Wye	M	28023	154	1965	71-03	7	1	3	0		2
Dove	M	28033	8	1965	72-03	16	0	1	3	3660	1
Dove	M	28046	83	1969	71-03	16	0	0	0		1*
Hamps	M	28041	40	1968	72-03	1	0	0	1	6484	0
Manifold	M	28038	46	1965-82	72-82	0	0	1	0		
Manifold	M	28031	149	1964	68-03	35	1	0	0		1*
Cober	SW	48801	27	1988	88-03	11	0	0	0		1
Cober	SW	48006	40	1968-89	68-89	0	0	0	0		1
Rea Brook	M	54018	178	1962	78-03	7	0	0	1	130	0
Teme	M	54008	1135	1956	69-03	6	0	0	1	274	6
Alt	NW	69032	90	1963	78-03	2	0	0	1	215	2*
Petteril	NW	76010	160	1970	75-03	250	0	0	0		1
Dove	A	34007	134	1966	79-03	5	5	2	1	453	2
Wenning	NW	72009	142	1970	76-03	33	0	0	0		2
Wenning	NW	72807	127	1957	90-03	25	1	1	0		2
Ancholme	A	29009	27	1974	79-03	5	4	0	0		1
Wensum	A	34011	162	1966	80-03	7	8	2	3	257	1
Wensum	A	34004	571	1960	79-03	9	3	8	1	3088	5
Bevern Stream	S	41020	35	1969	81-08	2	0	0	0		1
Ems	S	41015	58	1967	81-03	5	1	0	0		1-2
Lavant	S	41023	87	1970	81-03	39	5	2	3	366	2-3
Meon	S	42006	73	1958	82-03	12	2	2	0		0
Bourne (Hants)	S	43004	164	1964	92-03	1	0	0	1	2847	2
Yeo	SW	52006	213	1962	63-03	7	0	0	0		2
Isle	SW	52004	90	1962	62-03	11	0	1	1	162	2
Parrett	SW	52007	75	1966	66-03	10	1	0	0		0
Axe	SW	45004	289	1964	64-03	1	0	0	0		8
De Lank	SW	49003	22	1966	69-03	2	2	1	1	121	1
Camel	SW	49001	209	1964	64-03	5	0	0	0		4
Arrow	M	54007	319	1977	78-03	4	0	0	1	239	3
Uck	S	41006	88	1964	81-03	2	0	1	0		?

2.5.3 Proposed catchment selection

Based upon the best gauging stations identified above, ten gauging stations/catchments were proposed for the subsequent modelling (Figure 2.9). These catchments contain the range of vulnerable soils (Table 2.3), significant areas or numbers and varying temporal trends (Table 2.4), of the important land uses (late harvested, autumn sown, managed grassland / sheep and fruit). Unfortunately further discussion with local Environment Agency staff identified data quality issues with three of the gauging stations which had not been identified in the HiFlows-UK database. Thus the Ancholme (Anglian region), Petteril (North West Region) and Stour (Midlands region) catchments were removed. The availability of rainfall data is variable, from storage raingauges (Table 2.5) and high resolution TBR data, both in terms of numbers of gauges and record length (Table 2.6 and 2.7).

Table 2.3 Proportions of vulnerable soils within the ten proposed catchments

Catchment	Sandy loams (%)	Silty soils (%)	Wet, loamy and clayey soils (%)	Total vulnerable soils (%)
Blyth	0	1	85	86
Bain	11	15	31	57
Stour	0	3	74	77
Wye	47	3	7	56
Teme	17	10	29	57
Petteril	0	17	51	68
Ancholme	0	0	50	50
Isle	10	2	54	65
Axe	13	6	49	67
Parrett	16	3	39	58

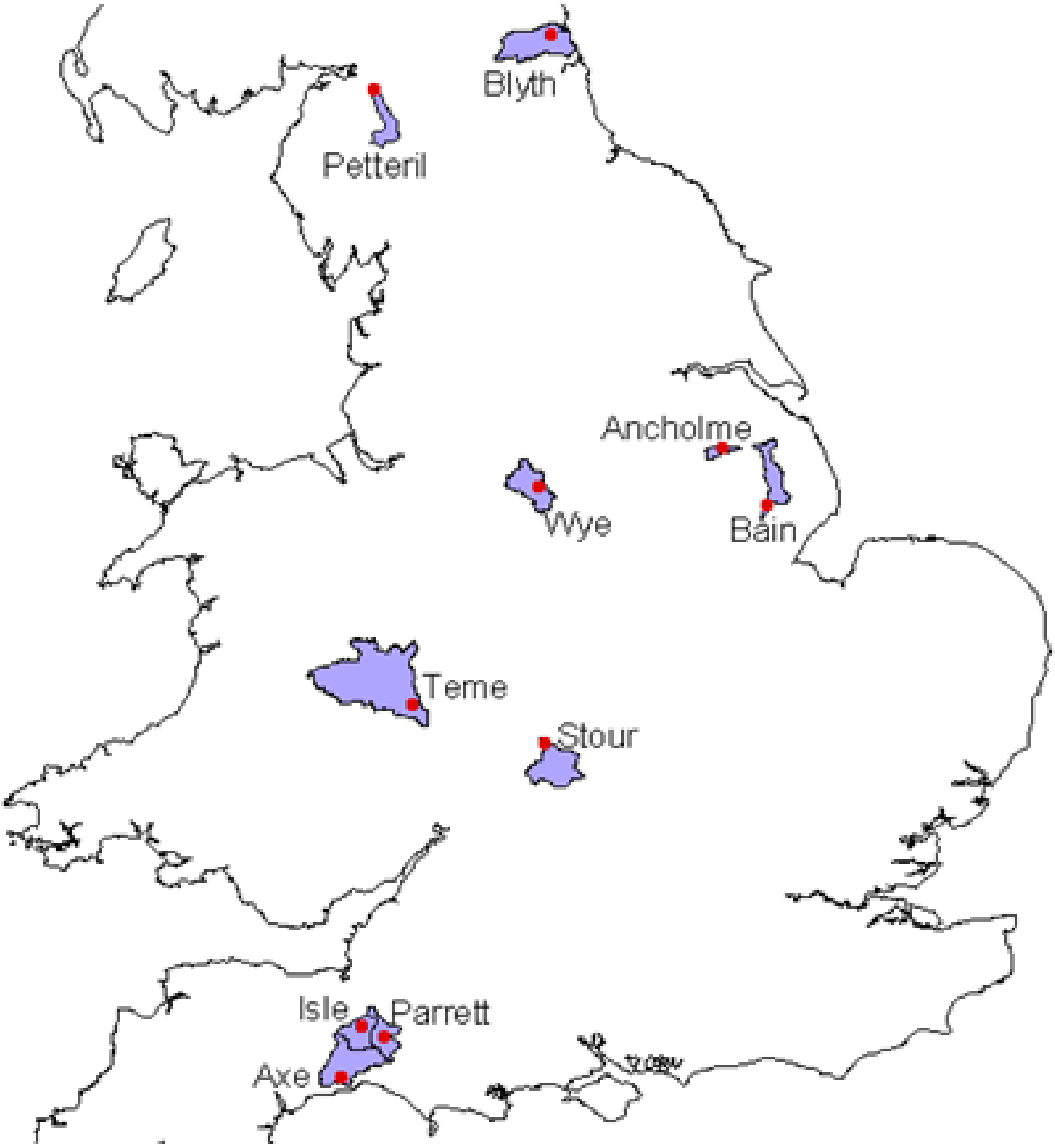

Figure 2.9 Proposed catchments (red dots indicate HiFlows UK gauging stations

Table 2.4 Temporal trends in production area of key land management types within the ten proposed catchments

	Land management types		
Trend	Autumn sown	Late harvested	Managed grass
Increasing	Blyth	Axe, Isle, Parrett	Wye
Decreasing		Blyth	Teme, Blyth,
Constant	Parrett		
Varying	Stour, Axe and Bain	Bain	Axe

Table 2.5 Storage raingauges used in catchment analysis

Catchment	Gauge Ref	Name	Period	NGR
Teme	443991	Ludlow W.Rem works	79-03	SO516 731
Teme	440707	Knighton	61-99	SO286 725
Isle	5201022OB	Puckington	80-03	ST376 183
Isle	5203101OB	Seavington	84-03	ST396 161
Parrett	5203138OB	Haselbury Plucknett	71-03	ST463 110
Parrett	5203103OB	Hard'ton Mandiville	84-03	ST511 115
Axe	352686	Axminster Lyme Rd	56-00	SY307 977
Axe	352343	Chard Junc	79-03	ST339 046
Axe	352519	Wambrook	68-03	SY2912 0731
Wye	107875	Hargatewall	88-03	SK117 752
Wye	107494	Buxton	91-03	SK058 734
Wye	107821	Peak Forest	78-03	SK118 800
Bain	145499	Donington-on-Bain	71-01	TF237 826
Bain	144272	Thimbleby	68-85	TF237 699
Bain	135116	Cadwell	71-03	TF282 814
Blyth	7683	Blagdon Hall	70-03	NZ212 771
Blyth	7036	Capheaton	70-03	NZ038 805
Blyth	7335	Burnside	73-93	NZ044 717

Table 2.6 Record length of TBR data within proposed ten catchments

Catchment	Region	TBR data period
Blyth	NE	1986-02*
Bain	A	61-64, 65-71, 77-02, 87-02, 87-02, 87-96, 87-02
Stour	M	79-02, 79-02, 81-02, 01-02
Wye	M	80-02, 02
Teme	M	80-02, 81-02, 82-02, 84, 86-97, 00-02
Petteril	NW	91-02
Ancholme	A	87-02
Isle	SW	66-85, 95-05
Axe	SW	98-02, 98-02, 98-02, 98-02, 98-02, 98-02, 98-02,
Parrett	SW	-

* It appears likely that 2002 is the date when the TBR database was created, rather than the true end of the data period

Table 2.7 Recording TBR raingauges used in catchment analysis

Catchment	Gauge Ref	Name	Period	NGR
Teme	1792	Brimfield	86-97	SO503 682
Teme	1271	Craven Arms	80-03	SO437 811
Teme	1774	Bickley	00-03	SO631 713
Teme	1387	Bettws-y-Crwyn	81-03	SO203 814
Teme	1412	Bishops Castle	82-03	SO338 873
Isle	5201017SC	Chard	95-03	ST3393 1197
Isle	5201017DN	Chard	66-85	ST332 095
Parrett	None	None	None	None
Axe	R45403	Weycroft Bridge	98-03	ST3072 0002
Axe	R45404	Bonehayne	98-03	SY21682 94734
Wye	3578	Tideswell	80-03	SK155 746
Wye	3572	Chapel Res	85-03	SK155 746
Bain	S04	Fulsby	87-03	TF241 611
Bain	S07	Belchford	87-03	TF296 754
Bain	S08	Stenigot	87-03	TF259 829
Blyth	7533	Darras Hall	86-03	NZ147 712
Blyth	5782	Wallington Logger St	94-03	NZ032 847
Blyth	5784	Wallington Hall	83-94	NZ035 843
Blyth	17651	N/Hall Farne School	91-03	NZ204 672

Only 5 of the recording raingauges listed above were formally quality assessed as part of an earlier TBR performance review carried out for the Environment Agency. These were Chard, Darras Hall, Tideswell, Bickley and Bishops Castle. Over the 2000-2004 data period investigated, as part of the Environment Agency project, each of these 5 TBRs had few reasonably short periods when the TBR record was rejected, such as damage, blockage, or frozen components.

2.6 Conclusions

Based upon a spatial and temporal analysis of soil and landuse data and availability of good quality hourly flow gauging data and the availability tipping bucket rainfall data, the following seven catchments have gone forward to the next stage of the project

- Axe
- Blyth
- Bain
- Isle
- Parrett
- Teme
- Wye (Derbyshire)

These catchments cover a range of sizes (<100 km^2 to >1000 km^2), have a regional distribution (Anglian, Midlands, South West and North East), significant proportions of the vulnerable soil types and major land use systems and a range of trends in these land use systems (Figures 2.10-14),. However, following the stakeholder workshop on 28th November 2006 and stakeholder suggestions from the project's WIKI site, further catchments in the West Weald, Upper Thames, South Downs, as well as the Lugg catchment and a forested catchment were assessed for data availability and quality - the Lugg and the Irthing were eventually added to the catchment selection.

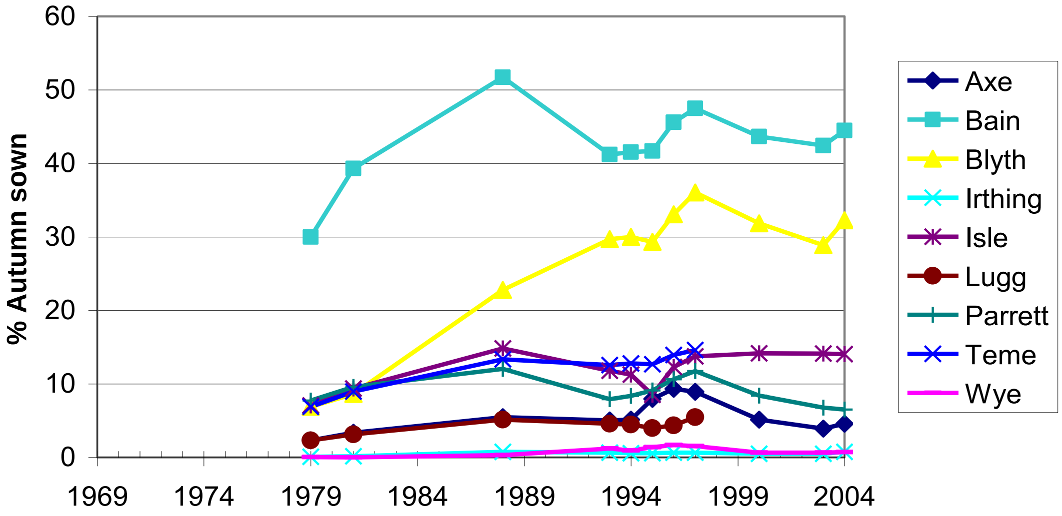

Figure 2.10 Change in percentage area of autumn sown crops (1979-2004)

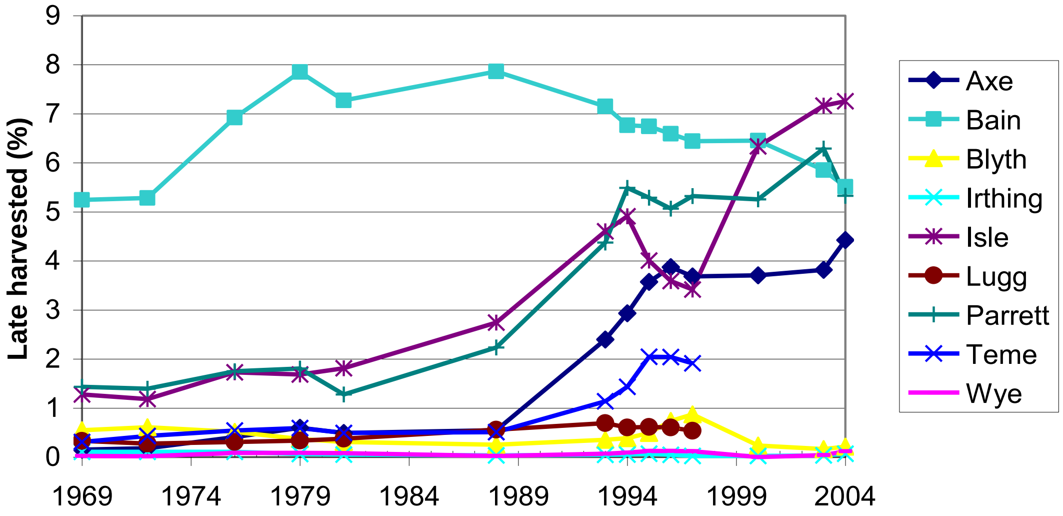

Figure 2.11 Change in percentage area of late harvested crops (1969-2004)

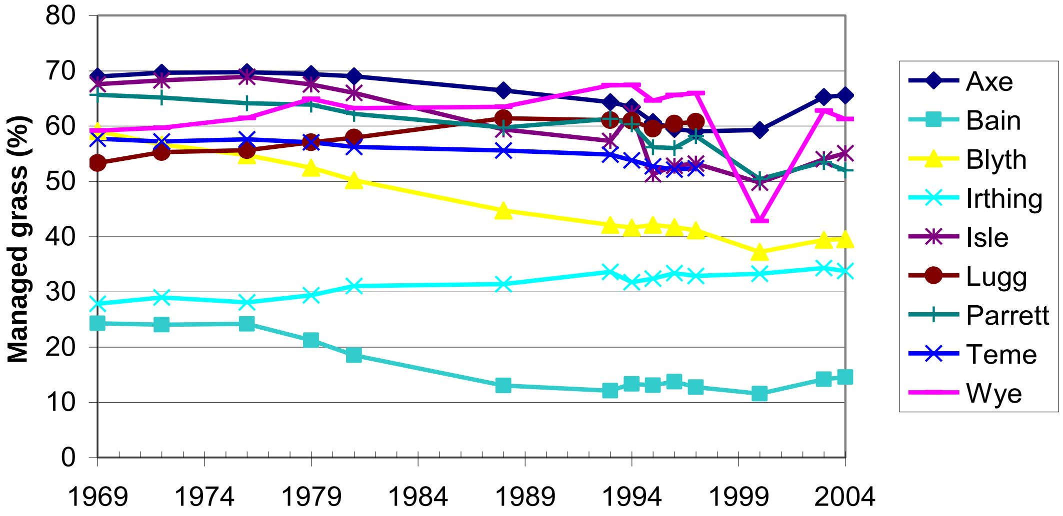

Figure 2.12 Change in percentage area of managed grassland (1969-2004)

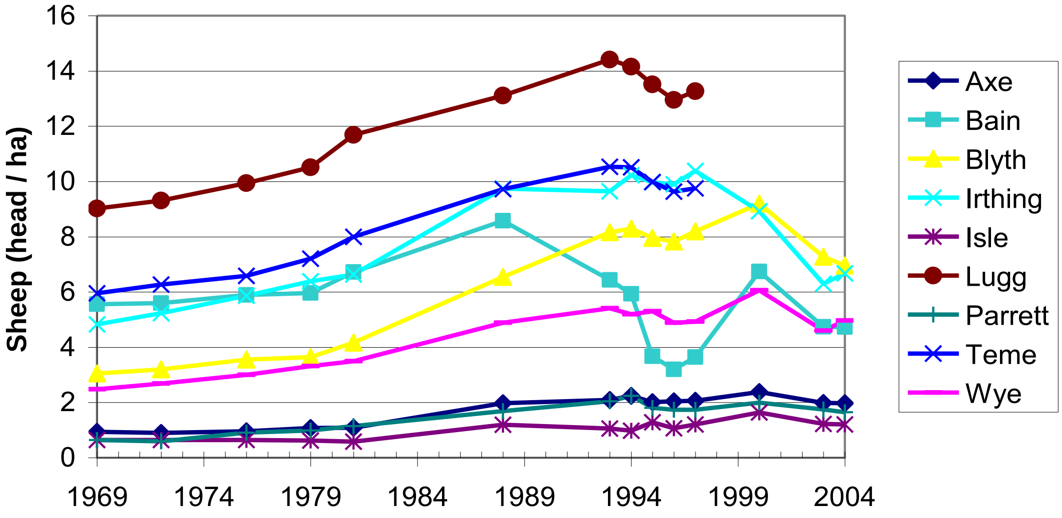

Figure 2.13 Change in the number of sheep per hectare of managed grassland (1969-2004)

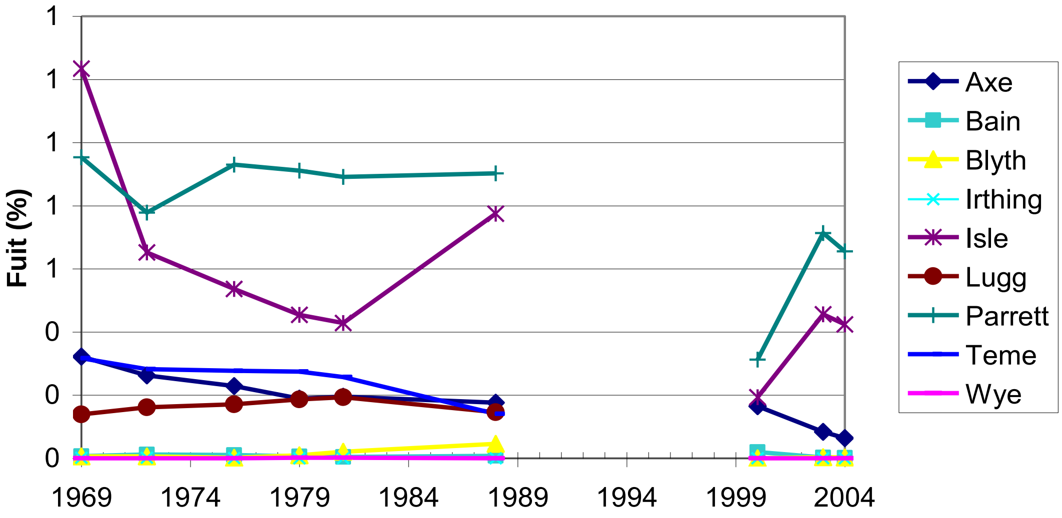

Figure 2.14 Change in percentage area of fruit (1969-2004)

The selection of these nine catchments was largely driven by an analysis of broad scale national data sets. As a final element of the process, interviews were carried out with key informants in two of the shortlisted catchments (Axe and Lugg) as a means of semi ‘ground-truthing’ their selection. The results of these interviews are described in Appendix 2.

