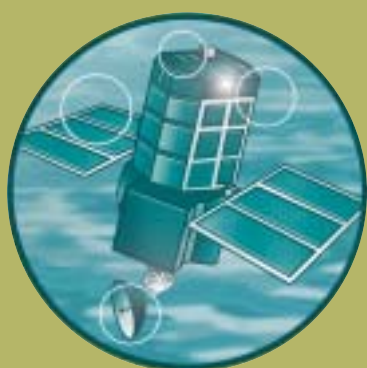


# Review of impacts of rural land use and management on flood generation

## Impact study report

R&D Technical Report FD2114/TR



ENVIRONMENT  
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Department for Environment  
Food and Rural Affairs

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

# Review of impacts of rural land use and management on flood generation

## Impact study report

R&D Technical Report FD2114/TR

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### **Statement of use**

This report is aimed at those involved in land management. It provides the current position of knowledge and science with respect to land use management and its impact on flood generation. It will be of benefit to those seeking to reduce flood risk through specific land management practices, and those who wish to assess the impact of specific management practices on flood risk.

### **Dissemination Status**

Internal: Released Internally

External: Released to Public Domain

**Keywords:** agriculture; land use; land management; rural; runoff; flooding; flood prediction; flood risk; mitigation; water resources; climatic variability; climate change; soils; groundwater; modelling; cultivation practices; monitoring; agri-environment schemes; socio-economic policy; Foresight scenarios; CAP reforms.

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# Executive summary

**Background:** A review of the impacts of land use and management on flood generation has been carried out by a team drawn from the disciplines of agriculture, soil science, hydrology, hydrogeology and socio-economic science. The findings are reported here in the form of an Impact Study Report. Research requirements identified through the review are presented in a companion report (the Research Plan). The reporting for Project FD2114 is completed by two reports on a Short-term Method for predicting impacts, to be used in the preparation of Catchment Flood Management Plans (CFMPs).

This report is addressed primarily to those engaged in research, policy-making or practice in the field of Flood Defence. It assumes the reader has a good understanding of hydrological processes, the hydrological functioning of catchments, catchment modelling and flood estimation methods.

**Objective:** To review the factors contributing to runoff and flooding in the rural (managed, not natural) environment, and to scope out the research needed to improve the identification of the management policies and interventions to reduce the impact of flooding.

**Overview:** The overview of Land Use Management and Flooding (Section 2) summarizes the approaches used to study impacts under the headings of field experiments, available data, models and flood analysis and prediction methods. Two disciplinary perspectives are taken (Agriculture and Soils Management, and Hydrology) and the strengths and weaknesses of each are identified. Catchment modelling is reviewed critically in relation to current capacity to predict the impacts of land use and management changes on flood generation. This overview is supported by Appendices A, B and F.

**Current land use and management:** Section 3 summarizes an extensive review of the current state of managed land in England and Wales. Land use is summarized under the headings of: arable (including cereals, oilseed rape, maize and root crops); annual feed crops; woodland; grassland livestock and field under-drainage. This is followed by a review of current farming practices in terms of impacts on soil structure and runoff. Mitigation practices are then considered under a number of headings, including cover crops, minimum tillage, hillslope runoff control, use of machinery, and retention structures and wetlands. This section is supported by Appendix C.

**Review of assembled sources:** The sources cover a wide range of monitoring and modelling studies (Section 4) carried out across a range of scales, from plot to large catchment. A brief summary of each source is provided. Section 5 summarizes the main socio-economic sources, categorized in terms of the drivers-pressure-state-impact-response framework. Section 4 is supported by Appendices A, B and E, and Section 5 by Appendices D and E.

**The critical assessment** (Section 6) is conducted using the Source-Pathway-Receptor framework. Changes in local-scale surface runoff are the Source where 'local-scale' includes plots, fields, small hillslopes and areas at field

edges. The effects then propagate through the surface water network - the Pathway. The Receptor is the flood impact. The Critical Assessment considers evidence from field experiments, modelling and socio-economic studies, and quantifies the current state of knowledge about impacts from the evidence. Implications for water resources are also considered. Section 6 includes an analysis of various hypotheses concerning the impacts of land use management on flooding. Responses are given in Appendix G to supplementary Stakeholder Questions provided following a meeting where the findings of the Critical Assessment were first presented. The hypotheses subsection and the responses to the Stakeholder Questions could be informative to those who do not wish to read all of the detailed sections of the report.

**Future land use management:** This is considered under the headings of climate change and the socio-economic drivers for future land use (Section 7). Increases in storm rainfall in the autumn/winter months are expected across the UK in future years, which may lead to increased surface runoff generation at the farm scale. There are good opportunities to mitigate source runoff using an integrated runoff management approach at the farm scale which can also generate other benefits by reducing erosion and agricultural pollution. Future Agri-Environmental Schemes, CAP reforms and long-term Foresight scenarios are considered to illustrate how farming in the UK is expected to evolve in the future, and the expected responses to these futures are discussed.

**Conclusions and research recommendations:** The main conclusions drawn from the review can be summarized as follows:

- Significant changes in land use and management practices in the last fifty years have resulted in the intensification of agricultural land use. There is much evidence to confirm that patterns of land use and farming practices are a direct response to the incentives provided by agricultural policy, modified by local and farm factors;
- There is substantial evidence that changes in land use and management practices affect runoff generation at the local scale, but the effects are complex;
- There is only very limited evidence that local changes in runoff are transferred to the surface water network and propagate downstream;
- Analysis of peak runoff records has so far produced very little firm evidence of catchment scale impacts of land use management;
- There are many measures that can be taken to mitigate local flooding by delaying runoff, such as using grass buffers, temporary ponds, and appropriate ditching. An integrated approach is needed in applying these measures so that the maximum overall benefit is gained for flood and pollution mitigation and erosion reduction;
- There is considerable uncertainty about how effectively land managers will respond to any promotions or policies related to particular flood prevention or mitigation measures;
- Rainfall-runoff modelling to predict impacts is in its infancy: there is no generally-accepted theoretical basis for the design of a model suitable to

predict impacts, it is not known which data have the most value when predicting impacts, and there are limitations in the methods available for estimating the uncertainty in predictions;

- A considerable amount of high-quality field data on impacts will be needed to support the development of robust methods for predicting impacts.

The main research recommendations are summarized below. These are addressed in the Research Plan, which maps a way forward in defining and implementing best practice in flood prevention and mitigation and for operational assessment of the likely effects of prevention and mitigation measures. In designing the research plan, a wide view is taken of how management decisions about flood prevention and mitigation will be made in the future, including how an integrated whole-catchment multi-function approach to decision making will evolve.

- There is a need to learn what can be learned about the flood impacts of changes in rural land use and management that have taken place in the past;
- There is a need for an electronic map identifying the catchments that are vulnerable to local and downstream flooding as a result of changes in rural land use and management;
- There is need for field trials of flood mitigation measures, to build up the knowledge base;
- There is a need for best practice to be established, both for selecting which flood prevention and mitigation measures should be used to meet local needs and how these measures should be promoted;
- A coherent approach is needed in modelling the flood impacts of changes in land use and management. Ideally, this would represent socio-economic, agricultural and hydrological effects and responses. It would be in the form of a decision-support tool for estimating the likely outcome of implementing flood prevention and mitigation measures and the outcomes when policies and promotions are used to encourage the uptake of measures. The tool would take account of uncertainty, could be used to examine future scenarios for climate, land use and management, and would give a basis for rigorously testing rainfall-runoff modelling so that issues related to the theoretical basis of modelling and the value of data can be addressed;
- A solid research base must be established and maintained if real progress is to be made in assessing the flood impacts of changes in rural land use and management and in establishing best practice for flood prevention and mitigation.

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**Appendix A: Review of UK data sources relating to the impacts of land use and management on flood generation**

**Appendix B: Data analysis and modelling at the catchment Scale**

**Appendix C: Current state of managed rural land and mitigation measures**

**Appendix D: Socio-economic review of likely future change scenarios**

**Appendix E: Ongoing monitoring, modelling and socio-economic studies**

**Appendix G: Stakeholder feedback**

**Appendix F: River engineering and flood plain management**

# 1. Introduction

## 1.1 Background

Recent large flood events in the UK and Europe have raised major concerns about existing levels of flood protection and the management of flood risk in the future. Land use and land management practices have undergone major changes over the past fifty years, and, in particular, there has been major intensification in farming in the past 15-20 years. There is therefore an urgent need to gain a comprehensive understanding of the impacts of current land management practices on runoff, and the extent to which the impacts register at a range of catchment scales. This understanding needs to be embedded within catchment models which can generate the predictions needed to underpin decision-making in catchment flood management, particularly in relation to land use and management.

In 1993, the Ministry for Agriculture Fisheries and Food (now Defra) advocated a strategic catchment-wide approach to flood defence (MAFF, 1993). The first fruit of this strategy was the programme of Shoreline Management Plans, which commenced in 1995. The Defra/EA initiative for a programme of Catchment Flood Management Plans (CFMPs) followed. The new CFMPs lie at the centre of catchment planning and will in due course form the flood management component of Water Framework Directive plans.

The impact of rural land use management on catchment flood response is a critical issue for CFMPs, and closely intertwined with the wider issues of farming, forestry and the rural economy. Information on the impacts of agricultural practices on runoff is far from comprehensive, and there are significant methodological issues to be addressed in extrapolating small-scale experimental observations for catchment-scale application. In order to progress the necessary research, Defra has commissioned the present project FD2114, which forms part of the Broad Scale Modelling Hydrology Programme (Calver and Wheeler, 2001).

In order to cover the range of disciplines involved, a consortium covering agriculture, soil science, hydrology, hydrogeology and socio-economic science has been assembled. The membership and expertise of the consortium members is summarized in Table 1-1.

Before policies can be formulated to mitigate any impacts of land use and management on flooding, all of the relevant evidence which is dispersed throughout the agricultural, soils and hydrological literatures must first be examined. This understanding needs to be expressed within the framework of predictive models which can support policy-making.

<b>Organization</b>	<b>Expertise</b>
University of Newcastle upon Tyne (Coordinator)	Catchment experimentation and modelling, flood risk estimation
ADAS	Hydrology, Agri-environment
British Geological Survey	Floodplain delineation; groundwater flooding
Centre for Ecology and Hydrology	Hydrology and modelling
Institute of Grassland and Environmental Research	Crop husbandry and soil erosion
Cranfield University: National Soil Resources Institute Institute of Water and Environment	Soil hydrology, soil spatial variability and pollutant transport. Resource economics and management
Lancaster University	Hydrology, modelling, and uncertainty

**Table 1.1 Consortium members and expertise**

## 1.2 Objectives and scope

The programme of work for Project FD2114 is divided into 2 parts, each with an overall objective:

**Part 1 Objective:** To review the factors contributing to runoff and flooding in the rural (managed, not natural) environment, and to scope out the research needed to improve the identification of the management policies and interventions to reduce the impact of flooding.

**Part 2 Objective:** To deliver in the short term an improvement in the estimation of the effects of changes in rural land management on flood generation to the CFMP programme.

The scope of the work required to address the Part 1 Objective is defined by the set of Tasks prescribed in Table 1.2. The report follows the logical progression of these Tasks, and is divided into two parts:

**FD2114/TR** constitutes the Impact Study Report (Tasks 1.7).

**FD2114/PR1** defines the Research Plan (Tasks 8.12).

The Part 2 Objective is addressed in Project Records PR2 and PR3 which deal with the development and implementation of a Short-term Method for predicting the impacts of land use and management on flooding within CFMPs.

FD2114/TR of the report is structured in relation to the Tasks as follows:

- The Task 1 Review is addressed by FD2114/TR as a whole, supported by a set of Appendices (Table 1-3). The assembled material is defined by the set of references included at the end of the FD2114/TR and is summarized and reviewed in Sections 2 to 4;
- Ongoing initiatives and unpublished material are reviewed in Appendix E (Task 2), and assessed in appropriate sections of the Report;
- Section 3, supported by Appendix C, reviews the current state of managed rural land in England and Wales, and lists potential land use interventions that may be used to mitigate flood risk (Task 3);
- A review of likely future change scenarios (Task 4) is given in Section 7, based on the studies in Section 5 and supported by Appendix D;
- The key UK data sources on impacts are provided in Section 4 (Task 5), supported by Appendix A;
- The Task 7 report incorporating the critical assessment of the assembled sources is summarised in Section 6.

Appendices A-G are presented separately from this Report.

<b>Task 1</b>	Carry out a comprehensive literature review of field, analytical and model sources across soils, agriculture and flood hydrology disciplines via a multidisciplinary team, bringing together all the main strands of research and practice in this field.
<b>Task 2</b>	Carry out a comprehensive review of on-going initiatives not yet encapsulated in the literature.
<b>Task 3</b>	Develop an understanding of the current state of managed rural land in England and Wales from the viewpoint of flood risk. List the potential land management measures and other interventions that might be adopted to mitigate this. Impacts on water resources should be assessed and any clashes noted. Include an appreciation of the uncertainties involved in such forecasts.
<b>Task 4</b>	Carry out a review of likely future change scenarios. Comment on how desirable changes from the point of view of using land management measures for flood management might be achieved in social, financial and institutional terms, and the practicability of these. This should include consideration of <i>Environmental Futures. Foresight, Office of Science and Technology (DTI, 1999)</i> . These futures were used in developing the EA's new strategy for water resources: <i>Water Resources for the Future: A Strategy for England and Wales (Environment Agency, 2001b)</i> .
<b>Task 5</b>	Identify key UK data sources on impacts.
<b>Task 6</b>	Carry out a critical assessment of the overall picture provided by assembled sources, encompassing both scientific and rural socio-economic issues.
<b>Task 7</b>	Draft a report covering individual impact study information in succinct form, the conclusions drawn from this, and the rationale of the derivation of the conclusions.
<b>Task 8</b>	Draft a Research Plan for the recommended research programme for the impacts of rural land use on flooding. Hydrological research

	may be both within FEH and in continuous simulation runoff modelling. This should, like the BSM hydrology scoping study, propose a medium term near-user programme which could be funded by Defra/EA and a longer term programme perhaps encompassing longer field work projects which could be discussed with NERC and other Research Councils. This should include recommendations as to how ongoing programmes such as LOCAR and CHASM could be used to forward this research area.
<b>Task 9</b>	Produce clear descriptions of all recommended research projects on the Defra/EA Shortform template, suitable as the specification for tender documents and include in the draft Research Plan. These should include the objectives, key customer purpose and descriptions of all research projects.
<b>Task 10</b>	Present the projects within a logical framework of user needs, serving users concerned with both long-term catchment planning and land management.
<b>Task 11</b>	Address funding limitations by prioritising the projects recommended.
<b>Task 12</b>	Ensure that all research projects carried forward are truly necessary, responsive to user needs and provide good value for public money.
<b>Task 13</b>	Circulate the draft Impact Study report and Research Plan and consult with users and experts. This could include setting up a project website.
<b>Task 14</b>	Finalise, print and disseminate the Impact Study report and Research Plan. This should include a small coloured fly sheet to publicise the research programme.
<b>Task 15</b>	Carry out all measures to ensure uptake of the research is in accordance with the Defra / EA requirements following its research on <i>Improving the Implementation and Adoption of Flood and Coastal Defence R&amp;D Results (Defra/EA, 2002)</i> .

**Table 1.2 Tasks defining scope of review and research plan**

<b>Reports</b>	<b>Title</b>	<b>Lead</b>	<b>Tasks</b>
Part A	Review of impacts of rural land use and management on flood generation	Newcastle	Includes a summary of all task outputs, and incorporates the Task 6 and 7 reports.
Appendix A	Review of UK data sources relating to the impacts of land use and management on flood generation	Lancaster	5
Appendix B	Data analysis and modelling at the catchment Scale	Newcastle	1
Appendix C	Current state of managed rural land and mitigation measures	ADAS	3
Appendix D	Socio-economic review of likely future change scenarios	NSRI	4
Appendix E	Ongoing monitoring, modelling and socio-economic studies	Newcastle	2

**Table 1.3 Appendices in relation to the Task**

## **2. Overview of land use management and flood generation: processes, data, models and methods**

This Section commences by introducing the Source–Pathway–Receptor framework which is used in this Report to assess the evidence that changes to land use and management might have generated or enhanced flooding in UK catchments. Runoff generation processes in natural and changed landscapes (the Source) are then considered, followed by a brief review of runoff routing through the catchment river channel network (the Pathway). The definition of the flood impact (the Receptor) is then discussed.

The different perspectives provided by the disciplines of agriculture and soils, and hydrology, are reviewed based on field experiments, available data, and modelling. Model calibration, validation and predictive uncertainty are assessed in the context of predicting the impacts of land use and management. Finally, flood analysis and prediction methods are reviewed from the standpoints of identifying change in flood records, and of predicting impacts on the flood frequency curve. Empirical statistical analyses of links between impacts and their perceived causes are also considered.

This Section is supported by a more detailed review in Appendix B.

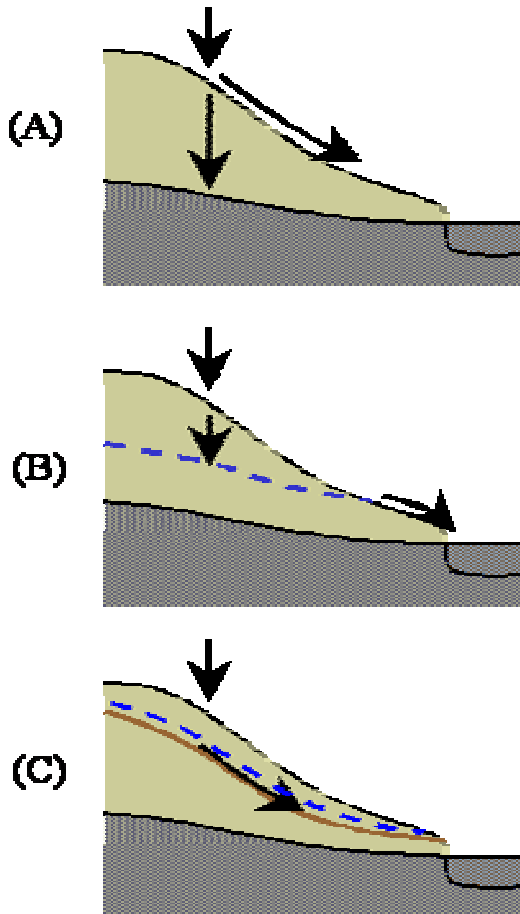
### **2.1 The Source - Pathway - Receptor Framework**

The Source-Pathway-Receptor (SPR) Framework can be applied at a range of scales from a local field or hillslope to that of a large catchment. In this framework, changes in 'local-scale' runoff and drainage are the Source. The local scale includes plots, fields, small hillslopes and areas at field edges. The effects then propagate along the Pathway - the surface water channel network. The Receptor is the location where the flood impact takes place e.g. through inundation of an urbanized floodplain. In what follows, the Source, Pathway and Receptor are considered in turn, and some key questions emerge concerning impacts and impact propagation through the catchment.

### **2.2 Runoff generation processes in natural landscapes**

Within a natural landscape, runoff generation is controlled by interactions between climate, landforms, soils, vegetation and geology. The climatic controls are exercised through storm precipitation, which provides the driver for runoff generation, and evapotranspiration, which controls the antecedent conditions through soil moisture. Vegetation controls runoff generation primarily through evapotranspiration and soil moisture. Landforms influence where the landscape runoff is generated, while the geology controls water tables and the exchanges between aquifers and streams during flood events.

The hydraulic properties of the surface and near surface have a direct effect on runoff generation. These properties vary with the degree of wetness (soil moisture content) and with soil type and condition. The overall result is that the relationship between runoff generation and the surface and near-surface hydraulic properties and moisture status is quite complex and very variable in time and space. Three concepts are widely used to describe and characterise runoff generation (Figure 2.1):



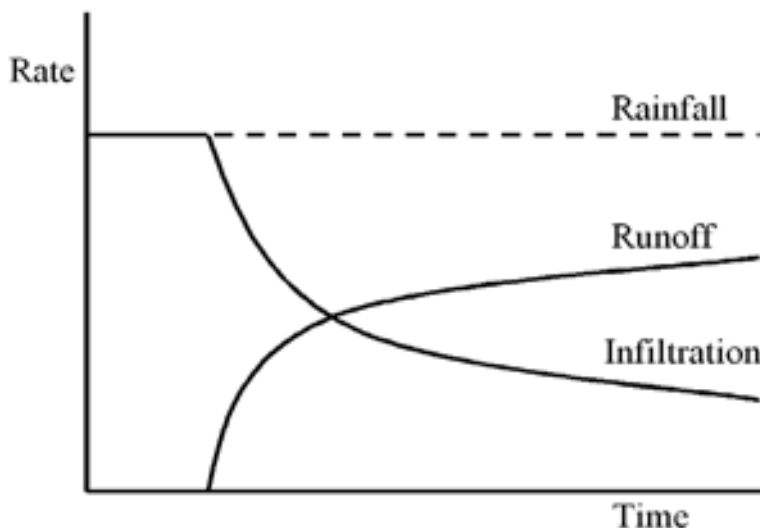
**Figure 2.1 Runoff generation processes: (A) infiltration excess runoff, (B) saturation excess runoff and (C) subsurface storm runoff**

- A. Infiltration excess runoff:** this occurs when the rainfall intensity exceeds the infiltration capacity of the soil. Figure 2.2 shows hypothetical infiltration and runoff responses under steady intense rainfall for a location where the water table is deep and the subsoil is permeable. Initially, all the rain water infiltrates and the soil wets up rapidly. The driving potential needed to infiltrate all the rainwater into the soil depends on the extent and hydraulic properties of the wetted zone, and gradually increases as the zone extends downwards. A time is finally reached when the potential (gravity) is insufficient, and beyond this time there is infiltration excess runoff. Rainfall intensities are not normally high enough to generate infiltration excess runoff in natural rural landscapes in the UK, but it does occur



where the hydraulic properties of the soil have been badly degraded through poor land management (e.g. where there is a poorly-permeable soil crust). There is usually considerable spatial heterogeneity in the infiltration excess runoff response, reflecting heterogeneity in the soil's hydraulic properties, and runoff generated at one point can infiltrate downslope.

- B. Saturation excess runoff:** this occurs when rain falls on saturated ground. Generally, there is a strong link between topography and the distribution of saturated areas in a catchment, with valley bottoms being prone to saturation. After prolonged rainfall, though, saturation can occur almost anywhere, especially where the soil structure has been degraded through poor land management. For some saturated areas, the saturation is created and maintained by the combined action of rainfall and inflowing subsurface lateral flow. The runoff rate can exceed the rainfall rate in these areas and surface runoff can persist after the rainfall ceases. The 'variable source area' concept is sometimes used when describing saturation excess runoff in a catchment. This is simply the concept that the total saturated area, and hence the total area for saturation excess runoff, will expand and contract over time in response to rainfall. It is sometimes also called the 'dynamic contributing area' concept.
- C. Subsurface storm runoff:** this occurs when infiltrated water moves laterally through the subsurface towards seepage zones and the river channel. Typically, this occurs in hillslopes in forested catchments where a highly permeable topsoil overlies a less permeable subsoil and a 'perched' water table develops during storms.



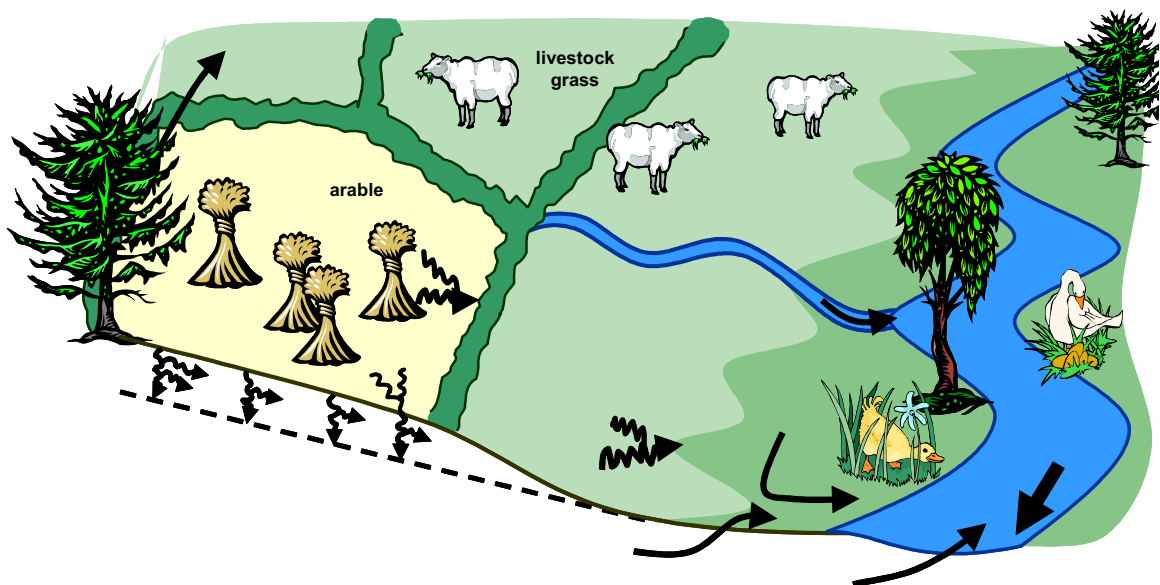
**Figure 2.2 Infiltration excess runoff under constant rainfall**

In addition to the runoff mechanisms considered above, groundwater can also be a source of flooding. Clearwater flooding is associated with a catchment-wide or regional groundwater level rise. This is a particular problem over the Chalk outcrop of southern England, and can start many weeks after a prolonged

high rainfall event. Alluvial groundwater floods are associated with high river flows, with water flowing out through the banks of the river into the hydraulically connected alluvium, causing flooding behind embanked flood defences.

Over the past century, the UK landscape has been transformed as a consequence of major changes in land use and management. There are few, if any, catchments in the UK which have not been affected in some way by man-made activities. To provide a reference point for assessing the impacts of land use and management on runoff generation, a typical pre-war (1930s) agricultural landscape at the hillslope scale is considered during a storm event in Figure 2.3.

Key characteristics of this pre-war landscape are:



**Figure 2.3 Pre-war agricultural landscape at the hillslope scale**

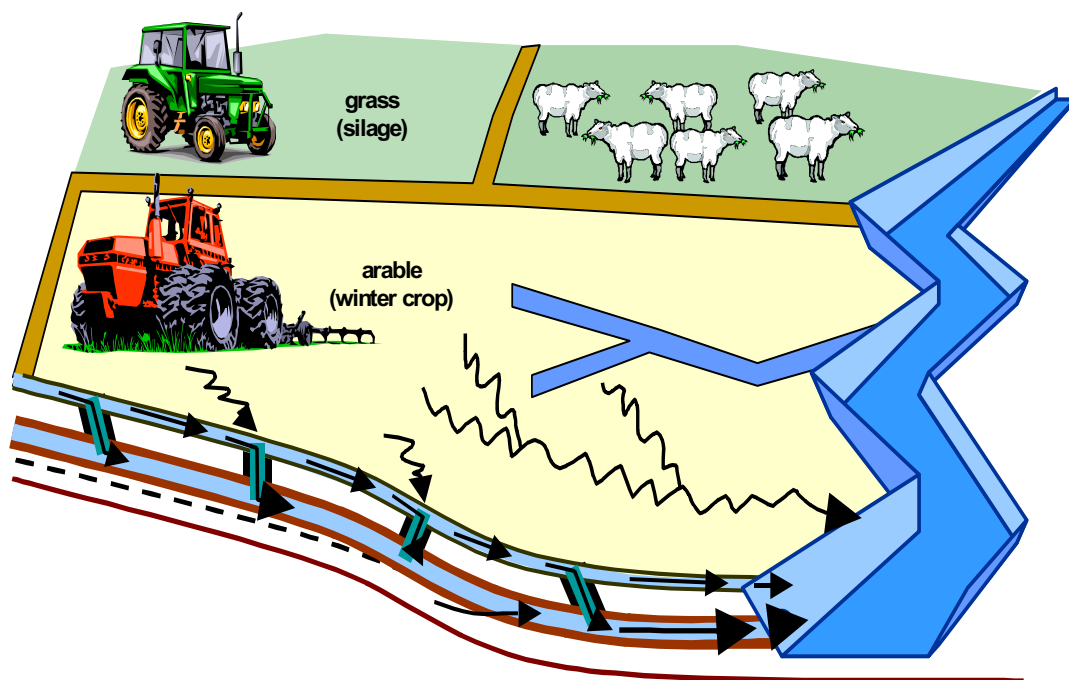
- small fields, dense hedgerows and numerous trees which disconnect runoff pathways;
- a relatively uncompacted well structured soil (although there is no direct evidence for this);
- overland flow reinfilters as it moves downslope;
- the soil column can fill to reach field capacity and saturation;
- infiltration reaches the water table which responds to create an expanding runoff source area downslope;
- a natural meandering river with an active variable runoff source area and riparian zone.

The overall natural flood response of this landscape will be controlled by a substantial soil moisture storage capacity, long disconnected flow paths, and a small but active variable source area.

## 2.3 Runoff generation processes in changing landscapes (the Source)

Since the second world war, the UK landscape has undergone major changes as a result of the drive for self-sufficiency in food production, and the effects of the Common Agricultural Policy. These changes are depicted in Figure 2.4 for the same hillslope element considered in Figure 2.3, and can be summarized as follows:

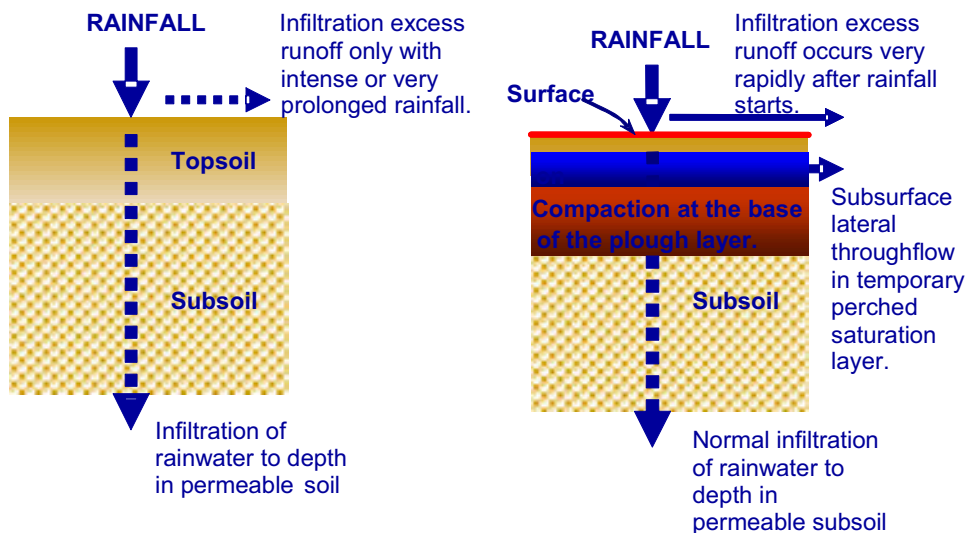
- loss of hedgerows and larger fields;
- cultivation practices causing deeper compacted soils (with reduced storage);
- land drains connecting the hill top to the channel;
- cracks and mole drains feeding overland flow to drains and ditches;
- unchecked wash-off from bare soil;
- plough lines, ditches and tyre tracks concentrating overland flow;
- tramlines and farm tracks which convey runoff quickly to water courses;
- channelized river with no riparian buffer zone.