3. APPLICATION OF METHODS OF ANALYSIS

3.1 Introduction to methods of analysis

Two types of methods for the identification of change based directly on the analysis of the available data are presented in this report. The first is based on dynamic harmonic regression, which allows any trends and changes in amplitude of frequency components to be detected in a single hydrological time series (here catchment discharge). The method is presented in more detail in Technical Appendix 3, where it is shown how the parameters of the time series model are identified recursively, allowing non-stationary changes in the characteristics of the time series to be identified, together with estimates of uncertainty in the modelled components. This therefore represents a significant advance on simple methods of trend analysis.

The second methodology is concerned with identifying change in the dynamic response of the catchment. To do this the *Data-Based Mechanistic* (DBM) modelling approach of Young (e.g. Young, 2001) is used. The method of analysis is based on modelling the rainfall-flow relationship using a combination of a nonlinear transformation of the input and a linear transfer function (impulse response hydrograph). The structure of this modelling methodology is shown in Figure 3.1. The novelty of this method of rainfall-runoff modelling is the way in which State Dependent (SDP) estimation is used to identify the catchment nonlinearity from the data in a non-parametric way, rather than defining a prior mathematical structure for the model (Young, 2000, 2001, Young *et al*, 2001). The model components are identified directly from the data rather than being imposed a priori. In this way, changes in either the nonlinearity or the transfer function dynamics might be detectable, noting that the models attempt to relate the inputs to outputs in a way that effectively conditions for any climate variability or change. The analysis methods are described in detail in Technical Appendix 3. They will be applied to the catchments chosen in WP1 of this project as described in Section 3 above.

The results of applying the methodology will be described below in detail for the Axe catchment and briefly for the other catchments, with the full results presented in Technical Appendix 4. For the Axe catchment alone, a further analysis step has been carried out to test for changes in the event dynamics by carrying out a classification of events by antecedent conditions and peak flows.

Both of the above analyses are applied to the 9 chosen catchments (Table 3.1).

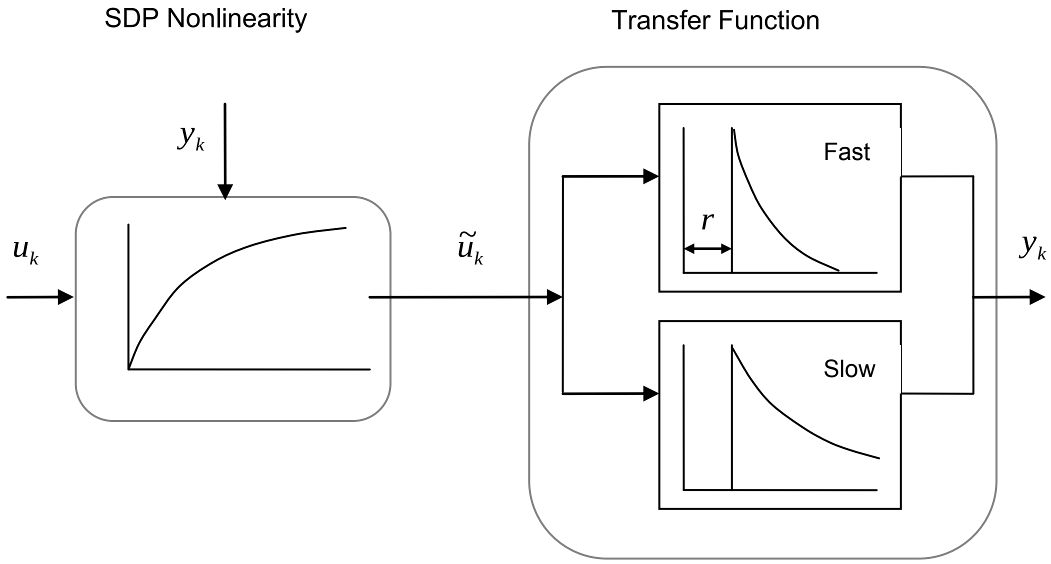

Figure 3.1 Schematic structure of the Data-Based Mechanistic (DBM) model with State Dependent Parameter (SDP) nonlinearity: ***u_k* is model input (rainfall) at time step *k*, *y_k* is model output (discharge) at time step *k*, *r* is a time delay**

Table 3.1 Hydrometric data available for each catchment

Catchment	Catchment area (km2)	Flow record	Tipping bucket record		Storage gauge record	
Blyth	269	1963-2003	1986-2003	1983-1994	1970-2003	1973-1993
			1994-2003	1991-2003		1970-2003
Bain	197	1979-2003	1987-2003	1987-2003	1970-2003	1973-1993
				1987-2003		1970-2003
Wye	154	1971-2003		1980-2003	1988-2003	1978-2003
				1985-2003		1991-2003
Teme	1134	1969-2003	1981-2003	1986-1997		1979-2003
			1982-2003	1980-2003		1961-1999
Isle	90	1962-2003		1995-2003		1980-2003
				1966-1985		1984-2003
Axe	289	1964-2003	1998-2003	1995-2003	1968-2003	1956-2000
			1998-2003	1966-1985		1979-2003
Parrett	75	1966-2003		1995-2003		1971-2003
				1966-1985		1984-2003
Lugg	203	1981-2003	1991-2003	1993-2003	1966-1990	1968-1996
						1961-2003
Irthing	335	1975-2003	1992-2003	1992-2003	1961-2003	1969-2003
				1992-2003		1990-2003

3.2 The Axe catchment

Background information on Axe catchment, Devon, South West, is available on the Hiflows UK website. The catchment area to the gauging station below Whitford Bridge is 288.5 km^2. The discharges are measured using a Compound Crump profile weir, total width 21.3m, low flow section 7.6m broad. There is a cableway on site. The Structure limit is at 2.1m stage and some drowning occurs at high flows. Overspill occurs at 1.65m on left bank and in large floods there is considerable bypassing. Velocity area rating is available to above modular limit, with bypassing included in the rating. The rating is confirmed to bankfull but there is some doubt beyond. Many higher flows are out of bank.

This is a complex catchment of moderate relief draining Chalk and Greensand headwaters. Middle and lower reaches Keuper Marls, Lias Clays and more Greensand. Land use is primarily pasture and meadowland, with low intensity arable agriculture, some woodland and minor industrial development.

Discharges are influenced by groundwater abstraction/recharge. There are abstractions for public water supply and industrial/agricultural purposes, while flows are increased by effluent returns.

Digital water level observations on Axe at Whitford start on the 05 Nov 1964 and end on the 30 Sep 2003. Daily rainfall measurements are available for the years 1956-2003, however a only short period of full hourly rainfall measurements is available (1988-1992). Due to the fact that Isle catchment, with much more extensive hourly rainfall records, is situated very close to Axe, the Isle rainfall data have been used to allow a much longer period to be analysed. Figure 3.2 presents available hourly rainfall and flow data for Axe.

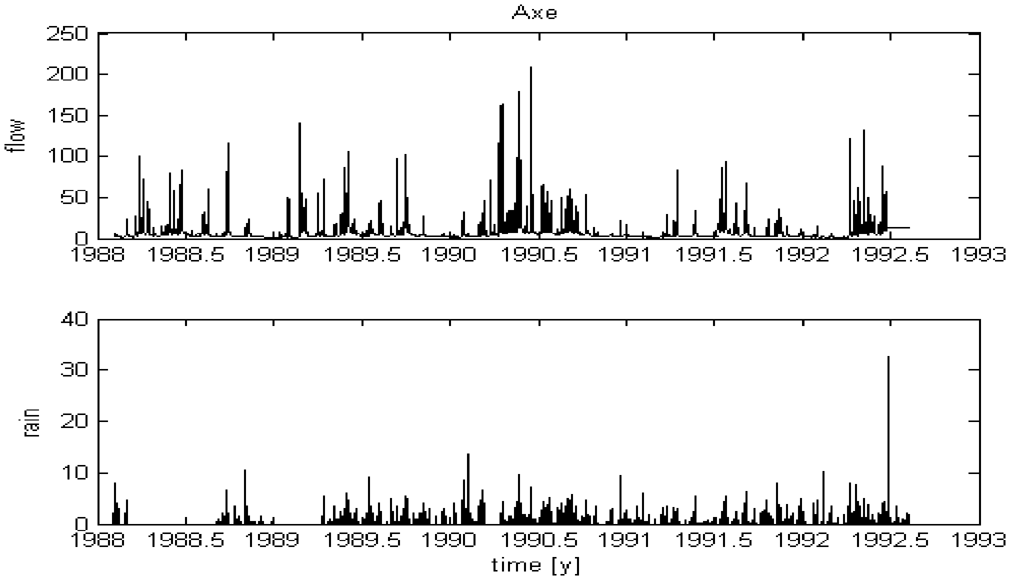

Figure 3.2 Flow and rainfall data for Axe

3.3 Testing for trends using Dynamic Harmonic Regression: application to the Axe catchment

Dynamic Harmonic Regression (DHR) analysis provides an estimate of any non-stationary trend in a single time series, together with confidence limits that can be used to test for the significance of the trends. Here, this method has been used to model log transformed monthly values of both rainfalls and discharges. The resulting estimates are shown in Figure 3.3 where red dotted lines show the confidence limits and the observations are marked by dots. Under the assumption that the errors in the trend estimation are normally distributed, a normal test for the significance of the variations in the trend can be carried out. In the case of the Axe this reveals no trend in rainfall but a significant positive trend in discharge.

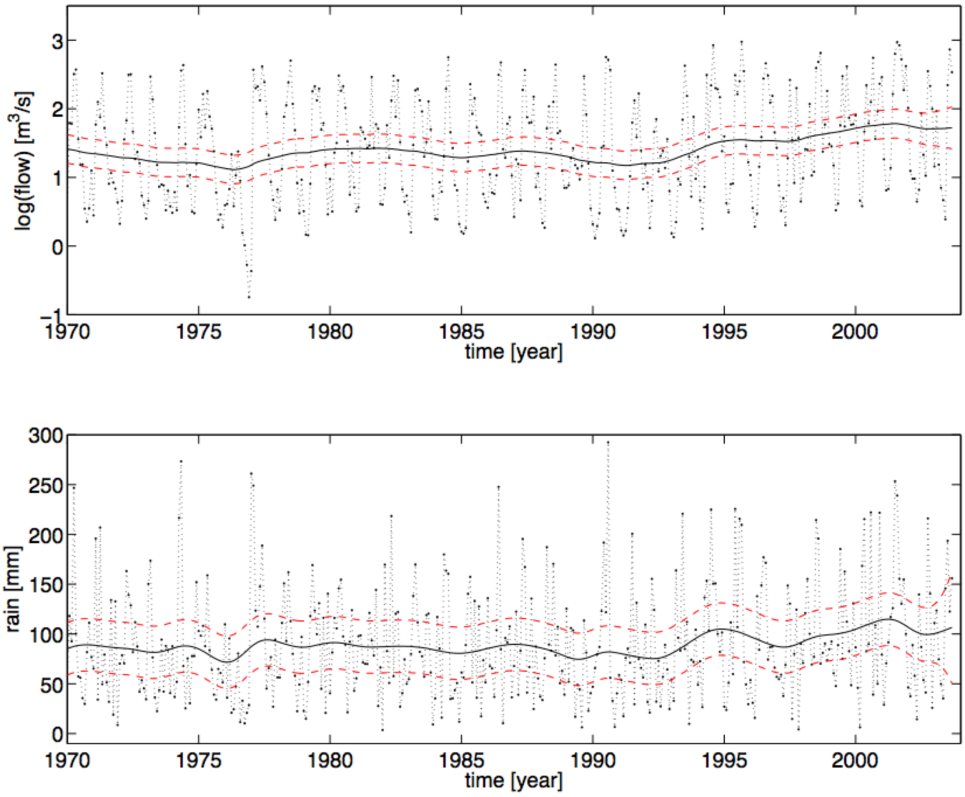

Figure 3.3 Comparison of trend of logarithm of monthly flow (upper panel) and monthly rainfall (lower panel); red dashed line denote 0.95 confidence bounds for the trend, black dots with a dotted line denote the observations.

In order to obtain a more direct quantitative comparison, Figure 3.4 presents estimated trends in rainfalls and flows on a common scale for the period 1970-2003. The discharge series have been normalised by scaling to be equivalent to the cumulative rainfall over the whole time period. The figure shows flow values increasing relatively more than rainfall for the time period starting at the end of the nineties (1998 onwards).

3.4 Testing for trends using Dynamic Harmonic Regression: results for the other catchments

The conclusions of the analysis for longer term trends over all the catchments are summarised in Table 3.2. Full details of all the analyses are given in Technical Appendix 4.

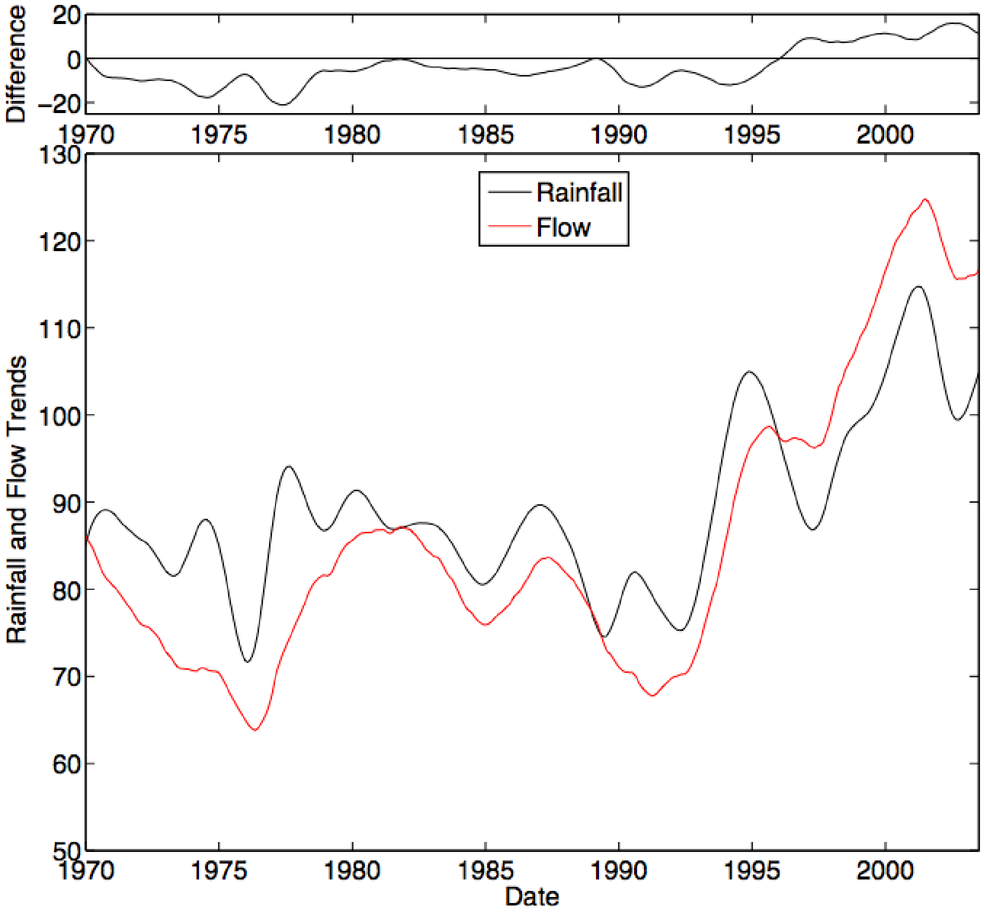

Figure 3.4 Nonstationary trends in monthly rainfall and flows in the Axe catchment scaled to equal total volumes

Table 3.2 Results of analysis of trends in monthly rainfalls and flows for all the catchments in the study

	DHR Trend in Monthly Rain	**DHR Trend in Monthly Flow**
Axe	None	Positive
Bain	None	None
Blyth	None	None
Irthing	None	None

Isle	None	Positive
Lugg	None	None
Parrett	None	None
Teme	None	None
Wye	None	None

3.5 Testing for changes in catchment dynamics: application to the Axe catchment

We applied DBM modelling approach to the hourly flow and rainfall data in an investigation of potential change in the hydrograph characteristics over time. The form of the model is shown in Figure 3.1. With a 2nd order transfer function that can be represented as parallel fast and slow pathways as shown in Figure 3.1, there are effectively 5 model parameters, one defining the nonlinearity; 2 defining the proportion of the transformed rainfall going through each pathway, and 2 defining the mean residence time in each pathway.

The application of DBM modelling approach required the choice of the time periods for the analysis. In order to facilitate the procedure, we decided to apply two stages of analysis. The first stage was aimed at an exploration of the modelling potential of the datasets and catchments characteristic features. This approach was applied to all 9 catchments under consideration. The second stage consisted of modelling groups of events classified by antecedent conditions, in order to investigate whether estimated changes to the catchment dynamics might depend on the hydrological conditions. These latter results are reported below in Section 3.7.

The first stage of the analysis was based on selected wet periods extracted from the full period of available data, in order to minimise the effects of dry antecedent conditions on the initial analysis. The length of the analysis periods was chosen to cover the full high-flow season from Autumn to Spring, with exceptions where data were missing. We identified 21 periods for the Axe catchment, the majority of which had a length of 4760 hours (198 days). During the analysis of the rainfall-flow relationship it occurred that the flow records had to be delayed by 5 to 10 hours to bring them into conformity with the rainfall measurements.

The SDP analysis resulted in the identification of a nonlinear SDP gain that is parameterised using an exponential relationship identified from the shape of the nonlinearity estimated during initial nonparametric SDP identification. The estimation of the single parameter γ in this SDP nonlinearity (see below) was carried out simultaneously with the estimation of the parameters of a linear stochastic transfer function (STF) model that quantifies the dynamic characteristics of the hydrograph. We identified a linear second order STF model [2 2 0] (i.e. a STF model with 2nd order denominator, 2nd order numerator and no advective time delay) for all the chosen periods. This model has a form:

$$y_k = \frac{b_0 + b_1 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}} \tilde{u}_k + \xi_k \qquad \text{Equation 3.1}$$

where z^{-1} is the backward shift operator, i.e. $z^{-r} y_k = y_{k-r}$. Based on initial analysis of the data from these catchments, a general parametric form for the nonlinearly transformed or "effective" rainfall is defined by

$$\tilde{u}_k = s_o \left(1 - \exp\left(\gamma\, y_k\right)\right) u_k \qquad \text{Equation 3.2}$$

with the single parameter γ that is estimated simultaneously with the STF model parameters, b_0, b_1, a_1, a_2 using the SRIV procedure from the CAPTAIN toolbox . The normalising constant s_0 is derived from the assumption that mass balance is maintained in the catchment and is not estimated. A summary of the model parameters identified for the different periods of data is given in Table 3.3.

Table 3.3. DBM model parameters for the Axe catchment.

Start of event	a_1	a_2	b_0	b_1	γ	R_T^2
19-Sep-1966	-1.9201	0.9202	0.0385	-0.0383	0.0817	0.8769
30-Sep-1966	-1.9155	0.9158	0.0360	-0.0358	0.0977	0.8886
30-Sep-1967	-1.9053	0.9057	0.0291	-0.0289	0.0722	0.9176
30-Sep-1968	-1.9108	0.9109	0.0388	-0.0387	0.0590	0.8398
30-Sep-1969	-1.8816	0.8821	0.0412	-0.0407	0.0576	0.9035
30-Sep-1970	-1.8952	0.8955	0.0359	-0.0357	0.0236	0.7893
30-Sep-1971	-1.8901	0.8904	0.0463	-0.0460	0.0453	0.8543
30-Sep-1972	-1.8921	0.8923	0.0413	-0.0412	0.0337	0.9323
30-Sep-1973	-1.8681	0.8689	0.0489	-0.0483	0.0507	0.8956
30-Sep-1974	-1.8791	0.8798	0.0460	-0.0456	0.0672	0.9129
30-Sep-1975	-1.9084	0.9088	0.0205	-0.0203	0.0589	0.9412
30-Sep-1976	-1.9015	0.9017	0.0358	-0.0357	0.0225	0.8506
30-Sep-1977	-1.8892	0.8893	0.0466	-0.0465	0.0453	0.9483
30-Sep-1978	-1.9213	0.9214	0.0385	-0.0384	0.0502	0.9704
31-Oct-1996	-1.9154	0.9157	0.0341	-0.0339	0.0616	0.8849
01-Nov-1997	-1.8872	0.8877	0.0509	-0.0504	0.0501	0.9132
10-Jan-1999	-1.8567	0.8580	0.0422	-0.0415	0.0098	0.8645
30-Nov-1999	-1.8911	0.8918	0.0485	-0.0481	0.0428	0.9395
31-Oct-2000	-1.8530	0.8538	0.0613	-0.0608	0.0304	0.8851
01-Nov-2001	-1.9100	0.9102	0.0358	-0.0357	0.0232	0.8521
17-Oct-2002	-1.8932	0.8936	0.0578	-0.0574	0.0601	0.9145

The parameters a_1 and a_2 define the residence times for the slow and fast components of the second order TF model, while combined parameters b_0, b_1, a_1, a_2 are used to derive the model gain and proportions between the fast and slow flows (see below). The parameter γ defines the nonlinear relationship used to linearise the transfer function component of the model.

The nonlinear gain, $g_k = s_0 \cdot (1 - \exp(\gamma \cdot y_k)$, obtained for all the models shown in Table 3.3, is shown in Figures 3.4 a, b. Note that the confidence limits plotted on these, and all similar plots in this report, are those arising from the uncertainty in the parameters of the identified nonlinearity.

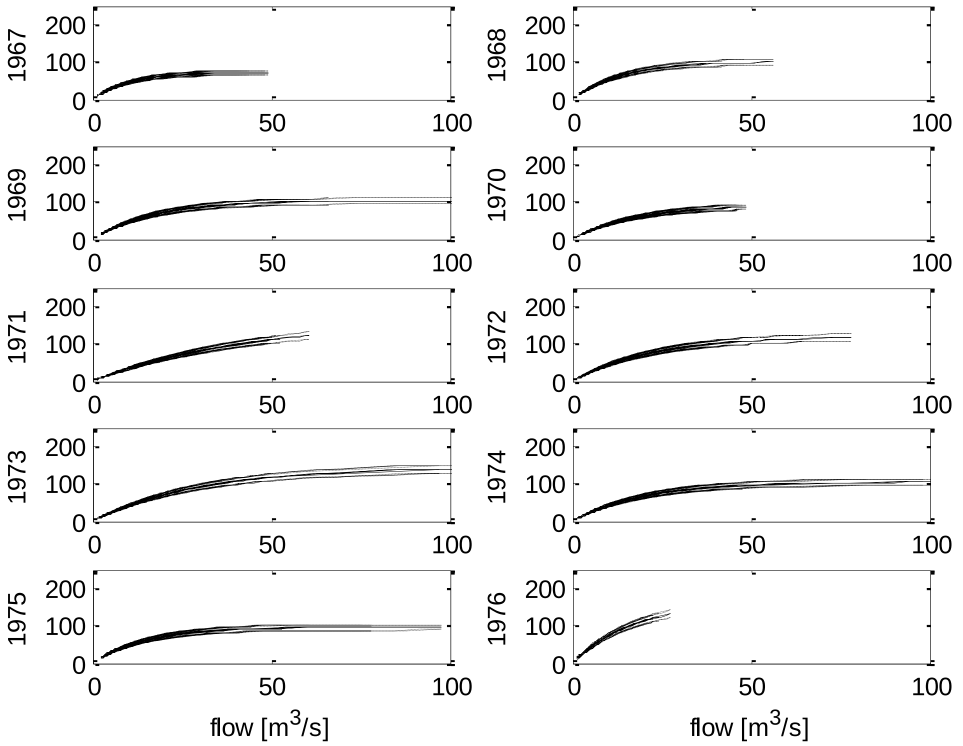

Figure 3.5a Nonlinear gains for the years 1967-1976 with 0.95 confidence bounds

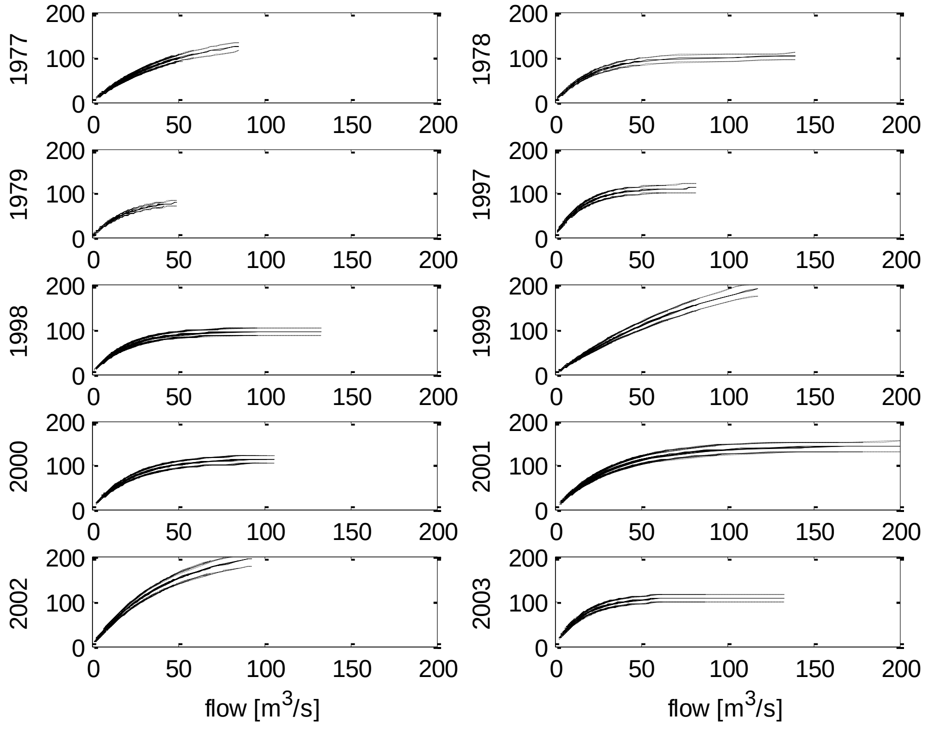

Figure 3.5b Nonlinear gains for the years 1977-2003 with 0.95 confidence bounds

Following the description of the methods given in Technical Appendix 3, the transfer function can be decomposed into quick and slow catchment system responses.

These decomposed components take the following form:

$$\text{Fast Component:} \quad y_{1,k} = \frac{\beta_1}{1+\alpha_1 z^{-1}} u_{k-\delta}$$

$$\text{Slow Component:} \quad y_{2,k} = \frac{\beta_2}{1+\alpha_2 z^{-1}} u_{k-\delta}$$

Equation 3.3

where $\alpha_1, \alpha_2, \beta_1, \beta_2$ are parameters derived from (1) and the total observed flow is the sum of these two components and a model error, i.e. $y_k = y_{1,k} + y_{2,k} + \xi_k$. The associated residence times (time constants), T_1, T_2, steady state gains, G_1, G_2, and partition percentages, P_1, P_2, are given by the following expressions:

$$T_i = \frac{\Delta t}{\log_e(\alpha_i)};\ i=1,2 \qquad G_i = \frac{\beta_i}{1+\alpha_i};\ i=1,2 \qquad P_i = \frac{100 G_i}{G_1+G_2};\ i=1,2$$

Equation 3.4

From the model identification in each period of data, the estimated parameters of the STF model (1) are obtained together with their covariance matrix. The uncertainty of residence times, proportions and gains can then be estimated by sampling from the covariance matrix using Monte Carlo analysis. The results of the MC analysis for the proportions are presented in Figure 3.6.

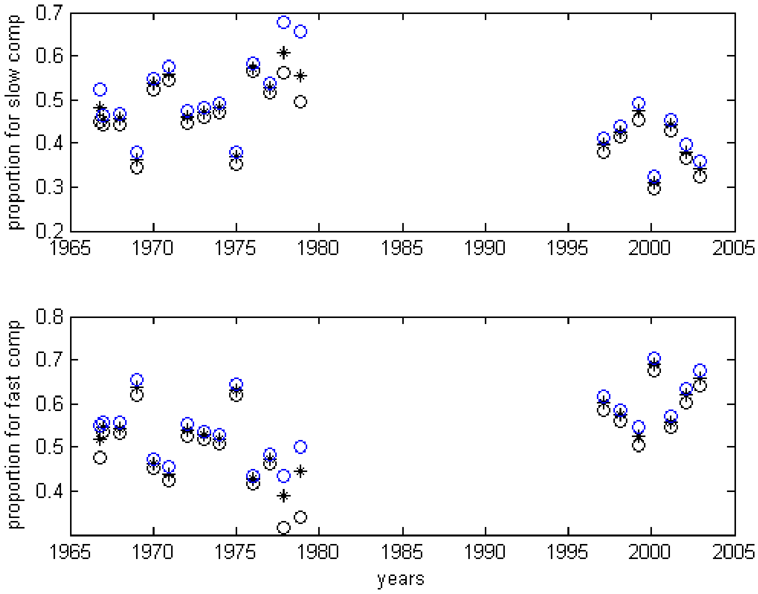

Figure 3.6 Proportions (black dots) with 0.95 confidence bounds (black and blue circles) for Axe catchment

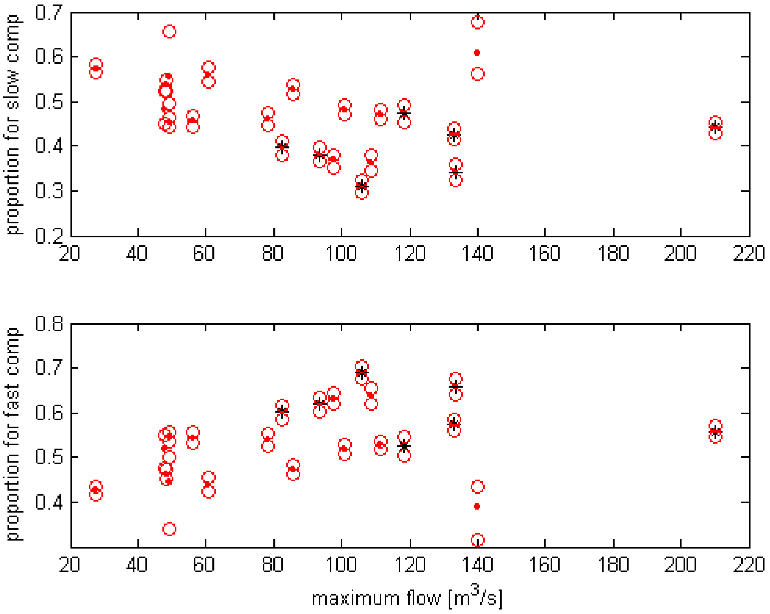

Figure 3.7 Proportions (red dots) with 0.95 confidence bounds (red circles) against maximum flow, Axe catchment. Black stars denote events from the years 1995-2003

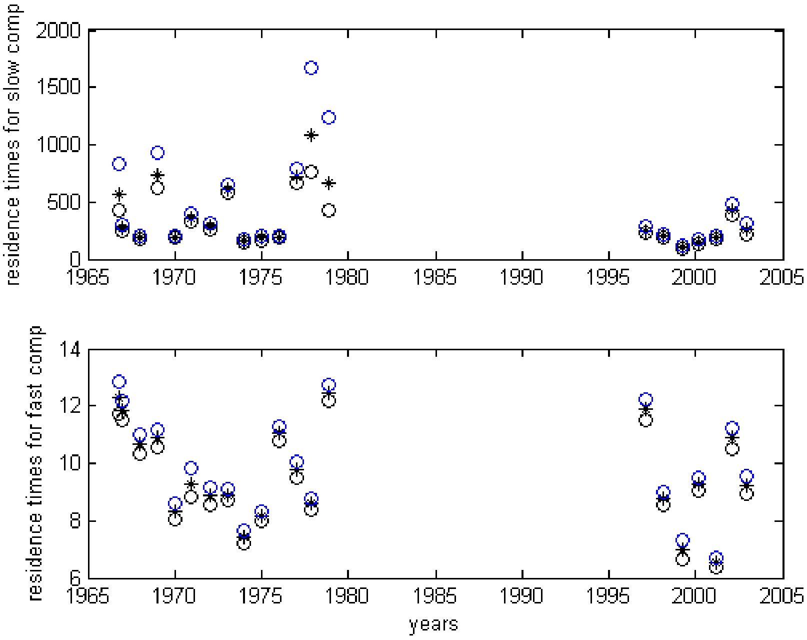

Figure 3.8 Residence times (hours) (black dots) with 0.95 confidence bounds (black and blue circles) for Axe catchment

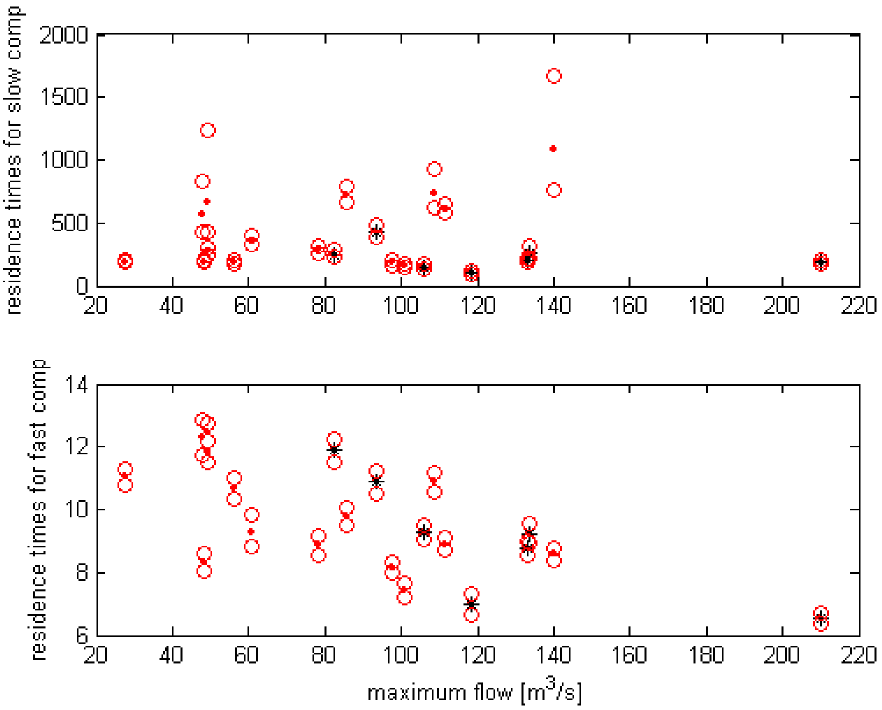

Figure 3.9 Residence times (hours) (red dots) with 0.95 confidence bounds (red circles) against maximum flow, Axe catchment. Black stars denote events from the years 1995-2003

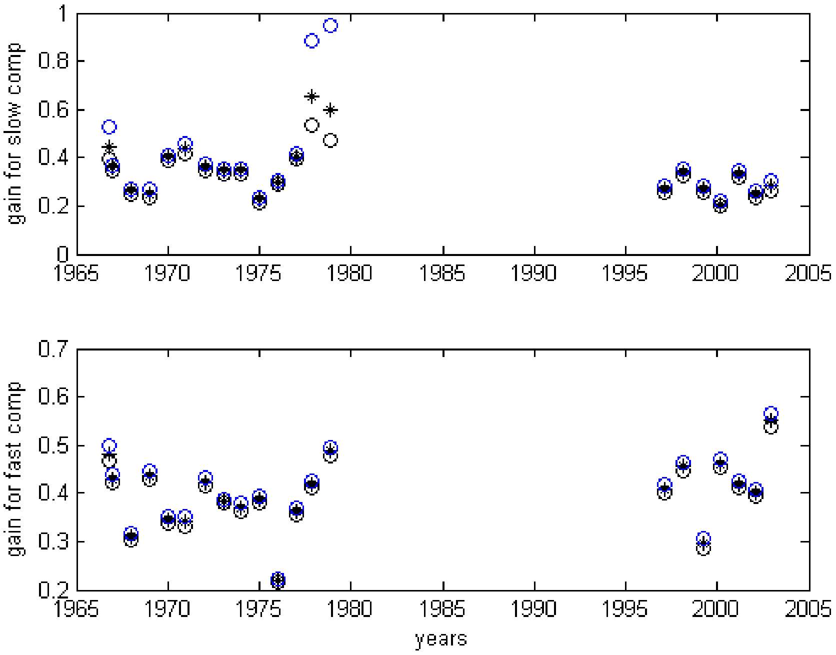

Figure 3.10 Gains (black dots) with 0.95 confidence bounds (black and blue circles) for Axe catchment

The results of the analysis indicate that the proportions for both fast and slow components and residence times for the fast component of DBM models show a trend with the maximum flow in the periods but no strong change with time is identified, given the variability evident from period to period (Figures 3.6-3.10). There is no evidence of any relationship between total rainfall in the period and these derived variables (not shown here). Figure 3.11 shows the goodness of fit for the models.

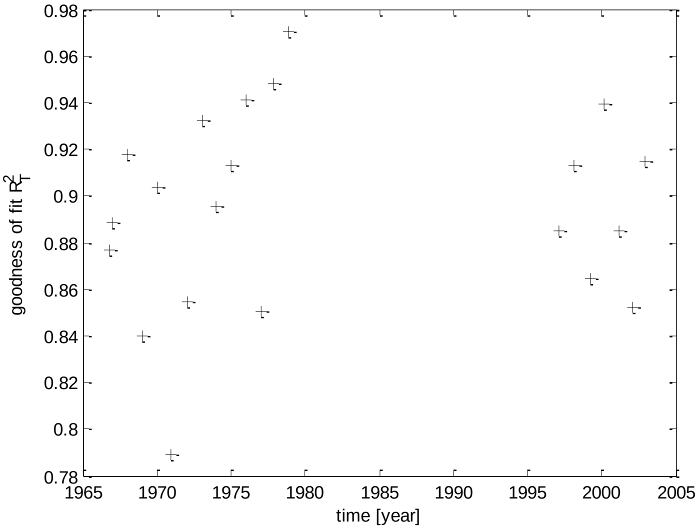

Figure 3.11 Goodness of fit (R_T^2) for all the models related to the Figures 3.6-3.10

3.6 Testing for changes in catchment dynamics: results for the other catchments

The conclusions of the analysis for changes in catchment dynamics using the DBM methodology over all the catchments are summarised in Table 3.4. Full details of all the analyses are given in Technical Appendix 4.