**Figure 2.4 Recent agricultural landscape at the hillslope scale**

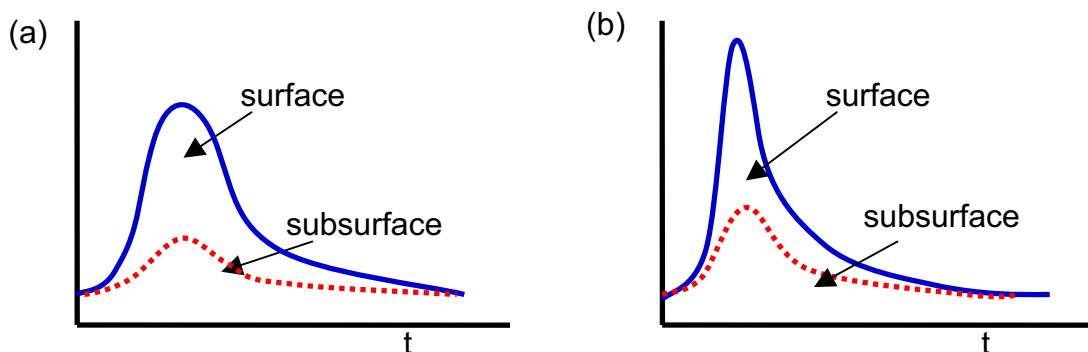
In this landscape, there are therefore several interacting factors which will have influenced changes in runoff generation and its delivery to the channel network e.g. the extent of soil compaction, the efficiency of land drains, the connectivity of flow paths etc. A key factor is the impact which soil structure degradation

(due to compaction) can have on runoff generation. By influencing the soil structural conditions that determine both the inherent storage capacity, macropore structure and flow pathways within the upper soil layers and their saturated hydraulic conductivity, land management can significantly affect the local generation of surface and subsurface runoff. This is illustrated in Figure 2-5, for a naturally permeable free-draining soil. Management practices which cause soil compaction at the surface reduce the infiltration capacity of the soil and can lead to infiltration excess runoff. Similarly, practices which leave weakly structured soils with little or no vegetative cover can also lead to infiltration excess runoff, as the result of the rapid formation of a surface crust with very low moisture storage capacity and hydraulic conductivity. Practices which result in soil compaction at the surface or at the base of a plough layer significantly reduce soil storage capacity and macroporosity in the upper layers resulting in significant decreases in both the maximum and minimum infiltration rates and thus the early onset of infiltration excess runoff for any rainfall event. They also result in early initiation of rapid lateral throughflow in upper soil layers, where this may not have been a runoff mechanism before such compaction occurred.



**Figure 2.5 Management-induced changes to infiltration excess runoff and rapid subsurface lateral flow**

There is a range of management practices that result in such soil structural degradation and these are discussed more fully in section 3.2 of this report.



**Figure 2.6 Hypothetical responses of hillslope elements to the same storm rainfall showing the partitioning of surface and subsurface runoff: (a) pre-war landscape; (b) recent landscape**

Apart from the soil degradation factor depicted in Figure 2.5, several other factors associated with land use and management can potentially influence runoff generation. For example, the maintenance of land drains has declined since the 1980s when subsidies ceased, and many of these may have become blocked and do not function effectively. Overall, the hillslope element in Figure 2.4 can be expected to generate more surface runoff and to deliver it more rapidly to the surface water network than that shown in Figure 2.3. Hypothetical pre-war and recent hillslope element responses are shown in Figure 2.6 (a) and (b). However, due to the natural complexity and heterogeneity of the landscape and the interactions between the various factors, the resulting overall change in runoff generation cannot easily be predicted, even at this local scale. Moreover, the landscape within a catchment is a complex mosaic of elements similar to that in Figure 2-3 and Figure 2-4, all with different responses and overlain by a range of land management practices, and there is then the key issue of how the responses of these elements combine to generate the overall catchment response.

In this Report, a distinction is drawn between **local scale** runoff generation, which takes place at the hillslope/first order catchment scale, and runoff generation at the larger **catchment scale**, which is taken here to be greater than 10km<sup>2</sup>.

At this stage, three key questions can be posed:

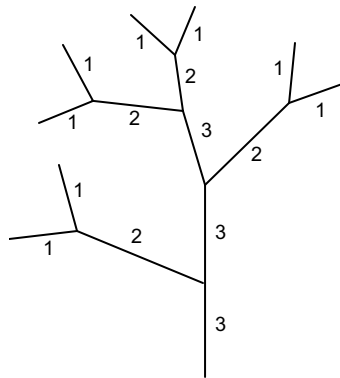
1. At the local scale, how does a given change in land use or management affect local scale runoff generation?
2. How does a local scale effect propagate downstream, and how do many different local scale effects combine to affect the flood hydrograph at larger catchment scales?
3. How can adverse effects be mitigated using economically and environmentally acceptable measures?

These key questions and other issues are addressed in the later sections of the Report.

## **2.4 Runoff routing through the river channel network (the Pathway)**

A catchment river channel network can be characterized in terms of an ordering system; a Horton-Strahler ordering system is shown in Figure 2.7. First order streams collect runoff from landscape elements similar to those shown in

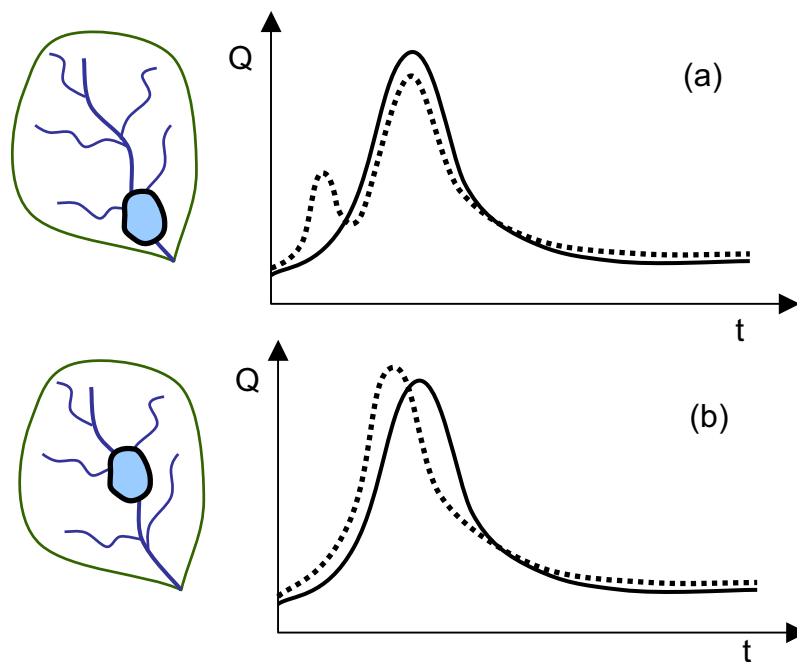
Figures 2.3 and 2.4, and transmit the runoff downstream to higher order links and eventually to the catchment outfall. In steep upland channels, flood peaks are subject to little attenuation as they move downstream. As runoff is routed through higher order streams, the shape of the flood hydrograph will reflect increasingly the properties of the channel network, such as its shape, the slopes and roughnesses of individual links, and attenuation induced by flood plain storage effects when out-of-bank flooding occurs. However, the magnitude of the flood peak will also reflect the volume and timing of runoff from landscape elements delivered into the channel network, and the extent to which the timings of the peaks of tributary hydrographs are in phase or out of phase with the main channel hydrograph or with each other. This will all vary as a function of the magnitude of the flood, as travel times are a function of water depth and the spatial distribution of rainfall over the catchment. Flooding is generated when landscape runoff delivered to the channel network exceeds its capacity to convey the runoff to the catchment outfall, leading to the inundation of rural and/or urban riparian/floodplain areas. This is referred to here as **Flood Generation**.



**Figure 2.7 Horton-Strahler ordering of a catchment river channel network**

As has been the case with the UK landscape, UK river channels have also undergone substantial modifications over the past 70 years as a result of land drainage schemes or flood protection works for urban and rural floodplain areas. Channels have been subject to a number of different modifications, depending on the circumstances e.g. straightening, resectioning, embanking, culverting and the construction of weirs and sluices. More recently, there has been a substantial move towards the restoration of channels and floodplains to their natural states and functions, as part of biodiversity and natural flood mitigation schemes.

As previously noted, a comprehensive review of evidence for the effects of these modifications and other river management interventions is outwith the scope of this review (a brief overview is included in Appendix F), but it is clear that these modifications will have changed the natural routing processes in many UK catchments. Therefore, these effects should be taken into account when assessing the evidence that changes to runoff generation processes at the local scale (Section 2.3) may have affected flood generation at larger catchment scales. However, disentangling the different effects on flood generation at the catchment scale is a formidable challenge. The overall effect on catchment-scale flood generation will be a function of the spatial location and extent of the landscape areas and river channel reaches affected, and on the relative timings of runoff contributions from both the affected and unaffected landscape elements. This is shown schematically in Figure 2.8 which illustrates the possible impacts on a flood hydrograph of the spatial location of an area affected by soil compaction. In Figure 2.8a, the affected area is in the lower end of the catchment, where compacted soils generate rapid surface runoff which precedes the main hydrograph, reducing the peak of the latter. In Figure 2.8b the affected area is further up the catchment, so that the rapid surface runoff coincides with the rising limb of the hydrograph and increases the peak. This is an over-simplification of reality, since the affected area will be distributed irregularly across the catchment, but it does illustrate that the relative timings of runoff contributions can be important.



**Figure 2.8 Possible impacts on a flood hydrograph due to the spatial location of change (solid line pre-change, dashed line post-change)**

It also follows from the above analysis that the technical effectiveness of mitigation measures must be viewed in terms of their spatial locations within the catchments, and their effects on runoff generation and delivery to the channel network. Local-scale mitigation measures (e.g. at the farm scale) can be viewed as 'prevention at source', but, since their effect will essentially be to delay or attenuate the delivery of runoff (e.g. by changing the partitioning of surface and subsurface runoff through increased infiltration), the overall effect on the catchment flood hydrograph will depend on how these changes affect the hydrological functioning of the catchment as a whole, given that they will interact with other ongoing changes (e.g. to river and floodplain management).

## 2.5 Impacts, flood hazard, flood risk and prediction uncertainty

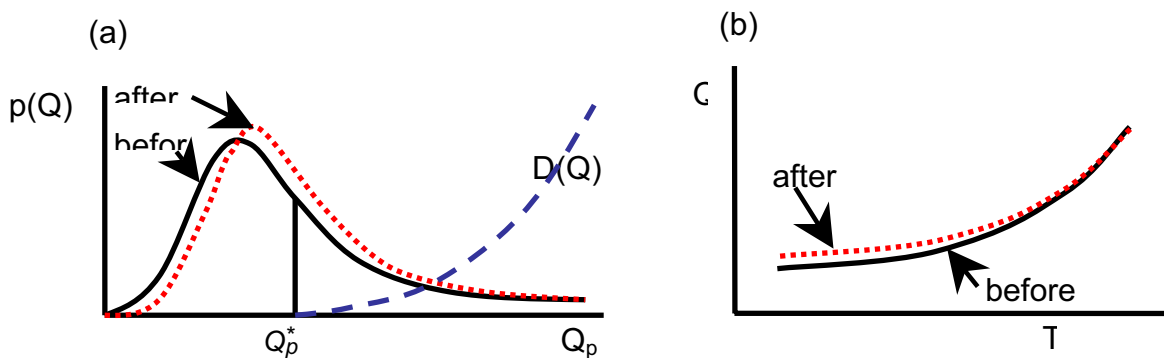
In the Source-Pathway-Receptor framework, the Receptor is the location where the impact takes place e.g. through inundation of rural or urban floodplains. The extent of floodplain inundation depends on both the peak discharge and volume of runoff associated with a flood hydrograph, so changes to the latter provide a basis for quantifying impacts. However, from a flood protection standpoint, impact needs to be defined in terms of **Flood Risk**, which is derived from a combination of the probability that a critical peak discharge is exceeded, defined as **Flood Hazard**, and the consequent economic damage. This is depicted



graphically in Figure 2.9(a), where flood hazard is defined using the probability distribution of annual maximum peak discharges. Formally, flood risk is defined as:

$$E(D) = \int_{Q_p^*}^{\infty} p(Q)D(Q)dQ$$

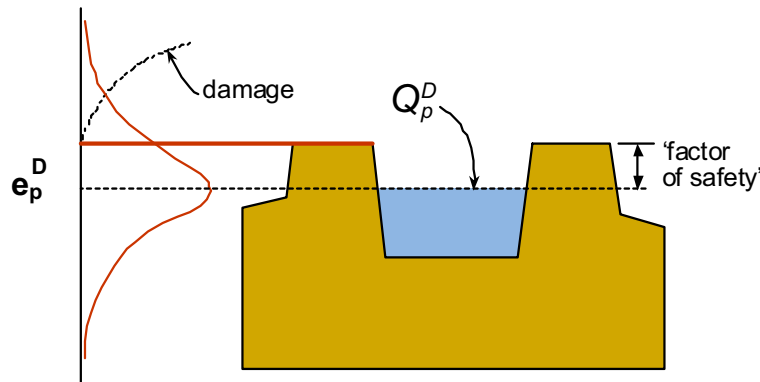
where  $E(D)$  is expected damage (which is equated with Flood Risk),  $p(Q)$  is the probability density of peak discharge  $Q_p$ , and  $D(Q)$  is a damage function for exceedances of a critical discharge  $Q_p^*$ . Also shown in Figure 2.9 is a probability distribution associated with a hypothetical change to the peak discharge regime that might result from land use management or other changes within the catchment. For this example, the changes have affected mainly the lower end of the discharge regime, and so the impact on flood risk will not be very significant. Changes affecting the high end of the flow range will, however, have a significant impact on flood risk. The probability distribution of annual maximum peak flows is more conventionally expressed in terms of the flood frequency curve; hypothetical curves corresponding to the 'before' and 'after' probability distributions in Figure 2.9(a) are shown in Figure 2.9(b). As already indicated, the focus on flood risk derives from the need to design flood protection measures, or to otherwise reduce flood risk to an acceptable level. In designing flood protection works, the cost of the works must be balanced against the reduction in flood risk, quantified in terms of expected damage. This is conventionally done using benefit/cost analysis, leading to the choice of a design flood discharge  $Q_p^D$  which defines the level of protection.



**Figure 2.9 Schematic of (a) the probability distribution of annual maximum discharges, and (b) the flood frequency curve before and after a change within the catchment**

From the foregoing discussion, it is evident that the flood frequency curve must be specified to enable flood risk (and changes to this) to be quantified. However, the estimation of the flood frequency curve using currently available methods (e.g. the FEH statistical or rainfall runoff methods) can only be achieved subject to significant **Prediction Uncertainty**. This leads to the situation depicted in Figure 2.10 where uncertainty in the estimate of the design flood is shown through the probability distribution of estimation error. One way

of dealing with this uncertainty is to increase the protection level relative to the design discharge as shown in Figure 2.10, thus incorporating a ‘factor of safety’. The issue of how to determine the factor of safety is not considered here. If the cost of providing this factor of safety is large, then there is a justification for



investing in the collection of more data and/or the development of an improved prediction method to reduce the uncertainty.

**Figure 2.10: Schematic of flood protection works, showing the probability distribution of estimation error  $e_p^D$  (defined as the difference between the true design flood  $Q_p^D$  and its estimate  $\hat{Q}_p^D$ ) for the design flood  $Q_p^D$ , and the factor of safety.**

At this stage, a few pertinent observations can be made about the possible impacts of land use and management changes on the flood frequency curve, flood hazard and flood risk. Firstly, impacts are likely to be catchment specific, and dependent upon the natural catchment characteristics (topography, soils etc.) as well as the land management practices within the catchment, and vulnerability to economic damage. Secondly, changes to the flood generation mechanisms within the catchment need to be viewed ultimately in terms of impacts on the flood frequency curve, flood hazard and flood risk, as do the effectiveness of mitigation measures i.e. these will not be effective unless they can be shown to mitigate flood risk. Again, the effectiveness of mitigation measures is likely to vary from catchment to catchment.

It is also evident from the foregoing discussion that, when the term ‘impact’ is used in relation to flooding, its meaning must be qualified. The quantification of impacts in terms of flood risk is beyond the scope of this Review, and so impacts will therefore be assessed in terms of effects that can contribute to flood generation. Changes to runoff generation and routing processes that might affect the flood hydrograph and the flood frequency curve will be considered as evidence of such effects, as well as effects which can be quantified directly from runoff records.

## 2.6 Disciplinary perspectives

In relation to water flow, the primary research interests of the agricultural and soil scientists have historically differed from those of the hydrologist. This is reflected in the nature of the field experiments and data collection performed by the two groups. Data and observations provide the basis for the conceptualisation of any model, so consequently it is unsurprising that the characteristics of the hydrological models produced by these two groups also differ. Here, experiments, data and modelling are reviewed from the two disciplinary perspectives, and the strengths and weaknesses of each are highlighted.

### Field experiments and data

#### Agriculture and soil management

Typically, agricultural and soil scientists are interested in the impacts that farming practices have on the physical condition of the soil in relation to sustainable agricultural production. Field experiments have therefore been conducted in those areas where farming is most intense and profitable, i.e. the lowlands. As noted in Section 2.3, areas of intense agricultural production are very different from the natural landscape, with the introduction of drainage systems, large amounts of near surface soil disturbance, particularly in arable areas, the addition of chemicals and manures onto the land etc. As a result of these interests, the range of experiments conducted is quite broad, focusing on soil moisture, nutrient management, soil erosion, and the interaction of soil water with local drains and ditches. Experiments are usually conducted over small scales, ranging from point measurements, supported by laboratory work, to agricultural field scale experiments.

#### Hydrology

Hydrologists are primarily concerned with improving the understanding of runoff generation and how this subsequently migrates through river channel networks. Experiments are therefore typically conducted in natural and semi-natural upland landscapes where complications due to man-made influences are lowest. Experiments have been performed over a variety of spatial scales, ranging from point scale experiments for the analysis of the influence of soil and vegetation on water infiltration, through to the hillslope scale for the understanding of the role of the landscape attributes on the generation of runoff, up to the small catchment scale (typically up to 10 km<sup>2</sup>) where river channel processes are of importance. More recently, there has been a move towards 'multi-scale' experiments in mesoscale catchments (~100 km<sup>2</sup>) in which nested measurements are taken at a range of scales to improve the understanding of the links between the processes operating at different scales.

All of the partners within this multi-disciplinary project have access to experimental data that could be used in future studies of the impacts of land use and management practices on flood generation; the analysis of such data is beyond the scope of this Review. Details of plot and small catchment data sets are provided in Appendix A. Additionally, both the partners and various

other organisations have been involved in the development of regional and national data sets that allow the characterisation of the landscape from varying viewpoints. A sample of these datasets, the majority of which are available in digital format, is provided in Table 2.1. The majority of these data are spatial in nature, but others are time series measurements relating to specific points on the land surface. The spatial data are usually derived from the extrapolation of field and point scale measurements or from the analysis of remotely sensed data, the use of which is becoming more prevalent in the environmental sciences, but which only provides indirect evidence of the hydrological variables needed for the estimation of flood runoff generation. The purpose of these data is often to provide information for the modelling of water fluxes over and through the landscape.

<b>Data Resource</b>	<b>Provider</b>	<b><u>A</u>gric., <u>E</u>co., <u>F</u>or., or <u>H</u>ydrol</b>	<b>Description</b>
<b>Land use and vegetation</b>			
National Inventory of Woodland and Trees	FC	F	Consists of two separate surveys; (1) the Main Woodland Survey covering woodlands > 2 ha and (2) the Survey of Small Woodland and Trees covering small woods, groups of trees, linear features and individual trees.
ALC	Defra	A	The Agricultural Land Classification (ALC) maps provide the grade of agricultural land in England and Wales based on soil, climatic and site factors.
CORINE (MARS)	EEA	A	The Coordination of Information on the Environment (CORINE) land cover classification of EC countries, derived from satellite images. (Monitoring Agriculture from Remote Sensing)
CS2000	CEH	A	The UK Countryside Survey 2000 (CS2000) land cover census data. Includes field observational data on habitat types, hedgerows and plant species, and a satellite image based land classification (LCM2000).
Natural Areas	EN	E	A subdivision of England based on wildlife and natural features. Developed for nature conservation needs.
'Crop Calendar' dataset	NSRI	A	A set of regionalised dates for specific crop growth stages that are important input parameters for crop growth models. The dataset is intended to support a more realistic estimation of changes in water balances, particularly with respect to future changes in cropping patterns and rotations. This is an ongoing project funded by the Environment Agency.
<b>Soils</b>			
HOST	CEH, NSRI, MLURI, DANI	A/H	Hydrological classification of soils of the UK.
LandIS	NSRI	A	National soil database for England and Wales, comprises NATMAP (a digital soil map), point data, soil type related property and interpretive data, NSI (a national inventory of topsoil properties) and agroclimatic data

<b>Geology</b>			
BGS	BGS	H	BGS possess the major repository for Quaternary geological data (including floodplain maps), bedrock geology, aquifer properties and hydrogeological information.
<b>Hydrological data</b>			
NWA	CEH	H	The National Water Archive (NWA) contains a wide range of holdings, including time series data (river flows and groundwater levels, soil moisture and meteorological data) and spatial series (catchment boundaries, digitised rivers)
Met. Office	Met. Office	H	Archives of rainfall and MORECS evaporation and soil moisture data.
Flow data archive	EA	H	Archives of flow data and rainfall.
ECN	CEH	H	Environmental Change Network (ECN) gathers information about the pressures and responses to environmental change in physical, chemical and biological systems.
<b>Topography</b>			
IHDTM	CEH	H	National digital elevation grid and matching flow path data derived from OS maps.
FEH CDROM	CEH	H	Morphometric catchment descriptors.
LANDMAP	Uni. Manc., UCL	H	Fine resolution elevation data for the UK and Ireland, derived from satellite.
LiDAR	EA	H	Fine resolution elevation data of flood plains and coastal areas, derived from airborne imagery.
SAR	EA	H/E	Fine resolution elevation data for the UK derived from airborne radar surveys

**Table 2.1 Sample data sources of use in hydrological modelling**

## **Modelling**

A natural progression from experimentation and data collection is the activity of modelling. A model can be thought of as an encapsulation of both understanding and one's beliefs about a system, and can also be used as a hypothesis testing and predictive tool. The multi-disciplinary team involved in developing this review includes experts in agriculture, soil management and hydrology. In terms of modelling hydrological processes, both sets of specialists would claim to be able represent each other's subjects in some way.

A summary of the typical attributes of models developed by agricultural and soil scientists and hydrologists are given in Table 2-2, while a more detailed examination of catchment modelling is provided in Section 2.7 and in Appendix B. Given the large number and wide variety of applications for which models have been developed, only broad generalisations about the modelling approaches taken by the two disciplines can be provided here. Table 2-2 is

therefore only intended as a guide and should be treated as an historical perspective.

Attribute	Agricultural	Hydrology
Application scale	Field	Catchment
Process description basis	Point and field observations	Point through to catchment observations
Key processes	Soil structure and fertility, drainage, pollution (pesticides, nitrates etc.)	Runoff generation and stream flow
Supporting data	Land use and management practices and soils	Topography, vegetation and soils
Soil infiltration representation	Techniques developed from data analysis	Physical reasoning or theoretical understanding
Channel flow and overland flow representation	Simple time delays	Physical reasoning or theoretical understanding
Prediction time step	Daily/monthly	Hourly
Software	Free, supported, graphical front ends	A mixture of free and propriety software with corresponding levels of support; often low usability
Main development groups	USDA, UK government agencies, universities, research institutes	Universities, research institutes, consulting firms

**Table 2.2 Typical characteristics of agricultural and hydrology models**

### **Agriculture and soil management**

The agriculturalist is interested in the influence of the soil moisture status on plant growth and pollution transport at the field scale. Model predictions are therefore usually only required at daily to monthly time intervals, typically at the field scale. Where predictions are required over agricultural catchments, the movement of runoff and propagation through the river channel network is implemented in a simple fashion based on time delays. This is in part due to the neglect of the spatial variations in terrain, a result of the emphasis on 1-D process understanding. Rainfall is partitioned into soil water and runoff using methods derived from data analysis rather than physical understanding. Due to the variety of agricultural interests, these models incorporate a large number of process descriptions, including those associated with plant growth, pollutant transport (e.g. nutrients and pesticides), drainage systems and erosion.

### **Hydrology**

The flood hydrologist is typically concerned with relatively short-term catchment flow dynamics, with model predictions usually made at hourly intervals. Process descriptions are derived from 2-D/3-D understanding, resulting from the

emphasis on the hillslope and catchment. Great emphasis is placed on the representation of infiltration processes, runoff generation mechanisms and river channel processes, requiring the need for terrain, soil and river network information. Natural vegetation processes are usually well represented, but agricultural crop cycles are not. Also, agricultural management practices including harvesting, tillage and subsurface drainage systems are often not considered.

The project partners appreciate the historical differences between the research areas and fully appreciate the need for cross-fertilisation and closer integration in the future. This also supports the case for future research into runoff being multifunctional, i.e. driven by flood defence, water resources and water quality needs. This move towards multidisciplinary, multifunctional research has been matched by more joint agency funding, as seen recently under Defra, EA, EN and FC initiatives, and the involvement of Defra and the EA in Government research programmes funded through the UK research councils.

## **2.7 Catchment modelling**

### **Model structures**

There are several good general texts and papers on rainfall-runoff modelling:

- Beven (2001) is the standard textbook on rainfall-runoff modelling, and describes the philosophy and practice in some detail. Some of the definitions used here are based on the glossary of terms in this book;
- Singh and Frevert (2002a) describes 23 of the most popular models for small catchments (i.e. catchments < 250 km<sup>2</sup> in area). Most of these chapters were written by the model developers, so this is a useful reference;
- Singh and Frevert (2002b) is a companion to Singh and Frevert (2002a), but for large catchments;
- Singh and Woolhiser (2002) has extensive lists of models and associated references;
- Wheeler (2002) has several sections relevant to rainfall-runoff modelling in the context of flooding in the UK.

Based on the above general references, there are probably well in excess of 100 rainfall-runoff models currently being used worldwide. They are used for a wide variety of purposes, whenever estimates are needed for runoff rates or volumes, such as in flood prediction and forecasting, water resource planning and environmental impact assessment. The reason why there are so many models is partly because organisations prefer an in-house model, under their own control, but also because, as the general references show, there is no consensus about the best modelling methods to use. Ten models are listed in Table 2.3, approximately in order of increasing complexity. The models in the list were chosen because they are well known and are typical examples of their type and style of model. Some of the detail in Table 2.3 corresponds to earlier

sections in this report: the agricultural and hydrological genesis of the models (column 2) was discussed in Section 2.6, while runoff generation processes (column 5) were described in Section 2.2.

Model	Agric. or Hydr.	Type	Style	Runoff generation	Routing
FEH (Institute of Hydrology, 1999)	H	Percentage runoff / unit hydrograph	Lumped	Storm runoff based on HOST & other factors.	Unit hydrograph
EPIC (Williams, 1995)	A	Empirical lumped	Lumped	Infiltration excess (SCS)	None
PDM (Moore and Clark, 1981)	H	Conceptual probability distribution function	Lumped	Fast surface & slow subsurface drainage	Exponential decay of routing storage
ARNO (Todini, 1996)	H	Conceptual distribution function	Semi-distributed	Saturation excess & slow subsurface drainage	Advection-diffusion network
TOPMODEL (Beven, 1997)	H	Quasi-physical topographic distribution function	Semi-distributed	Saturation excess & groundwater exfiltration	Network width function (and others)
UP (Ewen, 1997)	H	Upscaled physically based	Hydrological response units	Parameterised based on physically-based modelling	Advection-diffusion network
SWATCATCH (Hollis et al., 1996)	A	Empirical distributed	2D grid	Rapid, intermediate & base flow (HOST)	None
ANSWERS (Beasley et al., 1977)	A	Quasi-physical distributed	2D grid	Infiltration excess (SCS)	Stage-discharge relationship
LISFLOOD (De Roo et al., 2000)	H	GIS physically-based distributed	2D GIS grid	Infiltration excess & saturation excess	Kinematic wave
SHETRAN (Ewen et al., 2000)	H	Physically-based distributed	3D finite-difference grid	Infiltration excess, saturation excess, groundwater exfiltration & subsurface drainage	Diffusion wave

**Table 2.3 Models and classification**

There are several descriptions and terms used in the table that have particular relevance for modelling the impact of rural land use and management on flood



generation and which will be used in later sections of this report. These are listed and defined below:

<b>Conceptual</b>	Based on qualitative descriptions of the processes thought to be controlling runoff.
<b>Distributed</b>	The model inputs and landscape properties are described spatially, and state variables, such as soil moisture, vary in space.
<b>Distribution function</b>	Function (usually for probability or topography) which defines the (usually spatial) variation of properties in a catchment or land area.
<b>Empirical</b>	Based directly on measured data.
<b>HOST</b>	The Hydrology of Soil Types classification of the soils of the United Kingdom (Boorman et al., 1995). There are, for example, methods which relate the standard percentage runoff (SPR - the percentage of rainfall that causes a short-term increase in flow at the catchment outlet) to the HOST class. SPR can then be used in the calculation of parameters in rainfall-runoff models.
<b>Hydrological response unit</b>	Parcel of land surface defined in terms of soil, vegetation and topographic characteristics thought to be hydrologically homogenous.
<b>Lumped</b>	The model inputs and state variables, such as soil moisture, are catchment averages, and so do not vary in space.
<b>Physically-based</b>	The model parameters are based on small-scale physics (such as hydraulic conductivities, defined in terms of Darcy's law).
<b>Quasi-physical</b>	Partly physically-based or some elements physically-based or some clear link to physical properties or information.
<b>SCS-CN</b>	United States Department of Agriculture Soil Conservation Service curve numbers (Rallison, 1980). There are tables giving the curve numbers for a wide range of different land uses and soil conditions. These numbers can be used in the calculation of storm runoff.
<b>Semi-distributed</b>	Lying somewhere between lumped and distributed; the spatial representation is typically based on sub-catchments.
<b>Unit hydrograph</b>	Storm runoff hydrograph from a unit volume of effective rainfall.
<b>Upscaled physically based</b>	Lumped, but with parameters based on simulation results from physically-based distributed modelling.

The models incorporate several types of routing components (i.e. methods for conveying runoff in the streams and rivers). These are summarized briefly below.

<b>Advection-diffusion</b>	Diffusion wave approximation to St. Venant equations, solved analytically (linear) or numerically (non-linear) on a grid or network.
<b>Kinematic wave</b>	Kinematic wave approximation to St. Venant equation.
<b>Network width function</b>	Histogram of number of reaches in the channel network at a given distance from the outlet. Used in conjunction with advection-diffusion routing.

### **Infiltration within a catchment model**

In catchment models, the partitioning of rainfall into surface flow, subsurface flow, and evapotranspiration loss is controlled by the soil physics and hydrology component. It is this component which must represent the local effects of management practices such as tillage and the effects of different cropping practices and land uses. In some models it must also represent field scale surface flow and land drainage, if they are not represented explicitly.

To be useful, a soil physics and hydrology component must represent the way that infiltration is affected by soil condition and management history. However, although there are dozens of models used to represent infiltration, none of these is capable of properly representing the natural complexity of water flow in soils and the way it is affected by factors such as:

- soil mineralogy;
- soil water chemistry;
- interactions with vegetation, worms and moles and the root runs and burrow holes these create;
- diurnal and seasonal thermal cycling, including the effects of freeze-thaw;
- stress cycling by farm animals and vehicles;
- moisture cycling and the effects of expansion and shrinkage;
- natural vertical preferential flow path development;
- rainfall impact and crust formation and degradation.

Another limitation of the existing infiltration models is that they cannot properly account for the effects of spatial variation in any or all of the above factors. There is therefore always some form of lumping in the way that infiltration is modelled in soil physics and hydrology components. For example, in a distributed catchment model, the landscape is divided into elements such as hillslopes, gridsquares, land patches, or agricultural fields, and each element is treated as a uniform area with a single soil type (e.g. a sandy loam) or a single soil profile in which the soil type varies only with depth, and infiltration is modelled as uniform over the area. In reality, as a result of spatial heterogeneities of soil properties, infiltration excess runoff may be generated

over only part of a model element, depending on antecedent conditions and rainfall intensities.

Practical soil physics and hydrology components neglect most of the factors affecting water flow and use simple models which have parameters that depend only on soil type. It is common to use saturated hydraulic conductivity as a parameter, because values are readily available for a wide range of different soil types (a saturated soil with a saturated hydraulic conductivity of 1 m/day will transmit 1m/day of water under a head gradient of 1m/m). The available values are based on measurements made at the point-scale in the field or in the laboratory. Some components have further parameters, such as parameters describing how the hydraulic conductivity varies with moisture content (it decreases extremely rapidly with moisture content). It should be noted that, like saturated hydraulic conductivity, these parameters are usually based on point-scale field or laboratory measurements so have scale and complexity problems in that they are not strictly applicable at the scale of the modelling elements and take no account of many aspects of the natural complexity of water flow in soils. It has proven particularly difficult to model the time variable effects of macropores and surface crusts on infiltration and hillslope flow pathways.