It is clear that, as in the Axe catchment results presented above, in most of the catchments there are no clear changes identifiable over time, given the variability from period to period of the analysis. This variability may arise as a result of both natural variability and data quality. In some cases there appear to be relationships between the best estimates of the summary parameters in a period and the maximum flow in that period suggesting some nonlinearities in the response that the model is not totally capturing (see also Section 3.7 below). Notably in the Irthing, Isle and Lugg, there is a tendency for the fast residence time to decrease with maximum flow in the period.

Table 3.4 Results of analysis of changes in catchment dynamics for all the catchments in the study

	Analysis of DBM derived variables (fast and slow components, proportions, mean residence times and gains)
Axe	No clear change with time, some relationship with maximum flow.
Bain	No clear change with time, slight tendency for proportions of fast and slow components to change with time
Blyth	No clear change with time or hydrological conditions
Irthing	Slight tendency for proportions and gains to change with time; fast residence time reduces with maximum flow
Isle	No clear overall changes with time, possible changes in recent period. Fast residence time tends to decrease with maximum flow in period
Lugg	Slight tendency for proportions to change with time; fast gain shows some tendency to increase with time (except 2000); fast residence time decreases with maximum flow in period
Parrett	No clear change with time or hydrological conditions
Teme	No clear change with time or hydrological conditions
Wye	No clear change with time or hydrological conditions

3.7 Testing for change in catchment dynamics: application to different classes of events in the Axe catchment

To test the possibility that the possibility for identifying change might be dependent on the nature of particular events, the DBM analysis was repeated for the Axe catchment using a simple event classification. In the time available it was not possible to explore different ways of classifying events, and there was a requirement that there should not be too many classes so as to ensure that there would be a sufficient number of events in each class and for both the pre-1980 and post-1995 period. Thus, a simple four-fold classification was used, based on the peak flow in an event and an index of antecedent conditions, that was here taken to be the rainfall in the three days prior to the peak. A plot of all the events used in the analysis and the ranges of values for the antecedent conditions and peaks for the different classes are shown in Figure 3.12. The definitions of the classes is shown in Table 3.5.

To carry out the DBM analysis, the events in each class are concatenated and the identification algorithm applied recursively to each event in succession. The final parameter estimates at the end of one event could be used as initial estimates at the beginning of the next event. This was carried out in two stages. In the first, the simplest first order model is identified over all events in each class for the pre-1980 and post-1995 events separately. This was then used to identify and parameterize the SDP nonlinearity that was then fixed for all events in the two periods. In each period, the nonlinearity was applied before identification of 2nd order models with fast and slow pathways for each event. Most events in all 4 classes could be fitted well (rt2>0.8), but some could not be modeled well. Events with rt2<0.5 are excluded from the plots that follow.

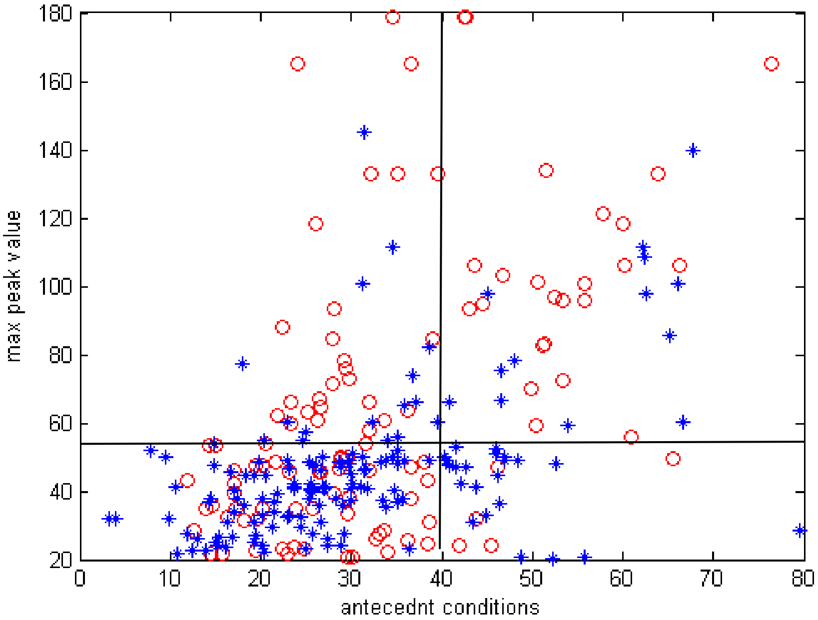

Figure 3.12. All events chosen according to 2 by 2 classification, peak values against antecedent conditions. Blue crosses: pre-1980; red circles: post-1995. Lines show boundaries of event classification

Table 3.15 Definition of Event Classes

Class	Antecedent conditions (mm)	Peak height (m^3s^{-1})
I	3-40	20-55
II	40-80	20-55
III	3-40	55-180
IV	40-80	55-180

3.7.1 Analysis of Class I events.

Class I events have the smallest peak flows and the lowest antecedent rainfall. This class has the most events of all the classes. Concatenated hydrographs for the events are shown in Figure 3.13. Identified nonlinearities are shown in Figure 3.14 for the pre-1980 and post-1985 periods and show some differences. Fast and slow component residence times are shown in Figure 3.15 where it is seen that all the post-1995 residence times are low, but of the same order and variability as those identified for pre-1972 events. The 1973-1980 period shows generally longer apparent residence times and much greater variability (Figure 3.14).

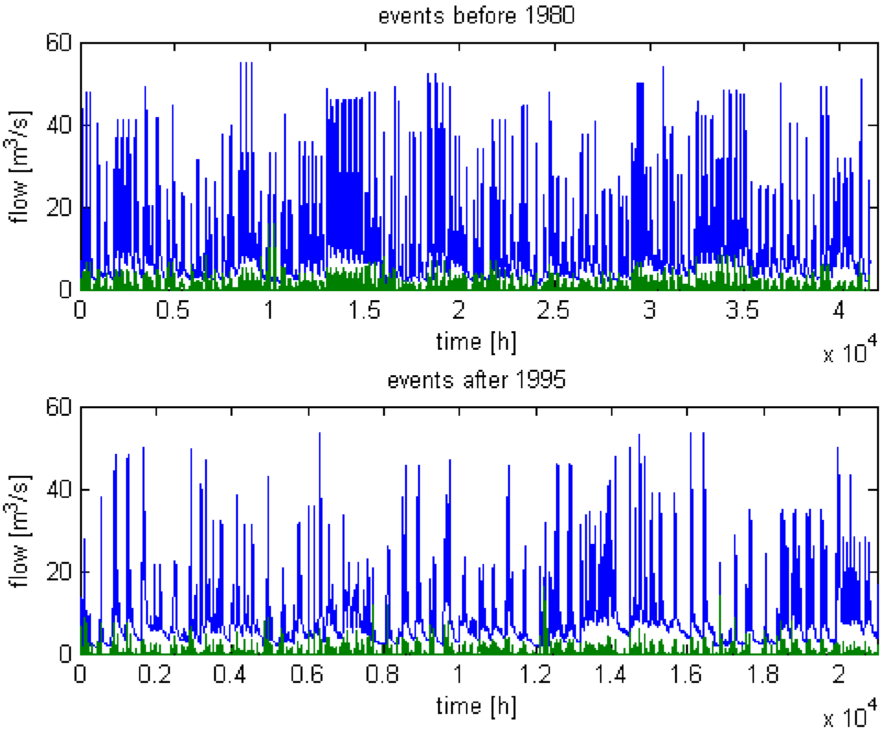

Figure 3.13 Concatenated Class I events (rainfall in green; flow is blue) : pre-1980 (top), post-1995 (bottom)

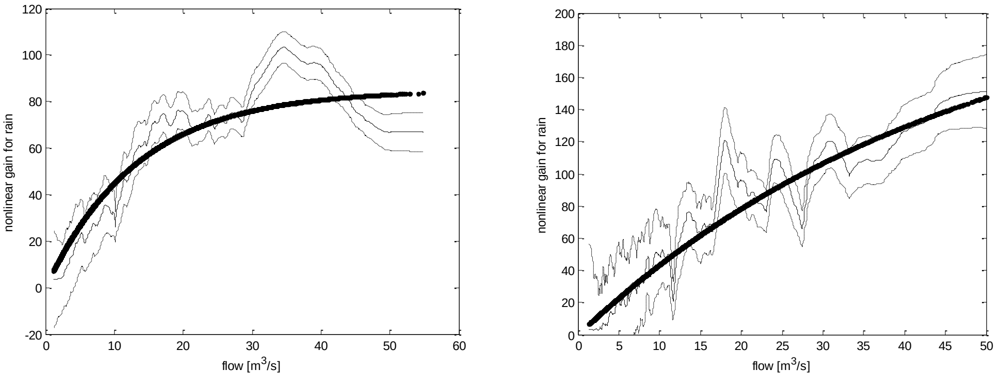

Figure 3.14 Identified SDP nonlinearity for Class I events: pre-1980 (left) and posr-1995 (right). Solid lines represent fitted parameterized nonlinearity.

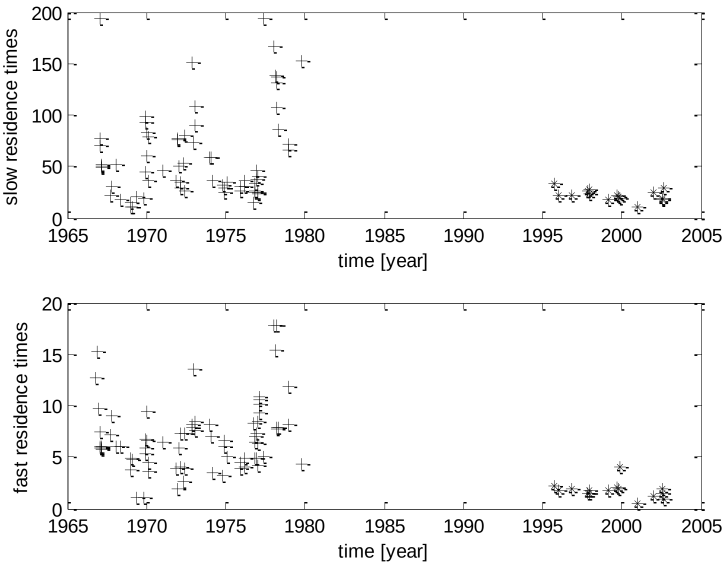

Figure 3.15 Results of second order TF analysis with nonlinear gain on the input: Slow and fast component residence times (hours) for Class I events with rt2>0.5 and real roots

3.7.2 Analysis of Class II events.

The concatenated events for Class II are shown in Figure 3.16. These are events with relatively high antecedent rainfalls but relatively low peak flows. This Class also showed a significant difference in the identified nonlinearities between the pre-1980 and post-1995 events, shown in Figure 3.17 (but note the limited number of post-1995 events. This class shows an apparent decline in the fast component residence time in the pre-1980 period, but the events post-1995 are within the same range. The slow flow component also shows a decline in the pre-1980 period, and low values in the post-1995 period (Figure 3.18).

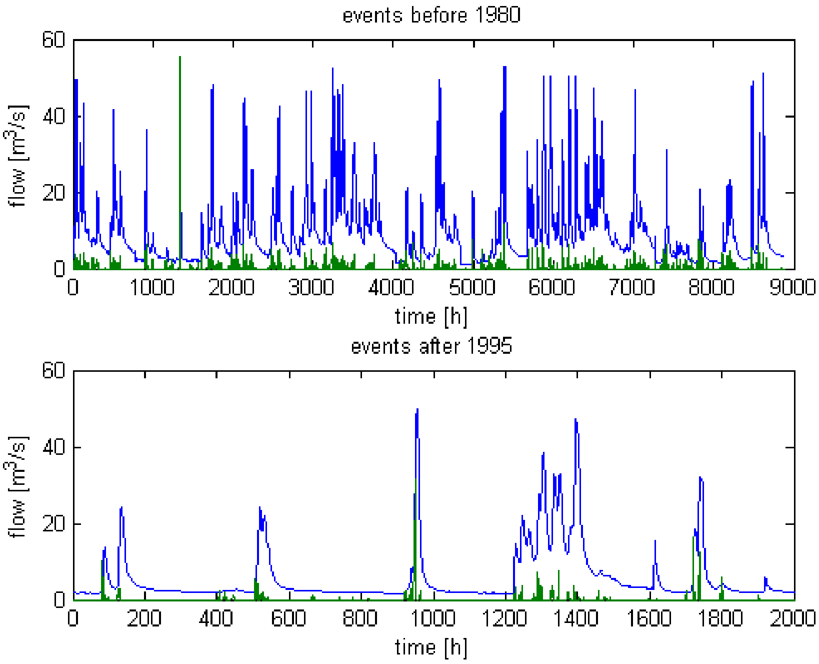

Figure 3.16 Concatenated Class II events (rainfall in green; flow is blue) : pre-1980 (top), post-1995 (bottom)

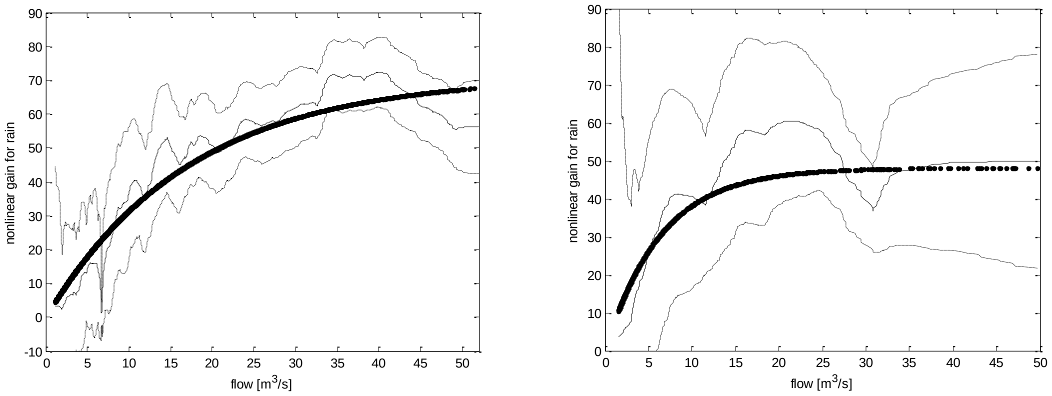

Figure 3.17. Identified SDP nonlinearity for Class II events: pre-1980 (left) and posr-1995 (right). Solid lines represent fitted parameterized nonlinearity.

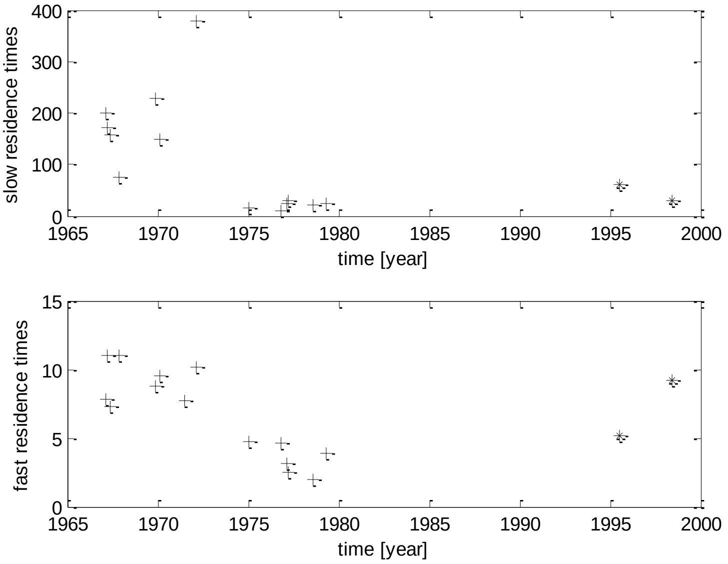

Figure 3.18 Results of second order TF analysis with nonlinear gain on the input: Slow and fast component residence times (hours) for Class II events with rt2>0.5 and real roots

3.7.3 Analysis of Class III events

The concatenated Class III events are shown in Figure 3.19. These are events with relatively low antecedent rainfalls but relatively high flow peaks. The slow component residence times show a similar apparent decline to the Class II events in the pre-1980 period, staying low post-1995 (Figure 3.20). The range of the fast component residence time is similar in both periods.

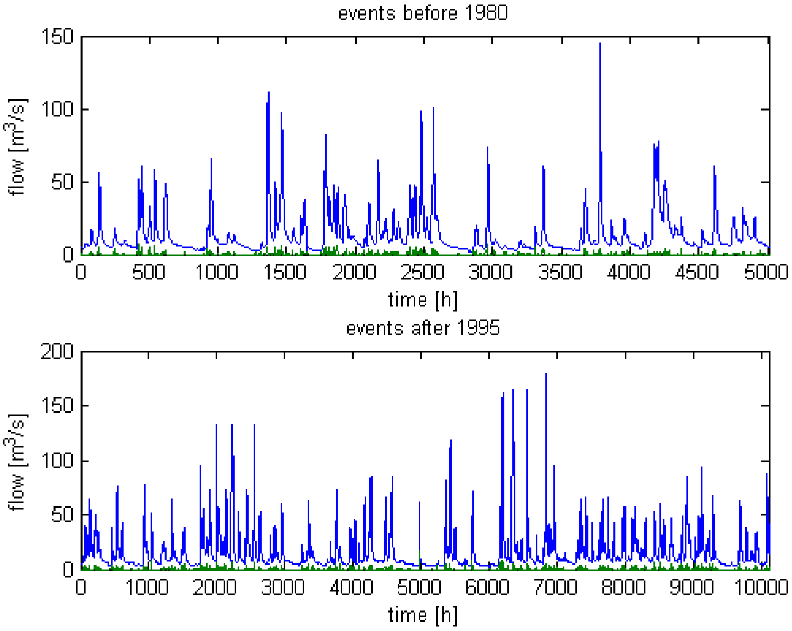

Figure 3.19 Concatenated Class III events (rainfall in green; flow is blue) : pre-1980 (top), post-1995 (bottom)

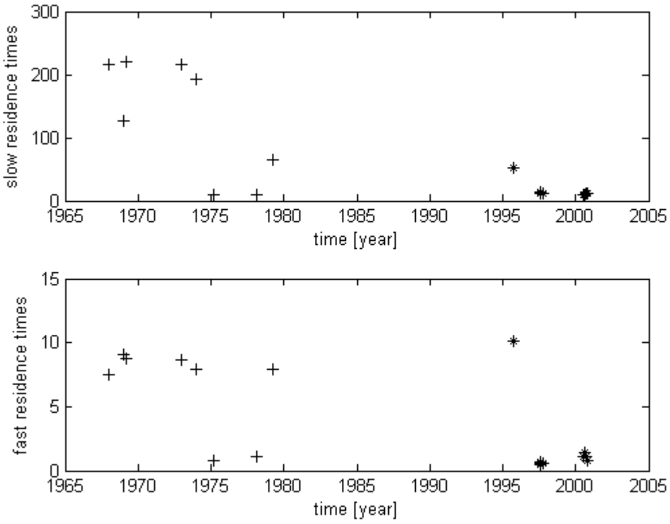

Figure 3.20 Results of second order TF analysis with nonlinear gain on the input: Slow and fast component residence times (hours) for Class III events with rt2>0.5 and real roots

3.7.4 Analysis of Class IV events

The events with both high antecedent rainfalls and high peak flows are shown in Figure 3.21. The slow residence times for the post-1995 events are low relative to the range pre-1980 (Figure 3.22), but the range of fast residence times is similar in both periods.