To give an example of modelling the effects of soil change, consider how soil compaction would be represented in a single land element in a distributed catchment model in which saturated hydraulic conductivity is the only parameter. Compaction affects the soil porosity, the connectivity of the soil pores, the microscopic sub-pore interactions between the soil water and the soil solids, and may vary significantly over scales of a few centimetres or metres. The modelling would, however, simply involve decreasing the saturated hydraulic conductivity for the element by an amount based on some auxiliary information on the link between compaction and conductivity. And this auxiliary information, whatever its form (e.g. spot measurements made on compacted soil in the field), is likely to have its own scale and complexity problems.

There is a wide range of different types of infiltration equations described in the general texts (e.g. Hillel (1982), Kutilek and Nielsen (1994)). These include quasi-physical equations such as Philip's equations and physically based equations such as Richards' equation. The design of the soil physics and hydrology component used in a given catchment model tends to match the design of the other components: so, for example, a distributed physically based model would usually use Richards' equation with constant soil parameters.

### **Model calibration, validation and prediction uncertainty**

Ideally, a discussion on modelling and its use in predicting the impacts of rural land use and management on flood generation would be strongly evidence-based, relying on clear analyses in the open scientific literature about the relative merits of methods and models that have been properly tested for this purpose. In reality, there are very few examples of such testing and analysis; exceptions include Parkin et al. (1996) and Bathurst et al. (2004). The points made below are therefore based on (1) an understanding of the purpose; (2) the general references above; (3) Table 2-3 and its associated references; and (4)

the (very limited) existing modelling studies, described and referenced in Section 4.2, in which predictions of impact were made.

The main role of impact modelling is to bring knowledge to the application, so that good estimates can be made for impact assessment. This knowledge is incorporated in the form of the model, the modeller's experience in using the model, and, particularly, in the way the available data are used by the model and modeller.

Consider the nature of a practical validation test for the use of a given model to predict a given impact at a given site. This would involve carefully testing the model's performance using historical data for similar impacts at similar sites, including estimating and testing the uncertainty in the predictions. Stronger testing would involve 'blind' testing in which historical impacts are predicted without sight of the impact data (because predictions of future impacts are, effectively, made 'blind'). No validation work of this sort and quality has been reported in the open scientific literature.

The modelling methods used in rainfall-runoff modelling tend to be generic, rather than application specific. Nearly all the models and methods described in the general references and Table 2.3 have the potential to be applied, in some fashion or other, to modelling the impact of rural land use and management on flood generation.

Whatever the type and style of model, the approach to predicting an impact is likely to involve the following three steps: (1) calibrate a model against historical rainfall and other forcing data; (2) alter the model's parameters to their post-change values; and (3) run simulations using the post-change parameters.

There are two types of available data: local and proxy. The available local data will usually include some of the following:

- Digital elevation maps;
- Geology maps;
- Soil maps;
- Land use maps;
- Historical runoff records;
- Historical records for rainfall and other forcing data;
- Synthetic forcing data (e.g. for possible future conditions);
- Property and response data from local surveys and monitoring and local research sites;
- Data on the proposed changes in land use and management.

The available proxy data can include:

- Data on physical properties for given types of vegetation, soil, river channels, etc;
- Model results and data sets for previously modelled catchments.

A model which can be used with confidence to predict the impacts of future changes at a range of scales will need to make full use of proxy data, especially proxy data for sensitivities to physical change or historical impacts (i.e. type k data). There are at least three relevant sources for type k data:

- Results and data sets for previous modelling of historical impacts (no high-quality examples exist);
- Regionalized parameter data relating to a specific model. Sefton and Howarth (1998) calibrated the IHACRES unit-hydrograph-based model (Jakeman et al., 1990) for 60 catchments and then created regression equations for the model's parameters. The explanatory variables of the regression equation are physical catchment descriptors such as the fraction of land area in grass, so the coefficients of the regression equations are (effectively) sensitivities to land use change;
- Generally applicable regionalized parameter data. An example of this is the SCS curve number, as used in EPIC and ANSWERS (Table 2-3). The SCS curve numbers can be used to calculate storm runoff, and so can be used to estimate the sensitivity of runoff to changes in land use and soil conditions. Another example is the HOST classification, as used in FEH and SWATCATCH (Table 2-3).

Downstream flood impacts will be dependent on the timing and changes in timing of the upstream local runoff and on the flood hydrograph magnitude and changes in magnitude. It is difficult to conceive of a model suitable for representing the integration of these dependences over time and space which does not have either a distributed nature, or an explicit channel routing network, or, at least, a method for generating a distribution function which takes into account the locations of the land areas undergoing changes in use and management.

Calibration and the estimation of uncertainty are likely to be important parts of any operational method for predicting impact:

- Recent progress in this area is summarised in Duan et al. (2002), including methods based on multi-criteria optimisation and methods in which parameter uncertainty is handled using Bayesian inference;
- Practical methods which have the potential to be adapted to estimating uncertainty bounds for predictions of impact include the GLUE method (Beven and Binley, 1992) and the 'blind' testing method (Ewen and Parkin, 1996).

These practical methods require that the model is run repeatedly (e.g. Monte Carlo simulation) so that a link is established between parameter uncertainty and prediction uncertainty. In practice, though, there are unresolved problems that have yet to be tackled:

- Not all the prediction uncertainty is associated with parameter uncertainty or should be treated as parameter uncertainty (Kavetski et al., 2002; Beven, 2002; Beven and Young, 2003);

- It is likely that there are magnitude and timing-related problems associated with estimating an impact by taking the difference between two simulations (i.e. pre-change and post-change simulations). This is similar in nature to the numerical problem that can arise when taking the difference between two large numbers.

## 2.8 Flood analysis and prediction methods

### Statistical approach

To support policy-making in catchment flood risk management, it is not sufficient to make predictions of one or more floods; the full flood frequency curve must be predicted, so that risk (defined as the product of hazard and damage) can be assessed across the full range of probability in a way that properly reflects the changing balance of surface and subsurface runoff conditions with changes in antecedent conditions and rainfall magnitudes. Traditionally, two approaches have been taken to this problem:

- the statistical approach in which historical records of peak discharges are analyzed and described by a probability distribution;
- the rainfall-runoff approach in which a probabilistic/stochastic description of rainfall is linked to a rainfall runoff model to derive the distribution of peak discharge, storm volume etc.

Both are exemplified by the methods employed in the UK Flood Estimation Handbook (Institute of Hydrology, 1999), which are reviewed here from the standpoint of predicting the impacts of land use and management on the flood frequency curve. The statistical approach is summarized here, while the rainfall-runoff approach is outlined in the following section.

The basis of the FEH statistical approach is that an appropriate probability distribution is used to characterize the relationship between peak discharge  $Q_p$  and its probability of exceedance. Typically, the Annual Maximum (AM) peak discharge (the largest observed flow in a water year) is taken to be the random variable described by the probability distribution. The three parameter Generalized Logistic (GL) distribution is the preferred FEH choice for describing AM data in the UK, fitted using L-moments (Hosking and Wallis, 1997). L-moments is regarded as a very reliable method for assessing exceedance probabilities of extreme environmental events when data is available from more than one site.

If a sufficiently long record of annual maximum discharges is available at the site of interest, and the return period  $T$  for prediction is not too large relative to the length of record  $n$  ( $T < n/2$ ; FEH, Vol. 1, Table 5.2), the GL distribution can be fitted to the at-site data. If, however, the necessary data are not available and/or a flood estimate with a high return period is required, then a regional analysis must be conducted in which the GL distribution is fitted to the pooled regional data, standardized by an Index Flood (which in FEH, is taken to be

QMED – the median annual maximum flood). With the FEH methodology, the subject site for prediction is first identified, and a homogeneous pooling group of sites is then formed using similarity measures based on catchment area, standard annual average rainfall (SAAR) and a soils characteristic. The data for each site are standardized by the index flood, and the GL distribution is then fitted to the standardized pooled data using L-moments.

For application at an ungauged subject site, a prediction of QMED is required to estimate a peak discharge with a specified return period. Initially, this is based on a regression equation linking QMED with catchment descriptors (area, SAAR, soil drainage type and storage attenuation due to reservoirs and lakes, and, where necessary, an urban adjustment factor). The initial QMED estimate is then adjusted by assessing the accuracy of the QMED equation at selected similar gauged catchments - described as donors (upstream, neighbouring, or downstream) and analogues (more distant but otherwise similar in terms of AREA, SAAR and soil type).

A fundamental underlying assumption of the statistical approach is that the flood generation process is stationary i.e. the statistics (QMED, variance, number of floods per year etc) are not varying with time. Climatic variation/change and land use changes are possible reasons why this assumption might not be justified.

In the FEH study, an extensive analysis of trends in flood records was carried out; this is reviewed in Appendix B, and considered also in Sections 4 and 6. Apart from a limited number of records, no statistically significant evidence of trend was found that could be attributed to land use or climate change. However, considerable temporal variability in QMED and the number of floods per year nationally was found to be strongly linked to natural climatic variability.

The FEH statistical approach is therefore based on the assumption that land use change has not had a significant impact on flood generation over the period analyzed (essentially 1940-1990). Moreover, land use did not appear as a significant variable in the regression of QMED on catchment characteristics. Therefore, the FEH statistical approach cannot provide a basis for predicting the impact of land use and management on flood risk.

### **Rainfall-runoff approach**

Two variants of rainfall-runoff modelling are employed for predicting a flood magnitude with a specified probability of exceedance:

- an event-based approach in which a depth/duration/frequency description of rainfall is linked with a storm event-based rainfall-runoff model to predict a flood hydrograph with the required probability of exceedance;
- a continuous rainfall-runoff simulation approach in which a stochastic model of rainfall is linked with a continuous rainfall-runoff simulation model to derive the probability distribution of any desired property of the flood hydrograph.

The FEH rainfall-runoff method exemplifies the contemporary application of the event-based approach (FEH, Vol. 4). The method is based on the regionalization of a rainfall depth/duration frequency relationship, a percentage runoff (PR) equation and a triangular unit hydrograph (UH) across the UK. Both PR and the parameters of the triangular UH ( $Q_p$  the peak ordinate;  $T_p$  the time to peak) are derived from regressions on catchment characteristics. For PR, the explanatory variables are Standard Percentage Runoff (SPR) (which itself is predicted from the HOST soil class classification), an antecedent Catchment Wetness Index (CWI) derived at the start of the storm event, the storm rainfall depth and the extent of urbanisation in the catchment (URBEXT). URBEXT is the only land use descriptor that emerged as significant in the regression equation for PR. None of the regression equations for  $Q_p$ ,  $T_p$  incorporated a significant explanatory variable representing rural land use. Therefore, in its present form, the FEH rainfall-runoff method does not provide a basis for predicting rural land use change impacts. However, since a method for predicting land use change impacts was needed within the Modelling and Decision Support Framework (MDSF) used in developing Catchment Flood Management Plans (CFMPs), some empirical adjustments were made to the FEH rainfall-runoff method. The impact of land use management practices that increase soil compaction can be assessed by increasing SPR by a factor of 1.15; reductions in  $T_p$  are also recommended which are dependent on soils, drainage and PR values. As noted in Section 1, an improved short-term method for predicting land use impacts based on the FEH approach is being developed as part of FD2114, and this is described in Reports C1 and C2.

The continuous simulation (CS) approach is based on using a continuous time series of rainfall (measured or generated using a model) as input to a rainfall-runoff model to derive a continuous time series of discharge; a frequency analysis of the required flood hydrograph characteristic (e.g. peaks, volumes) can then be performed. While the CS approach offers considerable advantages over the event-based approach (e.g. a consistent treatment of antecedent conditions), there are still some research challenges that need to be overcome before the approach can be used routinely. Firstly, a regionalized stochastic space-time rainfall model is required to generate inputs to the rainfall-runoff model. A single site stochastic model has been regionalised for the UK by Cowpertwait and O'Connell (1997), while spatial temporal models are being developed for regionalisation by Onof et al. (2000). Secondly, a regionalized CS rainfall-runoff model is required for application at ungauged or poorly-gauged sites. Progress in developing the CS approach for widespread application is reported by Lamb et al. (2000) for the PDM distribution function model. Specific case studies involving the use of the CS approach to predicting land use change impacts are reviewed in Section 4. Difficulties associated with rainfall-runoff modelling have been discussed in Section 2.7 above (and in Appendix B), particularly in the context of predicting land use change impacts.

### **Empirical studies**

A variety of empirical studies has been reported in the literature in which various hypotheses about land use change impacts have been made and explored to a greater or less extent using some form of data analysis. The study of Samson



(1996), in which a link was hypothesised between floods and sheep, is an example; circumstantial evidence was put forward, but a cause effect relationship not proven. A more extensive study of this kind is reported by Lane (2003) in which an apparent increase in flooding in York was linked to upland sheep stocking densities and land management practices. The hypothesis was explored using regression analysis, providing some evidence of a link. However, the large natural variability of rainfall made it difficult to draw any firm conclusions. This and other studies of this kind are reviewed in more detail in Section 4.

## Summary and findings

Over the past century, the UK landscape has been transformed as a consequence of changes in land use and management. Potential changes to local, hillslope-scale, runoff generation and delivery to the channel network have been discussed and illustrated; evidence for these impacts is assessed in Section 6.1. Impacts on flood generation at the catchment scale will depend on the spatial distribution and temporal variation in land use management activities and their effects on runoff generation (magnitude and timing), and on interactions with channel modifications that affect the routing of runoff through the channel network.

Agricultural and soil scientists have a good understanding of the managed lowland environment at the local scale, but the majority of the experiments and modelling have centred on 1-D processes, with flow routing often neglected. The hydrologist has a more complete 2-D/3-D understanding of runoff generation and stream flow processes at sub-catchment and catchment scales. However, the research has typically been performed in semi-natural upland environments. To increase understanding of the effects of land use and management on farm and catchment scale runoff generation, there is a need for cross-fertilisation and closer integration between these disciplines. Numerous rainfall runoff models have been published in the literature, some of which are, in principle, suitable for use in predicting land use change impacts, but there is a lack of evidence-based studies in the open literature on the merits of different methods and models. Typically, model validation is not performed rigorously, with inadequate testing and estimation of uncertainty in predictions.

To support policy-making for flood defence, impacts need to be defined in terms of changes to flood risk, which is based on probability of exceedance (flood hazard) and damage. Therefore, predictions of the impacts on the flood frequency curve are required, not just impacts on an individual flood hydrograph. The FEH statistical approach is the most widely used statistical method for this purpose, but it is based on the assumption that land use change (other than urbanization) has not had a significant impact on flooding. Similarly, the FEH rainfall runoff method, which can also be used to predict the flood frequency curve, does not account for land use changes other than urbanization. An empirical modification of the FEH rainfall runoff method which takes account of land use management changes, is proposed in Reports C1 and C2 on this project. The use of continuous simulation for the prediction of the flood frequency curve has several attractive features; it removes the need for the specification of design storms and includes the effects of antecedent soil moisture conditions. However, a major research challenge that must be addressed is how to use this approach to predict the effects of land use management changes on the flood frequency curve.

### 3. Review of land use and management

This Section defines the current agricultural, horticulture and forestry systems in place in the UK and provides a broad review of the key changes over the last 100-150 years. The major impacts of both these changes and the associated changes in farming practices on local runoff generation are then detailed, and potential mitigation measures are highlighted. A more detailed review of literature sources is provided in Appendix C, and this should be referred to for a more complete analysis.

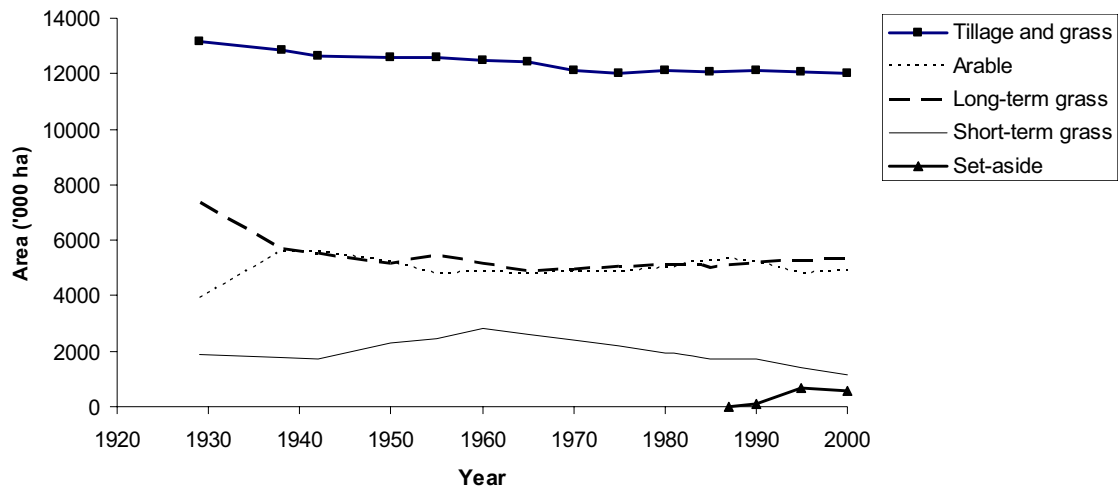
#### 3.1 Current land use

Modern agriculture is largely a consequence of the 1947 Agricultural Act, which sought to attain self-sufficiency in food production, and entry into the European Community (1973), which resulted in a rapid rise in the areas under some specific crops. Key changes in rural land use during the last 100 years are:

- General progressive change from spring to autumn sown cereals;
- Increased mechanisation, changes in trafficking, including an increased use of on-farm contract machinery;
- An increase in the total number of grazing animals;
- Loss of permanent pasture;
- More intensive use of grassland;
- An increase in field under-drainage;
- An expansion in woodland cover (approximately doubling), mainly achieved by increased upland plantings;
- Changes in field sizes, with the removal of hedges and the infilling of ponds.

The net result of these changes has been the intensification of agricultural land use. However, the peak of this intensification may have passed as alternative, environmentally friendly, land use options are becoming more prominent. Key changes in UK land use and management are summarised below (the statistics, derived from Government census data, relate to the UK unless otherwise stated).

The total areas under arable ('tilled land'), short-term grass (<5 years) and long-term grass (>5 years) and set-aside are shown in Figure 3.1. The greatest reductions in permanent pasture and greatest increases in tilled land occurred at the time of the last war. Thereafter, changes in the areas of the respective land uses were relatively small. Set-aside was introduced in the late eighties.



**Figure 3.1 UK land use area, 1929-2000, based on Government census data**

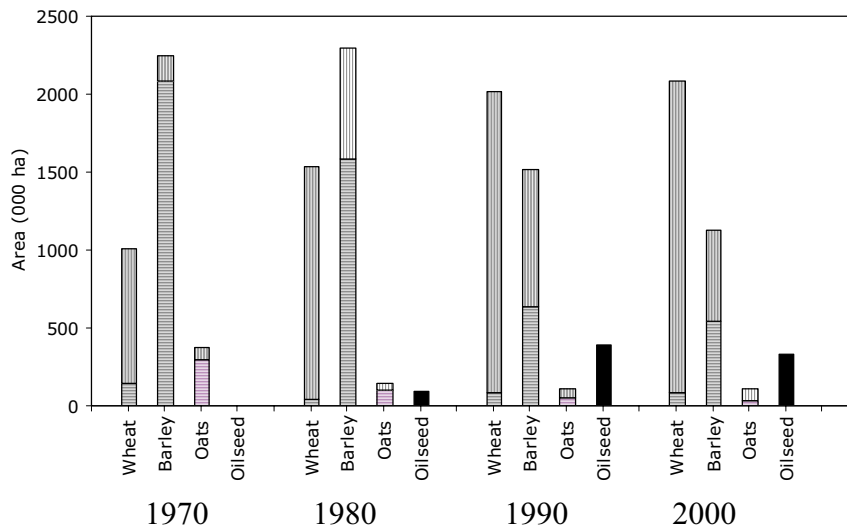
### Cereals, oilseed rape and maize

There has been no significant change in the area under arable cultivation since 1950 (Figure 3-1). However, the proportional areas of wheat, barley and oat cultivation have changed significantly (Figure 3.2).

- The area sown to oats has been in continual decline, falling from 1,257,000 ha in 1950 to 126,000 ha in 2002;
- Between 1950 and 2002 the area of barley increased from 719,000 to 1,101,000 ha, with a peak in the 1970s of over 2,000,000 ha (Figure 3.2);
- Wheat cultivation is up from 1,003,000 ha in 1950 to 1,996,000 in 2002.

Additionally, there has been a shift from spring to winter sowing of cereals (Figure 3.2). In 1962, the percentage of winter-sown wheat was 70% and the percentage of winter-sown barley was 10%. By 1998 these percentages were 97% and 65% respectively.

Oil seed rape, maize (grown mainly for silage) and set-aside have become more prominent over the last several decades. Oilseed rape cultivation (sown August/September) began in the 1970s as a break crop in cereals, but has since overtaken oats in terms of cultivated area (Figure 3.2). Maize has been introduced over the last 15 years, and accounted for 120,000 ha in 2001. The area in the UK under set-aside has risen from 110,000 ha in 1990 to 567,000 ha in 2000. This is mainly used as a break crop, often being drilled with non-food oilseed rape.



**Figure 3.2 Cereal and oilseed rape cultivated areas, 1970-2000. Cereal crops are separated by sowing time; lower bars indicate spring sowing, upper bars winter.**

### Animal feed crops

There has been a marked decrease in forage legumes due to high labour costs and low productivity compared to other arable crops. The increased area of maize is mainly as silage to replace grass silage or hay on livestock farms, typically in western areas. Compared with grass, maize requires the soil to be cultivated each year. The area of whole wheat crops is increasing as an alternative to maize.

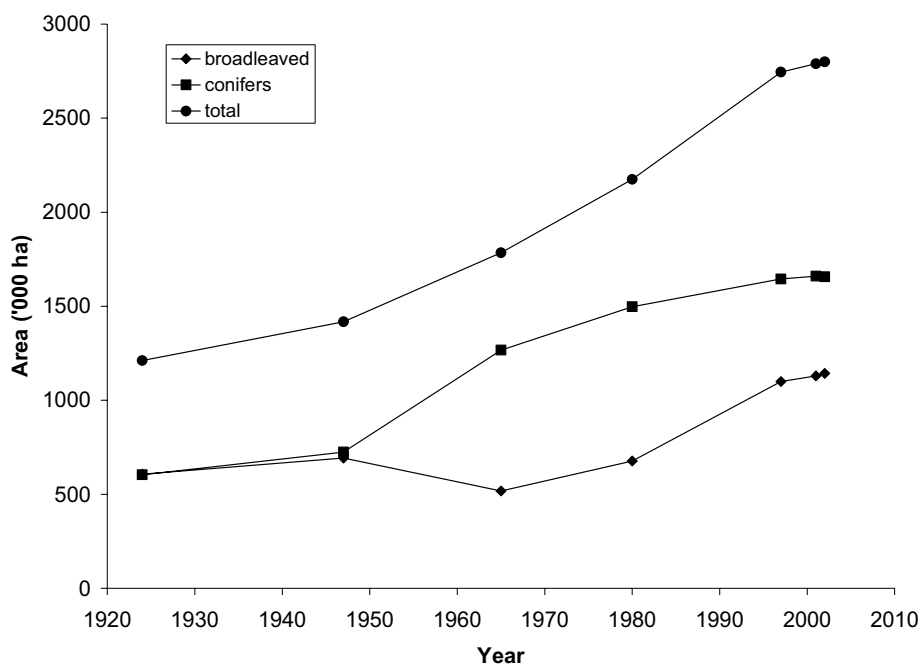
### Root crops

In 2001 there were 126,000 ha of potato cultivation, down from 500,000 ha in 1950, of which 61% were irrigated. Irrigation increased due to grant incentives to increase investment after the 1976 drought. The continuing need for more investment in irrigation is due to market demands of improved quality and continuity of supply. Although the potato area has decreased markedly, the crop's impact on soil condition should not be underestimated, because of the impacts of machinery developments and growing methods, described later. Carrot cultivation, much of which is irrigated, increased from 67,000 to 147,000 ha in the period 1937 to 1990. Sugar beet was introduced in the 1920s, accounting for a cultivated area of 173,000 ha in 2000, down from the 1980s peak of 213,000ha.

### Woodland

In the UK, forestry has its own governing organisation, the Forestry Commission, and it is subject to a different regulatory regime than agriculture and horticulture. The total UK area of forestry and farm woodland increased to

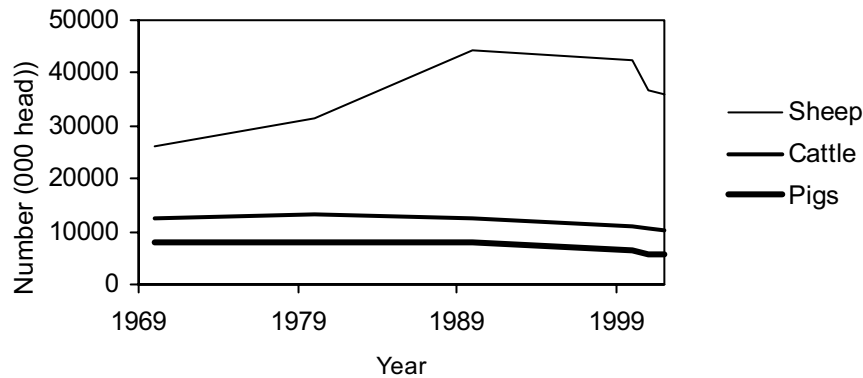
2.8 million ha in 2002, from a base of c.1.2 million ha in 1924 (Figure 3-3). During 1980-1990, private plantings exceeded Forestry Commission plantings in every year. Around 11 per cent of the UK is covered by forest and woodland. The area covered by forest and woodland has increased by 29 per cent since 1980. There was an increase in the area of broadleaved species of around 42 per cent between 1980 and 2002. Around 13 thousand hectares of new woodland were created in 2002, the majority of it broadleaved. There has been little change in conifer forest cover in recent years with a decline in new planting.



**Figure 3.3 Woodland plantings, 1924-2002**

### Grassland/livestock

Livestock numbers have risen over the past century. Between 1866 and 1980, the number of cattle increased threefold to 13,426,000, but this number has since declined to 10,345,000 in 2002. Sheep numbers rose rapidly in the 1980s (a 60% increase above 1960 levels), largely due to a decline in the profitability in suckler calf, milk and beef production and the introduction of CAP for sheep meat (Figure 3-4). Pig numbers increased from 4,500,000 in 1937 to 5,588,000 in 2002, down from a peak of 8,100,000 in 1970 (Figure 3-4). There has been a movement to outdoor pig production, a trend which may increase as a consequence of legislation banning sow stalls (an indoor farming practice) and other animal welfare issues. Accompanying the increase in numbers, there has been a move towards longer grazing seasons, and a change from hay to silage as a feed crop.



**Figure 3.4 Livestock numbers, 1937-2002, based on Government census data**

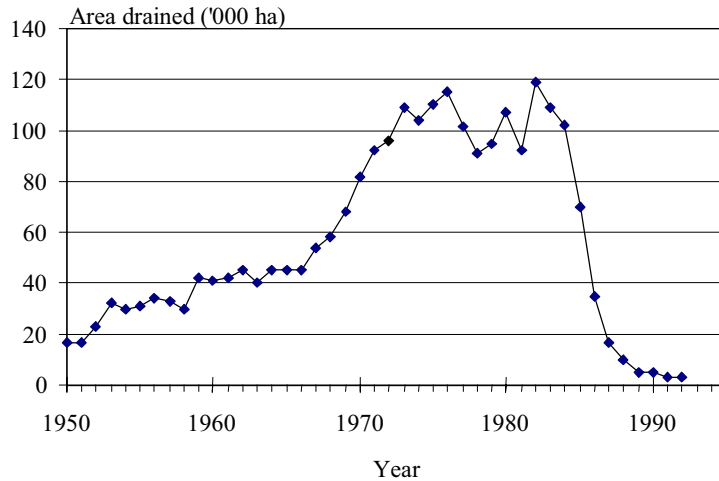
### Field under-drainage

Virtually all fields requiring drainage for effective farming will have some form of drainage installed, and many will have experienced several attempts at under-drainage over the last 250 years. Several factors led to a significant increase in the number of land drainage schemes in the 1960s and 1970s (Figure 3.5):

- The introduction of plastic pipes in the 1960s paved the way for significant expansion in the mechanisation of the drainage operation, including trenchless installation methods;
- MAFF research proved the benefits of drainage, the advantages of using permeable backfill, and of carrying out appropriate secondary treatments (i.e. subsoiling and mole drainage);
- The political/economic climate encouraged the change from grassland to arable production, in response to entry into the EU and the increase in capital grants promoting increased productivity;
- The Strutt Report (Strutt, 1970) identified drainage as an essential element for many soils to reach their agricultural potential.

However, drainage grants ceased in 1985, since when there have been few new drainage schemes (Figure 3.5).

Another component of the grant-aided drainage period was the widespread replacement of open ditches by piped ditches, especially in eastern England, to maximise the arable production area and permit the use of larger machinery.



**Figure 3.5 Annual area of land under-drainage installed in England and Wales, 1950-1992**

### 3.2 State of current farming

This section summarise how the changes in land use, farming patterns and management practices detailed above have impacted on the current state of land in the UK. Much of the evidence quoted refers to individual field, plot and hillslope studies that are reviewed in more detail in section 4.1.

Typically, natural vegetations such as woodland are much less susceptible to high rates of runoff and erosion than row crops such as potatoes (Table 3.1). This is due to the degree of protective coverage the foliage provides, the impacts of agricultural practices on soil structure and infiltration rates (e.g. see the range of typical infiltration rates in Table 3.2), the time at which machinery is required on the land, and the effects of agricultural practices on the concentration of flow. Maize was not included in the original assessment by Armstrong et al. (1990), but it is likely to fall in the 'high risk' <sup>1</sup>(see footnote) category, for reasons described later. Spring cereals present less of a risk than winter cereals, on average, because the soil is either left uncultivated or roughly cultivated (ploughed) before spring cereals are established. This compares with the fine seedbed required for establishment of the winter cereal. Late-established winter cereals pose a threat because they have less chance of developing protective crop cover before winter, yet have a fine seedbed.

<sup>1</sup> In the literature reported on here, the use of the term 'risk' is less precise than that defined in Section 2.5, and follows the more colloquial usage of the term.



<b>Least Risk</b>		Forestry / Woodland
		Permanent Pasture
		Spring Cereals
		Autumn Cereals
		Short Term Grass Ley
<b>Greatest Risk</b>		Sugar Beet / Potatoes / Horticultural Crops

**Table 3.1 Relative erosion/runoff risk of various land uses (Armstrong et al., 1990). Note: indicative only, showing relative effects.**

Soil cover	Final infiltration rate (mm/hr)
Old permanent pasture	60
4/8 yr old pasture	36
3/4 yr old pasture, lightly grazed	30
Permanent pasture heavily grazed	24
Strip cropped, mixed cover	11
Arable	10
Bare soil cultivated	9
Bare soil crusted	5

**Table 3.2 The effects of surface cover on infiltration (Holtan and Kirkpatrick, 1950)**

### General cultivation practices in all arable land

Primary cultivation loosens the soil and involves inversion for weed control or crop residue incorporation. Secondary cultivation involves the preparation of a seedbed. These activities result in breakdown of soil aggregate size and stability (Silgram and Shepherd, 1999; Tebrügge, 1993), an increase in porosity of the plough layer (Addiscott and Dexter, 1994) and an increase in the rate of organic mineralization, which results in further reduction of soil aggregate stability, all of which makes the soil more susceptible to compaction (Addiscott and Dexter, 1994). Such disturbances also disrupt the connectivity and continuity of macropores (Harris and Catt, 1999) and reduce the earthworm population.

In addition, the impact of successive arable cultivations can build up over the years, creating a layer in the lower part of the topsoil below the seedbed that is, in general, more compacted and less permeable than either the overlying seedbed or, in the case of permeable, free-draining soils, the underlying subsoil layer (Coutadeur et al., 2002). Such subsurface compaction can be particularly severe in the zones over which machinery wheels have passed and results in increased surface runoff compared to zones where there has been no trafficking (Hawkins & Brown, 1963; Davies et al., 1973).

As a result of the reduction in aggregate stability and the disruption of macroporosity and earthworm activity, there is an increased tendency for soil structure in the plough layer to change significantly over the growing season.

Immediately after sowing, individual aggregates are surrounded by macropores and the soil surface is rough, with significant capacity for depressional storage. Over the season, the aggregates settle, the plough layer becomes less porous and the soil surface becomes increasingly capped and smooth, reducing infiltration and increasing runoff.

There is an increased use of contractors to undertake cultivations and harvesting operations. Although there is increased use of low ground pressure tyres, the economic pressures on some contractors mean that they do not always have ideal conditions when placing machinery on the land. This may result in soil compaction during sowing and harvesting, especially in the late autumn/winter period. Under wet conditions, machinery leaves deep wheel ruts which become drainage channels within the fields, possibly leading to rill or gully erosion. This can be a particular problem for maize, late-harvested potatoes, sugar beet and some vegetables that are typically harvested in the winter, such as brassicas and carrots (which have an extended harvest period to maintain continuity of supply).

The use of tined or disc cultivation is now increasing to replace deeper mouldboard ploughing. They have a higher work rate to allow operations to be completed in more suitable conditions, and usually a reduction in cost. Use of these implements can result in less soil disturbance and a reduction of the depth of compaction from heavy cultivation and harvesting machinery (Pidgeon and Soane 1978). These techniques are less effective in achieving a seedbed in wet conditions. For example, the extreme conditions of the wet autumn of 2000 saw the need for farmers to plough to 'force' a seedbed where minimal cultivation techniques could not cope (Shepherd, 2001).

### **Cropping rotations and pest management**

The widespread use of pesticides, especially pre-emergence herbicides, now allows continuous arable cropping (especially in eastern England). The resulting loss of grass leys and over-winter root crops means that fields have less crop cover over winter.

Application of pesticides and fertilizers following sowing has resulted in the production of wheeling lines ('tramlines') within arable fields. The soil under these lines is dense and compacted with significantly reduced infiltration (Davies et al., 1973). Such lines form preferential surface channels for flow and can be a major contributor to surface runoff, resulting in erosion events (Reed, 1986). However, restricting traffic to the tramlines reduces the overall damage to a field.

### **Cereals, oilseed rape and maize**

The shift to autumn-sown cereals has significantly increased the area of bare soil surfaces during the late autumn and winter periods, compared with the time when many more fields were in grass. This increases the risk of runoff during this time and increases the risk of surface capping on some soils and locations, following heavy rainfall. The increasing use of autumn sown oilseed rape has

been accompanied by practices such as heavy pressing of seedbeds following sowing (often in September). Such practices increase the likelihood of compaction and easily result in increased surface runoff.

However, all of these factors must be considered in terms of risk. Timeliness of cultivation and crop establishment reduces the risk of runoff and erosion. For example, establishing a crop in early autumn often means that the land is cultivated when soil is at its driest to depth, so reducing compaction by equipment. Early autumn establishment (sown by October into a good seedbed) means there are roots drying out soil and stabilising the surface in autumn, and crop cover can develop to reduce the impact of rainfall. The main problems are with late sown or established crops when there will be more bare soil. The increased acreage of maize planted over the last 15 years (mostly for silage production, replacing grass silage or hay) has had a significant impact at the field/farm scale. Maize is particularly sensitive to weeds, so is often treated with herbicides, resulting in bare soil between wide rows. Fields to be planted with maize are typically bare from harvesting the previous crop (September/October) to crop establishment (April/May), with little coverage in the early growing season (May/June). This combined with the fact that the crop tends to be concentrated in the western and wetter parts of the UK, means that there is increased likelihood of surface runoff from autumn and winter rainfall events. Previously, these fields would have been in grassland for hay or grass silage, which would have decreased runoff risk. Impacts are usually exacerbated as (wide) rows are planted down-slope to aid machinery, and harvesting is often performed by contractors who do not allow for ideal conditions. An additional problem is that this land is typically available and used to spread slurry or farmyard manure over winter. This can cause soil rutting, compaction, and increased runoff.

### **Root crops**

The increased growing of potatoes on lighter soils, and use of irrigation to increase continuity of yield and quality, has increased the risk of runoff / erosion problems. De-stoning and ridge furrow patterns may concentrate water movement and increase the likelihood of soil compaction and reduced infiltration.

The small number of factories now processing sugar beet combined with the increased size and traction of harvesting machinery means that harvesting the crop can take place any time between late September and February. As with carrots, increased trafficking of fields over the winter period, when the soil is likely to be at its wettest and its bearing strength at its lowest, increases the risk of soil compaction and reduced infiltration. Other root crops such as Swedes, often grown on a contract basis, can also cause significant soil degradation.

### **Grassland / livestock**

To reduce the cost of animal housing and to increase the proportion of grazed grass in animal diets, the grazing season has been extended, leading to increased treading and resulting in compaction and sealing of the ground

surface and the appearance of bare patches. Such problems lead to significantly increased surface runoff (Heathwaite et al, 1990) which is exacerbated by the fact that most grazing areas are in western regions of the country with high rainfall. Sheep, in particular, cause severe compaction (Godwin and Dresser, 2003), and the increases in their numbers during the 1980s (Figure 3.4) is likely to have increased runoff from grazed land. In addition, stock grazing in riparian areas modify stream banks and reduce their resistance to erosion at higher flows. The increasing use of outdoor production methods for pigs is also likely to have increased in-field runoff through a loss of vegetation and increased soil compaction.

### **Field under-drainage**

Typically, only those drains installed within the last 40-50 years have the potential to deliver effective drainage under modern farming. In the north and west, steeper slopes and the presence of permanent pasture provides stable soil structures and self-cleansing velocities, thus slowing the degradation of drainage systems. Moorland drainage to improve land for grazing stock and grouse is now discouraged, but the historical impacts will remain without restoration.

The impacts of drainage on runoff are highly influenced by local characteristics including soil and drainage types, drainage intensity, and rainfall and topographic characteristics. The potential impact of field drainage is dealt with in Section 4 of this report.

### **Peat drainage and moorland gripping**

There is only limited information available about the response of peat catchments and the impact of peat drainage and upland gripping. Evans et al. (1999) suggest that increasingly dry summers, such as that of 1995, might lead to a deterioration of upland peats and changes in runoff generation. Robinson et al. (1985, 1998) have shown how moorland gripping and drainage for forestry planting can increase the runoff response of peat areas under wet conditions, but induce increased storage between storms leading to larger antecedent deficits (see also Hudson et al., 1997; Robinson et al., 1991; Nicholson et al. 1989).

At Leadburn, S. Scotland, David and Ledger (1988) studied the effect of plough drainage of deep peat prior to planting with conifers. The drains affected 30% of the area and 50% of the vegetation cover. They showed that the drains themselves acted as major source areas for runoff by comparing ditches with and without covers.

### **Hedgerows**

Increased mechanisation has resulted in increased field sizes and a reduction in hedgerows, which provide an effective and economic way of slowing runoff and reducing soil losses through erosion (Dewald et al., 1996). In pastoral Somerset the average field size increased from 5.5ha in 1945 to 9.5ha in 1995. In arable

Cambridgeshire this increase was from 6.5ha to 16ha. Since 1945, a 50% reduction in hedgerows has been recorded (Robinson and Sutherland, 2002). However, between 1990 and 1998, the decline in hedgerow length was halted (Petit et al., 2001).

A secondary impact resulting from the removal of hedgerows is that many traditional 'catch water ditches' that intercept water at field boundaries have also been removed as field sizes have increased.

### **Environmentally developed agricultural systems**

Over the last two decades, there has been a significant and increasing move towards more environmentally 'sympathetic' farming systems in some parts of the industry and, in particular the development and introduction of 'Organic' and 'Integrated' Cropping or Farm Management systems. Whilst these more environmentally friendly farming systems may have immediate benefits to wildlife, their effects on hydrology and runoff generation have not been researched.

Within the EU, organic farming is a legally defined production system as set out under Council Regulation (EEC) 2092/91 and its amendments (Anon., 1991). Within the regulation, each member state is required to establish a competent authority to implement the regulation. Within the UK, until 2003, this authority has been the UK Register of Organic Food Standards (UKROFS) providing baseline organic standards for the UK (Anon., 2001) and approving and monitoring the work of UK certification bodies. Within the UK, there were twelve certification bodies at the start of 2003 (Anon., 2003), which set their own organic standards (based on, and with the UKROFS basic standard as a minimum) and register organic producers and processors. It is the production system that is being certified.

Organic farming prohibits the use of artificial/synthetic fertilizers and pesticides, although, where direct intervention is required, a small range of approved inputs may be used in a controlled manner. To maintain soil fertility, there is a focus on rotation and the use of animal manures and compost, whereas pest, disease and weed control is achieved through rotation, choice of varieties, timings of cultivations and habitat management to encourage natural predators. The aim is to encourage the development of a healthy environment, enhancing landscape features, wild plants and animal species by, for example, maintaining hedges as an important wildlife habitat.

Organic farming production has increased rapidly over recent years and accounted for 4% of all UK farmland in 2001. The Government has proposed that the sector could experience a three-fold increase, to around 10% of UK agriculture, whereas others have proposed a more ambitious target of 30% of production, with 20% of the retail food market organic by 2010. However, at present, the majority of organically managed land is grassland, mostly as rough grazing and permanent pasture.

There are few UK studies on the relative benefits of organic or conventional systems for soil quality (Shepherd et al., 2003). However, such studies as have been done and those from other countries tend to show benefits for organic systems. Organic farmers pay particular attention to their soils, and it is a fundamental tenet of organic farming to operate a sound rotational system to 'feed the soil' so as to maintain organic matter content and to keep it in good condition. However, organic matter additions are also made in conventional agriculture and, in some situations, the return may be similar or greater than in organic systems. Soil structure can benefit from regular returns of organic matter, and the evidence is that soil structure is at least as good under organic practices. Earthworm numbers tend to be greater in organic systems and studies into the microbial response of soils to organic management indicate there are benefits in many but not all situations and not always in all the attributes measured. The low concentration of soluble nutrients, the absence of most pesticides and reduced use of veterinary medicines such as antibiotics and ivermectins can also be expected to benefit soil organisms.

Integrated crop management (ICM) combines good farm husbandry, which is already done by many farmers, with a whole farm long-term approach that reduces the need for agrochemicals and takes the impact of farming practices on the environment into consideration. Each farm is allocated a programme tailored to the location, soil type, markets, storage facilities, farm layout and environmental vulnerability. The corner stone of this policy is to use longer rotations (minimum 5 years), thus allowing higher yields with lower pesticide application and a reduction in weeds, pests and disease. Minimal tillage methods are promoted (e.g. direct drilling into stubble), maintaining the organic content at the surface, thereby encouraging earthworms and retaining soil moisture.

### **3.3 Mitigation measures**

Good soil husbandry, cropping practices and general management for the reduction of runoff and erosion are now being widely promoted; for example, see the EA Best Farming Practice booklet (Environment Agency, 2001a). There is also a focus on adopting land management techniques that reduce diffuse pollution of water, some of which will also benefit water retention and reduced soil erosion. There is considerable synergy between diffuse pollution control and the management of water in the soil profile and landscape. These linkages need to be strengthened.

Additionally, there are several schemes that are not directly focused on the issue of land use management practices and flooding, but can be expected to have a positive influence. English Heritage is promoting minimum tillage strategies to reduce the risk to archaeological sites from mechanical damage. The Farming and Wildlife Advisory Group (FWAG) are promoting a wide variety of environmental and biodiversity measures, including the introduction and management of set-aside, woodland and coppice, grasslands and ponds (FWAG, n.d.), which may have a beneficial effect on runoff generation. A

number of possible strategies for the reduction of runoff are highlighted below. Assessments of their potential impacts are given in Section 4 of this report.

### **Cover crops**

A vegetative cover helps bind the soil particles, increases surface roughness and reduces the effects of the rainfall's kinetic energy. Grass and clover crops can be sown as an 'understorey' or 'intercrop' to row crops such as maize but can significantly reduce yields (Goeck and Geisler, 1989). However, as an alternative to cover crops, the application of mulch may be suitable for crops susceptible to competition (Geelen et al., 1995; Kwaad et al., 1998; Wurfel, 2002) and the use of such mulches reduces the likelihood of soil capping.

### **Minimum tillage**

Conservation tillage is an all encompassing term that refers to leaving previous residues on the soil surface, or only partially incorporating them, thus reducing the overall bare soil, reducing surface sealing and increasing infiltration, aggregation and providing resistance to water movement. The introduction of shallow seedbeds can also maintain a solid soil matrix below, reducing the effects of compaction and maintaining macropore connectivity. Minimal tillage techniques are becoming more widespread and can have significant benefits on soil organic matter content, structure and biological activity. There is also plentiful evidence that they can significantly reduce surface runoff (see section 4). However, an unpublished paper by the Austrian Government (Withers, Pers. Comm.) reviewed 123 published papers worldwide. It was found that minimum tillage had a 50% chance of reducing erosion, but the results were very site specific. Clearly, further work on the impacts of minimal cultivation practice need to be considered.

### **Hillslope surface runoff control**

Ploughing and the planting of row crops across slope reduces overland flow velocity, and provides opportunities for infiltration and evaporation (Clements and Donaldson, 2001). Evidence from the USA shows that contour ploughing in most crops can significantly reduce surface runoff but its effectiveness is likely to decrease over the season as surface sealing occurs (Schwab et al., 1993). However, in the UK, contour ploughing is not always practical, primarily on safety grounds but also due to the complexities of slope angles, slope directions and irregular field shapes.

Grass buffers, ditches and hedges slow runoff and increase the likelihood of re-infiltration. Contour grass strips can possibly be used as a 'soakaway' in arable systems, braking, filtering and infiltrating runoff (Auerswald, 1998; Melville and Morgan, 2001). Cross ridges and bunds can also be used to dam a downslope orientated main furrow. However, such structures need to be engineered and used appropriately as overtopping may cause gully erosion.

The pilot Defra Entry Level Agri-environment Scheme (ELS) includes options for the maintenance of hedgerows and development of adjacent buffer strips. Many

farmers now use set-aside as a formal part of their crop rotation. Rather than leaving the land un-cropped, non-food oilseed rape is often cultivated. Set-aside can provide a buffered area alongside a stream or river, but, in the UK, this is rarely designed as a means of reducing surface runoff to the watercourse.

### **Machinery**

Reducing loads, decreasing tyre pressure and increasing tyre widths reduces the intensity of compaction associated with wheelings and tramlines. Terra tyres and tracked vehicles are particularly suited for weakly structured soils and wet conditions as they significantly reduce the vertical stress on soil surfaces compared to conventional tyres (Lebert and Burger, 1989). Chisel ploughing to break up compaction caused by down-slope tramlines is usually found to be beneficial in the reduction of runoff (Clements and Donaldson, 2001), but the impacts can be detrimental on steep slopes. Care must be taken to prevent these areas from developing gully erosion.

### **Grassland / livestock**

Conversion of arable land to grassland is a potential mitigation measure that may be applicable to specific soil and landscape conditions. On grassland itself, the most effective mitigation measure is likely to be a restriction of the grazing season to avoid those times when the soil is at or near to field capacity and its bearing strength lowest. Once compaction has occurred, surface infiltration can be increased by the use of techniques such as mini-moling (Godwin and Spoor, 1977), slot cutting and spiking. There is also some evidence that the introduction of deep burrowing earthworms into pasture increases infiltration (Stockdill, (1982).

### **Woodland**

Conversion of arable or intensively used grassland to woodland has significant potential to reduce total runoff in the long term, providing it is not accompanied by the installation of an intensive drainage system; however, the implications for water resources may need to be considered (Section 6.4). The Woodland Grant Scheme (WGS) operated by the Forestry Commission provides grant aid for the creation of new or the management of existing woodlands. In conjunction with this scheme is the Defra Farm Woodland Premium Scheme (FWPS), the main aim of which is to provide financial support for farmers wishing to convert agricultural land to woodland.

New crops, such as *Miscanthus* (a tall perennial grass), which are being introduced for energy and biomass production can afford significant amounts of protection to the soil surface (Loxton, (2003), whereas, in both arable and grass fields, sacrificing the least productive areas to copses and non-grazed areas provides an opportunity for upslope runoff to re-infiltrate (Baines, 2003).



## **Retention structures and wetlands**

The principal aim of any headwater soil management or runoff detention feature is to attempt to slow the outflow from the smaller sub-catchments, and thereby reduce the peak of the hydrograph for the main catchment outflow. The use of on farm storage ponds and ditches, and the creation of wetland areas have also the potential to attenuate runoff, so long as they provide increased storage and buffering capacity in headwater catchments. However, such structures need to be carefully designed to ensure that storage capacity is adequate and discharge mechanisms do not cause secondary problems. In the UK, the maximum size for an above ground lagoon without engineering certification is 25,000 m<sup>3</sup>. For an on-farm pond that is lower than the surrounding land there is no capacity limit. The targeted re-creation of on-farm wetland areas also has the potential to store excess waters during storm events and thus attenuate peak flows. Intercepting run-off pathways is a major management factor. This can be as simple as relocating a farm gate (up slope rather than at the field bottom, for example).

In principle, all of the above interventions can be beneficial in delaying/attenuating the runoff hydrographs of small sub-catchments, but care is needed to ensure that the changes in timing do not bring sub-catchment responses into phase. For example, non-headwater detention can be risky, as this can bring runoff delivery from lower catchment areas into phase with the upper catchment flood hydrograph (see Section 2.4).

## **Riparian area management**

The bias in river restoration and river engineering schemes towards large rivers (Appendix F) neglects the role of upland streams, and lower order streams and man made ditch networks in the lowlands. Poaching by animals and active ditch maintenance (see below) is likely to be occurring across much of the landscape. Exclosure of the rivers to animals must be matched by suitable water feeding features, or specific zones on the river that are protected from poaching effects (i.e. armoured with stones as suggested by the EA (2001)). The use of buffer strips is now occurring in the UK (particularly where a government scheme is in operation such as Environmentally Sensitive Areas (ESAs) and now the Entry Level Scheme (ELS)). However, just having a buffer strip may not protect the river from poaching, and so buffer strips in livestock areas also need an exclosure fence or hedgerow. In arable systems, buffer strips that are bypassed by land drains into well maintained ditches will not seriously effect runoff rates. Buffer strips or buffering strips (i.e. a non riparian area that is intercepting and buffering flow) can be made to operate better within the existing drain and ditch network, if ditches are blocked or drain flow is returned to the surface. This may in fact be occurring naturally as more and more land drains collapse since they are not being maintained to their usual level.

A case study in the US (USEPA, 1993) demonstrated that it is relatively easy to restore rivers in livestock systems without damaging the profit of the farmer. A series of good management practices was set up such as fencing off rivers. There was also no need to reduce stocking densities if a good livestock rotation

scheme was put in place. The speed at which the rivers restored themselves was quick and clearly flow attenuation is occurring (Figure 3.6).



**Figure 3.6** A single stretch of river before and after good livestock management practices were introduced (USEPA , 1993).

### **Ditch management**

Evidence from studies on farms suggests that pro-active ditch maintenance is carried out specifically for the rapid removal of runoff and often acts as an extension to the land drains. The creation of new ditches, and the channelisation of natural watercourses increase conveyance, leading to the rapid removal of runoff and the loss of the implicit storage capacity of the land and channels. Artificial ditches and drains increase the drainage density of the land and enhance the speed of runoff delivery to the main channel network.

Ditch management advice in COGAPs may encourage some lowering in ditch maintenance as it may lower pollution levels, but little solid incentive is given to farmers to reduce ditch maintenance at present.

A study in New Zealand (Sukias, 2003) has allowed a number of ditches to overgrow with vegetation. The study showed clear evidence of rapid weed growth and sedimentation giving rise to tortuous flow paths. The benefits in terms of pollution and erosion mitigation were evident, and, clearly, the on line storage capacity of the ditches improved and the flow speed was reduced. This raises an issue about the long-term maintenance strategy for ditches.

The direct blocking of ditches is also possible (R. Parret study EA 2000, and Heathwaite et al., 2004, see below), and can give rise to substantial on line storage. This type of storage capacity can be used in areas dominated by high runoff and could have great potential impact in land-drained areas. However, there is a perceived fear that water logging and sedimentation will block drains and induce drain collapse. Thus, there is an issue concerning the strategic positioning of blocked ditches in terms of the size and volume of the temporary ponds they cause, the long-term maintenance of ditches and their impact on land drain functioning.

### **Agri-environment schemes**

The literature review confirms (Appendix C) that agricultural policy has been a major determinant (a driver) of land management and where this has resulted in intensification of land use, both grassland and arable, there have been consequences for 'runoff induced soil erosion' and 'localised flooding'. There was no hard evidence from the literature to show that ESA and Countryside Stewardship Scheme (CSS) interventions, as they affect the landscape (and related farm management practices), actually had consequences for flood generation. Much of the literature, though, implies that if intensification enhances runoff generation then extensification (and other explicit measures to prevent or retain runoff) might be expected to mitigate runoff generation at the local scale, and, in this context, reference has been made to the potential contribution of agri-environment schemes.

But this is speculative, and the evidence does not support it. One reference in particular (Souchere et al 2003) mentions that ESA interventions to date have had limited impact. This is clearly a research need.

## **Summary and findings**

The total areas under arable, grassland and rough grazing have remained reasonably constant over the last 50 years; however, livestock densities, crop types and management practices have changed significantly. The key changes in arable cultivation have been a shift from spring to winter sown cereals and the introduction of new crop types, most notably maize and oil seed rape. Livestock numbers, in particular sheep, have risen significantly over the last century, which, more recently, has been accompanied by a longer grazing season. There has also been an increase in the area of woodland, with a move from coniferous to deciduous new plantings.

In many cases, land use changes and the accompanying management practices have been linked to increased erosion and farm scale runoff, and the degradation of soil structure. Of particular concern are winter practices that leave the soil surface bare or require the use of heavy machinery on the land, and also those actions that increase the surface and subsurface connectivity of the landscape.

There are a number of mitigation strategies that have been proposed for reducing farm scale runoff, including measures to provide increased protection to the soil surface, reduce flow connectivity, increase retention and storage, and alternative land uses.

Key studies of the impacts of modern farming practices on soil properties and runoff and the effectiveness of mitigation measures for reducing farm scale runoff are summarised in Section 4, and are appraised in the Critical Assessment (Section 6.1).

## 4. Review of impact monitoring and modelling studies

This Section reviews key literature sources on the impacts of land use change on flood runoff generation in rural catchments. In particular, the sources relate to the impacts of afforestation/deforestation, field drainage of different types and agricultural cultivation techniques on runoff generation.

The monitoring and modelling study sources reviewed here have first been separated into those that cover the plot, field and hillslope scales and those that relate to the catchment scale. Studies in the former category have then been separated into those that deal with impacts on surface runoff and those that deal with impacts on drainage flows, and where possible, each source has also been summarised according to:

- which of the land management practices it covers;
- the inherent soil hydrological setting and the type and season of weather events covered;
- whether the results suggest an impact or no impact.

A detailed review of plot and field scale sources is provided in Appendix C.

Catchment-scale sources relate to experimental small catchment monitoring and data analysis studies which have been carried out mainly in the uplands, and to larger catchment studies which are based on the analysis and/or modelling of routinely monitored rainfall and runoff data. A detailed review of the former is provided in Appendix A, and of the latter in Appendix B. Although not within the scope of the Review, a brief review of some sources relating to river engineering and flood plain management is included here; this is supported by Appendix F.

Each source is identified by the author(s), with the exception of the long-term catchment monitoring sources in which there have been several key studies, which are identified by the catchment name.

### 4.1 Plot and field scale sources

#### Monitoring studies

##### *Sources dealing with impacts on surface runoff:*

#### UK

**Auserwald (1998):** Monitored the effects of grass ley set-aside on runoff, erosion and organic matter levels in sandy soils in east Shropshire. Erosion rates were significantly decreased by grass leys, even on steep slopes.

Suggested that grass strips could be used as an effective interceptor and 'soakaway' for runoff in arable fields.

**Burt and Slattery (1996):** Monitored seasonal changes in soil properties and surface runoff in a small sub-catchment of the River Stour, Oxfordshire. Discussed the difficulties of predicting the impacts of cultivation on runoff and erosion.

**Davies et al. (1973):** Monitored the impacts of surface trafficking on surface infiltration for field plots in a free-draining Lincolnshire silt (Romney series). There was a significant reduction in surface infiltration from plots with increased trafficking.

**Edwards et al. (1994):** Monitored the impact of different arable surface conditions on 'depressional storage' from field plots on a 4° slope on a free draining sandy loam soil in Bedfordshire. Depressional storage was significantly different under smooth, compact, seedbed, mouldboard ploughed and compact ridged (both up-down and across slopes) surfaces.

**Hawkins and Brown (1963):** Monitored the impacts of tractor wheelings during ploughing on runoff from field plots. Runoff from plots with wheelings in every furrow was greater than that for plots with wheelings in every other furrow which, in turn, was greater than that for the non-wheeled control.

**Heathwaite et al. (1989; 1990):** Experiments with rainfall simulators on runoff plots in the Slapton catchment, South Devon (Grass). Results showed that heavy grazing significantly decreased infiltration and increased surface runoff.

**James et al. (2003):** Artificial soil slope studies of the impact of the Aqueel, a device for creating indentations in a loose soil surface, on depressional storage. The volume of depressional storage created by the Aqueel decreased significantly with increasing slope angle.

**Martyn et al. (2000): Clements and Donaldson (2002):** Monitored the impact of different management systems on runoff from maize field plots under three free-draining soil types. Runoff was significantly reduced (from 433 to 10 m<sup>3</sup>/ha) by chisel ploughing stubble in autumn and marginally reduced by a winter cover crop or Italian rye grass undersowing.

**Melville and Morgan (2001):** Studied the influence of grass density on the effectiveness of grass contour strips for control of erosion on low angle slopes. Plot studies on sandy soils in Bedfordshire showed that grass strips significantly reduced erosion and runoff compared to bare soil. Two different grass species were used in the strips but there were no significant differences in runoff or erosion from them, despite different growth characteristics.

**Spiers and Frost (1985):** Monitored the impacts of different types of seedbed preparation on surface infiltration on field plots. The creation of increasingly fine seedbeds significantly reduced surface infiltration capacity.

## France

**Coutadeur et al. (2000):** Studied differences in the near-saturation hydraulic conductivity of different zones in the plough layer and upper subsoil of a free-draining calcareous silt loam soil that had been continuously cropped with maize since 1962. The site was located in the western part of the Paris Basin. Near saturated hydraulic conductivity in the lower part of the plough layer was, on average, six times less than in the overlying seedbed layer and three times less than in the underlying subsoil layer. In the lower half of the plough layer, below the seedbed, hydraulic conductivity below machinery wheel tracks was less than half (40%) of that between wheel tracks.

## Netherlands

**Geelen et al. (1995):** Studied the impact of soil tillage on crop yield, runoff and soil loss under various farming systems of maize and sugar beet on loess soils (sandy/silt). The use of straw mulches significantly reduced soil loss and runoff in maize and sugar beet without affecting yield. Soil tillage in autumn also reduced runoff and soil loss but the use of winter rye as a cover crop had no effect.

**Kwaad and Mulligen (1991):** Monitored runoff from two high intensity rainfall events on field plots of a loess (fine sandy/silty) soil under different maize management systems. Rainfall runoff coefficients were 42% for conventional management, 47% for direct drilled management and 15% for plots that were tilled in autumn and spring.

## Denmark

**Sibbersen et al. (1994):** Monitored runoff from field plots under different agricultural crops. Runoff from pasture plots was significantly lower than from plots under wheat, barley or a barley catch-crop.

## Germany

**Goeck and Geisler (1989):** Plot studies of erosion control in maize fields, Schleswig-Holstein. Sowing white clover as an 'understorey' in maize significantly reduced runoff. In addition, there was no effect on yield if the clover was sown when the maize was 15-30 cm high.

**Schafer (1986):** Plot study experiments to assess catch crops for erosion control in maize production. Winter cover crops reduced runoff by 88% compared to bare fallow plots

## USA

**Cruse et al. (1995):** Plot and field studies on different combinations of strip intercrops in the USA. A 4.6 m wide strip cropping of maize, soya and oats/berseem clover significantly reduced runoff and also increased yields and reduced the need for nitrogen fertilizer in the maize crop.

**Duley and Russell (1939):** 'Classic' field plot studies of the impact of different straw management and tillage practices on runoff percentages. Demonstrated significant reductions in the percentage runoff by 'conservation practices' such as leaving straw on the surface or incorporating it during cultivation, compared to conventional ploughing or disking.

**Holtan and Kirkpatrick (1950):** Summary of results from large plot studies of the effects on soil infiltration of agricultural grassland of different ages of establishment and crop vegetation cover. Infiltration depth decreased over time and with decreasing age of grassland establishment, intensity of grazing and arable crop cover.

**Rauzi and Smith (1973):** Field plot studies of infiltration on pasture land with different grazing intensities. Infiltration rates were significantly lower on the 'heavily' grazed plots compared to the 'light' to 'moderately' grazed plots (4.8 vs. 5.6 – 5.9 cm/hr).

**Schwab et al (1993).** Plot and field studies investigating the impact of contour tillage and management on surface runoff in the USA. Surface runoff was reduced by up to 75-80 % after initial tillage and planting but then reduced over the season to 20% by the yearend.

**Young and Voorhees (1982):** Field studies comparing infiltration on 'wheeled' and 'non-wheeled plots' on an 'organic-rich', free-draining loam soil in Minnesota. Infiltration rates over the time of rainfall duration were significantly higher on the non-wheeled plots than on the wheeled ones (approximately 10 to 20 mm hr<sup>-1</sup> greater from 5 to 100 minutes after rainfall initiation).

**Zemenchick et al. (1996):** Monitored runoff and soil loss from field plots of the forage crop Lucerne under different management options. Plots sown with brome grass mixed with Lucerne did not significantly reduce runoff or soil loss compared with conventional Lucerne.

### **Australia**

**Charman (1985):** Monitored runoff from simulated rainfall on field plots on two different soil types under different arable management techniques. The percentage runoff successively decreased from conventionally tilled plots (40-45%) to reduced tillage plots (17-35%) to direct drilled plots (2-15%). Soil type and management both significantly affected the results.

**Tullberg (1996):** Monitored runoff from arable field plots under different management techniques. Runoff was significantly reduced (48% lower) compared to conventional tillage on plots where trafficking was controlled and crops were direct drilled.



### **Sources dealing with impacts on drainage flows:**

**Leeds-Harrison et al. (1982):** Monitored the impacts of different sub-soiling techniques on drain discharge from field plots on a 'mole-drained' clay soil. Significant differences in drain discharge from different sub-soiling techniques were observed. Increasing the effectiveness of sub-soiling increased peak flow rate and decreased the time to peak discharge.

**Reid et al. (1990):** Monitored storm drainage from different soils containing mole and tile drains. 'Timely' seed bed preparation and deep soil loosening gave a significant decrease in the amount of storm drainage.

### **Sources dealing with erosion and runoff**

**Reed (1979; 1983):** Monitored water erosion episodes in arable fields on sandy soils in the West Midlands of England. Statistical analysis of the factors associated with water erosion on more than 1000 sites showed that up/down slope cultivation direction (Reed, 1979) and compaction (Reed, 1983) were significant factors in 95% of recorded water erosion cases.

## **4.2 Catchment scale sources**

### **Monitoring studies**

#### **UK**

##### **Plynlimon, Wales. 2 sub-catchments:**

Wye at Cefn Brwyn (Grassland); Severn at Plynlimon (70% Forest). (Kirby et al. (1991); Robinson and Dupeyrat (2003); O'Connell et al. (2003); Neal (1997))

Long-term comparison of flows in a largely forested sub-catchment and largely grassland sub-catchment. Demonstrated that interception loss appears to be the main factor controlling differences in catchment water yield, with a significant reduction (15-20%) in yield from a catchment with 75% conifer forest cover and 50% canopy cover relative to a grassland catchment. However, the differences in water yield have changed through time, such that by the mid 1990s, evaporation losses were lower from the forested sub-catchment compared to the grassland sub-catchment, partly due to forest harvesting and restructuring. Probability plots of annual maximum discharges (scaled by area) from the two catchments, standardized by area, show no significant differences. Interpretation of results is difficult (as with most paired catchment studies) because of differences in geology, soil, topography and rainfall - especially extreme event - characteristics.