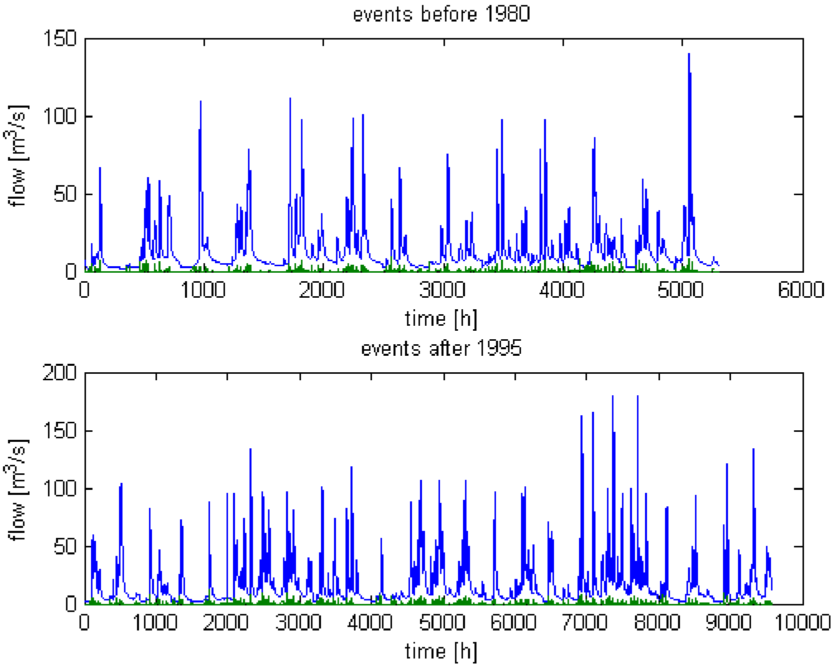

Figure 3.21 Concatenated Class IV events (rainfall in green; flow is blue) : pre-1980 (top), post-1995 (bottom)

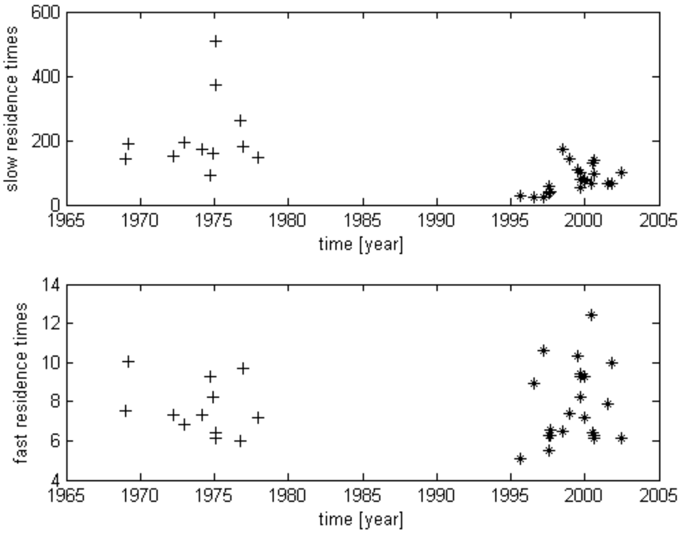

Figure 3.22 Results of second order TF analysis with nonlinear gain on the input: Slow and fast component residence times (hours) for Class IV events with rt2>0.8 and real roots

3.7.5 Summary of Analysis of Classified Events

The analysis of the different classes events has shown some more consistent changes in the catchment dynamics than the earlier year by year analysis. In particular, there is some suggestion that the slow component residence times have declined since the 1960s (Classes I, II, III and IV), suggesting a tendency towards steeper recession curves. There is less evidence that the fast component residence times are changing significantly.

This preliminary conclusion must be qualified by two factors. The first is that the nature of the selection of events means that the recession curves included in the analysis are incomplete. The second is that the fact that some events are not well fitted suggests that there are some inconsistencies remaining in the event data. This preliminary analysis therefore needs to be supplemented by a proper uncertainty analysis and a deeper study of ways of classifying events to maximize the information obtained from this type of analysis.

3.8 Limitations of the Analysis Methodology

The main limitation of the DHR and DBM analyses, as with any model-based method of statistical analysis, is that their success is dependent on having adequate amounts of relatively reliable data that satisfy the statistical assumptions on which the model, as well as the estimation of its parameters, are based. In particular, there is an implicit assumption that the residuals can be considered as randomly distributed. This has not generally been the case for the DBM analyses reported here. Inconsistencies in the measured rainfalls and discharges have led to non-stationary structure in the model residuals. Such inconsistencies or anomalies in the data and violation of the assumptions can lead to biases and ‘outlier’ effects. These can have a deleterious effect on both the parameter estimates and their estimated uncertainty (e.g. standard errors), so making the statistical significance of any estimated changes more difficult to evaluate quantitatively. Further work needs to be done on the effect of the classification method on the structure of the residuals, the analysis of the concatenated events and the uncertainties in the resulting parameter estimates before any firm conclusions can be drawn in respect of the significance of these results.

3.9 Conclusions from WP2

The analysis of the datasets from the chosen catchments were dominated by the year to year natural variability and some inconsistencies in the rainfall and flow data, making it difficult to identify the significance of apparent changes in behaviour. Only two of the catchments showed any consistent changes in the long term hydrological series, with both the Axe and Isle showing a positive increase in flow over time. These are adjacent catchments in the south-west.

The DBM analysis of catchment dynamics also showed relatively few apparent changes, with four of the catchments showing no clear changes at all (see the full results in Technical Appendix 4). Several of the results showed that the identified model parameters showed some relationship with maximum flow in a period, suggesting that there were some nonlinearities (or anomalies) in the data that were not being fully captured by the model.

This led on to an additional analysis for the Axe catchment data, in which pre-1980 and post-1995 events were classified into four classes on the basis of antecedent rainfalls and peak flow. In three of the classes there appeared to be consistent changes in the slow flow component residence times (including within the pre-1980 period). These preliminary conclusions are subject to a more complete examination of the uncertainties and different ways of classifying the events, but this would appear to offer a better strategy for the identification of change.

4. A METHODOLOGY FOR PROVIDING DATA SETS WITH IMPOSED CHANGE AND RESULTS OF ANALYSIS

Test hydrographs were created to test the sensitivity of the detection methods, to see how small a change can be detected. To make this possible, a method was developed (the Juke Method) that allows the effects of hypothetical imposed changes in land use and management to be injected into observed hydrographs in a hydrologically consistent manner. The test hydrographs are simply predictions for the hydrographs that would have been measured if the imposed changes had taken place.

Imposed changes can take many forms. They can be unrelated to anything actually experienced in the catchments, or can counteract things known to have taken place (e.g. the land drains actually installed in 1950-60 were not installed). The Juke Method uses the Juke Model, which is being developed as part of wider research on the effects of changes in land use and management. When combined, the method and model give considerable control and flexibility when creating test hydrographs.

The Bain and Lugg catchments were selected for testing. These each have a gauged sub-catchment, giving internal flow data which helps improve the quality of the test hydrographs. Although the intention was to determine the sensitivity of the detection methods, only one test hydrograph was tested for each catchment. These were for an extreme level of land degradation that would have substantially increased the storm runoff from the land. In the event, this extreme degradation was not detected in the testing, so there was no reason to create test hydrographs with less extreme levels of degradation.

The test hydrographs were created by a team of researchers, and then used in testing by a different team. Two auxiliary factors make the testing more robust than it might at first appear: (1) the testing team were accidentally misinformed about the time periods affected by degradation; and (2) testing for a third catchment not considered in the wider testing also produced a similar outcome (the upper Eden, Cumbria).

The method and test hydrographs are described here, along with the essential features of the Juke Model and the outcome from testing.

4.1 Method

The problem of developing a suitable method for creating a test hydrograph is discussed in some detail below (Section 4.1.1), but the method finally adopted (the Juke Method) is basically as shown in Figure 4.1: part of the observed hydrograph is spliced to part of a synthetic hydrograph created using the Juke Model. In testing, the expectation is that systematic change will be detected between the first and second parts of the test hydrograph. It is centrally important to this method that the synthetic hydrograph is a modified version of the observed hydrograph, and the modification involves injecting the effect of a prescribed change in land use and management. With this approach, the synthetic hydrograph retains the variability and inconsistencies of the observed hydrograph (including in its relationship to the observed rainfall), and provided the injection is done in a hydrologically consistent manner the resulting test hydrograph will be physically reasonable. Note that it was an arbitrary choice to split the total period into only two periods and to inject the change into the first rather than second period.

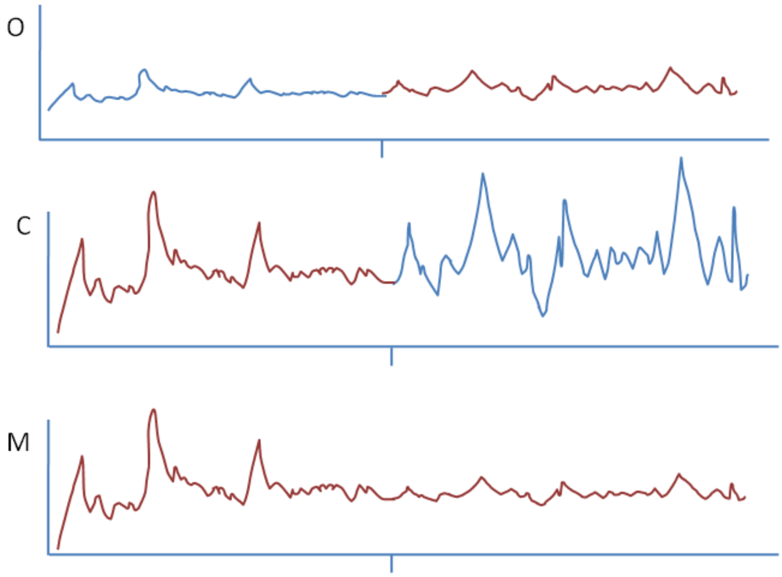

Figure 4.1 Creating test hydrograph M by splicing together the red segments from observed hydrograph O and synthetic hydrograph C

4.1.1 Development of method

In Table 4.1, the test hydrograph is time series M, and the observed is time series O. The table also includes hydrographs simulated by a rainfall-runoff model: C has the imposed change and U does not. Given an existing rainfall-runoff model, the simplest way to create a test hydrograph would be to: (1) calibrate the model to get U; (2) create C by running a simulation after changing the model's parameters to represent the imposed change; and (3) create the test hydrograph M by splicing together segments from U and C, so that it contains periods with and without the imposed change.

Table 4.1 Observed and simulated hydrograph timeseries

Timeseries	Change imposed?	Type	Comment
C(t)	yes	simulated	parameters modified for effects of imposed change
M(t)	yes	simulated	test hydrograph, a prediction for what would have been measured if there had been imposed change
O(t)	no	observed	observed hydrograph
U(t)	no	simulated	parameters calibrated against O(t)

For this simple approach, what is assumed for the periods of imposed change is:

$$M(t) = C(t) \qquad \text{Equation 4.1}$$

The obvious choice for a rainfall-runoff model is a physically-based distributed model (PBDM) such as SHETRAN (Ewen*, et al.*, 2000). PBDMs work on a fine grid or GIS pixel layer and have distributed parameters that are physical properties, such as hydraulic conductivities for soils. They can therefore simulate the effects of changes in the spatial and temporal patterns of land use and management, expressed as changes in the physical properties. There is a range of other approaches to rainfall-runoff modelling (Beven, 2001) which could be used in a similar fashion. Recently, Rose and Rosolova (2007) modified the lumped parameters in the Probability Distributed Moisture (PDM) model to represent the effect of various land use and management changes in the Ripon catchment, and their modelling could easily be used to create test hydrographs in the fashion described above.

The recent detailed review carried out in Project FD2114 (O'Connell*, et al.*, 2005), however, did not find any models which had been validated for predicting the effects of changes in land use and management on flood response. There are limitations in the mathematical structure of the existing models, and an almost complete lack of validation data. Given the lack of data, and that collecting new data on change effects takes several years, comprehensive validation is unlikely for any model in the near future.

Even if there were a validated model, there is second problem. By the very nature of the task of detecting change effects, the test methods must work despite the presence of variability and inconsistencies in the rainfall and discharge observations. This means that the variability and inconsistencies (e.g. the error structure) in the test hydrographs should be similar to that in the observed hydrographs. Typically, however, calibrating a rainfall-runoff model gives time series U and C with falsely attenuated high frequency responses and systematically distorted low frequency responses, so the error structures in time series U and C do not match that in the observed time series O.

This second problem can be partly eliminated if there is “perfect” calibration (U=O), and some progress can be made with the first problem (i.e. lack of validation) if the test hydrograph, M, can be written as:

$$M(t) = O(t) + \delta(t,O) \qquad \text{Equation 4.2}$$

where the modification, δ, is strongly linked to the observation, O, and is the result of the injected change. There will, of course, still be the problem of whether the modification δ is valid.

The method that evolved from Equation 4.2 (i.e. the Juke Method) relies on: (1) the fact that the Juke Model can be calibrated perfectly (i.e. with zero residuals); and (2) that every element (component) of the model is simple and physically interpretable. As a consequence of (2), the effect of every element is transparent, and there is scope for modifying any or all of the elements when injecting the effects of land use and management change.

4.2 Juke Model

The Juke Model runs on a grid, with square cells typically 50m to 250m in size. It comprises a set of seven computational elements (**Error! Reference source not found.**), five of which are distributed (represented as grids in the figure), and two of which are lumped. The distributed rainfall is r and the hydrograph observed at the catchment outlet is q*. It is assumed the hydrographs have fast and slow components: the calibrated discharge is therefore $q^*_{slow}+q^*_{fast}$ (=q*) and the modified discharge is $q^*_{slow}+q_{fast}$, where q_{fast} includes the effect of change.

The dotted lines in the figure show that the observed hydrograph is used internally within the model, in the latching, matching, and network routing modelling elements. The terms ‘latching’ and ‘matching’ are unconventional in rainfall-runoff modelling, and will be explained below. In conventional rainfall-runoff modelling, the observed hydrograph is used only for external calibration, and is not used internally.

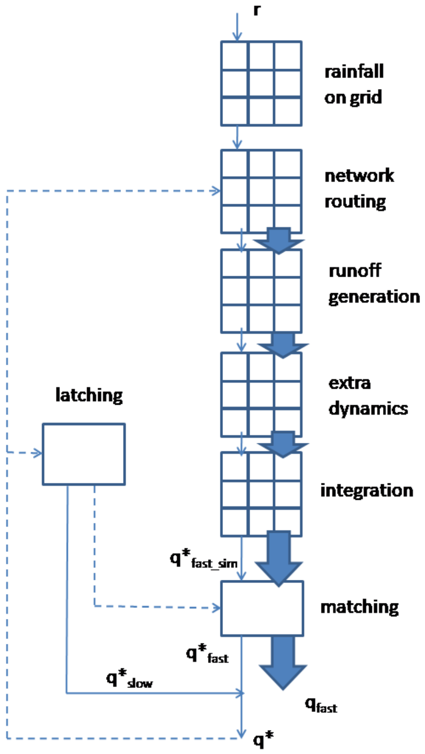

Figure 4.2 Juke Model

A word of caution is needed here, for those familiar with rainfall-runoff modelling. The Juke Model contains many new, unfamiliar, features. A common problem faced when describing the model has been to get the listener/reader to take the model at face value. It cannot be stressed enough that it is not a conventional rainfall-runoff model with some “magic” box on the output (i.e. the matching element) that eliminates the residuals. If you insist of thinking of it like this (consciously or unconsciously) you will probably find yourself tripping up at several points in this report. The best way to visualise the model is as an entity (the matching element) that allows perfect calibration in a physically reasonable fashion, and this entity is fed by distributed modelling designed specifically to match various constraints and purposes. The main constraint is that the matching element must be physically reasonable (i.e. it must make sense as a modelling element, in that it can be interpreted physically, so it cannot just be a “box of noise” designed to cancel out modelling errors and residuals).

The distributed modelling is unusual in that it: (1) is forced by the observed hydrograph; (2) has no explicit representation of losses such as evaporation; and (3) is designed so that, in the modified simulation, the signals of change (i.e. the effects on discharge) are controllable in a physically consistent way and arrive at the matching element in the correct fashion, where they are processed by the calibrated information that the matching element contains.

The model is also unusual because it is programmable and has its own programming language. Much of its mathematical structure can be specified as lines of program script. This script is read from an input file and is then processed and used by the model (in much the same way as, say, the observed rainfall data are read from an input file and are then processed and used by the model). The use of scripts helps make the representation of change transparent and controllable. For the Bain and Lugg simulations, the matching element is programmed as a time-varying ratio. This can be interpreted as a form of rainfall/runoff ratio or as a partition factor for separating fast and slow responses. Factors of these types are common in conventional rainfall-runoff modelling. Rather than being related to soil moisture conditions, as such ratios often are in conventional rainfall-runoff models, it is here calibrated as a time series. Plots of this ratio are presented later (it is called the matching gain because it is used in the modelling as a multiplier). These plots show that the ratio is physically reasonable. It is not noisy, and has the sort of behaviours and magnitude expected for rainfall/runoff ratios and partition factors.

4.2.1 Information flows

When creating test hydrographs, the Juke Model is run twice. First it is calibrated perfectly against the observed hydrograph, then it is rerun after the computational elements are modified for the imposed change. The slim downward pointing arrows in the figure are for the fast information flows in the calibration simulation, and the thick downward pointing arrows are for the fast information flows in the modified simulation (i.e. the simulation giving the hydrograph C in Table 4.1).

4.2.2 Latching element

The information flows for the slow component of the hydrograph are on the left hand side of the figure. This involves latching, in which the simulated slow hydrograph latches to (and is therefore equal to) the observed hydrograph, at times depending on the hydrological state of the catchment. Several variation on how this is done have been tested, but a very simple approach is taken here in which the slow component is assumed to comprise all the discharge below some threshold, $q_{threshold}$. In this case, the latching amounts to nothing more than a crude (but simple and effective) method for hydrograph separation: $q^*_{slow} = MIN(q^*, q_{threshold})$, and $q^*_{fast} = q^* - q^*_{slow}$.

4.2.3 Matching element

In the calibration simulation, the matching element takes the simulated fast hydrograph from the distributed modelling, $q^*_{fast\_sim}$, and converts it to q^*_{fast}. One way to approach the problem of matching would simply involve calculating the difference between $q^*_{fast\_sim}$ and q^*_{fast} for the calibration simulation, and storing the difference timeseries in the matching element. The stored timeseries would then simply be applied in the modified simulation. This, however, would not give a physically reasonable matching element, because the difference timeseries will be large and rapidly fluctuating.

The matching element used in the Bain and Lugg simulations is quite similar to the above. During the calibration simulation, the time-varying ratio $q^*_{fast} / q^*_{fast\_sim}$ is saved, where $q^*_{fast\_sim}$ is the output from the distributed modelling. In the modified simulation, this ratio is then used as a multiplier (i.e. a gain), to multiply the output from the distributed modelling to give q_{fast}. Remember, though, that it is not just good luck that this relatively simple approach gives a physically reasonable matching element. The distributed modelling was designed to achieve this outcome.

A more elaborate approach was developed for matching, which can handle timing problems that cannot be eliminated when designing the distributed modelling, but this was not needed here (the gain was found to be well behaved, as will be seen in Section 4.5, where some results are presented).

The matching element automatically accounts for losses such as evaporation, because losses are not taken into account in any of the preceding modelling elements.

4.2.4 Rainfall on grid element

The rainfall-on-grid element is simple: the rainfall rate on a cell is the observed value at the nearest gauge with valid data.

4.2.5 Network routing element

The network routing element calculates the outcome if all the rainfall falling on the grid is routed to the catchment outlet, via a network generated from a DEM. In reality, the flow celerity in a network channel depends on the flow rate, so if all the rainfall is routed through a conventional routing model, the results will be wrong in terms of both travel time and flow volume. Here, though, the flow hydraulics are assumed controlled by the observed hydrograph, with the aim of producing results that have the right travel times. The flow volume is then, effectively, corrected in the matching element.