**Llanbrynmair, Wales.** (Forest). Hudson et al. (1997); Robinson (1990).

A long-term study of the hydrological effects of new plantation forestry in an upland moorland catchment. Ploughing in preparation for tree planting disrupted

the vegetation, resulting in a decline in actual evaporation. Evaporation increased to greater levels than for the original moorland in the early stages of forest growth due to the effects of the dense understorey of dwarf shrubs on interception and transpiration losses.

**Coalburn, England.** (Forest). Robinson (1986), Robinson and Blyth (1982); Robinson et al. (1998); Robinson (1990); Archer and Newson (2002).

Now the longest running experimental catchment in the UK. Monitored catchment discharges over a period of more than 30 years, starting in 1967. The various analyses of the study data have revealed significant increases in storm runoff and decreases in the time to peak immediately following drainage (though with significant scatter for individual storms), with a recovery to pre-drainage responses after about 20 years. This recovery was interpreted as being the result of forest growth and a decrease in the efficiency of the surface drains, although to a proportionately smaller degree.

**River Irthing, incorporating Coalburn, England** (blanket peat, forest, moorland, pasture) (Archer, 2003).

Comparison of the flow records of the River Irthing and the nested Coalburn catchment. In the Coalburn, the number of runoff events increased after pre-forestation drainage, and then decreased with the onset of canopy closure. In contrast, the number of runoff events in the Irthing did not change until the approach of canopy closure, when the change mirrored that of the Coalburn.

**Forest of Bowland, Lancs:** 2 sub-catchments: Bottom's Beck (Forest); Crossdale Beck (Grass); Law (1956).

A paired catchment study of the effects of forests on water yield, supplemented by a plot-scale study of surface runoff under planted conifers. Suggested that runoff generation from forest plantations was as large, if not greater than from pasture, at least in the early stages of the growth cycle.

**Balquhider, Scotland:** 2 sub-catchments: Monachyle (mainly grassland); Kirkton (41% forest). (Johnson and Whitehead (1993); Robinson (1990); Calder (1993b)).

Comparison of flows in a largely forested sub-catchment and largely grassland sub-catchment. Based on this and other UK studies, Calder (1993b) concluded that conifer forests will reduce water yield irrespective of whether they replace grass or heather moorland. It was found less easy to generalise about the effects of conifer afforestation on low flows; although high evaporation rates from mature, closed-canopy forest can reduce low flows. Land drainage, which is often associated with upland forestry, may increase low flows in the short to medium term.

**Ray, Buckinghamshire (Grendon Underwood).** (Grass). Beven (1980); Robinson and Beven (1983); Robinson (1990).

Investigated the impacts of field drainage on stream flows from two field plots (2500 m<sup>2</sup>) on a heavy clay soil of the Denchworth series and under permanent pasture. The plots had low amplitude ridge and furrow topography. One plot was mole drained in the furrows; the other left undrained such that the furrows saturated easily in the winter period. Results were inconclusive and suggested that river channel improvements accounted for a much greater contribution to high flows than did field drainage.

**Catchwater drain, Humberside** (Grass/Arable). Tang and Ward (1982); Robinson et al. (1985); Robinson (1990).

Monitored the effects of field underdrainage and secondary treatment on storm discharge peaks in a 16 km<sup>2</sup> research catchment (clay loam soils). Rapid flows were observed through mechanically induced fissures, but these fissures deteriorated rapidly. There was evidence of a change in the response of streamflow to storm rainfall, with peak flows occurring earlier and of greater magnitude.

**Leadburn, Scotland** (Moorland and approx 50%forest). (David and Ledger (1988)).

Monitored the impacts on catchment runoff arising from planting conifers in peat moorland (peat bog soils). Results suggested that plough drains in peat moorland are a major source area for runoff.

**Sompting catchment, South Downs** (Arable, grass and woodland). Evans and Boardman (2003).

Demonstrated significant impact of land management practices on curtailing runoff-generated 'muddy floods' within the catchment, even during the rainfall events of October and November 2000. However, there is no associated river flooding in this catchment - a chalk catchment with shallow silty soil and a weak river response.

**Uck and Bourne, S.E. England.** (Mixed grass, arable, orchard and forest). Holman et al. (2001), Hollis et al. (2003).

Survey and comparison of soil conditions under different crop regimes in relation to the 1999/2000 and 2002/2003 floods. Suggested timing of flood response in relation to rainfall and soil conditions between the two years was very different, but no proper analysis of flow records or soil moisture balances carried out.

**Tone and Parrett, Somerset.** (Mixed grass and arable). Palmer (2002; 2003a) Surveys, in late winter and early spring 2002 and 2003, of soil structural conditions in soil landscapes under typical land uses. Structural conditions classified using the same methodology as for the Uck and Bourne studies. Found that 75% of sites visited showed some form of degradation and that most of the un-degraded sites were under permanent grass. Levels of degradation were dramatically different in different soil landscapes (but no statistical analysis

was carried out to quantify differences). The soft sandstone landscape was the worst, with 50% of sites severely degraded, often in fields where autumn-sown cereals followed root crops.

**Upper Avon (Wylfe, Nadder and Pewsey catchments)** (Mixed grass and arable). Palmer (2003b).

Survey, in early spring 2003, of soil structural conditions in soil landscapes under typical land uses. Structural conditions classified using the same methodology as for the Uck and Bourne studies. Found that over 50% of sites under autumn-sown cereals were highly or severely degraded. Levels of degradation were dramatically different in different soil landscapes (but no statistical analysis was carried out to quantify differences). 95% of sites in the Greensand landscape were highly or severely degraded whereas 90% of sites under grass on the Chalk landscape were un-degraded.

**Severn and Yorkshire Ouse** (Mixed arable, grass, horticulture and woodland). Holman et al. (2001)

Targeted survey of soil conditions under different crop regimes, in relation to the 1999/2000 floods. Three separate 10 km x 10 km areas were surveyed in each catchment. Soil conditions visually assessed and classified and results for each crop regime extrapolated to catchment level using Defra agricultural census data. Extensive degradation related to specific crop regimes found in both catchments. Assessed the possible impacts of such degradation on run-off generation using 'conservative' and 'extreme' assumptions for degradation-related increases in soil HOST-SPR.

**Den Brook and Drewston catchments, South Devon.** (Grass). (Haygarth et al, in prep.).

An ongoing IGER / Lancaster University catchment experiments at Drewston and Den Brook, near North Wyke.

**CHASM (Catchment Hydrology And Sustainable Management).** (<http://www.ncl.ac.uk/chasm>).

An ongoing study, coordinated by the University of Newcastle, to gain new understanding of how catchment response changes with scale, and to establish new protocols for linking field experimentation, landscape classification, modelling and prediction. Multiscale catchments are being carried out in four predominantly upland mesoscale catchments (~100 km<sup>2</sup>), and a key issue is how, what and where to sample so as to reduce predictive uncertainty. One of the main research themes is flooding, and the aim is to gain a better understanding of the natural controls on the flood frequency curve, and to build this into new physically-based approaches to flood risk estimation.

**LOCAR (Lowland Catchment Research)**  
(<http://www.nerc.ac.uk/funding/thematics/locar>).

An ongoing (NERC) thematic programme to improve understanding of the hydrological functioning of lowland catchments, particularly stream-aquifer interactions, and to study linkages with aquatic ecology. Intensive monitoring is being performed in two Chalk catchments in southern England and a sandstone catchment in the Midlands.

## **Europe**

**European Basins.** (Forest). Robinson et al. (2003)

A review of results from 28 monitoring sites throughout Europe found a relative consistency of results between regions and sites. It was concluded that the potential for forests to reduce peak flows is much less than has often been widely claimed, and that forestry appears to "... probably have a relatively small role to play in managing regional or large-scale flood risk". Significant local scale impacts are likely only for the particular case of managed plantations on poorly drained soils.

## **USA**

**Grand Junction, Colorado.** (Grassland). Lusby (1970).

Monitored the effect of grazing on a salt-desert type rangeland. Runoff from a grazed sub-catchment was 30% higher than from an ungrazed sub-catchment.

**Ohio Watershed.** (Grassland). Owens et al. (1997).

Monitored runoff and sediment losses from a small pastured watershed in eastern Ohio over 20 years. Annual runoff and sediment loss was reduced from 10% of precipitation to 2% when animal grazing was restricted to the summer months only.

**Western Washington.** (Forest) Bowling et al. (2000).

A paired catchment study of the changes in streamflow associated with logging for 23 western Washington catchments. Found an apparent increase in flood peaks for treatment (greater harvest) relative to control (lesser harvest) peaks. Many of the events were generated by snowmelt.

## **Groundwater flooding**

**Finch et al. (2004)**

Described a clearwater flood event in the Pang catchment (Birkshire Downs) during the winter of 2000/01. The flood was a function of both the heavy winter rainfall and the antecedent conditions, in terms of groundwater levels being close to the maximum recorded for the summer and autumn. A combination of aerial photographs and water temperature measurements were used to identify local zones of effluent groundwater. The results are discussed in the context of the geological and groundwater conditions, and a suggestion made as to how areas prone to such flooding could be identified.

**Kneale (2000)**

Described a clearwater flood event on the River Derwent (North Yorkshire) during March 1999, and examined some of the problems in forecasting and preventing groundwater floods.

**Bennett (1996)**

Explored the use of statistical methods for predicting UK groundwater levels from rainfall data.

**Robinson et al. (2001)**

Presented a case study of groundwater flooding in the Thames region during the winter of 2000/01. They found that this groundwater flooding event was not just the result of a single episode of exceptional rainfall and recharge, and that the effects of the winter 2000/01 rainfall were compounded by the coincidence of a high summer minimum groundwater level caused by the cumulative effect of rainfall over the previous years (antecedent conditions). This was a consequence of the long response time of the predominantly Chalk catchments.

**Burt et al. (2002)**

A study of high flow and out-of-bank flood events for the River Severn in Shropshire. A conceptual model was developed from the analysis of field observations, explaining the complex interactions between hillslope, floodplain and channel bank subsurface exchanges during periods of high flow.

**Defra (2004)**

This report is accompanied by numerous maps and ArcGIS packages detailing groundwater flooding vulnerability for the whole of the UK. It covers the frequency, vulnerability and impacts of flooding caused by rising groundwater in a variety of settings that include: permeable catchments, urban conurbations and mining areas. It also considers the synergy with water resources and source protection. One of the main conclusions was that groundwater flooding was almost entirely confined to Chalk aquifer regions. It has been exacerbated by land-use practices that have resulted in drainage channels being neglected or constricted. One of the principal mitigation scenarios suggested involves conveying surface water away from the vulnerable aquifers as rapidly as possible e.g. by drainage straightening or diversion.

**Modelling studies****UK****Godwin and Dresser (2003) River Parrett.**

Investigated the effects that improved soil management could have on runoff generation and peak flows in the 1650 km<sup>2</sup> Parrett catchment (55% grass and 45% arable). The authors identified four potential models (simple empirically based equations) for use in the study, of which the SCS-CN approach was selected after preliminary simulations using a 30 ha hypothetical sub-catchment. The SCS triangular unit hydrographs was then used to assess flood

timing and peak flows for a 75 km<sup>2</sup> subcatchment with the introduction of good practices. The hydrograph peak was predicted to occur 1.5 hours later and with a 20% reduction in peak flow, but runoff volume was unchanged. Major uncertainties associated with these predictions were not acknowledged.

**Calder et al. (2003)** Nottinghamshire.

Predictions of recharge resulting from land use changes were made for an area of Nottinghamshire. Simulations performed using HYLUC (Hydrological Land Use Change), a physically based, daily model, specifically designed for water balance studies involving afforestation. Recharge under pine and oak were found to be 25% and 50%, respectively, of that under grass.

**Crooks and Davies (2001)** Thames catchment.

Modelled land use changes over a 30-year period in the Thames catchment above Kingston (10,000 km<sup>2</sup>). Used the distributed conceptual CLASSIC model, with a 30 km grid resolution. Land use derived from ITE land cover (1993) and change from 1945 to 1990 based on statistics for distribution of cultivated land, permanent grass, woodland, urban. Model calibrated using measured rainfall and run-off from 1981-90 (validated using data from 1961-91). Soils classified in terms of hydrological response; groundwater, semi-impermeable or urban. Effects of land use change on flood frequency in the 30-year period were very small, possibly because main changes in land use were from 1939 to 1945.

**Gilman (2002)** Severn.

Land use maps were used to predict areas where changes such as reduced grazing, reversion to moorland or scrub, or planting of forest on presently grazed hillslopes, might be expected to occur. Simulations of various possible land use changes within the catchment were carried out, using a semi-distributed empirical model, to investigate the resulting changes in peak discharge, for a selection of medium-sized flood events. It was concluded, land use changes on higher ground, e.g. extension of deciduous woodland on slopes, reversion of improved grassland and reduction in grazing of moorland, will significantly affect flood peaks, but only if land use over a large area is changed. Also, the magnitude of land use impacts on flows at the outlet depends on location of change within the catchment.

**Sefton and Howarth (1998)** UK catchments.

Study used the conceptual lumped sub-daily IHACRES model. The model was firstly calibrated for 60 catchments. Regressions were established relating the calibrated model parameters ('dynamic response characteristics': DRPs) and physical catchment descriptions (PCDs), based on aspects of morphology, soils, land use and climate. Two gauged catchments were then treated as ungauged, and the model was parameterised using the DRP-PCD relationships. Results compared favourably with those obtained by direct calibration. The authors proposed that DRC-PCD relationships could be used in the estimation of land use change.

## Europe

### **Fohrer et al. (2001)** Dietzhaler catchment, Germany.

Modelled potential impact of future land use change scenarios (derived from an agro-economic model) in the Dietzhaler catchment, Germany (82 km<sup>2</sup>). Used SWATmod (adaptation of SWAT) based on HRUs, soil water balance, SCS curve number approach. A split-sample approach was used for model validation. Different land use change scenarios did not significantly change the catchment water balance 'due to compensating effects in a complex catchment'. Increasing grass at the expense of forest amplified peak flow rate (but this was not quantified).

### **Bormann et al. (1999)** Krumbach catchment, Germany.

Modelled potential hydrological effects of changes in land use and farming practices induced by policy changes and other drivers, in the Krumbach catchment, N. Germany (16 km<sup>2</sup>). Used a modelling approach which linked SIMULAT, a 1D SVAT (Soil-Vegetation-Atmosphere-Transfer) model to KINEROS, an event-based distributed surface routing model. Simulations were for a design storm and the model was not calibrated or validated against measured flow data. Local soil data probably used to parameterise the different ecotopes used to represent the catchment. Different arable management options in different parts of the catchment gave significant changes in peak discharges, runoff volumes and timing of hydrograph response. But the management changes were simulated using changes to the model surface roughness parameters.

### **De Roo et al. (2001)** Oder and Meuse catchments.

Modelled effects of land use changes on floods in the Meuse (32457 km<sup>2</sup>) and upper Oder (5916 km<sup>2</sup>) catchments. Used LISFLOOD, a physically-based distributed model incorporating topography, soils and land use as well as overland flow and channel flow. Model calibrated and validated using measured data from flood events. Parameterisation of the model with respect to the effects of land use changes was difficult because of very limited data. Slight changes in land use in the Meuse between 1975 and 1992 suggested a slight increase in peak discharge of 0.2%. Considerable uncertainty attached to the model results.

### **Niehoff et al. (2002)** Lein catchment (within the Rhine basin).

Modelled effects of land use change scenarios on storm runoff generation in the Lein catchment (115 km<sup>2</sup>). Used WaSiM-ETH, a physically-based distributed model which has added simulation of soil macropore flow, rainfall and vegetation-induced changes in surface soil hydraulic conductivity and impermeability components within grids. Two storm events simulated (convective-summer and advective-winter). For a scenario in which 10% of the land was left bare, there was a marginal increase in runoff for the convective event and no increase for the advective event.



**Lukey et al. (2000)** Draix, France.

Considered the effects of land use on sediment yield and runoff in a small Mediterranean catchment (86 ha) using the SHETRAN physically based modelling system. The model was parameterised 'blind' (i.e. without access to runoff records) by selecting high, low and baseline ('best guess') values for four parameters (three soil properties and overland flow resistance). Monte Carlo simulations could not be performed for computational reasons; instead, all 81 parameter value combinations were run. Prediction bounds were then created by selecting the highest and lowest discharges at each time-step from the ensemble of simulations. These encompassed 64% of the observations, and the highest Nash-Sutcliffe efficiency for a single model run was 0.36 (evaluated post-parameterisation using the runoff record). To predict the effects of reforestation, the vegetation parameters were then set to the same values as those applied to the forested squares in the original application.

**EC-EUROTAS study final report (HR Wallingford, 2001)** Elbe catchment.

Modelled the impacts of climate and land use change scenarios on the hydrological regime (including flooding) of the Elbe catchment, downstream of the Czech-German border (80,000 km<sup>2</sup>). Used the HBV-D, a conceptual storage-based hydrological model (Bergstrom, 1995). Split-sample validation was performed, but the free parameters were not discussed in any detail. The model was run for 44 sub-basins (meso-scale catchments).

The study concluded that, for major catchments, regional impacts such as snowpack, snowmelt, evapotranspiration, etc. may override the impacts of land use change for many events. For smaller catchments, however, the impact of land use change on flood discharge appears to be larger. For the investigated meso-scale catchments, the impacts of realistic land use change scenarios on hydrological regimes were significant but their impacts on flood discharge were either weak or unclear. An increase in forested area gave a significant reduction in mean discharge, but the authors stated no general conclusions could be drawn with regard flooding.

**EC-FRAMEWORK study final report (Polytechnic of Milan, 2001)** European catchments.

Within this project, the impacts of land use change (including urbanisation) on a number of European mesoscale catchments was explored using a variety of catchment modelling approaches, including the SCS curve number approach, a distributed conceptual model (WBM) and a physically-based distributed model (SHETRAN). A stochastic rainfall generator was linked to the models to simulate the impacts of land use changes on the flood frequency curve. Both the rainfall and catchment models were calibrated using data for the selected catchments. The fractional area of urban within the catchments increased by approximately 10% to 15%, accompanied by a corresponding fall in the area of arable to approximately 50%. The results showed that vegetation changes did not have a significant impact on flood formation. It was found that major impacts can be created by urbanisation and engineering works, which can be either positive or negative. The effects can vary widely depending on the spatial scale of the system investigated. Most importantly, it was found that urbanisation might have a disastrous effect on an urbanised tributary due to local flood peaks generated, which at the same time might positively reduce the

flood peak in the main stream due to partial acceleration of flow. The study concluded that it is difficult to generalize results as each river basin has its individual characteristics which must be considered in a suitable model.

**O'Connell et al., (2003)**

Used a stochastic rainfall model and a simplified version of the ARNO model to show possible sensitivities of the flood frequency curve to land use changes for a synthetic catchment. Changes in soil moisture storage capacity led to upward shifts in the flood frequency curve.

**Australia**

**Nandakumar and Mein (1997) Australia.**

Used HYDROLOG, a daily, semi-distributed, rainfall-runoff model, based on simplified physically-based equations for simulating vertical fluxes. Applied to 5 temperate catchments in Australia. The percentage of eucalypt forest that was required to produce a statistically significant change in the flow (water yield) detectable at the 90% confidence level was then estimated for each. This ranged from 6 to 65%. Uncertainty in the predictions was examined before and after change using Monte Carlo simulation.

**Analyses of flood records**

**Institute of Hydrology (1999, vol. 3), Robson et al. (1998)**

A national analysis of trends in annual maximum (AM) flood records was carried out by CEH as part of the FEH development (Institute of Hydrology, 1999; Robson et al., 1998). The analyses do not show significant impacts of either climate or land use change, but the over-riding influence of year to year climatic variation means that general trends associated with climate or land use change are difficult to assess or dismiss. Emphasised difficulties with varying quality of high flow measurements. Also stated that the gauged records used in the study are rarely located in catchments experiencing major land use change (which may refer to land cover change only) and thus unlikely to show impacts. In addition, as part of the FEH development, a study of how to estimate the Index Flood QMED in ungauged catchments was carried out. This was based on a regression of measured the Index Flood on a set of 30 explanatory variables including catchment characteristics. There were only 4 significant explanatory variables of which soils (SPR-HOST and REHOST) was one. However, urban extent (URBEXT) was the only land use variable included in the analysis so the possible impact of other types of land use or land management was not investigated.

**Lane (2003)**

An empirical study of the apparent increase in flood magnitude and frequency in York since the 1940s. Three possible explanations were investigated: an increase in river conveyance, a change in rainfall patterns, and changes in land use and management.

No statistical evidence was found for either a change in river conveyance or rainfall patterns. However, the author noted limitations in the rainfall analysis; no account was taken of snowfall, the study was spatially limited as only three

station records were available, and data for the study of the intensity of individual events were unavailable.

Changes in land use and management in the catchment area upstream of York were discussed. The author noted that there are insufficient techniques available for the disentanglement of the land use change signal from climatic variations at the catchment scale.

### **Samson (1996)**

Suggested that increased stocking of sheep in the headwater catchments of the Swale and Ure (Yorkshire Dales) might have resulted in an increase in flood runoff production. Analysed flood records in the two catchments in relation to stocking densities and makes a reasonable case for a relationship. However, no quantitative analysis of rainfall, frequency analysis of flow records or impacts of other factors was carried out.

### **Orr (1999)**

Studied the impact of recent changes in land use and climate on the River Lune, Cumbria. Flood frequency was shown to have increased steadily since 1950. The increased frequency of intermediate magnitude floods was largely attributed to the introduction of land drainage schemes, but it was suggested that local climatic variability has become important since the 1970s. Over the last 30 years, a greater proportion of annual rainfall has fallen in winter, with a concurrent increase in wet day frequency. The more rapid runoff from upland areas observed over the last 25 years was attributed to an increase in rainfall intensity and heavy grazing, but the precise effects were not quantified at the catchment scale.

## **Analysis of the occurrence of local flooding**

### **UK**

#### **Boardman et al. (2003a).**

Analysis of 31 'muddy flood' flood episodes and 16 non-flood episodes between 1982 and 2000 in a South Downs catchment. The catchment was dominated by shallow silty soils over chalk, mostly under cereal rotations. Logistic regression model analysis carried out using 32 explanatory variables, grouped into three categories: 'geomorphology'; 'land use'; 'composite measurements'. Models used to predict the probability of occurrence and magnitude of muddy floods. A significant relationship between autumn-sown cereal fields, autumn rainfall and muddy floods was established.

### **Europe**

#### **Papy and Douyer (1991) Souchere et al. (1998) Pays de Caux, France.**

Studied 23 catchments in an intensive arable region. Demonstrated that runoff from more than 50% of the catchment area was produced along the direction of tillage.

#### **Verstraeten and Poesen (1999) Central Belgium.**

Investigated the spatial variation of small-scale flooding and muddy floods in rural areas in a medium sized study area (5516 km<sup>2</sup>) and the linkage with controlling factors. Areas suffering from muddy floods were found to have significantly steeper cultivated slopes compared to areas suffering from only small-scale flooding.

**Bielders et al. (2003)** Southern Belgium.

A regional survey of muddy floods and associated damages. Separated floods into 'Agricultural Runoff floods' (ARF's) and Valley Bottom floods (VBF's). ARFs were focussed mainly on areas of silty or sandy loam soils, which also have a much higher percentage of cropland than other areas. ARFs did occur in conjunction with VBF's but were also common where VBF's did not occur.

**Review studies**

**Acreman (Ed.) (2000)**

This edited book reviews the wide range of changes affecting UK catchments, notable climate change, land use change, river channel modifications and river regulation. Section 1 deals with the causes of change to the hydrology of the UK, Section 2 assesses the effects of these pressures on UK water resources and Section 3 examines the responses of government organizations responsible for the planning and management of water. This publication provides evidence as to why it might be difficult to identify a land use change signal in flow records in the presence of many other changes, measurement errors etc.

**Calder et al. (2004)**

Evidence presented to show that there is a growing disparity between the public perception and the scientific evidence relating to the causes of floods, their impacts and the benefits of mitigation measures. Suggested that this disparity has arisen through the extensive promotion of certain land uses and engineering interventions by vested interest groups in the absence of any effective dissemination of the scientific evidence which may allow a contrary view.

### **4.3 River engineering and floodplain management sources**

**Bailey and Bree (1981)**

Arterial channel improvements result in an increase in flood peaks, the 3 year flood value increasing by about 60%; in the *Q-T* relation there is a shift in the origin of the discharge values, with no change in the variance of the flood peaks; the unit hydrograph time to peak is significantly reduced and the peak ordinate is increased. Field drainage in both fine and coarse textured soils leads to fast evacuation of excess soil water thus providing storage for subsequent precipitation, and reduction of surface runoff; mole drainage of fine textured soils results in peaky hydrographs, but the peak values are less than comparative surface runoff and there is a small lag time: subsurface drainage

systems do not in themselves increase river flood flows, but may have an effect on the FSR soil index and catchment wetness index.

**Brooks A. (1987)**

Analyses channel adjustments downstream from a total of 46 channelization works located in low and high energy environments in England and Wales. The maximum increase of channel size was 153%. Channel enlargement is explained in terms of increased flood flows downstream from channelization works causing higher stream velocities, which in turn cause erosion, thereby increasing channel width and/or depth. Sites with erosion features appeared not to have yet attained new equilibrium conditions.

**Sear et al. (2000)**

A review of the nature, geographical extent and effects of modifications to UK river channels over the past seventy years. The widespread extent of the modifications has been shown through the EA's River Habitat Survey. The geomorphological, hydraulic and hydrological effects of the modifications are discussed, most of which have been undertaken in association with rural land drainage schemes designed to improve the conveyance efficiency of river channels, and flood protection schemes designed to confine high flows within river channels. More recently, river rehabilitation and the restoration of natural floodplains have become the dominant form of channel modification. Impacts on catchment flood hydrographs are dependent on the extent of the modifications, and on their locations within the channel network.

## Summary and findings

Key literature sources relating to the monitoring and modelling of impacts of land use management on runoff generation are summarized; these and other sources are reviewed in greater detail in Appendices A, B, C and F. Monitoring studies carried out at the plot/field scale are reviewed in terms of impacts on surface runoff and drainage flows; most of these studies have been carried out in the lowlands, and cover a range of land use and management practices, including cultivation activities and runoff mitigation measures.

Catchment scale monitoring studies have been carried out primarily in the uplands, and typically at scales of up to 10km<sup>2</sup>. Many of these studies relate to afforestation/deforestation impacts on runoff generation, and include consideration of drainage, forest roads and logging practices. Some lowland small catchment studies of field drainage and 'muddy' floods have also been reviewed, while recent field sampling studies of soil structural conditions in a number of UK catchments are also summarized. The groundwater flooding phenomenon is reviewed briefly, but no specific link with land use management is evident. Ongoing multiscale monitoring studies in mesoscale catchments under two national catchment research programmes (CHASM and LOCAR) are also included.

Catchment scale modelling studies have employed a range of model types, and predictions of impacts relate mainly to changes in vegetation. Unpublished findings from some EC projects are also reported. Statistical analyses of flood records aimed at detecting climate and land use changes are reviewed, together with analyses of the incidence and magnitudes of muddy floods. Although out of scope, a limited review of sources relating to the impacts of river channel modifications on runoff routing is included for completeness. Finally, some review studies illustrate the wide range of anthropogenic impacts experienced in UK catchments, and a disparity between the public perception and the scientific evidence relating to the causes of floods worldwide.

The key findings of the review of these sources are reported as part of the Critical Assessment conducted in Sections 6.1 - 6.2.

## 5. Review of socio-economic studies

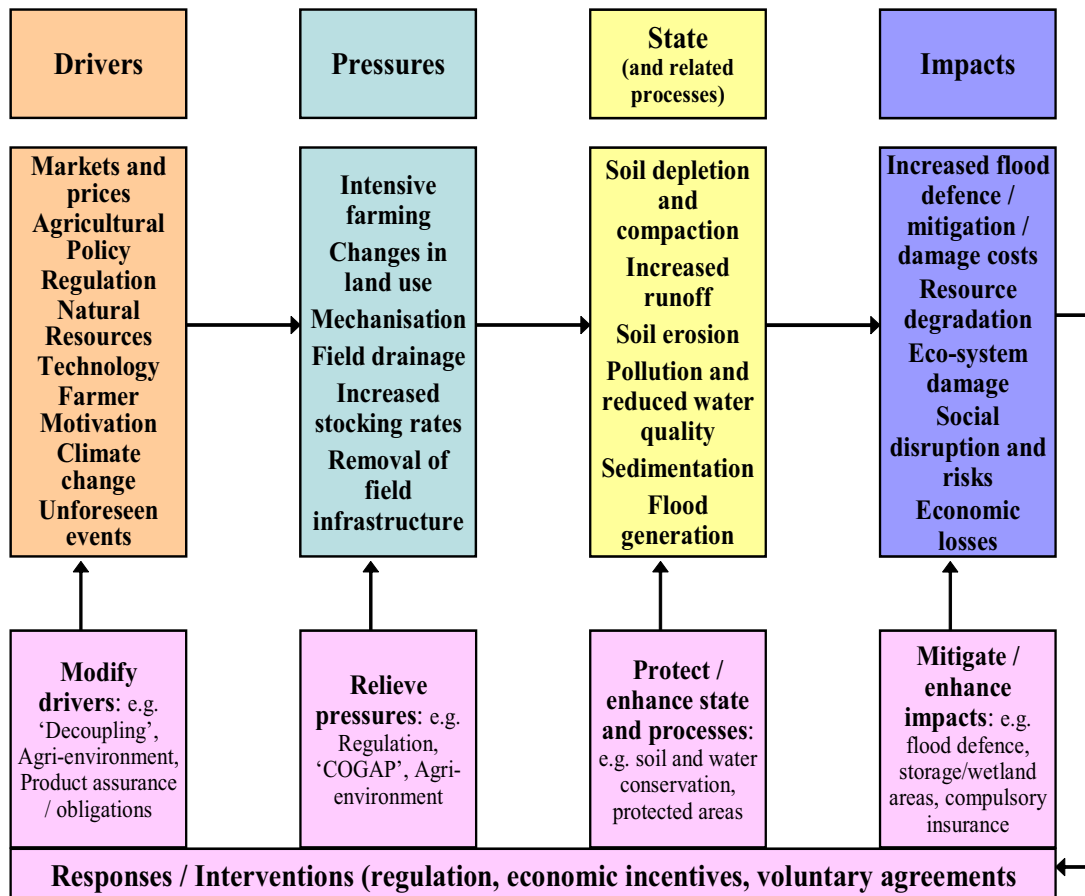
This section reviews literature relating to the socio-economic studies which refer to land management issues as they relate to runoff from farm land and associated flood generation. The review uses the Drivers-Pressures-State-Impacts-Response (DPSIR) Framework to classify relevant studies, although given the scope of the study, there is limited coverage of flood impacts except for local, mainly 'muddy' flood events. Reference is also made to the link between flood generation and diffuse pollution, although the two are not automatically linked. Details are presented in Appendix D which deals with the social, economic and policy aspects of flood generation.

### 5.1 DPSIR framework and flood generation from agricultural land

The broad anthropogenic context of flood generation on farmland can be set in the Drivers-Pressures-State-Impacts-Response (DPSIR) Framework (Fig. 5-1). The design of appropriate intervention measures to manage flood generation and related flood risk requires an understanding of this framework as it applies to rural land management. As referred to earlier, it is important to consider the historic dimension of land use and how changes in management practices over time have given rise to concerns about flood generation.

There is considerable evidence that agricultural commodity markets and agricultural policies, currently contained within the EU Common Agricultural Policy, are key **Drivers** that critically influence land use management. These in turn lead to **Pressures** on land and water resources generated by intensive agriculture, associated for example with changes in land use type such as the switch from grassland to arable, changes in farming practices such as intensive mechanisation within a given land use type, or changes in field infrastructure such as the installation of field drains or the removal of hedges.

In turn, these pressures can change the **State** of rural catchments, reducing the integrity and resilience of environmental characteristics and processes with potential to increase runoff, soil erosion and pollution. If unchecked, this can result in negative **Impacts** on people and the environment and the loss of welfare that this implies. A particular feature of runoff, water related soil erosion and pollution from rural land is that impacts, when they do arise, are mainly 'external' to the site of origin and are borne by third parties usually without compensation. In this respect, land managers may be unaware of or may have little personal interest in alleviating the potential impacts of runoff, unless they are instructed otherwise. Concern about impacts justifies **Responses** in the form of interventions that variously address high-level drivers, land management pressures, protect the state of the environment and mitigate impacts. Responses, which may involve regulation, economic incentives, or voluntary measures, are more likely to be effective, efficient and enduring where they modify drivers and pressures, rather than mitigate impacts.



**Figure 5.1 DPSIR framework applied to flood generation from agricultural land**

In reviewing the available socio-economic information to support the development of policy interventions designed to reduce flood generation, relevant studies have been categorised according to the DPSIR framework. The six sections below group the studies into those that deal with one specific component of the framework and those that cover some combination of the six components, which is the majority. Within each of the six sections, studies have also been separated into those that apply to the UK, those that cover other countries or regions, those that apply to Europe as a whole and those that have a more general application. A discussion of DPSIR components is contained in Appendix D.

## 5.2 Studies classified by components of the DPSIR framework

### Studies dealing mainly with Drivers.

#### UK

##### **Green (1986)**

Concludes that advances in productivity in UK agriculture have had an adverse effect on the environment, including those associated with erosion. Sees policy



polarising land use towards extremes of intensive production and countryside management. Argues for fundamental changes in agricultural policy and practice to achieve better integration of land use through appropriate forms of agricultural production.

### **Selman (1988)**

Study carried out at national level. Land use planning and regulation for agriculture and forestry is not included in the Town and Country Planning Acts. Therefore land use and landscape changes such as extensive land drainage for intensive farming and large scale afforestation have escaped the scrutiny of an independent environmental arbiter. Calls for a more integrated approach mainly through existing provisions, indicating reluctance for strong extra regulation.

### **Mather and Murray (1988)**

Reviews private sector afforestation and its impacts on other land uses. Assumes that afforestation decreases runoff and erosion risk and then examined issues of land ownership and use prior to afforestation. Hints at the need for land use regulation.

## **Studies dealing mainly with Pressures (and State)**

### **UK**

#### **Williams et al. (1995)**

A regional case study that found that large scale woodland establishment in mainly agricultural catchments may considerably reduce runoff but set-aside on arable clay land could increase flood risk if soil surface compaction is left untreated. Implies need for catchment scale land use planning.

#### **Boardman et al. (1996)**

Detailed assessment of erosion and flooding in localised areas as a result of a summer thunderstorm. Quantified these phenomena and examined their impacts in terms of damage. Concluded that the risk of erosion and off-site damage will increase if the area planted to maize and linseed increases.

## **Studies dealing mainly with Impacts**

#### **Penning Rowsell et al (2003)**

Contains comprehensive evidence-based data and methods on impact, cost and benefits of flooding for urban areas, agriculture, and environment for use in appraisal of flood management schemes. Chapter 9 deals with agricultural impacts of flooding.

Other studies mentioned below address impacts, notably Evans (1996).

## **Studies dealing mainly with Responses**

### **UK**

#### **Pretty et al. (2000)**

Estimates total external costs of UK agriculture in 1996 at £2,343m. based on financial costs. Helps identify policy priorities and measures to reduce environmental damage. Implied redirection of subsidies towards encouraging under-provided positive externalities and integration of all policy instruments to correct negative externalities.

**Morris et al. (2000)**

Explores farmer uptake of the Countryside Stewardship Arable Options agri-environment scheme. To be attractive, options must be perceived to be practical, offer adequate environmental and financial reward and fit in with a predominantly commercial farm business purpose. Identifies promotion mechanisms to encourage adoption.

**Newson (1990)**

Concerned with hydrological influences of forestry, and links to water supply and reservoirs. Illustrates the wider implications of encouraging woodland creation through policy to reduce runoff. Question of whether voluntary measures will work: water industry would prefer regulation.

**OXERA (2003)**

Appraises the use of alternative policy instruments to address pollution of water from diffuse agricultural sources, with some reference to runoff but not specifically flood risk. Concludes that non-regulatory methods are likely to prove most cost effective given the diffuse nature of the problem.

**Morris et al. (2004)**

Reviews scope for integrated washlands to provide biodiversity and flood management benefits, with case study examples of flood storage options, including review of land management and administrative options

**Burgess et al. (2000)**

Examined the relationship between conservationists and farmers. Found that farmers see themselves as 'natural conservationists' while conservationists see farmers as technicians ignorant of the workings of nature. Concluded that rigid, scientific prescriptions are often at odds with the more flexible, adaptable approach of farmers.

**Germany**

**Werner (1993)**

A national study that suggests the use of 'farm-gate' price policies to allow for income loss due to providing non-marketable goods and services. Stated that this makes non-marketable goods marketable and includes the cost of these in final consumer prices. Shows how landscape can be used to balance ecological and economic outputs.

**Europe**

**Bouma et al. (1998)**

Concludes major changes are to be expected as a result of technological, socio-economic and political developments as well as global environmental change. Suggests sustainable agricultural land use in some areas and nature development in others should

#### **van Mansvelt and Mulder (1993)**

European level study that compares basic requirements of sustainable development with some features of recent strategies such as integrated agriculture and low external input agriculture. Particular attention is paid to autonomous ecosystem management as applied in organic agriculture.

### **General**

#### **Smith (1996)**

Suggests bio-diversity should act as a measure of biophysical integrity. Suggests that economic instruments to implement a bio-diversity constraint would require new legal and institutional underpinnings but would conserve the potentially large economic use and option value of bio-diversity, thus removing the need for separate measures for its conservation.

#### **Yin and Pierce (1993)**

Outlines an approach to identify and assess the impacts of different land use policies on the resource base and some of the important issues to be considered in attempting to develop strategies to sustain the flow of goods and services from that land.

### **Studies dealing mainly with State - Impact- Response relationships**

### **UK**

#### **Robinson and Blackman (1990)**

Detailed assessment of the occurrence of floods caused by runoff from arable land on the South Downs, Sussex and their socio-economic impacts on local communities and the implications for public policy. Outlined the impact of off-farm flooding on public attitudes to present day land use and farming practice on the Downs and on agri-environment policy, both locally and nationally. Concludes on-farm costs of erosion are small but off-farm costs are larger.

### **Belgium**

#### **Bielders et al. (2003)**

Found the occurrence of erosion was positively correlated to the area of row crops and negatively correlated with winter cereals. Conversion to row crops strongly influenced by EU Policy. Scope to raise awareness, especially among lesser educated farmers and for the development, testing and demonstration of additional erosion control measures. Expansion of agri-environment measures was advocated.

#### **Verstraeten et al. (2003)**

Discusses changing attitudes towards soil erosion. Realisation that flooding (and need for mitigation) due to run-off from arable land in higher catchment. Points to inadequate information about erosion problems, and policies not clearly defined. Highlighted the importance of farmer participation in policy development and demonstration, but showed this is difficult with current administrative set up. Warns that rapid policy development could be unsuccessful.

## **Studies dealing with Pressure-State-Impact-Response relationships**

### **UK**

#### **Boardman et al. (2003a)**

General discussion about influence of socio-economic factors on land use. Describes the causes of floods and outlined society's response to alleviate floods. Concludes that the funding of agri-environment measures, which encourage land use change at vulnerable sites is the best approach to reducing present and future risk from muddy floods.

#### **Defra (2003b)**

Contains Government strategy for addressing diffuse pollution of water by agriculture, including a review of the links between land use and water pollution risk assessment, and the potential efficacy of intervention measures. Reference is made to measures to reduce the risk of soil erosion and runoff, including 'flood control', but there is no evidence or claim that this will contribute to a reduction of flood generation risk.

#### **English Nature (2002)**

Considers interventions to arrest diffuse pollution from farm land, including appraisal of cost effectiveness and suitability for given farming types, and possible grant aid mechanisms to encourage adoption. Soil management and runoff control measures are considered in terms of the control of diffuse pollution, but not with respect to the control of flood risk.

## **Studies dealing with the complete Drivers-Pressure-State-Impact-Response relationship**

### **UK**

#### **Potter (1986)**

Examines farmers' investment decisions in land improvement and landscape maintenance. Reports that countryside change was found to be both determined by policy, institutional and family influences and intentioned by farmers acting as problem solvers.

#### **Selman and Barker (1989)**

Draws attention to lack of integration of rural policies. Concludes that collaborative working amongst apparently conflicting interest groups has produced many positive consequences and provides an effective basis for resolving rural land use issues at the local level.

**Evans (1996)**

Comprehensive review of water soil erosion on farm land, with estimates of damage costs. Concludes that short term off-farm impacts are more severe than on-farm ones. Shows that farmers have little incentive to adopt run-off and soil erosion controls. If actions are taken to combat erosion then agriculture will be less efficient than now in its use of labour and capital, but more sustainable from a land management point of view in the longer term. Productivity will decline but more people will work the land. Measures would have to be taken to ensure farm incomes did not drop too low.

**Winter and Gaskell (1998)**

Presents research findings on the impact of the 1992 reforms on the British countryside as a basis for critical examination of the proposals in Agenda 2000. Focuses on arable and livestock responses. Comments that policy developments seem insufficiently based on a full understanding of the consequences of specific policy instruments for environmental management.

**Robinson (1999)**

Surveys farmers' perception of soil erosion and climate change and their effects on land use decisions. Farmers responded to a variety of external stimuli but resulting land-use decisions varied depending on personal preference, farm policy or convenience. Greatest costs of most erosion events found to be off-farm and felt by local authorities and other local landowners.

**Falconer and Ward (2000)**

General discussion on the use modulation, especially agri-environment schemes, to re-orient agriculture, with implications for land use and farm incomes. Provides insight into how reformed CAP, as a government response, will provide new drivers for land use and farming practice. Potential benefits and problems associated with the agri-environment measures are discussed.

**Sutherland (2002)**

Reviews agricultural problems and proposed targeted agri-environment schemes combined with large-scale habitat restoration, claiming that restoration of woodland, wetlands or flood meadows will help reduce flood risk. Suggests this be achieved through land purchase by bodies such as the National Trust.

**Environment Agency (2002)**

High level review of drivers, pressures and impacts and related costs of agriculture in England and Wales on natural resources. Identifies in broad terms potential flood risks associated with run-off from agricultural land, especially hill slopes, and proposes responses in terms of solutions, together with estimates of costs of implementation.

**France****Souchere et al. (2003)**

Discussed some effects of past, present and future CAP reforms. Used models, tested the consequences of grassland decrease in agricultural catchments to

show the value of grassland reintroduction. Agri-environment schemes were a good move but insufficient; main focus should be to preserve and extend permanent grassland.

### **Mathieu and Joannon (2003)**

Suggests there are two types of farmer, intensive commercially oriented arable farmers and more traditional extensive, mainly livestock farmers. Argues the latter are important for combating soil erosion and runoff, but they are disappearing. States that current CAP arrangements and agri-environmental regimes do not cater for these farmers.

## **Netherlands**

### **Hidding (1993)**

Concludes that physical planning has not been successful in guiding agricultural dynamics. Suggests new planning strategies.

## **Norway**

### **Lundekvam et al. (2003)**

Agricultural and environmental policies manifested by prices, support and different kinds of regulations have had significant impact on farmers behaviour in Norway. Further effects are expected in the future but they may be positive because there is a strong link between research and policy in Norway. Generally concludes that more environmentally sound agriculture can be achieved if such production is made economically profitable.

## **Europe**

### **Boardman et al. (2003b)**

Explores the influence of socio-economic factors on erosion processes and conservation measures, mainly in a western European context. Confirms the strong influence of production-oriented policy drivers on land use and environmental degradation, including soil erosion. Reports beneficial change associated with agri-environment schemes which change incentives, but argues for local solutions underpinned by science.

## **General**

### **Wiebe and Meinzen-Dick (1998)**

Makes the case for using partial property rights as a policy tool instead of regulation or land acquisition but recognises the potentially significant costs of monitoring and enforcing such a regime.

### **Loehman and Randhir (1999)**

Identifies the types of policies and social organisation that could better account for the effects of soil erosion/pollution on the stock of natural resources and suggested including these in decision making. Types of policy examined range from centralisation to complete decentralisation. Considers the type of

management information and knowledge needed by various actors in the social system to achieve efficient outcomes.

### **5.3 Diffuse pollution and implications for flood generation**

Runoff from farmed areas can be associated with diffuse sources of pollution to surface and ground waters (Defra, 2003b), and where this is the case there can be advantage of adopting an integrated approach to alleviation. Control of diffuse pollution from rural land requires modifications to land use, farming practices, the use of inputs and to pathways through which potential pollutions reach receiving waters (English Nature, 2002; Defra, 2003b). Indeed, interventions to reduce run-off of polluted water for the purpose of controlling diffuse pollution may in some circumstances contribute to the alleviation of flood generation and the mitigation of flood impacts. Defra (2003b), in its Strategy for the Control of Diffuse Pollution of Water from Agriculture, recognises that land management practices associated with soil erosion and runoff, such as those that reduce soil cover or compact the soil surface, can give rise to diffuse pollution. In this context, Defra points out that measures to control runoff include 'flood control' generally, and specific measures such as riparian land management, controlled drainage and barrier ditches. These and other methods to control pollution were screened in broad terms against criteria of effectiveness, practicability and cost from the point of view of pollution control, but they were not linked per se with flood management.

Similarly, English Nature (2002), reviewing the suitability and costs of measures to control diffuse pollution for selected arable and grassland farming systems, make reference to land and soil management as this affects runoff, but not specifically with respect to flood risk. This review, together with that made by OXERA (2003) considers the relative advantages of different policy instruments to control diffuse pollution. Common messages emerging from these studies include the considerable scope to reduce environmental risk through improved farming practices, the need to enhance farmer understanding of pollution problems and the extent to which their action can make a difference. A further message is that, given the diffuse nature of the problem, how a mix of economic and voluntary measures, supported by compliance requirements linked to grant aid, is likely to prove more cost effective than intensive regulation. These messages associated with diffuse pollution are relevant to the management of flood generation. Although flood generation and diffuse pollution may be linked, it cannot be automatically assumed that measures to alleviate one will necessarily alleviate the other. Where it can be shown they are associated, however, it makes sense to adopt an integrated approach

## **Summary and findings**

Key sources relating to socio-economic studies of policy interventions designed to reduce flood generation have been categorized and summarized in this section. The studies have been categorized using the Drivers – Pressures – State – Impacts – Response (DPSIR) framework. Under Drivers, Pressures, and State, issues associated with national policy-making and private sector initiatives are reviewed. Studies dealing with Responses relate primarily to the uptake of various agri-environment schemes, and relationships between conservationists and farmers. Studies falling under the complete DPSIR relationship deal with the design of rural land use strategies which balance production and conservation, the effectiveness of policy instruments, analyses of on-farm and off-farm impacts from socio-economic standpoints, analyses of farmers' investment decisions and behaviour in response to incentives and regulations, the effects of CAP reforms, and farmers' attitudes towards soil conservation and flood risk mitigation. Although there may be potential synergy between measures to control diffuse pollution and measures to control runoff, this link, and the contribution to flood mitigation, is not automatic. These two environmental challenges share common land use drivers and environmental pressures, are both 'diffuse' in nature and are likely to justify similar types of policy responses. In some situations, there may be scope to integrate policy interventions to address the two simultaneously, for example through compliance with COGAP or the requirements of agri-environment schemes.

The key findings of the review of these sources are reported as part of the Critical Assessment conducted in Section 6.3.



## 6. Critical assessment of assembled sources

### 6.1 Impacts of land management on flood generation

The field evidence for impacts of land management on flooding is summarised here. A Source-Pathway-Receptor approach (Section 2.1) is taken in presenting this evidence. Changes in local scale surface runoff and drainage are the **Source**. The local scale includes plots, fields, small hillslopes, and areas at field edges. The effects then propagate along the **Pathway** - the surface water network. Finally, the **Receptor** is the location where the flood impact takes place. This approach has been taken for convenience, and to promote an understanding of system behaviour, avoiding inappropriate focus on individual elements of the flood system. Some of the evidence is direct evidence for the effects of a change in land management. The other evidence is indirect, and shows that there is a link between runoff generation and land management, which suggests that changing the management will cause a change in the runoff or flooding.

#### **The source: evidence that changes in land management practices affect local runoff**

The assembled sources (Sections 3 and 4) provide substantial evidence that land management practices affect local surface runoff and the timing and magnitude of field drain responses. Where it is possible to draw comparisons, the UK-based studies are usually in close agreement with overseas studies, but it should be noted that the impact of field drainage is not considered in any of the overseas studies. A substantial proportion of the evidence, most of which is UK based, relates to the impact of a number of 'modern' farm management practices, such as increased stocking densities on grassland, the prevalence of autumn sown cereals, the increase of maize crops, and the production of fine seedbeds.

- There is quantifiable evidence that the differences between the surface runoff from different types of agricultural crops and land uses are related to the amount of surface cover through the year and to the age of grassland or woodland development. Final infiltration rates at the end of 60 minutes of rainfall can range from 60 mm hr<sup>-1</sup> on old pasture to 5 mm hr<sup>-1</sup> on bare crusted soil (Holtan & Kirkpatrick, 1950). Surface runoff during the autumn/winter period can be as much as 5 to 10 times greater from winter wheat than from grass (Sibbesen, 1994).
- There is quantifiable evidence for managed grassland in south west England that overgrazing and trampling by stock can decrease surface infiltration by up to 80% (Heathwaite, 1989) and can double surface runoff at the field and hillslope scale (Heathwaite, 1990). This is supported by similar studies from the USA (Rauzi and Smith, 1973) that showed that infiltration was reduced from 56 to 59 mm hr<sup>-1</sup> on light to moderately grazed plots to 48 mm hr<sup>-1</sup> on heavily grazed plots.

- There is quantifiable evidence for a range of soil types, both free-draining and with impeded drainage, that increased trafficking / tractor wheelings, and its timing with respect to wetness, either during ploughing (Hawkins and Brown, 1963) or during spraying and harvesting, decreases surface infiltration (Davies, 1973; Young and Voorhees, 1982). Infiltration rates reduced from 700 to 800 mm hr<sup>-1</sup> on untreated plots to as little as 1 to 6mm hr<sup>-1</sup> on plots with wheel slip. Surface runoff increased from 12% on unwheeled plots to 23 to 25% on wheeled plots. There is supporting statistical information that water erosion on free-draining sandy soils in the West Midlands of England is associated with soil compaction (Reed, 1983), and that cultivating and trafficking up-slope and down-slope is associated with 95 % of water erosion events on free-draining sandy soils in the West Midlands of England (Reed, 1979; Reed, 1986) and with 50% of catchment runoff from free-draining loamy soils in France (Papy and Douyer, 1991).
- There is quantifiable evidence, mainly from free-draining loamy and sandy soils, that the production of fine seedbeds reduces surface infiltration (Speirs and Frost, 1985) and also reduces surface depression storage from 16 mm equivalent to 6 to 7 mm equivalent (Edwards et al., 1994).
- There is quantifiable evidence, mainly from free-draining loamy, silty and sandy soils, that for maize cropping, ploughing in the autumn and spring can reduce field plot runoff by between 30 and 100 % compared to conventional management (Kwaad and Mulligen, 1991; Martyn et al., 2000; Clements and Donaldson, 2002). The success of other management techniques such as direct drilling, cover crops and soil mulches, appears to be much more uncertain and dependent on soil type. Results vary from an 80 % reduction of surface runoff using winter cover crops (Schafer, 1986) to no significant difference using under-sown rye grass or winter cover crops (Clements & Donaldson, 2002).
- There is much quantified information from specific sites to show that direct drilling or reduced cultivations can significantly reduce in-field runoff by 17% to 48% in a range of arable crops (Charman 1985; Tullberg 1996). However, unpublished information (Austrian Government) suggests that the success of direct drilling in reducing runoff and erosion is very site-specific and, on a silty soil in the Netherlands, direct drilling of maize crops slightly increased surface runoff (by 5%) compared to conventional management.
- There is quantifiable evidence from the USA that contour ploughing and field operations can reduce in-field runoff by up to 75 – 80 %, although such reduction decreases to about 20 % over the season (Schwab et al., 1993). In the UK the only evidence that cultivation and planting across slope reduces runoff comes from a single study on maize (Clements & Donaldson, 2001).
- There is quantifiable evidence that the carefully targeted use of grass strips in arable systems, can reduce edge-of-field runoff by as much as tenfold (Auerswald, 1998; Melville and Morgan, 2001).

- There is quantifiable evidence that field-drainage and associated subsoil treatments can increase or decrease peak drain flows and the time to peak flow by as much as two to three times either way; the behaviour appears to depend on the soil type and wetness regime (Leeds-Harrison, 1982; Armstrong and Harris, 1996; Robinson, 1999).
- There is a growing body of statistical data on the spatial extent of field sites showing evidence of reduced infiltration and increased surface runoff associated with 'modern' practices (Palmer, 2002; Palmer, 2003a; Palmer, 2003b; Souchere et al., 1998; Hollis et al., 2003; Holman et al., 2001). Depending on soil type and weather and soil moisture conditions during the preceding season, as little as 10 % and as much as 60% of sub-catchments may be affected by increased surface runoff.
- There is quantifiable evidence that specific types of arable and grassland management practices can significantly reduce surface runoff with respect to these 'modern' practices (see bullet points above). However, the remedial practices needed at a specific site will depend on the local combination of cropping and soil types.

**Note on Interpretation:** The figures quoted above apply specifically to the field sites studied. Wide variations in figures across different field sites are to be expected for the same land management practice due to topographic/soil variability. Moreover, the figures should not be applied at any catchment scale.

In summary, there is good evidence that local surface runoff is increased as a result of a number of 'modern' farm management practices such as increased stocking densities on grassland, the prevalence of autumn sown cereals, the increase of maize crops, and the production of fine seedbeds. There does not appear to be a strong link with soil type, but sandy, silty, and slowly permeable seasonally wet soils are more susceptible than others.

With respect to mitigation measures, there is good evidence that restricting the grazing/trafficking period can reduce the amount of local runoff on grassland and that afforestation can significantly reduce runoff in the long-term, when compared to the runoff from arable land or intensively used grassland. There is also good evidence that a range of land management practices such as the use of cover crops, minimum tillage, cultivating and planting across slope and the targeted use of grass strips can significantly reduce the amount of local surface runoff associated with arable systems in general and with specific crops such as autumn-sown cereals, maize and sugar beet. However, some of the practices, such as the use of cover crops may have negative impacts on crop yields and none of the practices are likely to be successful in all situations. Most require careful targeting with respect to specific topographic, soil, cropping and climatic conditions. There is also evidence that the impact of field drainage on flows into edge-of-field water bodies such as ditches and headwater streams varies with the type of drainage installed and with the associated secondary drainage practices and wetness regime of the local soil. Evidence, quantified in terms of runoff percentages etc. is site specific and cannot be extrapolated reliably to other sites, nor can it be used at the catchment scale.

## **The pathway: evidence that land management changes affect flow in the surface water network**

It was shown in Section 6.1.1 that there is a significant amount of direct evidence that land management practices affect local runoff. In contrast, there is very little direct evidence that changes in the land management practices affect the flow in surface water networks. The reason for this may be because there have been very few studies.

- There is quantifiable evidence for the effect of conifer afforestation, but it is difficult to interpret. Most catchment monitoring studies in the UK have focussed on upland catchments dominated by conifer forest or rough grassland (see Section 4.2). These have all shown that there is a tendency for the water yield to be less from forest than pasture. There is evidence that afforestation affects peak flows and times to peak. However, this evidence shows that the impact of forests on flood generation cannot be predicted simply by using the above-mentioned water yield data. In their general review of the history of forest hydrology, McCulloch and Robinson (1993) conclude that forests should reduce flood peaks, except for the effects of drainage and forest roads. In the Coalburn experiment, peak flows actually increased by 20% in the first 5 years after forest planting (decreasing to 5% after 20 years) and times to peak decreased (Robinson, 1986; Robinson et al., 1998). This is thought to be the result of plough drainage and ditching;
- A review of results from 28 monitoring sites throughout Europe (Robinson et al., 2003) concluded that the potential for forests to reduce peak flows is much less than has often been widely claimed, and that forestry appears to "... probably have a relatively small role to play in managing regional or large-scale flood risk";
- There is quantifiable evidence for the effect of field drainage, but it is difficult to interpret. Catchment studies generally do not have good information on the amount, location and timing of drainage works. Most of the monitoring evidence comes from the Ray and Catchwater catchments (Robinson, 1990), for which it was concluded that general statements on whether drainage 'causes' or 'reduces' flood risk downstream are oversimplifications of the complex processes involved. This study also indicated that river channel improvements had a much greater effect on peak flows than field drainage;
- There is evidence that large-scale channel modifications associated with major arterial drainage schemes can lead to significant increases in peak discharges (of up to 60%: Bailey and Bree, 1981) in comparison with unmodified rivers. Most of this evidence is for schemes in Northern Ireland and the Republic. Evidence of the effects of less extensive channel modifications associated with more localized rural and urban flood protection works has not been assembled and quantified, but increases in downstream peak discharges can be expected. A recent trend towards channel and floodplain restoration schemes can be expected to reverse these effects;

- There is indirect evidence from a single study in Belgium (Biielders et al., 2003) that many of the recorded local ‘muddy flood’ events generated by surface runoff from agricultural fields (see section 6.1.3 below), are not associated with ‘out of bank’ flood events in the surface water network. This suggests that surface runoff of sufficient magnitude to result in local ‘muddy floods’ is not always transferred to the surface water network in amounts large enough to cause ‘out of bank’ floods in the stream valleys;
- There is quantifiable evidence from the USA for an 8 % reduction in sub-catchment annual percentage runoff when animal grazing is restricted to the summer months (Owens et al., 1997). Additional studies showing a 30% increase in runoff from a grazed compared to an un-grazed sub-catchment is less relevant because it relates to salt-desert type rangeland (Lusby, 1970);
- The SCS runoff curve number approach has been validated for at least 24 small catchments in the USA. This, effectively, encapsulates field evidence from these catchments, and shows how storm runoff varies depending on different arable and grassland management practices and different soil types.

In summary, there is quantifiable evidence that both afforestation and field drainage can affect flows in the surface water network but the impacts can be very different, depending on the local soil type and specific management practices used.

In contrast, although there is good quantifiable evidence that a number of modern land management practices result in significantly increased in-field surface runoff and that specific mitigation management practices significantly reduce such runoff (see section 6.1.1 above), there are no studies in the UK or relevant parts of Europe that quantify how much of such in-field runoff is transferred to the surface water network or how it affects local stream responses. However, there is indirect evidence from a single study in Belgium that surface runoff of sufficient magnitude to result in local ‘muddy floods’ is not always transferred to the surface water network in amounts large enough to cause ‘out of bank’ floods in the local stream valleys.

The uncertainty related to transfer of surface runoff to the river network represents a significant gap in the knowledge base that requires addressing.

### **The receptor: evidence that land management changes impact on local and regional flood events**

There is very little direct evidence that land management practices can affect flooding at larger scales. The reason for this may be because there have been very few studies.

- National analyses of flooding trends (Institute of Hydrology, 1999; Robson et al., 1998) do not show significant impacts of either climate or land use change, largely because of the over-riding influence of year to year climatic variations which make trends associated with climate and land use difficult to identify. It is stated (Institute of Hydrology 1999, Vol 3, p 234) that most of the records used in the study were not from catchments experiencing major land use change, but land use may be equated here with land cover. Moreover the effects of river engineering and floodplain management are also present in such records;
- There is evidence from long-term studies in small catchments in the South Downs of South-East England that there is a significant relationship between the presence of autumn-sown cereal fields and local 'muddy floods' in autumn (Boardman et al., 2003a). There is also evidence that the frequency of these floods can be reduced using appropriate arable land management practices (Evans and Boardman, 2003). This evidence is supported by studies from France (Papy and Douyer, 1991; Souchere et al., 1998) and Belgium (Biielders et al., 2003; Verstraeten and Poesen, 1999);
- Biielders et al. (2003) have shown that 'agricultural runoff floods' do occur in combination with 'valley bottom floods'. But they are also common in areas where, and for events for which, valley bottom floods are not recorded;
- There is some evidence from the Yorkshire Dales, not based on a full quantitative analysis, to suggest that increased stocking densities in upland pastures may have resulted in increased flood runoff (Samson, 1996). A more detailed study on the Yorkshire Ouse catchment (Lane, 2003) did not establish a significant link between land use and flooding because of data limitations and the influence of climatic variability;
- Catchment-scale modelling studies can be regarded as a source of indirect evidence for flood impacts. However, a review of several studies (Appendix B) has not produced any useful, consistent evidence for impacts at the catchment scale, and none of the models can be regarded as fit-for-purpose (Table 6.1). The reasons for this, and the limitations of modelling in this context, are discussed in the following section.

Model	Catchment	Land use change impact study	Fitness for purpose
CLASSIC (Crooks and Davies, 2001) Distributed conceptual model	Thames at Kingston (10,000km <sup>2</sup> )	Assessed changes to the flood frequency curve due to alterations in land use between 1961 and 1990. Changes found to be small (figures not given).	Only considered changes in land cover. Macroscale model with coarse grid squares (20 km <sup>2</sup> ), and a simplistic soil representation.
HYDROLOG (Nandakumar and Mein, 1997) Semi-distributed physically based	5 temperate catchments in Australia (1.6- 520 ha)	Assessed the area of forest that would need to be removed for the detection of a change in runoff in the presence of input errors. For a 10% underestimation of rainfall up to 43% of the forest would need to be removed for detection.	Only considered changes in land cover. Limited representation of runoff generation mechanisms. Channel network not explicitly considered.
HBV-D (HR Wallingford, 2001) Semi-distributed conceptual model	River Elbe (80,000km <sup>2</sup> ).	No clear link between land use and flooding could be found for either (a) a 10% increase in urban or (b) a 10% decrease in agriculture.	Only considered changes in land cover. Model was designed for hydrological forecasting.
SWATmod (Fohrer et al., 2001) Semi-distributed conceptual model	Dietzholzer catchment, Germany (area 82 km <sup>2</sup> ).	A 35% increase in grassland resulted in a 9% increase in annual flow. The peak flows also increased (not quantified).	Model derived from SWAT, which was originally designed for the prediction of monthly water yield.
SIMULAT / KINEROS (Bormann et al., 1999) A coupled 1D SVAT and physically based modelling approach)	Neuenkirchen catchment (16km <sup>2</sup> ) in northern Germany.	Introduction of 12% winter fallow (at expense of winter cereals) resulted in an increase of 0 to 30% in peak discharge, depending on location of change within the catchment. Minimal tillage practices reduced peak discharge by 8 to 34%.	Only considered changes in land cover. No validation was performed. Effects of land use change on flooding only considered antecedent soil moisture and changes in surface roughness.
WaSiM-ETH (Niehoff et al., 2002) Physically-based model.	Lein catchment (115km <sup>2</sup> ) in south west Germany.	Studied a convective and an advective rainfall event (both having a return period of approximately 2 to 3 years). For a scenario in which 10% of the land was left bare there was a marginal increase in runoff for the convective event and no increase for the advective event. (Percentages not quoted)	Details of validation not provided. Only investigated two events. The effects of land cover on soil structure were incorporated, but difficulties encountered in their parameterisation.



LISFLOOD (De Roo et al., 2003) Physically-based model	Oder catchment (60,000km <sup>2</sup> )	Land use for 1780 was reconstructed from maps. It was found that although the area of forest actually increased from 1780 to 1995 the peak discharges also slightly increased. This was attributed to an increase in the area of urban.	Only considered changes in land cover. Given the size of the catchment, relevance to UK conditions limited.
SHETRAN (Lukey et al., 2000) Physically-based model	Draix catchment (86 ha)	Reforestation of the catchment resulted in a 60% increase in annual water yield.	Only considered changes in land cover. Significant uncertainty in parameter estimates.

**Table 6.1 Selected catchment scale modelling studies**

In summary, there is very little direct evidence that land management practices can affect flooding. The reason there is very little direct evidence may be because there have been very few studies. There is therefore a need for further studies aimed at detecting such effects, if they exist and can be identified in the presence of other flood generation factors. There is good evidence from the South Downs, northern France, the Netherlands and Belgium that specific arable management practices result in localised and seasonal ‘muddy floods’ and that some management practices can reduce the frequency of these floods. Modelling studies at the catchment scale can be regarded as a source of indirect evidence, but the models are found not to be fit-for-purpose in predicting impacts.