The network extends all the way from each cell to the catchment outlet, so it is a detailed and dense network with a very large number of flow segments. In effect, the routing integrates the patterns in rainfall and topography, while allowing for internal interactions at network confluences, using the observed hydrograph as a surrogate for information on the required dynamic state of the flows. Note that the runoff generation element does not actually give the outlet hydrograph, but gives a distributed output (this output could be described, loosely, as the distributed potential contribution to the outlet hydrograph, resulting from rainfall and routing). In the Bain and Lugg simulations, only the runoff generation element is modified, and this comes after the routing element in Figure 4.2. However, the routing will have a distributed effect on the change signal, because the distributed output from the routing element forces the runoff generation element (remember, don't think of Juke as a conventional model!).

Further details on the routing element are given in Section 4.4.1, which describes the parameterisation of the element for the Bain and Lugg catchments.

4.2.6 Runoff generation element

The runoff generation element controls how runoff is generated in each cell. If an imposed change in land use and management is represented in a modified simulation by modifying the runoff generation element, the signal of change this causes (i.e. the effect on the discharge) will propagate downwards in Figure 4.2 and will pass through the matching element (where it will be acted on by the calibrated gain described earlier, in Section 4.2.3).

Like most of the elements, the runoff generation element is programmable. When creating the test hydrographs for the Bain and Lugg, it was programmed to contain only a pattern for a spatially-varying multiplier (i.e. an array of numbers, on the grid). For the calibration simulation, this was a "pure" pattern, in that the cell-average for the multiplier was one. In the Bain and Lugg simulations, the effect of land degradation is injected into the model by altering this multiplier. Details on how the runoff generation element was parameterised and programmed for the Bain and Lugg modelling are given in Sections 4.4.2 and 4.4.3.

4.2.7 Extra dynamics element

Storage is ubiquitous and unavoidable in rainfall-runoff modelling, so the extra dynamics element has one programmable store per cell. In the Bain and Lugg modelling, the stores are linear and the cell parameter is assumed uniform and constant (so, effectively, there is a single, lumped, store with a single constant parameter). Remember, the store is associated with the fast component of the hydrograph, not the slow component. The time constant for the store was calibrated against the early parts of the storm flow recessions.

One of the important roles of the extra dynamics element is to make sure that the matching element is physically reasonable and transparent. If storage is not represented somewhere in the model, before the matching element, its effect will end up in the matching element, making the interpretation of the matching element's role much harder.

4.2.8 Integration element

The integration element is simple: it adds up the contributions from the cells.

4.3 Potential for representing various imposed changes

Before proceeding to the description of the application to land degradation in the Bain and Lugg catchments, in Section 4.4, a wider look is taken here at the potential of the Juke Method and Model to create test hydrographs for various types of changes in land use and management.

It is important that the imposed changes in land use and management are reasonable, in that they are consistent with the nature of the catchment and the actual drivers for change (e.g. drivers such as agri-environmental catchment management schemes). For example, a complete test of the sensitivity for detecting land degradation, say, would require test hydrographs for a range of different degrees of degradation, and the patterns associated with these test hydrographs would have to take into account the likely interaction between the catchment properties and the drivers for change (e.g. if is there a driver for stock density reduction, affecting soil compaction, where will the reductions take place, and how efficiently will they take place).

The Juke Method, combined with the Juke Model, has the potential be a very powerful and flexible tool for generating test hydrographs. Table 4.2 gives some idea of the scope for representing land use and management change. It shows how the modelling elements can be altered to represent various general types of change. At a higher level, general changes in agri-environment practices and forestry, for example, can be mapped to more than one of the changes listed in the table.

Table 4.2 Examples of things that can be modified in the Juke computational elements to represent various land use and management changes, with subjective estimate of importance (1 is highest importance)

Land use or management change	**Network routing element**	**Runoff generation element**	**Extra dynamics element**	**Latching element**
Floodplain management	celerity at floodplain cells (1)	runoff from rainfall on surface water (3)	fast storage on floodplain cells (1)	baseflow modification (3)
Land drainage	celerity at drained cells (2); celerity affected by change in flow volumes (4)	enhance/degraded runoff for affected cells (1)	storage on drained cells (2)	baseflow modification (3)
Land use or crop type	celerity affected by change in flow volumes (4)	enhance/degraded runoff for affected cells (1)	fast storage on affected cells (2)	baseflow modification (3)
Moorland management	celerity on moorland (3); celerity affected by change in flow volumes (4)	enhance/degraded runoff for affected cells (1)	fast storage on moorland cells (1)	baseflow modification (3)
Soil degradation	celerity affected by change in flow volumes (4)	enhance/degraded runoff for affected cells (1)	fast storage on affected cells (2)	baseflow modification (3)

The main effects to be detected by change-detection methods are effects on fast discharges, associated with flooding. Baseflow modification is included in the latching column in Table 4.2 for use with change-detection methods that rely on detailed mass balance calculations.

A wide range of types of spatial data sets could be used to create basic patterns. For example, say that a given change takes place only in riparian zones and floodplains. What is needed is a binary map that shows whether or not each cell lies in an affected location. This could be generated in several ways, including being taken directly from a custom drawn map or indirectly from a map of alluvial deposits or from a topographic index generated from the DEM.

Before a test hydrograph can be created, the following must be decided:

1. Where (grid cell by grid cell) do the imposed changes take place?
2. Which data are required and how should the mathematical structure and parameters of the Juke Model change?

Superficially, Item 2 above looks the most important and difficult. The importance of Item 1 should not be overlooked, however. By controlling the extent of change it controls the magnitude of change in the flood hydrograph. Also, the calibration against the observed hydrograph creates, in effect, a realization for the unmodified spatial hydrology using the Juke Model. By controlling the location of change, Item 1 therefore gives the link to the spatially-varying features that affect the hydrograph, such as the rainfall field, the landscape, and the channel network.

4.4 Application to Bain and Lugg catchments

The Bain and Lugg catchments were described in Section 2. Table 4.3 gives the time periods for the Bain and Lugg test hydrographs. The start and end dates were not selected for any reason connected with land use and management. They are simply the start and end dates for the available data sets. For each catchment, the imposed change applies for approximately the first half of the total period, ending when there is low flow in July.

Table 4.3 Time periods for test hydrographs

Catchment	Start	End of imposed change	End
Bain	1/1/1992	12/7/1997	27/3/2003
Lugg	1/10/1985	1/7/1994	31/12/2003

4.4.1 Parameterisation of routing element

The routing element works with a dense dendritic flow network derived from a DEM. This represents the flow pathways originating at every cell and ending at the catchment outlet. The cell size was 250m for the test hydrographs for the Bain and Lugg. Each cell has a celerity, and this is assumed to depend on the cell's scale and the observed hydrograph, where "scale" is defined as the upstream flow area, given as a fraction of the total catchment area. Scale is calculated in such a way that the scale for the cell at the catchment outlet is one and the scale for a single cell at the head of the network is 1/N, where N is the total number of cells in the catchment.

It is the nature of rainfall and flow in catchments that the peak rates of flow for an event tend to vary systematically with scale. It was assumed that:

$$q_p = baq_p^* \qquad \textbf{Equation 4.3}$$

where q_p is the peak rate at all locations where the scale is a, and q^*_p is the corresponding peak discharge at the catchment outlet. The mean value for the factor b, calibrated against the rainfall and flow peaks for the full period of the records, is given in Table 4.4. Note that rainfall is assumed to take the scale of a single cell.

Table 4.4 Parameters for peak scaling

Location	**Bain**		**Lugg**	
	A	b	a	b
Rainfall	2.93x10^{-4}	16.9	1.62x10^{--4}	12.8
Subcatchment	0.325	0.571	0.545	1.23
Outlet	1	1	1	1

The aim is to obtain a universal equation for discharge that applies at all times (not just during peak flow) everywhere on the catchment. Here it is simply assumed that the scaling derived above using the data for peaks will actually apply at all times, so subscript p in Equation 4.3 can be dropped. The generalised form of Equation 4.3 is therefore:

$$q = baq^* \qquad \textbf{Equation 4.4}$$

which gives the discharge q at all locations with scale a, when the discharge at the catchment outlet is q*. Also, it is assumed that linear interpolation can be used to calculate factor b for scales lying between the tabulated values.

When extracting the peak magnitudes from the records, the time differences between the peaks were also extracted. These give travel times, which were used to calibrate a universal equation for the celerity on the network, which in turn was used to determine the time-dependent travel time for flow from each cell to the catchment outlet.

The network celerity, c, is given by the following (the required form of this equation was guessed, by visual inspection):

$$|c| = \delta - \frac{\phi}{|q| + \frac{\phi}{\delta}} + \eta \qquad \textbf{Equation 4.5}$$

This has three parameters (Equation 4.5). Note that the celerity depends on the discharge, q, so depends, via Equation 4.4, on the observed hydrograph. To calculate the travel time for the rain falling on a cell therefore requires knowledge of: (1) the observed hydrograph; (2) the flow pathway that originates at the cell; and (3) the time-dependent celerity at each cell the pathway crosses. Celerities for three locations in the Bain catchment are shown in Table 4.5.

Table 4.5 Routing parameters

Parameter	**Units**	**Bain**	**Lugg**
δ	m/s	1.49	1.45
φ	m/s	0.291	3.30
η	m/s	0.0272	0.0383
k	h	18	24

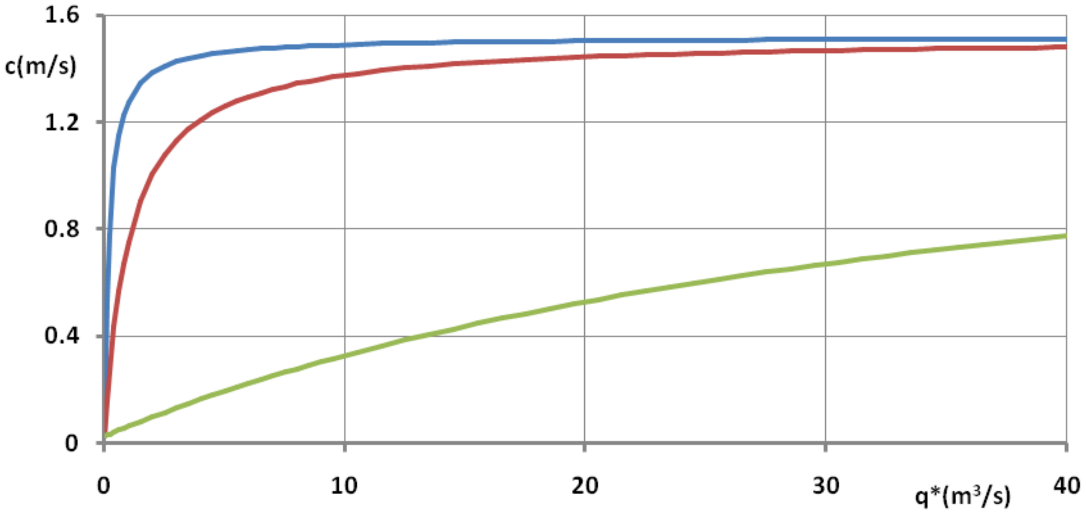

Figure 4.3 Celerity for Bain, at outlet (blue), subcatchment outlet (red), and cell at the head of network (green)

With this celerity equation, for each cell it is possible to calculate the time, τ, at which runoff was generated to contribute to the outlet discharge at the current time, t (i.e. the travel time from the cell to the outlet is t- τ). Once τ is known, the potential outlet discharge, q_r, for rainfall r on the cell can be calculated as follows:

$$q_r(t) = r\big(\tau(q^*(t))\big) \qquad \textbf{Equation 4.6}$$

where q*(t) is the observed hydrograph at the catchment outlet. This, when calculated for all the cells, gives the distributed output from the routing element.

Note that Table 4.5 includes values for the time constant, k, for the linear store in the extra dynamics element. When handling the travel times from rainfall to flow, to be consistent with the model as a whole, the routed rainfall was passed through this store before the magnitude and timing of the peaks were detected. Of course, this was not done when handling the travel times between flow gauges.

There are numerous ways in which this approach to routing could be criticised, and there is considerable uncertainty in the calibration against the observed peaks, but this approach does give results that are consistent in time and space with the flood responses, and it can be used to study the potential effects of spatially-variable land use and management change and network modifications. It manages this despite being a top-down approach, depending only on a DEM and rainfall-runoff records.

4.4.2 Land degradation data for the test hydrographs

The imposed change for the test hydrographs for the Bain and Lugg is land degradation associated with poor land management practices, defined using the FD2114 tabulated data from Packman et al. (2004), which were derived based on an analysis of the Hydrology for Soils Types (HOST) classification (Boorman, *et al.*, 1995).

The HOST data set for a catchment comprises classification data, that give the fraction of each cell associated with each HOST class. For each class, a standard percentage runoff (*SPR*) is given by Boorman et al. (1995). This is a measure of the “normal capacity of the catchment to generate runoff” (Institute of Hydrology, 1999, Vol. 4, p. 7). These values are listed in Table 4.6, along with the degradation-induced increase in *SPR* suggested by Packman et al. (2004).

Given *SPR* on the catchment grid, the simplest way to create a pure pattern (i.e. a spatially-varying value with an average of one) is to divide the grid *SPR* values by the grid average *SPR* value.

Two patterns are required for the runoff generation element: a pure pattern that applies for the observed discharge and a modified pattern that applies when change is imposed. These patterns are used, effectively, as rainfall multipliers. The standard percentage runoff is also, intrinsically, a rainfall multiplier, because it is designed to play a major role in deciding the percentage of rainfall that is expected to result in fast discharge (Institute of Hydrology, 1999). The patterns for *SPR* and degraded-*SPR* can therefore be used directly in the runoff generation element.

Note that this is an extreme implementation of the HOST degraded-*SPR* data, which effectively assumes that the full effect of degradation applies across the catchment. It therefore probably gives an upper limit for the effect on the hydrograph.

4.4.3 Juke scripts for land degradation

The Juke Model contains no data or equations relating to land use and management. Also, although it can recognise a few types of appropriate generic formats for data sets (e.g. general classification systems and accompanying metadata tables), it does not expect or demand any particular data or data types for land use and management. This approach was taken in recognition of the fact that the data requirements and mathematical structure for modelling land use and management are uncertain.

The Juke Model must therefore be given land use and management data in a generic format and must be instructed on how these data are to be used. This is achieved using scripts, written in a custom-designed language, which are entered as part of the input data set. When scripts are interpreted by the model, they cause the necessary data structures to be created and invoke GIS-type arithmetic, causing scalar, vector and matrix arithmetic to be performed on the grid. This allows land use and management to be specified easily, in a transparent manner.

Table 4.6 HOST metadata [after Packman et al. (2004)]

Class	*Spr*	*Spr*_inc	Description
1	2	12	Free draining permeable soils on chalk and chalky substrates with relatively high permeability and moderate storage capacity
2	2	12	Free draining permeable soils on 'brashy' or dolomitic limestone substrates with high permeability and moderate storage capacity
3	15	12	Free draining permeable soils on soft sandstone substrates with relatively high permeability and high storage capacity
4	2	13	Free draining permeable soils on hard but fissured rocks with high permeability but low to moderate storage capacity
5	15	12	Free draining permeable soils in unconsolidated sands or gravels with relatively high permeability and high storage capacity
6	34	10	Free draining permeable soils in unconsolidated loams or clays with low permeability and storage capacity
7	44	0	Free draining permeable soils in unconsolidated sands or gravels with groundwater at less than 2m from the surface
8	44	0	Free draining permeable soils in unconsolidated loams or clays with groundwater at less than 2m from the surface
9	25	0	Soils seasonally waterlogged by fluctuating groundwater and with relatively slow lateral saturated conductivity
10	25	0	Soils seasonally waterlogged by fluctuating groundwater and with relatively rapid lateral saturated conductivity
11	2	0	Drained lowland peaty soils with groundwater controlled by pumping
12	60	0	Undrained lowland peaty soils waterlogged by groundwater
13	3	12	Soils with slight seasonal waterlogging from transient perched water tables caused by slowly permeable subsoil or substrate layers
14	25	15	Soils seasonally waterlogged by perched water tables caused by impermeable subsoil/substrate layers
15	48	0	Permanently wet, peaty topped upland soils over relatively free draining permeable rocks
16	29	18	Relatively free draining soils with a moderate storage capacity over slowly permeable substrates with negligible storage capacity
17	29	18	Relatively free draining soils with a large storage capacity over hard impermeable rocks with no storage capacity
18	47	12	Slowly permeable soils with slight seasonal waterlogging and moderate storage capacity over slowly permeable substrates with negligible storage
19	60	0	Relatively free draining soils with a moderate storage capacity over hard impermeable rocks with no storage capacity
20	60	0	Slowly permeable soils with slight seasonal waterlogging and moderate storage capacity over impermeable clay substrates with no storage capacity
21	47	13	Slowly permeable soils with slight seasonal waterlogging and low storage capacity over slowly permeable substrates with negligible storage capacity
22	60	0	Relatively free draining soils with low storage capacity over hard impermeable rocks with no storage capacity
23	60	0	Slowly permeable soils with slight seasonal waterlogging and low storage capacity over impermeable clay substrates with no storage capacity
24	40	9	Slowly permeable, seasonally waterlogged soils over slowly permeable substrates with negligible storage capacity
25	50	10	Slowly permeable, seasonally waterlogged soils over impermeable clay substrates with no storage capacity
26	59	0	Permanently wet, peaty topped upland soils over slowly permeable substrates with negligible storage capacity
27	60	0	Permanently wet, peaty topped upland soils over hard impermeable rocks with no storage capacity
28	60	0	This soils type, eroded peat, is not mapped separately in England & Wales
29	60	0	Permanently wet upland blanket peat

Here is the line of script used to create the pure pattern for HOST *SPR*:

gam = (host . spr) / (host . spr AV no_c)

The value of *gam* varies over the grid and has an average of one. The HOST data set is input in a generic format for classification data, designed for specifying class data on a grid. It gives the land coverage fraction for each class in each cell, and has a self-describing file that contains metadata for each class (the metadata are the *spr* and *spr_inc* values shown in Table 4.6). The term "*host . spr*" in the script invokes matrix multiplication which calculates the cell average *SPR* for each cell. The total number of cells in the catchment is *no_c*, and the term containing operator *AV* calculates the grid average *SPR*.

For the modified simulation, the pattern is:

gam = (host . spr + host . spr_inc) / (host . spr AV no_c)

Note that all the *spr_inc* values are zero or positive (Table 4.6), so the modified average for *gam* is greater than one.

The Juke language has a large set of operators for scalar and matrix arithmetic, logical tests, etc, and there is a custom-designed parser in the model which translates the scripts, causing the required data structures and calculation processes to be created. One important practical advantage of working with generic data set formats and scripts is that it helps with quality assurance. For example, the approach used to generate different test hydrographs is convenient, transparent and reproducible, and does not rely on handling and storing multiple data sets.

4.4.4 Summary of data requirements

The complete set of data used to create the test hydrographs comprises:

1. A 50m digital elevation map (DEM) for each catchment.
2. Records from several rain gauges and two flow gauges (one at the outlet and one for a subcatchment) for each catchment.
3. Routing and extra dynamics parameters (Table 4.4 and Table 4.5 in Section 4.4.1).
4. $q_{threshold}$ (5 m^3/s for Bain and 15 m^3/s for Lugg).
5. Hydrology of Soils Types (HOST) data sets.
6. Scripts describing how to use the HOST data (discussed in Section 4.4.3).

4.5 Test hydrographs for land degradation

It is not possible to see the effects of change if the full test hydrographs are plotted, because storms will simply show up as vertical lines. The plots below are therefore for a few storms. Figure 4.4 is for the largest storm at the Bain catchment during the observation period. The flow return period is 25 years. Figure 4.5 is the corresponding figure for the Lugg catchment; the flow return period is also 25 years. As is to be expected, the temporal variations of the matching gains are quite similar to the temporal variations of the discharge, and as required the matching gains have the general behaviour and magnitude expected for rainfall/runoff ratios and fast/slow partition ratios.