## 6.2 Modelling the impacts of land use change and land management practices

In the published studies where the effects of land use change and land management practices have been estimated using rainfall-runoff modelling (Section 4.2 and Appendix B), the standard approach involves four steps: (1) calibrate a rainfall-runoff model and run simulations of the catchment in its state prior to land use and management changes being made; (2) change the model's parameters to reflect the changes in land use and management; (3) run simulations using the changed parameters; and (4) estimate the effects of the changes, based on the differences between the runoff responses in the step 3 'changed' simulations and the step 1 'unchanged' simulations. This approach relies on the simulations of runoff being accurate. In fact, because the effects of the changes are calculated based on differences in runoff, rather than absolute values, there is a general need for the simulations to be more accurate than is required in traditional uses for rainfall-runoff modelling, such as water resources management, where it is the absolute flow rates and volumes that are important.

None of the published studies has been carried through rigorously to the calculation of the change in flood risk associated with changes in land use and management (i.e. estimating flood impacts). Flood risk is related to the flood frequency curve, so flood impacts are related to the differences between the flood frequency curves for the 'changed' and 'unchanged' conditions. Estimates of impact can therefore be made by following steps 1 to 4 above, with the runoff simulation results in steps 1 and 3 being used to estimate the necessary flood frequency curves (long sequences of rainfall data from stochastic rainfall generators can be used). When rigorously estimating flood impacts, the uncertainty in the 'unchanged' and 'changed' flood frequency curves must be taken into account. This uncertainty comes from the runoff simulations, and originates as uncertainty in the forcing data (e.g. rainfall), uncertainty in the model parameters (e.g. saturated hydraulic conductivities), and uncertainty arising because of the presence of errors in the structure of the rainfall-runoff model (e.g. limitations in the way that infiltration is represented).

The existing methods for handling uncertainty (Section 2.5) can be used to estimate the uncertainty in the flood frequency curves, but they all have the severe limitation that they work with 'total' uncertainty, so cannot separate the different components of uncertainty. For example, they cannot separate the effects of uncertainty in the model parameters from uncertainty arising from errors in the model structure. This is a limitation because a clear understanding of the sources and effects of uncertainty is needed if progress is to be made in predicting impacts.

There have been no assessments of how good the simulations from rainfall-runoff models need to be if the resulting impact estimates are to be useful in decision support, such as when assessing the effectiveness of given mitigation practices. Also, there have been very few attempts (e.g. Ewen and Parkin, 1996) to assess how accurate rainfall-runoff models might be when used to model 'changed' conditions (for which, by their nature, there are no data for the

models to be calibrated directly against). There are some similarities with predicting flow in ungauged catchments, as this also involves modelling in which there are no data for calibration. Any general progress in improving predictions in ungauged catchments is therefore likely to help in predicting flood impacts (see Sivapalan et al., 2003).

As to specifying the best models to use when predicting impacts, no clear conclusions can be drawn from the reviews. There is no consensus among modellers as to the best types of rainfall-runoff modelling to employ for traditional uses, let alone for predicting impacts (e.g. see the extensive reviews in the references listed at the beginning of Section 2.5). Based on the reviews in the preceding sections of this report, however, some general comments and recommendations can be made. Modern modelling is distributed (so, for example, can make direct use of GIS datasets) and is capable of running continuous simulations (so can, for example, be used to run long term simulations when creating flood frequency curves). To meet the particular needs of modelling impacts, it is recommended that the modelling should be partly or wholly physically based so that the physical properties of local landscapes, soils and vegetation can be represented. Also, detailed modelling of surface water flow networks should be included, so that the effect of changes can be tracked downstream when analysing downstream impacts.

The problems of finding the best modelling approaches and handling uncertainty are both closely linked to the general problem of finding the types of data that have the most value in predicting impacts. For example, if there is a limited budget available and a catchment has to be instrumented so that flood impacts are predicted as accurately as possible, it is not known which measurements should be given the highest priority. This problem has not been tackled in the published studies. The three problems (i.e. finding the best modelling approaches, handling uncertainty, and finding the data types that have the most value) may have to be treated as a single problem, because they are probably inseparable. For example, if there were some consensus on how to model impact and a suitable model is chosen, some priority will have to be given to the measurements needed to set the model's parameters. Some of the parameters may have to be set directly (e.g. using measurements of soil properties), others set by calibration (e.g. using measurements of flow rates in the surface water network collected in a flow gauging campaign), and yet others set using databases containing parameter values successfully used in previous modelling (e.g. using soil measurements or surveys which define soil conditions and types which can then be related to database values for the effects of compaction on given soil types under given management practices). This is further complicated by the presence of uncertainty in the parameter values, which depends, at least in part, on the accuracy and spatial density of the instrumentation. Also, the uncertainty in the predictions will depend on how this parameter uncertainty translates to uncertainty in predictions of impacts (some parameters will need to be estimated more accurately than others), and this translation will depend on the structure of the model.

In many ways, therefore, the use of rainfall-runoff modelling to predict impacts is in its infancy and the published modelling studies (Section 4.2 and Appendix B)

simply give a preliminary indication of how rainfall-runoff modelling might be used to predict impact. For this reason, no catchment-specific or general conclusions are drawn here from the results published for the studies. Considerable progress will need to be made if robust methods are to be developed for predicting impacts, and this development will require a considerable amount of high-quality field data on impacts.

In summary, there are serious shortcomings in the rainfall-runoff models and methods available for use in the operational assessment of the impacts of land use change and land management practices. There are three fundamental unresolved issues: there is no generally-accepted theoretical basis for the design of a model suitable to predict impacts, it is not known which data have the most value when predicting impacts, and there are limitations in the methods available for estimating the uncertainty in predictions. Some general recommendations can, however, be made for a way forward in rainfall-runoff modelling for predicting impacts. The modelling should be distributed and be capable of running continuous simulations. It should also be partly or wholly physically based so that the physical properties of local landscapes, soils and vegetation can be represented, and it should include detailed modelling of surface water flow so that the effects of changes can be tracked downstream. A considerable amount of high-quality field data on impacts will be needed to support the development of robust methods for predicting impacts.

### **6.3 Socio-economic information to support policy development**

#### **Evidence for the uncertainty associated with socio-economic responses to future change scenarios**

The principal uncertainty associated with socio-economic responses to future change scenarios relates to a number of key drivers that determine land use and farming practice. The incentives provided by agricultural commodity markets and prices are a critical determinant of land use management decisions. These incentives are shaped by the interventions contained within the EU Common Agricultural Policy (CAP) that variously support farm production, farm incomes and the rural economy (Boardman et al., 2003b; Falconer and Ward, 2000; Green, 1986; Lundekvam et al., 2003; Morris et al., 2000). Changing agricultural technologies, partly influenced by a mix of factors within and external to the rural sector, also act as drivers for land use change (Bouma et al., 1998; Souchere et al., 2003). Existing regulatory regimes, as they define acceptable practices and permissible use, are key drivers (Selman, 1988; Selman and Barker, 1989). More recently, agri-environment schemes such as the Environmentally Sensitive Area (ESA) scheme and the Countryside Stewardship Scheme (CSS) have attempted to modify drivers in favour of environmental protection and the provision of public goods using a mix of

voluntary and economic measures (Lobley and Potter, 1998; Werner, 1993). The new 'entry level' stewardship scheme (Defra, 2003a) attempts to promote good environmental practice on all farms in return for an annual payment per hectare. Of course land managers, especially those involving family businesses, interpret these drivers with respect to their own personal circumstances and preferences, including motivations for countryside conservation (Morris and Potter, 1995).

The sources described in Section 5 of this report confirm the link between agricultural policy drivers and the pressures on land, water resources and flooding generated by intensive agriculture, whether associated with changes in land use type such as the switch from grassland to arable, or the adoption of farming practices such as intensive mechanisation within a given land use type. Increased pressure on land, in response to market and policy drivers, has direct consequences for increased runoff generation at the local scale (Environment Agency, 2002).

Indeed, evidence suggests that production oriented drivers on land managers are so embedded that CAP reforms in the early 1990s to reduce output and relieve environmental pressures did little to reduce the tendency towards intensification (Souchere et al., 2003; Winter and Gaskell, 1998). Subsequent attempts to extensify land use through measures to 'decouple' farm income from production have not alleviated the pressures on land and water in areas where the drivers to intensify are greatest. Furthermore, there is concern that a decline in commodity prices could in some cases encourage farmers to intensify or seek economies of large-scale production in order to protect income. Reduced real income could also reduce the scope for voluntary environmental measures (Potter, 1986).

A key message from the review of literature is that the greatest impacts of runoff from rural land in the UK occur beyond the site (and usually beyond the farm) of origin, but generally within a radius of a few kilometres from the site. From the standpoint of erosion and sedimentation, the impacts tend to be cumulative and long-term. For the most part, farmers do not perceive runoff as a problem unless it is associated with damage to personal property, major soil erosion risk, or could result in claims by an injured third party (Bielders et al., 2003; Robinson and Blackman, 1990; Robinson, 1999).

Evans (1996) reviewed the evidence of runoff events on farmers' fields associated with water erosion, citing impacts such as loss of crop yield, fertiliser loss, requirement to repeat cultivations or to re-establish crops, and damage to infrastructure. In some cases runoff induced erosion accounted for between £30 and £50/ha (1990 prices) loss of output or lost value of input. However, erosion and associated rills and deposits tend to affect relatively small parts of fields (typically 10%) such that average costs per ha are small (typically £3 to £5 /ha) when spread across whole field areas. Robinson and Blackman (1990) reporting water erosion and flooding on the South Downs estimated average on farm water erosion costs of between £18 and £35 /ha. They report that farm costs for one reported event were £13,000 compared to off-farm costs in excess of £400,000. A survey of 30 farmers in south east England (Robinson, 1999)

further confirmed that farmers were little concerned with the on-farm impacts of water erosion, supporting the view that any long term loss of productivity could be made good by general improvements in yields from improved crop varieties and agro-chemicals (Burnham and Mutter, 1993).

With respect to uplands, Evans (1996) estimates that, in one area of the Peak District between about 1970 to 1986, sheep numbers increased by about 50%, while the area of eroded moor increased by 4% per year. Evans suggests that this probably only resulted in a reduction of 0.1 % in the number of sheep actually carried on the moor. At UK agricultural sectoral level, Evans (1996) suggests that on farm costs for water related soil erosion and hence runoff for the whole agricultural sector are less than 0.02% of gross output. The short-term on-farm costs of erosion and runoff are relatively small.

The greatest impacts of runoff and related soil erosion from farmland, however, are away from the site (and usually the farm) of origin, but still at the local scale. While estimation of flood damage costs at catchment level goes beyond the scope of this report, (and there is, in any case, no evidence of impacts at the catchment scale) there is evidence (contained in Appendix D) to relate runoff from farmland to damage at the local scale. Evans (1996) estimates the total annual costs of water induced erosion events from farmland at between £24 m and £51m for the UK. The Environment Agency (2002) suggests that 25% of major flood events over the period 1970 to 1990 were associated with runoff from hill slopes, and that 57% of these events have been linked to erosion and deposition. On this basis, but no firm evidence, the Agency concludes that 14% of flood damage costs in England and Wales are attributable to hillslope floods and to agriculture, equivalent to £115m per year. While there probably is a degree of double counting and overestimation in some of these estimates, two key messages arise: first, the costs of erosion and related runoff from farm land are mainly felt off-farm (for the most part in the immediate vicinity); and second, the incentives for farmers to adopt erosion and runoff control measures are limited.

In summary, the links between socio-economic drivers, land use and the risk of flood generation are complex. They also tend to be location and context specific. The 'on-site' cost of runoff generation and related soil erosion to farmers is relatively small compared to the benefits of intensive farming. The incentives or requirements for farmers to adopt runoff control measures are limited under the present agricultural policy regime. There is uncertainty concerning how land managers respond to changes in important drivers such as agricultural and environmental policy, both in the short and long term. Nevertheless, there is evidence to suggest that it is possible to design locally relevant policy interventions that can reduce flood generation associated with land use, as discussed below.

### **Evidence for the effectiveness, efficiency and equity of using policy instruments to influence desirable land management practices.**

There is much evidence which confirms that patterns of land use and farming practices are a direct response to the incentives provided by agricultural and more recently agri-environmental policy, modified by a complex of personal, family, farm business, and external contextual factors (Gasson, 1988; Gasson and Potter, 1988; Moss, 1994). Response to policy incentives, modified by personal preferences, has been associated with water erosion risks and flooding (Biielders et al., 2003; Boardman et al., 2003b; Pretty et al., 2000; Robinson, 1999; Robinson and Blackman, 1990; Verstraeten et al., 2003).

Research into farmer participation in agri-environment schemes has provided insight into farmer motivation as well as responsiveness to environmental policy interventions. Different categories of adopters and non-adopters have been identified (Lobley and Potter, 1998; Morris and Potter, 1995; Wilson, 1996). For example, Morris and Potter (1995) surveyed 101 farmers in an Environmentally Sensitive Area (ESA) scheme in South-East England, of whom 55% were participants and 46% non participants. They compiled a participation spectrum which classified respondents into active adopters (52% of adopters) strongly motivated by environmental commitment, passive adopters (48% of adopters) who take part mainly for financial reasons, conditional non-adopters (37% of non-adopters) who might consider participation if a particular constraining factor such as an aspect of scheme design were to be relieved, and resistant non-adopters (63% of non-adopters) who were adamant in their self-exclusion. The authors conclude that the sustainability of ESA scheme, both in terms of achievement of purpose and funding feasibility, depends on the ability to convert a greater proportion of farmers into active adopters. Actions to push farmers along the participation spectrum included targeted promotional information campaigns for non-adopters, through advisory support and training for passive adopters, and the possibility of using active adopters as 'demonstrators of good practice'. A comparison of the ESA and CSS schemes revealed that adopters of the ESA scheme were predominantly motivated by financial gain, whereas the CSS scheme adopters demonstrated predominantly conservation motives (Lobley and Potter, 1998). Such observations on farmer motivations and responsiveness are important when considering interventions

to reduce the risk of flood generation. While a large cohort of farmers are active and voluntary conservationists (Burgess et al., 2000), financial inducements are clearly important for many farmers, and others may respond only if required to do so under a compliance regime.

The aforementioned studies question the sustainability of agro-environmental schemes which use financial inducements to engage otherwise disinterested farmers. They also raise concern of selectivity by farmers which results in policy 'deadweight': paying farmers for things they would do anyway, especially as agricultural policy reform reduces the gains associated with intensification (Froud, 1994). Countering this to some extent, Battershill and Gilg (1996), working amongst grassland farmers in the south west of England, argue that 'traditional', less intensive, and to some extent by default, more conservation-oriented farmers, are a suitable case for support. These at one time may have included a relatively large proportion of elderly farmers (Potter and Loble, 1992), but perhaps less so now. Thus, agri-environmental schemes which secure 'good practices' on traditional farms may be just as valid as preventing 'bad practices' on conventional farms, especially when the former, and the rural economy of which they are an important part, are under particular pressure (Harrison-Mayfield et al., 1998).

Land tenure, property and entitlement rights are critical, influencing the way in which land managers respond to regulation or incentives, especially willingness to adopt long-term solutions. Some responses may modify property rights, requiring compliance with specific conditions as part of entitlement to use (Hodge, 2000; Smith, 1996).

In summary, current evidence suggests that interventions which seek to reduce near-source drivers and pressures associated with land use change are likely to prove more effective and efficient than interventions to mitigate impacts, especially as the drivers themselves are policy driven. This involves discouraging inappropriate land use and farming practices where these are clearly linked to increased runoff and flood generation. The diffuse nature of rural land management and related flood generation suggest that, on its own, mandatory regulation would prove ineffective and inefficient, being difficult and costly to administer and enforce, and possibly insufficiently flexible to deal with local circumstances and practices.

Given the critical role of agricultural policy, it seems appropriate to include compliance with runoff control measures as a condition of support to farm incomes. The process of 'modulation', whereby farm income support is directed through agri-environment payments, can be used to 'incentivise' good practice. Defra's new entry-level stewardship scheme offers scope for this.

Given the evident responsiveness of farmers to financial inducements, the best approach would appear to be a mix of economic and voluntary instruments, supported by advice and technical support. In cases where risks are high, it may be necessary to regulate against particular practices. Such a 'fit for purpose' approach is compatible with the Environment Agency's recent



adoption of a diverse approach to environmental protection, much of it driven by a need to reduce the burden of regulation for all parties.

Experience of the adoption and diffusion of technology in the farming sector can help to design and promote appropriate soil and water conservation measures to reduce runoff and erosion from farmland. Proposals must offer relative advantage (including the advantage to farmers of the ability to demonstrate compliance with regulatory requirements), be practicable, and make a difference. It is important therefore that run-off control techniques are proven locally, are championed by opinion leaders, and supported through research and extension.

It is important to adopt a risk-based approach at the catchment level if policies to reduce flood generation from rural land are to be effective and efficient. It is important to be able to attribute particular land use and management practices to flood generation risk (defined in terms of probability and consequences) and from this determine the contribution of suitable and proportionate intervention measures. It is clear therefore that the links between land use and flooding at the catchment scale need to be assessed to inform a strategic approach, including choice of intervention measures and instruments. However, although the existing state of knowledge can reasonably identify runoff generation at farm level (and the efficacy of interventions to control this), it is not easy to connect this to flood risk at the sub-catchment and catchment scale. A catchment/coastal zone approach is thus likely to be required to capture the aggregated impact of interventions, especially of individually small measures such as on-farm run-off controls. It is usually more efficient to address the problem as near to the source as possible (prevention) rather than nearer to the receptor areas. There are also equity issues in terms of polluter pays, and provider gets. These have been alluded to in the review in terms of the principles of policy design. Clearly, if it can be shown that particular practices by one party gives rise to increased flood risk borne by a second party, or that a third party provides some flood mitigation service, then it seems reasonable that the first should pay and the second and third should be protected or recompensed in some way. There is a choice as to how this principle might be enacted through policy interventions. Interventions which target the 'polluter' may involve regulation, economic penalties or voluntary agreements to restrict or dissuade offending land use or soil cultivation practices. Interventions targeting the 'provider' are likely to involve payments in return for services rendered, such as those associated with on-farm retention ponds or washland storage.

Given the critical role of agricultural policy, it seems appropriate to include compliance with runoff control measures as a condition of support to farm incomes, especially those regimes which promote environmental protection. Agri-environment schemes, notably the Environmental Area Scheme and the Countryside Stewardship Scheme, are used by the Government in England and Wales to encourage the sustainable development of rural areas and deliver public benefits associated with land management. Although at present these schemes do not contain specific components for the control of runoff from

farmland flooding, there are a number of management options that may help to do so. These are discussed in Section 7.2 below.

Research is required to test and validate the linkages between land use practices and flood generation, and the likely suitability of measures for given circumstances and purposes.

In summary, current evidence suggests that interventions which seek to reduce near-source drivers and pressures associated with land use change are likely to prove more effective and efficient than interventions to mitigate impacts, especially as the drivers themselves are policy driven. This involves discouraging inappropriate land use and farming practices where these are clearly linked to increased run-off and flood risk. The diffuse nature of rural land management and related flood generation suggest that, on its own, mandatory regulation would prove ineffective and inefficient, being difficult and costly to administer and enforce, and possibly insufficiently flexible to deal with local circumstances and practices. Instead, the best approach would appear to be a mix of policy instruments: economic and voluntary measures, supported by advice and technical support, backed up, where necessary, by regulation against

## 6.4 Implications for water resources

There is an extensive literature on the impacts of land use change on catchment water yields. Much of this literature is concerned with quantifying the impacts of interception loss from upland conifer forests in the UK and elsewhere on water yield. Process and catchment-scale studies at Plynlimon, Balquhiddy and other locations in the UK have shown how interception loss can impact catchment water yield for different vegetation types and different climatic conditions. The results of these studies were generalized through a semi-empirical model by Calder and Newson (1979) which showed that, for the wet uplands of the UK, annual evaporation rates from mature conifer forested catchments (with 75% of their area forested, equivalent to 50% canopy coverage) may exceed those from grassland by 100%, and runoff could be reduced typically by about 15-20% (Calder, 1993a).

Forests can affect low flows through two mechanisms. Firstly, the high interception loss from conifer forests in wet periods and increased transpiration losses in dry periods (because of deeper root systems) both tend to increase soil moisture deficits in dry periods compared with those under shorter crops. These increased deficits lead to reduced dry season flows where part, at least, of the dry season flow is derived from the soil moisture reservoir (Robinson et al., 1998). (Under conditions of non-limiting soil moisture, transpiration from short crops is greater than that from conifer forests due to lower stomatal resistance, but the net evapotranspiration from forests is typically greater due to the high interception losses (Calder, 1993a).) Secondly, land drainage

operations, which are often associated with conifer afforestation in wet, temperate climates, tend to increase flows as a result of the initial dewatering (which may take a number of years), and the long-term effects of the alteration of the runoff regime. Since the two mechanisms have opposing effects, the net effect may be to either increase or decrease low flows or possibly to have no overall impact (Calder, 1993a). It should be noted, though, that there has been a move away from peat drainage and massive afforestation in the UK, and modern forestry (for afforestation and management of existing forests) is designed to deliver government policies of sustainable woodland management within the wider context of sustainable development.

In the case of UK lowland catchments, concern about the impacts of forests extends to groundwater recharge, and a number of studies have been carried out to assess the impacts of different land covers on recharge. The recently completed TADPOLE study (Calder et al., 2002) has shown, based on detailed measurements of soil moisture change recorded by both neutron and capacitance probes and on the locally calibrated HYLUC model, that estimates of recharge, expressed as a percentage of rainfall, were 25% for grass, 23% for heath, 17% for oak woodland and 6 and 8% for Corsican pine woodland on a drought-prone site overlying Triassic Sandstone in the English Midlands Roberts et al (2001) compared measurements of evaporation and soil moisture for broadleaf (beech) woodland at Black Wood, Hants, with measurements for nearby grassland. Some small seasonal differences were found, with slightly dryer soils under grass in spring (before the trees broke into leaf), but overall annual differences were negligible. These findings contrast sharply with other studies e.g. (Calder et al, 2002) showing dryer conditions beneath woodland, but the differences were attributed to edge effects in those studies, with rainfall intercepted by the sides and tops of trees. The Black Wood measurements were made in the centre of dense woodland made up of trees of relatively uniform size. This suggests smaller plantings of trees, with greater boundary to area ratios may have a greater impact on soil moisture. Work done by the Institute of Hydrology (now CEH) at Fleam Dyke, Cambs, and Bridgets Farm, Hants, compared soil moisture under grass and arable crops for shallow chalk soils and one clay soil. Some seasonal differences were found during the early growing season, but the effects on annual soil moisture balance were negligible.

The above results relate to the impacts of land cover on water yield and river flows. The issue to be considered here is whether there are any additional consequences for water yields and low flows deriving from the assembled evidence concerning the impacts of land use management practices on flood generation. Again, the evidence must be viewed as a function of scale, since local-scale impacts on the runoff regime may not be propagated to larger scales. The impacts to be considered are on (a) catchment water yields, (b) recharge and (c) low flows.

If the runoff generation regime is changed by land use management such that there is a decrease in infiltration and an increase in surface runoff at the local scale, the following questions need to be considered:

- might an increase in local-scale surface runoff alter the total larger-scale catchment yield?
- might aquifer recharge be reduced?
- might low flows be reduced?

In the case of (1), it is not apparent how an increase in surface runoff, and a consequent decrease in subsurface runoff would alter the total amount of runoff. However, its distribution over time might be altered, with consequences for surface water abstractions, if the impacts propagate in a systematic way to the catchment scale. Again, there is insufficient evidence available to answer this question, but it is not obvious how total catchment yield (i.e. the sum of surface and subsurface runoff) might be changed, although, as already noted, the partitioning of the surface and subsurface runoff could change.

In the case of (2), a decrease in infiltration could imply a decrease in recharge. However, surface runoff generated locally due to land management practices may infiltrate through a number of pathways before it reaches the stream network, and there is the question of how, on a heterogeneous landscape, local scale changes in infiltration might aggregate to impact aquifer recharge at the larger scale. This will depend on how widespread and systematic the land management changes are across a catchment. It is possible that reductions in recharge might occur, but again there is no available evidence that demonstrates that recharge is controlled by land use management (apart from the land cover control considered above). Nor has any evidence been reported linking land use management with declining aquifer levels. However, this does not imply that such impacts might not exist in some areas. Further research is needed to investigate this issue.

In the case of (3), a reduction in infiltration implies a reduction in the amount of water stored in the soil, which implies that low flows could be reduced during dry periods. Similarly, if soil moisture storage capacity is lost through soil compaction, then the impact would be the same. However, low flows in many lowland catchments are supported by aquifers, so the overall impact on low flows must involve consideration of questions (2) and (3) together. Given the complexities created by other impacts on the flow regime (primarily abstractions), it is difficult to draw any definitive conclusions concerning impacts on catchment water yields and low flows. It is likely that, overall; any impacts would be secondary in comparison with land cover impacts.

If measures were to be put in place to mitigate the impacts of current land use management practices on runoff generation, then the implications for water resources can be deduced from the above analysis. Any widespread increase in infiltration might lead to an increase in recharge, but could lead to the onset of saturated conditions and catchment scale flooding. This issue is discussed further in Section 6.5 (Hypothesis 2). Any increase in on-farm storage to mitigate local-scale flooding could generate local benefits, but the catchment scale impact depends on how much of this water becomes subsurface runoff. If the water were to be retained on-farm at the end of the winter and used for summer irrigation, for example, this could help ecosystem restoration by

reducing river abstraction for spray irrigation. However, the feasibility and potential for this would need to be explored in future research.

In summary, studies of the impacts of land use change on water resources have focussed heavily on the impacts of forests on catchment water yield, and the associated reductions in catchment water yield and recharge relative to grassland are well documented.

Here, the key issue is whether any changes to the runoff generation regimes associated with land use management practices might have implications for water resources. This issue has been analyzed by considering the following questions: (i) might any increase in local-scale surface runoff alter the total larger-scale catchment yield; (ii) might aquifer recharge be reduced and (iii) might low flows be reduced? In the case of (i), it is not apparent how small-scale changes in the partitioning of surface and subsurface runoff might alter total water yield. In the case of (ii) the main land use control on recharge is through vegetation cover, and widespread changes in infiltration would be needed to have a significant impact on recharge. Since there is a lack of evidence on what happens to source surface runoff off-farm (e.g. how much of it re-infiltrates), and of any evidence linking land use management with declining aquifer levels, there is uncertainty concerning impacts on recharge. In the case of (iii), increased surface runoff implies less water stored in the soil moisture reservoir, with potential impacts on low flows. However, low flows in many lowland catchments are supported by aquifers, so, based on the analysis of (ii), there is uncertainty about impacts on low flows. In the case of mitigation measures, any reversal in current management practices would need to be analyzed in the terms considered above. This issue and the potential impact of poor land management on recharge and low flows, should be investigated in future research.

## **6.5 An analysis of hypotheses about impacts**

It is apparent from the critical assessment of the assembled sources in Section 6.1 and 6.2 that there are significant gaps in knowledge concerning impacts, particularly at the catchment scale. There is quantified evidence of local-scale increases in surface runoff, but a lack of evidence of how these effects propagate to the catchment scale. However, this may reflect a lack of studies in which the evidence has been sought, and it cannot therefore be concluded that the evidence is absent. Further research is needed to uncover such evidence if it exists, and to assess the efficiency and effectiveness of mitigation measures.

There are therefore a number of unresolved questions concerning the existence of impacts and their likely magnitudes, and what if any, mitigation measures should be implemented, given the uncertainty about impacts and their mitigation. These questions need to be addressed by future research, but there is the immediate problem of how the Stakeholders (Defra, the EA, the Forestry

Commission and English Nature) should proceed in the interim. Following the presentation of the results of the Critical Assessment to the Stakeholders, a number of questions were posed to the Consortium, and the responses are included here as Appendix G. These responses provide additional insight into the problem of quantifying impacts at the present time. To further this process, a number of hypotheses about impacts and their mitigation are explored here. These draw on the available evidence, the knowledge base of the Consortium, and some indicative computer simulations. The hypotheses explore a number of aspects of impact assessment and mitigation, and are arranged as a hierarchy, with an overarching hypothesis explored first, followed by a supplementary set of hypotheses which explore specific aspects in greater detail.

**Hypothesis 1:** *“Flooding can be mitigated by altering current land management practices”.*

**Analysis:** This hypothesis must be analyzed at two scales: (1) the local (field/farm) scale and (2) the catchment scale.

In the case of (1), there is substantial evidence (Sections 6.1 and 6.2) that land use management practices can lead to enhanced surface runoff and local scale flooding, which can impact local communities. Mitigation measures could be put in place to control such flooding, but their effectiveness (performance, cost, governance issues) need to be researched further. Apart from benefits to local communities from flood mitigation, there are demonstrable wider benefits that can be gained through runoff control, particularly in mitigating soil erosion and the leaching of nutrients and pesticides. Therefore, an integrated approach to runoff, erosion and water quality management at the farm scale (Integrated runoff management) can potentially offer some flood protection to local communities while also generating wider benefits for the water environment.

At the catchment scale, impact assessment is much more complex, and there is no clear evidence that local scale impacts propagate to the catchment scale. This may be because local scale impacts are ‘drowned’ in the longer duration storms that are critical to flooding in larger catchments. It may also be because a typical catchment landscape consists of a complex mosaic of different landscape elements (different topographies/soils/vegetation/etc), only some of which will be impacted by changes in land management practices. Catchment scale impacts will depend on the spatial extents and locations of affected areas, and on the relative timings of the runoff contributions from the different elements. This issue has been analysed in Section 2.4. Finally, it may be that there have been relatively few studies in which evidence has been sought.

At the larger catchment scale, the analyses of runoff records that have been carried out have not revealed any evidence of significant impacts on flood response associated with land use changes (Section 6.1.3). This does not imply that impacts do not exist, but, apparently, they are not sufficiently large to be detectable in the presence of natural climatic variability. More studies are needed to look for evidence of such impacts. However, based on the current evidence, it cannot be assumed that local scale impacts affecting parts of a

catchment will lead to a significant overall impact, unless a large proportion of the catchment is affected, and, even then, the evidence needs to be identified. If there is a significant loss of soil moisture storage due to compaction, this can be expected to lead to an overall increase in flood generation and flood hazard (see Hypothesis 2 below). Conversely, mitigation measures implemented on impacted areas may not achieve significant flood mitigation at the catchment scale due to the natural attenuation of flood responses as they move downstream, unless a large proportion of the catchment area is affected. The possibility exists, therefore, that land management practices could amplify catchment-scale flooding in some cases, and that these impacts could be mitigated. This possibility has been recognised in developing the Short-term Method for predicting impacts (see Reports C1 and C2). However, more research is needed to address gaps in knowledge concerning catchment scale impacts and to assess the potential for their mitigation.

In summary, alterations to current land management practices can be put in place at the farm scale and can reduce flood risk for local communities, and generate wider benefits for the water environment. However, there is currently no evidence to show that such measures can mitigate catchment scale flooding, and research on both technical and governance aspects is needed to assess mitigation potential at large scales.