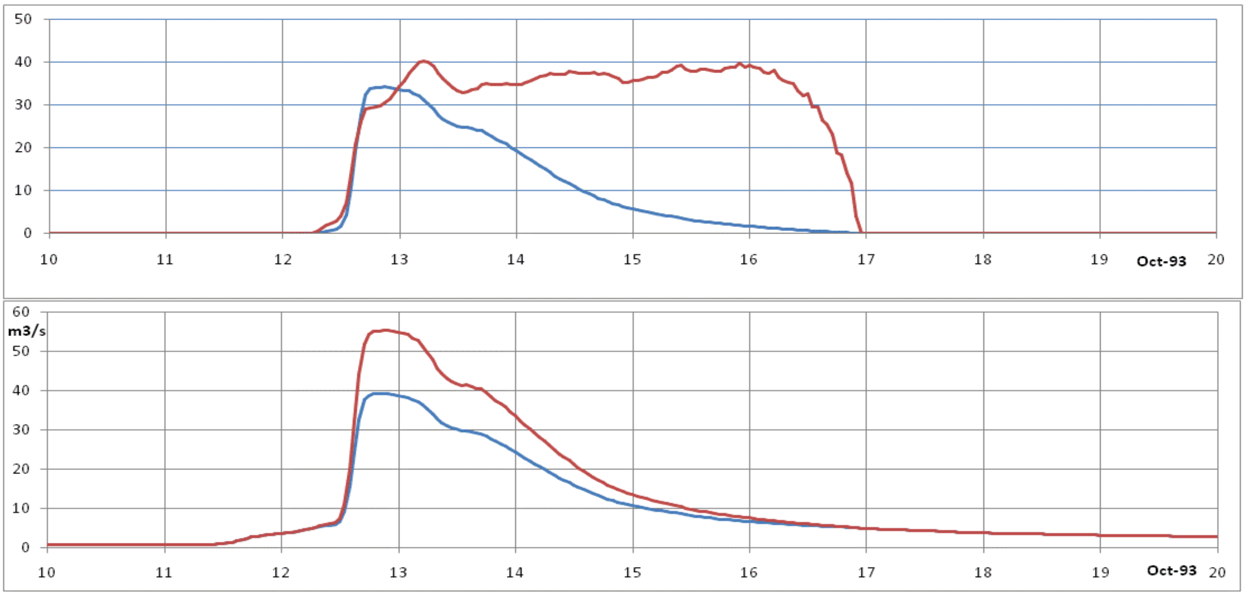

Figure 4.4 Bain for period starting 10 Oct 1993: upper figure - observed fast discharge (blue line) and calculated percentage matching gain (red line); lower figure - observed discharge (blue line) and modified discharge (red line)

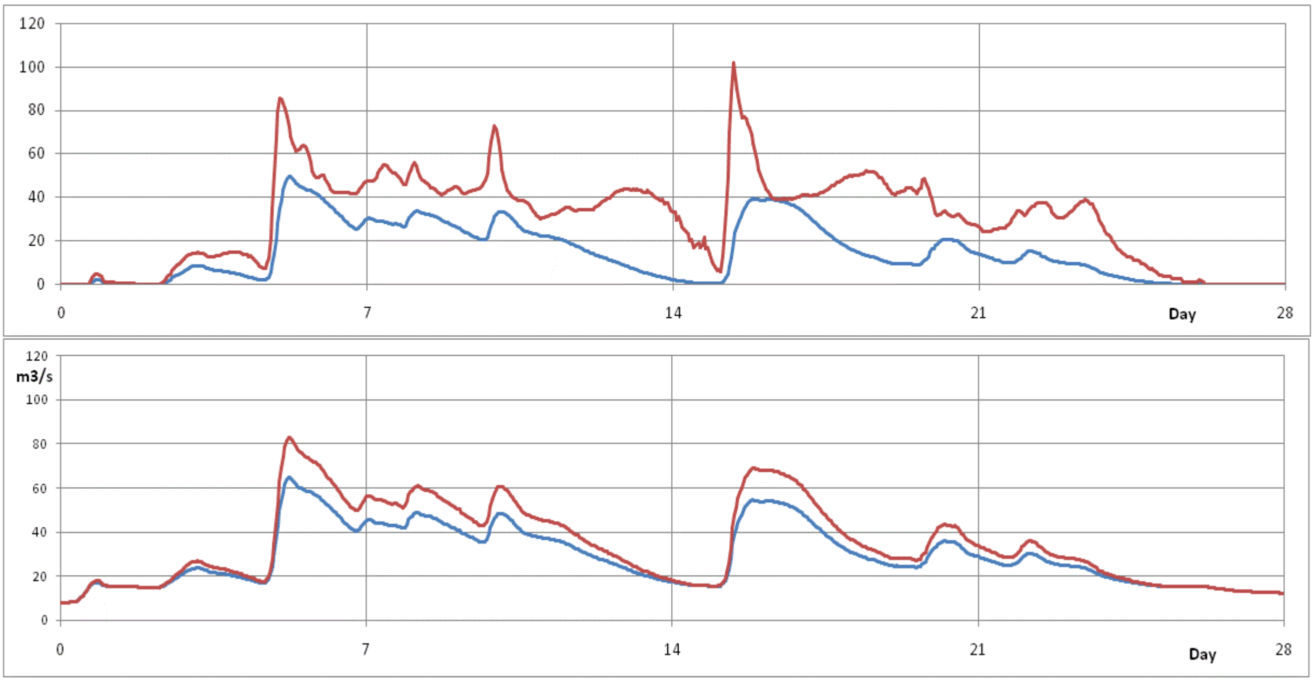

Figure 4.5 Lugg for period starting 23 Jan 1990: upper figure - observed fast discharge (blue line) and calculated percentage matching gain (red line); lower figure - observed discharge (blue line) and modified discharge (red line)

4.6 Analysis of test hydrographs for land degradation

A full description of the application of the DHR and DBM analyses to the modified Bain and Lugg catchments is presented in Technical Appendix 5. As with the unmodified data (Section 3) it was found that the variability from period to period was high, resulting in little evidence of consistent changes. Also as before, there did appear to be some relationship between the model parameters and the maximum flow in a period. It should be remembered that the Juke Method retains the variability and inconsistencies in the data, even though the individual event hydrographs are modified in a consistent way. It appears as if the data variability and inconsistencies dominate, making it difficult to identify the imposed changes. There was some evidence of small changes in the nonlinearities and gains for individual periods but these were small relative to the differences between periods. Changes to the identified residence times were small, but (as can be seen in Figure 4.4) the modifications had a greater effect on the volume of runoff than on timing (even though in principle there is the potential for timing change in the Juke Model).

4.7 Discussion

The imposed change caused a significant systematic increase in the storm discharge in the test hydrographs. However, there is considerable variability and inconsistency in the observed rainfall and discharge, and this is deliberately retained when creating the test hydrographs using the Juke Method. Whether detection is actually possible in practice will therefore depend on whether methods can be found that can reliably isolate the imposed change in the face of this considerable variability and inconsistency. With the analysis methods applied here and results reported in Appendix 5, even when modified and unmodified hydrographs are directly compared, the changes in the modelled nonlinearity are small compared with the variability over time.

The methodology used to produce the test hydrographs is new and a little complicated, because it tries to overcome the serious limitations in simpler methods that use existing rainfall-runoff models. If weaknesses are to be sought in the method and its application, apart from those related to its novelty, the most obvious weakness is the use of HOST *SPR* data on a grid with 250m cells. These data are strictly valid only at the catchment scale, because they were obtained using calibration at the catchment scale (Boorman*, et al.*, 1995). They are also subject to considerable uncertainty associated with the regression procedure used to derive *SPR*. However, the Juke Model is particularly adaptable, and can use a wide range of other types of data, by making use of its scripting language. The difficult question is: which data can (or should) be used when predicting the effects of changes in land use and management? This remains an open question (O'Connell*, et al.*, 2007a, O'Connell*, et al.*, 2004a,b), which is being addressed through new monitoring programmes (e.g. O'Connell et al., 2007b). As for the main weakness in the Juke modelling, there is no feedback between the matching and runoff generation elements, to help control the cell mass balances, which might have resulted in an overprediction of the change effect for the Lugg catchment when the matching gain approached 100%. An appropriate feedback method has since been designed.

Ground-truth testing in the Bain and Lugg catchments, particularly for the network geometry and flows, would help improve the hydrological representation of the catchments, and hence help improve the test hydrographs.

Although considerable effort has been expended to create high quality test hydrographs, it should be remembered that the HOST data for land degradation have not been validated, and neither has the Juke modelling of change effects (and as argued in Section 4.1, suitable comprehensive validation data for this purpose are unlikely to be available in the near future). The results given here for the effects of land degradation on the Bain and Lugg hydrographs should therefore not be used outside the context of this work.

5. IMPLICATIONS OF RESULTS FOR POLICY DECISIONS

5.1 Synthesis of the modelling insights

This study has confirmed the difficulty of identifying 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 natural variability and change in climate variables, particularly rainfall. Several of the 9 catchments prioritised for study have shown changes in rainfall characteristics over the period for which data is available, which might then impact stream discharges in nonlinear way as a result of consequent changes in runoff generation processes. It is worth noting that sequences of events may be important in the non-linearity of change, because of the way rainfall in one event will affect the antecedent conditions in subsequent events. Any changes in evapotranspiration will also affect antecedent conditions. Such variability in response is expected to be a result of both climate and land management effects, but the analyses presented here suggest that any effects of land management are masked by climate variability.

We note, however, that this may be in part a result of the limitations of the data available for both rainfall and discharges. Inconsistencies in the measured data series were apparent for most of the catchments studied here. Both the trends in catchment discharges and the descriptors of catchment response dynamics summarised by the DBM model parameters appear to show change over time, but in most cases recent changes show similar variability to past changes without clear indications of land use rather than climate related impacts. Robson (2002) also noted the difficulty of distinguishing change in flood frequency characteristics based on the analysis of longer term records than used here. The limitations of the available information on patterns and timing of change in land use land management and soil structural conditions also make it difficult to make direct links to the hydrological responses (see also the similar conclusions of Sullivan et al., 2004, in a study of the Camel catchment, Cornwall).

There are some intriguing exceptions to this, in particular in the results of the study of changes in catchment dynamics for different classes of events in the Axe catchment (the only catchment for which it was possible to carry out this form of analysis within the time scale of the project). This appears to show quite different trends in response for different classes of events, with an increase in the speed of the fast responses in one class, and a decrease in two other classes. The classification of events, by antecedent rainfall and peak flow during the wetter part of the year, was simple but this was necessary to try and retain a sufficient number of useable events in each class in each period studied. It would be useful to extend this analysis to include seasonal effects on inter-event evapotranspiration and to apply a similar analysis to other catchments. The concept that changes might be more detectable in some types of event than in others is, however, compatible with the results of the pulse analyses of Archer (2003, 2007) though the analysis presented here, by looking at the full rainfall-runoff event dynamics, allows for a greater degree of conditioning with respect to climate variability.

Tests of the analysis methodology using the reconstructed time series from Work Package 3 (WP3) showed that the variability in both nonlinearity and dynamics from year to year was greater than the impacts of the assumed change. This is again, in part, a result of inconsistencies in the observed data; the modification of the original time series using the Juke methodology was designed to retain any such inconsistencies. One result of this is that the assumptions of the analysis, in terms of the structure of the modelling residuals, may not then be properly met. The residual series exhibit non-stationary structure that cannot be readily represented statistically and that will necessarily lead to uncertainty and bias in fitting the model parameters.

It is worth noting that the changes in the WP3 reconstructed time series would be seen in the analysis of pulse numbers mentioned above. Changes in pulse durations would be less evident. In a separate analysis of the Axe data by Climent i Soler (2007) using the pulse method, it was inferred that change could be detected but the conditioning for changes in the climate forcing was somewhat simplistic. This study shows that it is rather difficult to provide an adequate conditioning for changes in the input (rainfall) characteristics. The DBM analysis, in that it is effectively event based, should detect significant changes in catchment dynamics if they are there, regardless of changing input characteristics, providing the inputs and outputs are adequately characterised and the changes are consistent. However, this study could not establish whether the differences in detected changes for different classes of events in the Axe catchment are a result of real differences in response or only data inconsistencies and bias in fitting parameters.

This then raises the question of whether improved data sets for examining the impacts of change and testing the analysis methodology could be made available in the future. Improved hydrological data would require improved information on rainfall input volumes at the catchment scales examined here and careful checking of discharge rating curves over time. Even when such data are available, however, it is clear that climate variability can still affect runoff processes and catchment dynamics. Recent studies at Pontbren carried out by Imperial College and CEH Bangor within the Flood Risk Management Research Consortium, for example, have shown how different antecedent conditions can have a major impact on runoff processes in two successive winter seasons.

5.2 Policy implications of the modelling results

The results of this study therefore do not confirm the anecdotal evidence that many rivers are becoming flashier as a result of the intensification of agriculture. If such changes have indeed occurred they may be as much the result of changing rainfall characteristics revealed here rather as a result of changing agricultural practice. Both monthly rainfalls and discharges showed time variable trends, although only for rainfalls in 2 catchments were the trends considered significant. These analysis of monthly data will not, however, reveal changes in short term intensities, which could also have an impact on the analysis of the hydrograph response dynamics.

The methods of analysis used in this study are relatively sophisticated in comparison to the simple trend analysis and ways of conditioning for climate change and variability used in the past. The results, however, are still subject to the types of data uncertainties noted earlier. Thus, the results do not provide strong evidence either for or against the hypothesis that agricultural and forestry practices have a significant effect on discharges and flood peaks at the catchment scales investigated here. Consequently our results do not provide any evidential support for significant impacts of rural land use management on flood runoff generation.

Our findings therefore suggest that a precautionary policy approach should be adopted. Evidence from small-scale observations and physically-based arguments still give a reason to believe that changes in land use/management could have an effect on large-scale, downstream flooding. This is not inconsistent with our findings that changes in response are difficult to identify, relatively to period to period variability and data inconsistencies.

For example, soil structural damage is evident in many catchments, though varying in time and space (Figure 5.1). This is despite generic guidelines and advice, such as Cross Compliance (Good Agricultural and Environmental Condition- GAEC), the Code of Good Agricultural Practice (Water Code: MAFF, 1998a; Soil code: MAFF, 1998b), the “Guide to better soil structure” (NSRI, 2002) and “Best farming practices: profiting from a good environment” (Environment Agency, 2003). However, it is too soon to ascertain whether the recent policy shifts away from production-based subsidies to environmental subsidies (e.g. Set-aside) and area-based payments have mitigated the impacts of the continuing intensification of production in both arable and grassland systems described in Appendix 1. It is possible that soil structural conditions would be worse without the current policy focus.

To improve conditions further land management practices, which can make a difference in reducing runoff during events locally, can be prescribed as part of sustainable integrated water management strategies based upon a risk based, outcome oriented approach. For a set of agricultural system / soil / landscape / antecedent conditions, it is possible to identify potential relationships between land management practices and flood generation risk such that ‘bad’ and ‘good’ practices can be clearly identified.

In most cases these practices will also deliver other associated ‘sustainability’ objectives as the potential to cause enhanced run off is linked to other detrimental environmental impacts – soil degradation, local “muddy floods”, sediment and nutrient transfers to stream channels, with consequent damages for the fluvial ecosystem. Therefore it makes sense to include flood risk management with other aspects of catchment and water resource management.

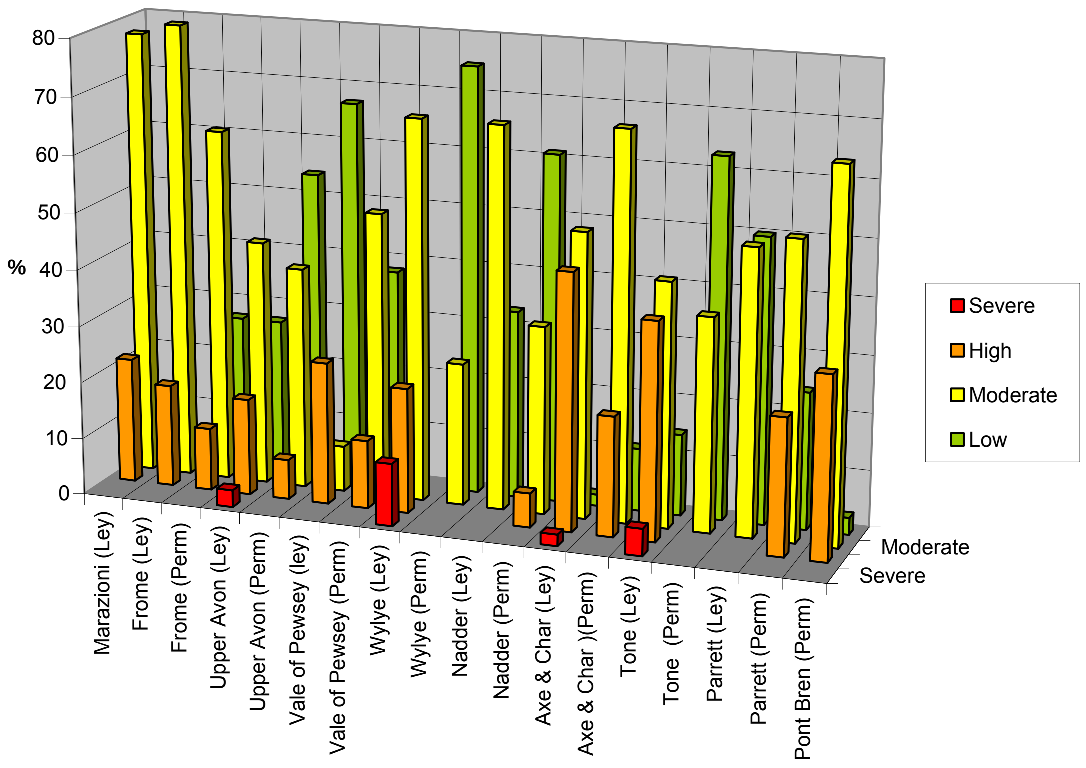

Figure 5.1 Synthesises of soil structural degradation under grassland observed in catchment surveys undertaken since 2001 by Cranfield University (from Clarke et al. 2008)

Thus, the policy implications of these findings are not to ‘do nothing’ but rather to encourage local controls of flood runoff generation wherever possible- an integrated approach whereby ‘flood management’ is embedded within an overall policy framework for sustainable land and water management. This integration of policy is a key point. There are a variety of ways of doing so that involve reducing runoff at source, reducing connectivity of runoff sources to stream channels, and creating additional local storages for runoff (O’Connell et al., 2007). Measures to control run-off are likely to have joint ecosystem services benefits as part of farm environment schemes but might also have costs in that reduction of flood runoff necessitates increased infiltration of water into the soil profile through improved soil structure and therefore may impacts on agricultural and forestry practice. Such measures are less likely to be justified for flood management reasons in catchments where there is little scope for effecting a reduction in runoff generation and flood risk. Therefore measures should be targeted to areas where the benefits, in terms of reduce flood impacts, are likely to be greatest. This implies the development of a methodology to identify which catchments would be most sensitive to land management change.

It is recommended that the costs and practicality of measures are assessed, both to farmers and society at large, as a basis for promoting effective interventions that appeal to land managers. The most cost effective measures are likely to be those that provide multiple benefits to land managers, the environment and society. These measures can be promoted through a range of policy instruments including voluntary measures and/or regulations that are linked to economic incentives such as single payment conditionality or environmental stewardship. This further suggests a need to integrate ‘flood risk management' components into other aspects of land management policy where possible. However, this project demonstrates that there will be a real difficulty of estimating the benefits of such measures in respect of any reduction of flood risk.

It should be noted that there may be costs of holding water in the landscape when floods are the consequence of sequences of events. Increased storage in one event, can mean that there is less storage available in a subsequent event if that water has not had sufficient time to drain or evaporate. Thus, for cases where fast runoff depends on volume filling, reducing runoff in one event might increase flooding in subsequent events. It is therefore important that catchment characteristics are understood when targeting measures to reduce runoff.

If, as this study has shown, the historical data available do not allow strong conclusions to be drawn about the effects of land use change and management on flood runoff and peak discharges, then it will also be the case that the impacts of runoff reduction measures might also be difficult to detect. It is possible that improving the quality of the data available might help in identifying such changes, whether directly through changes in hydrograph response or indirectly through improvements in soil structure, even if this was done only locally to monitor the performance of specific schemes. Such monitoring is already being carried out as part of the Pontbren studies in FRMRC and the SCAMP studies (Environment Agency R&D project SC060092),, but our understanding would be supported by further case studies in catchments with contrasting physical and land management characteristics, particularly in arable systems. At the catchment scale, improvements are required in both the estimation of inputs (rainfall) and discharge observations to avoid some of the inconsistencies that have become apparent in some of the data sets supplied to this project.

5.3 Recommendations.

1. Both climate variability, particularly rainfall variability, and land use and management affect changes in flood runoff. Changes in discharge should not be analysed without consideration of changes in catchment rainfall inputs.
2. The preliminary study of catchment responses within different event classifications was the most promising form of analysis developed during this project. Different classification schemes should be investigated to check the nature of changes, including a more complete uncertainty analysis. Careful quality control of existing datasets is necessary in carrying out such analyses. The method should also be tested against modified data sets produced by the Juke methodology.
3. Adequate information about past land management changes and soil conditions is not readily available but will need to be collected and made available in future for different land use categories if improved understanding of the links between runoff and land management is to be gained and used at catchment scales.
4. The results of this project show that there will be a real difficulty of estimating the benefits of such measures in respect of any reduction of flood risk. Further monitoring of studies aimed at reducing runoff should

be carried out to evaluate the effectiveness of different types of measure at the local level in the context of farm environment schemes

5. The difficulty in identifying consistent change given the limitations of the available data means that land management measures cannot be relied on as alternatives to more proven flood risk management options.
6. The difficulty in identifying consistent change given the limitations of the available data does not mean that change is not happening and should not be taken to imply a policy of doing nothing. Contextually relevant management practice guidelines (linked to land use, soil type, antecedent condition) should be developed and monitored to deliver multiple benefits including reduced runoff generation and local flood risk.

5.4 Further science needs

While points 4 and 5 effectively rule out for the moment reliance on land management measures as an alternative to more proven flood risk management options, there are indications that there may be some impacts hidden in climate variability and uncertain data and the limitations of model assumptions.

It is noted for instance that the failure to identify impacts may be in part a result of the limitations of the data available for both rainfall and discharges. It is also noted that there were changes in catchment dynamics for different classes of events in the Axe catchment. This appears to show quite different trends in response for different classes of events, with an increase in the speed of the fast responses in one class, and a decrease in two other classes.

It is therefore concluded that there is a strong case for continuing with the present research projects on land use and runoff experimentation and modelling in FRMRC2, in the NERC FREE programme and in project SC060092 (Multiscale Experimentation, Monitoring and Analysis of long-term land use changes and flood risk). By careful measurement and analysis, these promise to increase our understanding and allow progress towards providing improved predictive tools to assess sensitive locations, sensitive types of flood events, and robust FRM options in the future. These projects do, however, cover only a limited range of land management classes and there is a need to identify suitable sites for catchment scale studies of the impacts of changes in arable management practices.

6. PROJECT STAFF

Name	Affiliation	Contribution
Prof. Keith Beven	Lancaster University	Project Leader, Hydrological Modelling, WP2,3,4
Prof. Peter Young	Lancaster University	Time series analysis, WP2
Dr Renata Romanowicz	Lancaster University	Time series analysis, WP2
Steve Rose	JBA Consulting	Hydrological data, WP1
Dr Rob Lamb	JBA Consulting	Hydrological data and models, WP1
Dave Archer	JBA Consulting	Hydrological responses to land use change, WP1
Dr John Hollis	Cranfield University	Land use impacts on runoff generation, WP1, retired Sep. 06
Dr Ian Holman	Cranfield University	Land use impacts on runoff generation, mapping land use change, WP1
Prof. Joe Morris	Cranfield University	Change in Land Management, WP1
Dr Helena Posthumus	Cranfield University	Change in Land Management, WP1
Prof. Enda O'Connell	Newcastle University	Distributed hydrological modelling, WP3
Dr John Ewen	Newcastle University	Distributed hydrological modelling, WP3
Greg O'Donnell	Newcastle University	Distributed hydrological modelling WP3

7. REFERENCES

AEA (2007) Industry facts. Agricultural Engineers Association. Economics Department http://www.aea.uk.com/industry_facts.htm; accessed on 11/12/2007

Alakukku, L., P. Weisskopf, W.C.T. Chamen, F.G.J. Tijink, J.P. van der Linden, S. Pires, C. Sommer, and G. Spoor (2003) Prevention strategies for field traffic-induced subsoil compaction: a review. Part 1. Machine/soil strategies. *Soil and Tillage Research* 73(1-2): 145-160. doi:10.1016/S0167-1987(03)00107-7

Ansorge, D., and R.J. Godwin (2007) The effect of tyres and rubber track at high axle loads on soil compaction. *Biosystems Engineering* 98(1): 115-126. doi:10.1016/j.biosystemseng.2007.06.005

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, 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.

Ball, B.C., D.J. Campbell, J.T. Douglas, J.K. Henshall, and M.F. O'Sullivan (1997) Soil structural quality, compaction and land management. *European Journal of Soil Science* 45(4): 593-601

Beven, K.J., 1979. On the generalised kinematic routing method. *Water Resources Research*, 15(5), 1238-1242.

Beven, K J, 2001. *Rainfall-runoff modelling: the primer*, Wiley, Chichester.

Boardman, J. (1995). Damage to property by runoff from agricultural land, South Downs, southern England, 1976-93. Geogr. J. 161(2), 177-191

Boorman, D. B., Hollis, J. M., Lilly, A. 1995. *Hydrology of soil types: a hydrologically-based classification of the soils of the United Kingdom*. Report No. 126. Institute of Hydrology. Wallingford, UK. 137pp.

Burt, T.P. and Slattery, M.C. (1996). Time-dependent changes in soil properties and surface runoff generation. In: Advances in Hillslope Processes, Volume 1, Anderson MG, Brooks SM (eds.). Wiley: Chichester; 79-95.

Carof, M., S. De Tourdonnet, Y. Coquet, V. Hallaire, J. Roger-Estrade (2007) Hydraulic conductivity and porosity under conventional and no-tillage and the effect of three species of cover crop in Northern France. *Soil Use and Management* 23(3): 230-237. doi:10.1111/j.1475-2743.2007.00085.x

CEH/BGS (2003). Hydrological Data United Kingdom: Hydrometric Register and Statistics 1996-2000. Natural Environment Research Council. Centre of Ecology and Hydrology and British Geological Survey, Wallingford

Chambers BJ, Garwood TWD, Unwin RJ (2000). Controlling soil water erosion and phosphorus losses from arable land in England and Wales. J. Environmental Quality 29 (1): 145-150

Chambers, B.J. and Garwood, T.W.D. (2000). Monitoring of water erosion on arable farms in England and Wales, 1990-1994. Soil Use & Management, 16(2), 93-99.

Chamen, W.C.T., L. Alakukku, R. Jorge, S. Pires, C. Sommer, G. Spoor, F. Tijink, P. Weisskopf, and P. Van der Linden (2000) Equipment selection and field practices for the control of subsoil compaction – working group Methodologies and Data Acquisition. In: Proceedings of the third workshop of the Concerted Action on Subsoil Compaction, Uppsala, Sweden, June 14-16 2000, Report 100. Department of Soil Sciences, Swedish University of Agricultural Sciences, Uppsala, Sweden, pp 207-219

Chamen, W.C.T., L. Alakukku, S. Pires, C. Sommer, G. Spoor, F. Tijink and P. Weisskopf (2003). Prevention strategies for field traffic-induced subsoil compaction: a review. Part 2. Equipment and field practices. Soil and Tillage Research 73(1-2): 161-174.

Cheng, S.J. and Wang, R.Y. (2002). An approach for evaluating the hydrological effects of urbanization and its application. Hydrol. Process. 16, 1403–1418.

Clarke, M. et al. (2008). Scoping study to assess soil compaction affecting upland and lowland grassland in England and Wales. Final Report for Defra project BD2304.

Climent i 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

Colman, D. and T. Young (1989) *Principles of agricultural economics; markets and prices in less developed countries*. Cambridge, Cambridge University Press

Defra (2001, 2004, 2005, 2006) Farm Practices Survey. http://statistics.defra.gov.uk/esg/publications/fps/default.asp; accessed on 13/12/2007

Diao, X., A. Somwaru and T. Roe (2001) A global analysis of agricultural reform in WTO member countries. *Agricultural policy reform in the WTO - the road ahead.* Agricultural Economics Report (AERS02). M.E. Burfisher. Washington DC, Economic Research Service, USDA

Dobbs, T.L. and J.N. Pretty (2004) Agri-environment stewardship schemes and 'multifunctionality'. *Review of Agricultural Economics* 26(2): 220-237

Environment Agency (2003). Best farming practices : profiting from a good environment. Environment Agency, Bristol.

Ewen, J., Parkin, G., O'Connell, P. E. 2000. SHETRAN: distributed river basin flow and transport modeling system. *American Society of Civil Engineers Journal of Hydrologic Engineering* **5:** 250-258.

Fullen, M.A. (1998). Effects of grass ley set-aside on runoff, erosion and organic matter levels in sandy soils in east Shropshire, UK. Soil & Tillage Research, 46(1-2), 41-49.

Gilman, K, 1992, *Modelling the effect of land use change in the upper Severn catchment on flood levels downstream*, English Nature Research Report 471, English Nature: Peterborough

Harris, G.L., Howse, K.R. and Pepper, T.J. (1993). Effects of moling and cultivation on soil-water and runoff from a drained clay soil. Agricultural Water Management 23: 161-180.

Herzog, F. (2005) Agri-environment schemes as landscape experiments. *Agriculture, Ecosystems and Environment* 108: 175-177

Hiscock, K M, Lister, D H, Boar, R R and Green, F M L, An integrated assessment of long-term changes in the hydrology of three lowland rivers in eastern England, *J. Environmental Management*., 61, 195-214, 2001.

Hodge, I. (2001) Beyond agri-environmental policy: towards an alternative model of rural environment governance. *Land Use Policy* 18: 99-111

Holman, I.P., Hollis, J.M. and Thompson, T.R.E., 2002. Impact of agricultural soil conditions on floods – Autumn 2000. R&D Technical Report W5B-026/TR, Environment Agency: Bristol.

Holman, I.P., J.M. Hollis, M.E. Bramley, and T.R.E. Thompson (2003) The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales. *Hydrology and Earth System Sciences* 7(5): 755-766

Hooda, P.S., Edwards, A.C., Anderson, H.A. and Miller, A. (2000). A review of water quality concerns in livestock farming areas. Sci. Tot. Env., 250 (1-3): 143-167

Howorth, R and Manning, C, ????, Land use change and the water environment of the West Weald landscape over a 30-year period (1971-2001), West Weald Landscape Project Report, Henfield, W. Sussex.

Imeson, A.C. and Kwaad, F.J.P.M. (1990). The response of tilled soils to wetting by rainfall and the dynamic character of soil erodibility, In Soil Erosion on Agricultural Land, Boardman J, Foster IDL, Dearing JA (eds.). Wiley, Sons, Chichester, pp 3-14

Institute of Hydrology. 1999. *Flood Estimation Handbook*. Centre for Ecology and Hydrology. Wallingford, UK.

Kleijn, D. and W.J. Sutherland (2003) How effective are European agri-environment schemes in conserving and promoting biodiversity? *Journal of Applied Ecology* 40(6): 947-969

Latacz-Lohman, U., and I. Hodge (2003) European agri-environmental policy for the 21st century. *The Australian Journal of Agricultural and Resource Economics* 47(1): 123-139

Le Bas C, Houšková B, Bialousz S & Bielek P (2006). Soil Compaction : Identifying Risk Areas for Soil degradation in Europe by Compaction. In: Eckelmann, W., Baritz, R., Bialousz, S., Bielek, P., Carre, F., Houšková, B., Jones, R.J.A., Kibblewhite, M.G., Kozak, J., Le Bas, C., Tóth, G., Tóth, T., Várallyay, G., Yli Halla, M. & Zupan, M. (2006). Common Criteria for Risk Area Identification according to Soil Threats. European Soil Bureau Research Report No.20, EUR 22185 EN, 94pp. Office for Official Publications of the European Communities, Luxembourg.

Lingard, J. (2002) Agricultural subsidies and environmental change. *Encyclopaedia of Global Environmental Change*. John Wiley & Sons, Ltd.

Lobley, M., and C. Potter (2004) Agricultural change and restructuring: recent evidence from a survey of agricultural households in England. *Journal of Rural Studies* 20: 499-510

MAFF [Ministry of Agriculture, Fisheries and Food] (1998a).Code of Good Agricultural Practice for the Protection of Water / The Water Code. MAFF Publications, London.

MAFF [Ministry of Agriculture, Fisheries and Food] (1998b).Code of Good Agricultural Practice for the Protection of Soil / The Soil Code. MAFF Publications, London.

Martin, P. (1999). Reducing flood risk from sediment-laden agricultural runoff using intercrop management techniques in northern France. Soil & Tillage Research, 52(3-4), 233-245.

Martyn T M, Donaldson G, Clements R O and Lindsay J (2000). Soil erosion control in maize stubbles. In Proceedings of Sixth Research Conference, British Grassland Society, 29-30. C2.

Mayrand, K., S. Dionne, M. Paquin, and I. Pageot-LeBel (2003) *The economic and environmental impacts of agricultural subsidies: an assessment of the*

2002 US Farm Bill and Doha Round. Montréal, Unisfera International Centre

McDowell, R.W., Sharpley, A.N., Condron, L.M., Haygarth, P.M. and Brookes, P.C. (2001). Processes controlling soil phosphorus release to runoff and implications for agricultural management. Nutrient Cycling In Agroecosystems, 59 (3): 269-284 2001

Nix, J. (1968) *Farm Management Pocketbook*. 2nd edition. Wye College.

Nix, J. (1977) *Farm Management Pocketbook*. 8th edition. Wye College.

Nix, J. (1987) *Farm Management Pocketbook*. 17th edition. Wye College.

Nix, J. (1997) *Farm Management Pocketbook*. 27th edition. Wye College.

Nix, J. (2007) *Farm Management Pocketbook*. 38th edition. Wye College.

NSRI [National Soil Resoures Institute] (2002). A guide to better soil structure. Cranfield University.

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, Tellier S. 2004a. *Review of impacts of rural land use and management on flood generation: Impact study report.* Department of Environment, Food and Rural Affairs, Research and Development Technical Report FD2114/TR. Defra Flood Management Division. London. 142pp.

O'Connell P E, Beven K J, Carney J N, Clements R O, Ewen J, Hollis J, Morris J, O'Donnell G M, Packman J C, Parkin A, Quinn P F, Rose S C, Shepherd M. 2004b. *Review of impacts of rural land use and management on flood generation: Research plan*. Department of Environment, Food and Rural Affairs, Research and Development Technical Report FD2114/PR1. Defra Flood Management Division. London. 54pp.

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

O'Connell, E., Ewen, J., Mayes, W., O'Donnell, G. 2007b. Multiscale experimentation, monitoring and analysis of long-term land use changes and flood risk (EA Project SC060092): Inception Report. Environment Agency. London. 29pp.

Ogaji, J. (2005) Sustainable agriculture in the UK. *Environment, Development and Sustainability* 7: 253-270

Packman, J. C., Quinn, P. F., Hollis, J. M., O'Connell, P. E. 2004. *Review of impacts of rural land use and management on flood generation: Short-term improvement to the FEH rainfall-runoff model: Technical background*. Department for Environment, Food and Rural Affairs, Research and Development Technical Report FD2114/PR3. Defra Flood Management Division. London. 54pp.

Ragg, J.M., Beard, G.R., George, H., Heaven, F.W., Hollis, J.M., Jones, R.J.A., Palmer, R.C., Reeve, M.J., Robson, J.D. and Whitfield, W.A.D. (1984). *Soils and their use in Midland and western England*. Soil Survey of England and Wales Bulletin No. 12: Harpenden.

Reed, D. (1999). Flood Estimation Handbook Volume 1: Overview. Institute of Hydrology: Wallingford; 107.

Robinson, M, 1990, *Impact of improved land drainage on river flows*, Institute of Hydrology Report No. 113, Wallingford, Oxon, 1990.

Robinson, M. (1998). 30 years of forest hydrology changes at Coalburn: water balance and extreme flows. *Hydrology and Earth System Sciences* 2(2-3): 233-238

Robson, A, 2002, Evidence for trends in UK flooding, *Phil. Trans. R. Soc. Lond.* A**360**, 1327–1343

Rose, S., Rosolova, Z. 2007. *Ripon Land Management Project. Final Report*. Department for Environment, Food and Rural Affairs. Taunton. 54pp.

Skaggs, R.W., Breve, M.A. and Gilliam. J.W. (1994). Hydrological and water quality impacts of agricultural drainage. Critical Reviews in Environmental Science and Technology 241: 1-32.

Spencer, P., Higginson, N., Palmer, T. and Wass, P. (2004). HiFlows-UK. Paper presented to the Irish National Hydrology Seminar, Tullamore, Ireland

Sullivan A, Ternan JL and Williams AG, 2004, Land use change and hydrological response in the Camel catchment, Cornwall, *Appl. Geogr.* 34:119-137.

U.S. Soil Conservation Service (1986). Urban Hydrology for Small Watersheds. Technical Release 55, U.S Department of Agriculture.

Ward, N., T. Marsden and R. Munton (1990) Farm landscape change: trends in upland and lowland England. *Land Use Policy* 7(4): 291-302

Ward PJ, Renssen H, Aerts JCJH, van Balen RT and Vandenberghe, J, 2007, Strong increases in flood frequency and discharge of the River Meuse over the late Holocene: impacts of long-term anthropogenic land use change and climate variability, *Hydrol. Earth Syst. Sci. Disc.*, 4: 2521-2560.

Whitehead, P.G. and Robinson, M. (1993). Experimental basin studies- an international and historical perspective of forest impacts. J. Hydrol., 145(3-4), 217-230

Wilson, G.A. and K. Hart (2001) Farmer participation in agri-environment schemes: towards conservation-oriented thinking? *Sociologia Ruralis* 41(2): 254-274

Withers PJA, Hodgkinson RA, Bates A and Withers CM (2006). Some effects of tramlines on surface runoff, sediment and phosphorus mobilization on an erosion-prone soil. *Soil Use and Management* 22 (3): 245-255

Young, P. C.(1999). Nonstationary time series analysis and forecasting. *Progress in Environmental Science*, 1:3–48.

Young, P.C. 2000 Stochastic, dynamic modelling and signal processing: time variable and state dependent parameter estimation. In: *Nonstationary and Nonlinear Signal Processing*, (W.J. Fitzgerald, A. Walden, R. Smith & P.C. Young eds.), pp 74-114. Cambridge: Cambridge University Press.

Young, P. C., 2001, Data-based mechanistic modelling and validation of rainfall-flow processes. In: *Model Validation: Perspectives in Hydrological Science*, (M. G. Anderson and P. D. Bates eds.), Chichester: J. Wiley, 117-161.

Young, P. C., Pedregal, D. J., and Tych, W. (1999). Dynamic harmonic regression. *J. Forecasting*, 18:369–394.

Young, P. C., McKenna, P. and Bruun, J., 2001, Identification of nonlinear stochastic systems by state dependent parameter estimation, *International Journal of Control*, 74, 1837-1857.

Ergon House
Horseferry Road
London SW1P 2AL

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