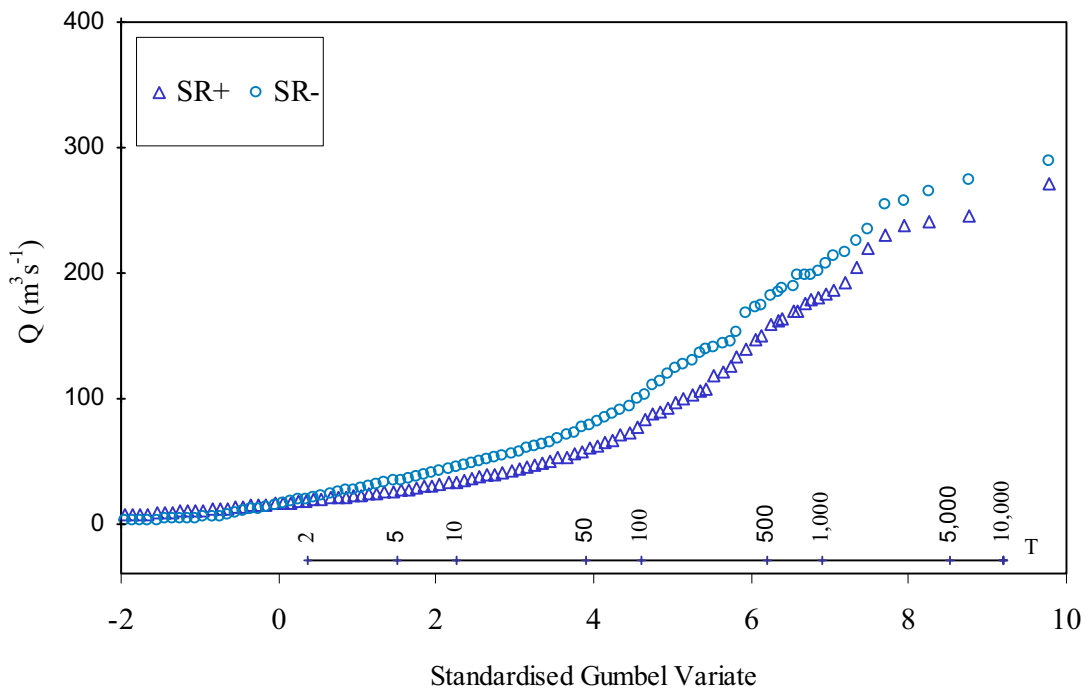
**Hypothesis 2:** *“An increase in infiltration can contribute to flood mitigation.”*

**Analysis:** The underlying rationale here is that, if surface runoff has been increased by land use management practices, alterations to such management practices which increase infiltration can mitigate flooding. The rationale is that infiltration rates should be restored to their natural values. While there are clearly benefits to be derived in reducing local scale flooding, the overall impact on catchment scale flood response and the flood frequency curve needs to be considered. Flood hydrographs are composed of surface and subsurface runoff (see Section 2.2), and a reduction in infiltration-excess runoff may lead to an increase in subsurface runoff. Soil moisture storage functions like a reservoir, and if there is a sequence of storms during a wet period, increased infiltration will lead to wetter antecedent conditions prior to a flood runoff event. This in turn will lead to more subsurface and saturation excess runoff, thus reducing the effect of decreasing infiltration excess runoff. Another factor to be considered here is the decline in maintenance of land drains, which, if blocked, cannot remove subsurface runoff.

Therefore, while this hypothesis may be appealing for the case of an individual storm, it does not necessarily follow that flood generation and flood hazard will be reduced overall. To explore the possible impact on the flood-frequency curve, an indicative Monte Carlo simulation has been carried out by linking a stochastic rainfall model with a rainfall runoff model; both are parameterized for a typical catchment in the south of the UK. Simulated flood frequency curves

are shown in Figure 6-1 corresponding to a different partitioning of surface and subsurface runoff in each case. For low return periods (within-bank floods), the annual maximum peak discharges for the higher surface runoff case are slightly larger than for the higher subsurface runoff case, and vice versa for higher return periods. This should not be regarded as anything other than an indicative result, which has not been validated, but it does support the logic of the above argument. More research is needed on this issue.

However, the effect of an increase in infiltration is closely interwoven with the available soil moisture storage capacity; for the above simulation, this remained constant for both cases. This issue is explored below under Hypothesis 3. Moreover, an increase in infiltration may result in increased recharge in groundwater catchments, and an enhanced risk of groundwater flooding. However, a recent study of groundwater flooding (Defra, 2004; Section 4.2.2) suggests that this problem applies almost exclusively to Chalk catchments.



**Figure 6.1 Flood frequency distributions for different partitioning of surface and subsurface runoff.** (ET, surface runoff and subsurface runoff accounted for 60%, 26% and 14% of the annual average precipitation (578 mm) in the SR+ simulation, and 65%, 11% and 24% in the SR- simulation.)

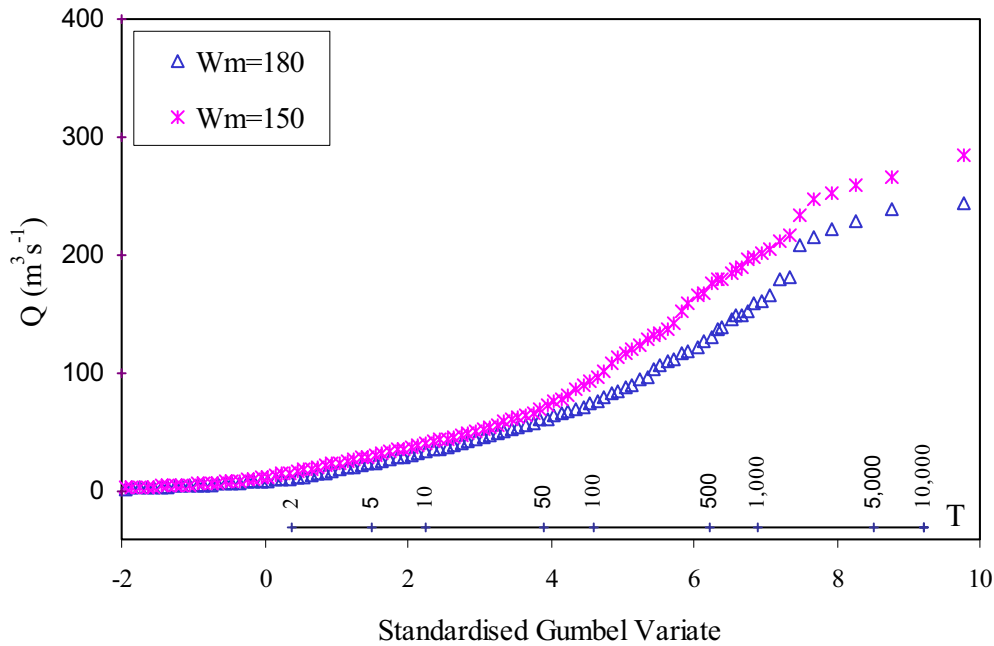


In summary, the restoration of infiltration rates towards their natural values should reduce surface runoff at the field scale, and mitigate on-farm and off-farm flood impacts. Moreover, there may be interactions with subsurface drainage, depending on the level of maintenance. However, there is a possibility that catchment scale mitigation of flood runoff may not be achieved due to a possible increase in subsurface and saturation excess runoff.

**Hypothesis 3:** “By increasing storage within the catchment, flooding can be mitigated.”

**Analysis:** This hypothesis needs to be examined in terms of the effects of subsurface storage in the soil, and surface storage through various interventions (ponds, bunds etc). In the case of subsurface storage, the main issue is the effect that soil compaction can have in reducing soil moisture storage capacity, leading to increased soil saturation and surface runoff generation. If the natural storage capacity of the soil can be restored, then this should mitigate surface runoff; however, the surveys of soil structure that have been carried out have not provided conclusive evidence that soil compaction is widespread, and there is some evidence to show that it may vary seasonally.

Using the same modelling framework referred to under Hypothesis 2 above, exploratory simulations have been performed to show the effect of increased soil moisture storage on the flood frequency curve. Figure 6.2 shows that if catchment soil moisture storage is increased by 20% (from 150mm to 180mm), there is a corresponding decrease in flood hazard, particularly for high return periods. Such an increase in soil moisture storage may not, of course, be feasible, and the simulations are only indicative, but they do demonstrate the sensitivity to storage changes. The effects of surface water storage (e.g. through source interception and storage of runoff) would be the same, but would need to be implemented across the whole catchment to be effective. This may not be possible for larger catchments, and their effectiveness will depend on the existence of sufficient incentives for farmers to manage and maintain such facilities on a widespread basis, and in the long term. There are therefore governance issues to be addressed here. However, surface storage measures, and the restoration of soil moisture storage lost through compaction, could form part of a farm-scale integrated runoff management plan, with benefits for erosion and nutrient pollution control, and the mitigation of local scale flood impacts. It should be noted that retention ponds are being considered as part of Defra’s strategy for the Control of Diffusion Pollution of Water from Agriculture (DWPA).



The extracted floods corresponding to the above plot

	Wm=1 50	Wm=1 80
Q5	30.8	24.4
Q10	41.2	33.9
Q50	71.6	61.7
Q100	95.6	75.8

**Figure 6.2 Flood frequency distributions for different catchment soil moisture storage capacities, showing the effect of increasing storage by 20% (from 150mm to 180mm)**

In summary, any increase in storage within the catchment, which could be achieved through the restoration of the natural storage capacity of the soil, or through impoundments at the farm scale, would be expected to reduce flood generation and flood hazard. However, the extent of the reduction would be dependent on the amount of storage provided, and there are governance issues associated with the diffuse nature of this flood mitigation measure.

**Hypothesis 4:** *“Reducing the speed of conveyance of runoff can mitigate flooding”.*

**Analysis:** The underlying assumption here is that, by delaying the movement of runoff to and through the drainage/channel network, greater attenuation of the flood hydrograph peak will be achieved, and flooding reduced. While this is a reasonable assumption, the effect depends on a catchment size and on the relative timings of the runoff contributions from the different landscape elements and sub-catchments. At the local scale, the connectivity of flow paths, and the speed of conveyance, is affected by the presence or absence of hedgerows, ditches, drains (surface and subsurface), tracks etc. As illustrated by the example shown under Hypothesis 1, a catchment-scale view must be taken of this issue, to ensure that any changes in the timings of runoff delivery to the channel network do not result in increases rather than decreases in peak discharges at the catchment scale. This is necessary given that natural conveyance has also undergone significant changes due to river engineering schemes.

In summary, any reductions to the speed of conveyance of runoff to the drainage/channel network resulting from mitigation measures should be assessed at increasing catchment scales to identify any adverse impacts that might occur through changing the timings of runoff contributions to the channel network. This recognises that river engineering schemes have also changed natural conveyance in many catchments.

**Hypothesis 5:** *“Forests reduce flooding” or “Forests increase flooding”.*

**Analysis:** Forests intercept precipitation, and this has sometimes led to the misconception that forests can 'absorb' floods, acting like a sponge. In the case of a flood-producing rainstorm, only a limited amount of rainfall (typically up to 5mm) is intercepted which will not in itself have a significant mitigating impact. The impacts of a forest on flood generation in a catchment depends on several factors, such as the proportion of area covered by forest, the stages of the forest life cycle (planting/growing/maturing/logging), and on how forestry operations are managed. Reductions in peak runoff might be expected due to increased evapotranspiration (interception loss/increased soil moisture deficits/decreased recharge and groundwater levels in lowland catchments), a greater proportion of subsurface runoff on forest hillslopes, while increases could result from land drains (early stages of forest growth), forest tracks combined with steep slopes, and poorly managed logging operations. Overall, no clear evidence has emerged to show that forests either mitigate or increase flooding to a significant extent.

The case of a recent flooding disaster in Indonesia (Bell et al., 2004) can be cited as an example of a speculative hypothesis about the cause of the disaster, which was initially attributed to illegal forest logging by the responsible

government minister. However, once he had visited the site and reviewed the available evidence, he concluded that the flood should be regarded as a natural disaster. This does not mean that widespread, indiscriminate and badly-managed logging cannot increase flooding. However, recent evidence has shown that, provided logging operations are carefully managed and scheduled over time, and that bare soil is not left exposed, any potential impacts can be mitigated.

In summary, neither of the above hypotheses can be accepted on the basis of the available evidence, as several interacting factors tend to cancel each other out.

**Discussion:** From the analysis of the above hypotheses about impacts and their mitigation, it is apparent that there are major gaps in knowledge concerning the effects of various interventions aimed at mitigating flood generation, particularly at the catchment scale. Hypothesis 1 looks at interventions collectively, and draws attention to the overarching factors that might limit their effectiveness, or indeed generate adverse impacts through changes to the timing of subcatchment hydrographs that result in these responses becoming more aligned. Hypothesis 2 examines the infiltration issue, and while local scale benefits can be derived from restoring infiltration towards its natural value, the resulting catchment scale impacts may be different due to increased subsurface and saturation excess runoff. An indicative model simulation has shown that flood hazard could actually increase if infiltration is increased, particularly in the case of groundwater catchments. Hypothesis 3 explores the effect of increasing/decreasing storage, whether through subsurface storage in the soil or in surface impoundments. Using an indicative model simulation, it is shown that a reduction in catchment soil moisture storage such as that resulting from compaction, could lead to an increase in flood hazard. Although no evidence of catchment scale impacts was found in the sources reviewed, the possibility exists that such impacts may occur in some catchments. Therefore a precautionary approach is advisable in preparing CFMPs, and the Short-term Method described in the Companion Reports C1 and C2 adopts this approach. Hypothesis 4 explores the conveyance issue, and while various measures can be implemented at the farm scale to delay runoff, the overall impact of such measures on the timing of sub-catchment runoff responses needs to be assessed before any catchment-wide use of such interventions is adopted. Hypothesis 5 explores the role of forests in flooding, and concludes based on the available evidence, that their overall impact is neutral.

### **Summary and findings**

In this section, Summaries and Findings are given at the end of each subsection, to ensure that the findings are matched to the different stages of the Critical Assessment.

## 7. Future land use management

### 7.1 Potential impacts of climate change

The UK climate has changed over the last century. In central England temperatures have risen by 1°C, and the decade of the 1990s was the warmest since records began in the 1660s. Winters across the UK have been getting wetter, with a larger proportion of the precipitation falling on heavy rainfall days (Hulme et al., 2002b). Recent extreme rainfall events in the UK have characteristically been multi-day, with unremarkable one-day totals. Fowler and Kilsby (2003b) have found significant decadal level changes in 5- and 10-day events in many regions from 1961-2000. The 50-year event in Scotland during 1961-1990 was found to have become an 8-, 11- and 25-year event in East, South and North Scotland respectively during the 1990s. In northern England, the average recurrence interval has also halved. This was found to be a consequence of both increased event frequency and changes in seasonality, with more events occurring in autumn months (Fowler and Kilsby, 2003a).

Whether these observed changes in rainfall have so far impacted upon river flooding is still under debate. Black (1995) suggested that climate change was the most likely factor responsible for the major floods recorded in western Scotland during the late 1980s and early 1990s. Robson et al. (1998) found no evidence of climate change in a UK wide study of trends and variations of floods. The IPCC (IPCC, 2001) stated 'the changes in frequency of extreme events cannot generally be attributed to the human influence on global climate'. However, detecting any trend in flooding will be difficult as the signal will be mixed with that from other forms of environmental change, including urbanisation, land use, reservoirs, river flow management/maintenance, drainage and flood alleviation schemes.

General circulation models (GCMs) are the primary tools for the investigation of the future effects of anthropogenic activities on the climate. There is significant uncertainty in the predictions of these models; they are based on scenarios of future emissions which are dependent on population, economies, energy technologies and other social factors, there are scientific uncertainties in process representation, and the bio-physical responses to such changes are unknown. The predictions are usually provided at a very coarse spatial resolution (typically 10,000 km<sup>2</sup>) and must be disaggregated (downscaled) to the smaller space scales required by catchment models. This regeneration of local sub-grid variability is usually performed using either statistical techniques or by using the GCM outputs as boundary conditions for fine-resolution regional climate models (RCMs).

Climate models predict increases in both the frequency and intensity of heavy rainfall in high latitudes of the Northern Hemisphere under enhanced greenhouse conditions (Jones and Reid, 2001; McGuffie et al., 1999; Palmer and Räisänen, 2002), which is consistent with the recent increases in rainfall intensity seen in the UK (Fowler and Kilsby, 2003a; Fowler and Kilsby, 2003b; Osborn and Hulme, 2002; Osborn et al., 2000) and worldwide (Frich et al., 2002; Groisman et al., 1999; Karl and Knight, 1998). The first analysis of

prospective changes in extreme rainfall over the UK was provided by Jones and Reid (2001) using results from the HadRM2 regional climate model. Their research suggested that there would be dramatic increases in the heaviest 1-day rainfall events by the end of the 21st century. This conclusion was echoed by Huntingford et al. (2003) who suggested, that for longer duration events, there will be even larger increases.

The most recent comprehensive assessment of future change in extreme rainfall across the UK has been undertaken by Fowler et al. (2004) and Ekström et al. (2004) using HadRM3H data. Fowler et al. (2004) found that HadRM3H may be used with some confidence to estimate extreme rainfall distributions, showing good predictive skill in estimating statistical properties of extreme rainfall during the baseline period, 1961-1990. Ekström et al. (2004) found that for short duration events (1 to 2 days) rainfall magnitudes will increase by 10 % across the UK. For longer duration events (5 to 10 days), rainfall magnitudes show a large increase in Scotland (up to +30 %), with greater relative change at higher return periods (25 to 50 years). In the rest of the UK, there are small increases in the magnitude of more frequent events (up to +10 %) but reductions at higher return periods (up to -20 %). This study provides information allowing the estimation of changes for the 2020s, 2050s and 2080s in line with the UKCIP02 scenarios (Hulme et al., 2002a) and gives uncertainty bounds around the estimates.

The majority of studies investigating the potential effects of climate change on river flows have been performed from a water resource perspective, typically concerned with monthly and annual flows (Arnell, 1998; Arnell and Reynard, 1996; Holt and Jones, 1996; Limbrick et al., 2000). Those studies in which high flow frequencies have been analysed often do not consider uncertainty, but there are some exceptions. To provide flood frequency curves, Kilsby et al. (1999) performed continuous simulation using long synthetic rainfall data series derived from downscaled GCM predictions. It was found that uncertainty in the parameter values of the catchment model was more significant than any potential change in precipitation regime. Cameron (2000) and Cameron et al. (2000) used TOPMODEL to assess the effects of climate change on the frequency of high magnitude events within the Wye catchment, within the GLUE uncertainty framework (Beven and Binley, 1992; Beven and Freer, 2001). The predicted increase in the 100-year event was found to be less than the current uncertainty in the estimation of that event, but that there was an increased risk of experiencing an event of a given magnitude with climate change.

Although climate change will undoubtedly result in a change in the flood frequencies of UK rivers, it is not possible to provide quantitative figures due to the large uncertainties involved. There are uncertainties in the climate models, the scenarios, the likely biophysical response of the Earth, and the downscaling techniques. Any hydrological modelling will introduce an additional source of uncertainty. Schemes to deal with the potential climate change impacts on river flows should therefore be flexible and reversible.

While the prediction of the quantitative impacts of climate change on flood risk is difficult and subject to major uncertainty, it is possible to make qualitative

assessments of how the expected changes and observed trend in UK rainfall regimes might interact with land use management and flooding. The general expectation of increased autumn/winter rainfall in the UK, with more frequent and more intense autumn storms, would suggest that the incidence of local-scale flooding may increase, unless current crop cultivation practices are altered to avoid exposed bare soils in the autumn/winter. Moreover, the tendency not to house animals during milder winters can be expected to continue, with trampling under wet conditions leading to soil compaction etc.

There is already evidence of an increased frequency of seasonal (autumn/winter) rainfall events in the lower return period range (<10 years) in the South and Midlands which, together with some evidence of increased short duration intensities, may also be linked to the increased incidence of muddy floods in Southern England. Moreover, the expected increase in the frequency of long-duration (5-10 day) heavy rainstorms (Fowler and Kilsby, 2003b) implies that events leading to widespread catchment saturation (similar to that which led to the autumn 2000 floods) may become more common. Catchments with significant areas affected by loss of soil moisture storage capacity (e.g. due to soil compaction) could therefore be subject to an increase in flood hazard (Section 6.5, Hypothesis 3). However, since there is some evidence to suggest that soil compaction may vary seasonally, the seasonal distribution of storms in the autumn/winter period will interact with this, and so the overall outcome is therefore uncertain.

Drier summers may be expected to lead to higher soil moisture deficits, which may reduce flood responses to autumn storms. However, shorter-duration intense storms may lead to increased surface runoff and localized summer floods due to soils becoming capped.

Drier summers may also lead to lower aquifer levels at the onset of winter, and a lower efficiency of aquifer recharge (due to the more intense nature of rainfall and the generation of more surface runoff), which could lower the incidence of groundwater flooding.

## **7.2 Future land use change: agri-environment schemes and CAP reforms**

Agri-environment schemes are one of the instruments available to government providing financial incentives to farmers to adopt practices that enhance the rural environment, in terms of biodiversity, landscape and historic quality. They form part of a wider suite of policy instruments to encourage the sustainable development of rural areas, with the aim of enhancing environmental, economic and community benefits in the long term. They are designed to implement the policy requirements of the EU's CAP Pillar II, which stresses the importance of building effective mechanisms for the delivery of public benefits through land management policy. In England, Agri-environment schemes now come under the England Rural Development Programme (ERDP).



Environmentally Sensitive Areas (ESAs) and the Countryside Stewardship Scheme (CSS) are the two main agri-environmental interventions. As yet, neither focuses specifically on the control or management of land with the objective of controlling runoff. Nevertheless, each has a number of land management objectives that are likely to reduce local surface runoff and may have a beneficial effect on flood generation.

### **Environmentally sensitive areas (ESAs)**

The first ESAs were introduced in England by MAFF (now Defra) in 1987, under the 1986 Agriculture Act. Since then, further ESAs have been introduced, bringing the total in England to 22. Each ESA has a series of environmental objectives that focus on desired outcomes and reflect the potential of the designated area. No two ESAs have exactly the same objectives but there is often a common theme running through those with a similar landscape type, e.g. the river valleys, the uplands, the coastal marshes, etc. By 2002 there were over 12,000 agreements covering in excess of 570,000 hectares.

Among the changes in land management practices specified in order to achieve the environmental objectives, the following are likely to result in reduced surface runoff as summarised in section 3.3:

- Arable reversion - reverting arable land to grassland;
- Retaining winter stubbles and growing spring cereals;
- Upland grazing management and stocking rate control;
- Boundary management and buffer strips;
- Grazing marsh and dyke management;
- River valley grazing management;
- Less intensive production;
- Raising and managing water levels to create wet grassland, wetlands or wet ditches and scrapes.

All ESAs have at least one of these in their list of options, but none has all of them.

Arable reversion, which features in over half the ESAs, could contribute to the reduction of local flood generation in that grassland is likely to cause less runoff than arable land provided that it is properly managed. Similarly, over-wintering stubbles followed by spring cereals are seen as beneficial compared with the exposed soils associated with winter cereals. It has been suggested that higher stocking rates and long grazing seasons have led to increased risk of runoff, so the upland prescriptions that reduce stocking rates and limit grazing should have a beneficial effect. It has also been suggested that buffer strips, mainly introduced to reduce pollution to watercourses may also reduce runoff. The benefits towards flood control that accrue from river and coastal grazing management, including ditch management for ecological gains, are less easy to define dependent upon the time of year, although managing grazing marsh and

water meadows traditionally, should increase the buffering capacity of the locality.

### **The Countryside Stewardship Scheme (CSS)**

The Countryside Stewardship Scheme (CSS) was introduced by the Countryside Commission as a pilot national agri-environment scheme in 1991. Following an independent review in 1995, responsibility for the scheme transferred to MAFF in 1996. CSS applies throughout England but is generally only available outside the ESA areas and is the main scheme targeted at the wider countryside. The Scheme has identified 6 landscape types (which include chalk and limestone grassland and old meadows and pastures) and 5 landscape features (which include historic features and arable land) as priorities for intervention. Each county has set specific targets for its important landscape types and features. Priorities and objectives are set for these areas in agreement with partner organisations and agreements are made with land managers that offer the greatest potential benefit for the payments made. Farmers and landowners enter 10-year agreements to manage their land in an environmentally beneficial way. By 2002, almost 14,000 agreements had been entered into, with over 343,000 hectares in agreement, together with almost 33,000 km of arable margins.

The range of management options that may bring benefits in reducing flood generation are similar to those of the ESAs:

- Arable reversion to grassland
- Creating and managing field margins in arable fields and intensive grassland
- Over-wintered stubbles
- Downland and upland grazing management and stocking rate control
- Regenerating heather on improved land
- Managing raised water level pastures and ditches

### **Other schemes in the England rural development programme**

There are several other schemes under the ERDP that, by definition, change the way that land is managed and thus have the potential for affecting the risk of flood generation. These include the Woodland Grant Scheme and the supplementary Farm Woodland Premium Scheme, the Energy Crops Scheme and the Organic Farming Scheme.

### **Future schemes**

All current 'Land-based Schemes', of which all the aforementioned are part, are currently under review by Defra to determine their format and scope for the future. Proposals have already been put forward for two new agri-environment schemes.

Following the Government's 'Strategy for Sustainable Farming and Food', a new 'broad and shallow', entry-level agri-environment scheme is being piloted in four areas (Defra, 2003a). It involves fixed annual payments per ha in return for compliance with generic good practice according to farm type. There is one specific component on soil erosion that, because the measures are designed to reduce runoff, could help to alleviate local flood risk, as well as those dealing with field margins, winter stubbles, and grassland management.

In addition, proposals are out for public consultation on a new Higher Level Environmental Stewardship Scheme to complement the Entry Level Scheme and replace the existing ones. It is proposed that this scheme will have a number of tiers with options designed to meet the environmental objectives of each of the tiers. One of the primary objectives of the scheme is the protection of natural resources, which includes soils, and a specific secondary objective is the improvement of flood management. It is anticipated that flood alleviation objectives will be met through the adoption of particular options that have the potential to increase water storage at the field and catchment level, including resource protection, wet woodland, wetland and inter-tidal options. There are also a number of less specific options that may contribute to the flood management objectives.

### **CAP reform**

The incentives provided by CAP have been a major driver of land use change, some of which have exacerbated runoff generation. The agreement on CAP reform by EU member States on 26<sup>th</sup> June 2003 confirmed the commitment to reduce direct production subsidies and to link income support payments to compliance with standards which protect the environment, animal health and welfare. There was an agreement to bring forward to 2005, the date of 'modulation' - the process whereby monies are transferred from direct payments (such as arable area and livestock headage payments) to expenditure on rural development, including agri-environment schemes. It was also agreed to increase the minimum rate of modulation to 5% of the total spend by 2007, although this is a small proportion of the 20% modulation that member states can apply if they wish. Defra is currently consulting national bodies on the implementation of proposals where there are major areas of national discretion. The timetable in the UK is planned to allow implementation at the earliest possible date of January 2005.

The CAP reform changes, through a mixture of extensification of farming, increased compliance, and wider participation in agri-environment schemes, are designed to reduce the environmental burden of farming. This changing policy framework will provide opportunities to promote and fund changes in land use and could be used to target vulnerable catchments where it can be established that such interventions will make a difference and are worthwhile.

### **Water framework directive and policy integration**

The aforementioned agri-environment schemes are a major policy mechanism for the design and delivery of locally relevant 'Programmes of Measures'

(POMs) to address environmental pressures, particularly diffuse pollution in the context of the targets for ecological water quality set under the Water Framework Directive (WFD). The WFD promotes an integrated approach to the management of water resources at the catchment level, including a commitment to 'contribute to the mitigation of the effects of flooding'. Defra's strategy for controlling diffuse pollution of water from agriculture also identifies a role for runoff and flood control. Simultaneously, the Environment Agency is implementing a strategic approach to Catchment Flood Management Planning. It is critical therefore that these initiatives are fully integrated in order to maximise policy efficiency and avoid policy conflict. In particular, it is important that the new agri-environment schemes planned (and funded) for introduction in 2005, should contain general measures to reduce runoff generation as part of good agricultural practice, and more specific and targeted measures where there is evidence of high risk of runoff and that such interventions will make a difference.

### **7.3 Future land use change: foresight scenarios**

This section considers the use of long-term scenario building, or horizon planning, to explore the link between rural land use and flood risk. It draws on work carried out by the Office of Science and Technology's Foresight Programme (DTI, 2002) and the recent Foresight Flood and Coastal Defence Project (Evans et al., 2003).

#### **Scenario building**

Scenarios are not intended to predict the future (DTI, 2002). Rather, they are tools for thinking about the future, assuming that:

- the future is unlike the past, and is shaped by human choice and action;
- the future cannot be foreseen, but exploring the future can inform present decisions;
- there are many possible futures: scenarios map a 'possibility space';
- scenario development involves a mix of rational analysis and subjective judgement.

Thus, scenarios are statements of what is possible; of prospective rather than predictive futures; propositions of what could be. They are often made up of a qualitative storyline and a set of quantitative indicators which describe a possible future outcome. The scenarios arise as a consequence of exploring the possible consequences of drivers of economic and social change, new trends and innovation, and of unexpected events.

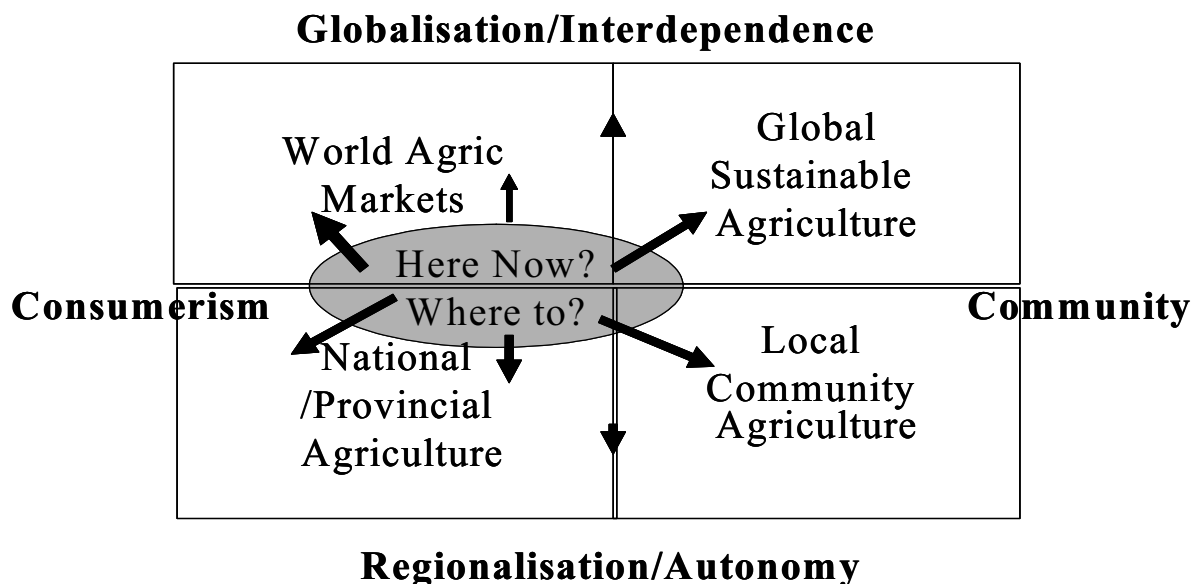
The Foresight Programme (Berkhout et al., 1998; DTI, 1999; DTI, 2002) constructed four possible futures that are distinguished in terms of social values and governance:

- **World markets** are characterised by an emphasis on private consumption and a highly developed and integrated world trading system;
- **Global sustainability** is characterised by more pronounced social and ecological values, which are evident in global institutions and trading systems. There is collective action to address social and environmental issues. Growth is slower but more equitably distributed compared to the World Markets scenario;
- **Provincial enterprise** is characterised by emphasis on private consumption but with decisions made at national and regional level to reflect local priorities and interests. Although market values dominate, this is within national/regional boundaries;
- **Local Stewardship** is characterised by strong local or regional governments that emphasise social values, encouraging self-reliance, self-sufficiency and conservation of natural resources and the environment.

The UKCIP02 study (Hulme et al., 2002a) on climate change also linked these scenarios to possible trends in greenhouse emissions and associated climate change. The climate change signals are high under World Market and Provincial Enterprise, and medium to low under Global Sustainability and Local Stewardship. The greater is the extent of climate change, the greater is the expected variation in storm intensity and the greater is the risk of flooding (although total precipitation may not vary greatly between scenarios).

### Possible futures and likely future change agricultural scenarios

The generic scenarios outlined above have been interpreted for the purpose of defining possible agricultural scenarios and these are illustrated in Figure 7.1.



**Figure 7.1 Possible agricultural futures**

The main drivers that shape agriculture under the possible futures are:

- EU agricultural environmental and regional policy (especially CAP reform);
- Trade liberalisation and the role of the WTO;
- Demand for and supply of agricultural commodities on world or national markets (as relevant) associated with population growth, economic prosperity and preferences;
- Technology development and applications;
- Priorities and interventions to deliver the required economic, social and environmental objectives.

These drivers, many of which are interconnected, combine with the political, economic and social imperatives contained within the scenario types. In turn these generate the input (such as crop prices) and output parameters (such as land use) which give the scenarios their particular distinguishing characteristics.

Drawing on this framework, it is possible to construct some of the key features of UK agriculture that might be associated with these futures. Land use (and the detail of farming systems, and the relative importance given to sustainable natural resource management and rural livelihoods) is likely to vary amongst the Scenarios and their rural sector characteristics. Flood generation in rural areas will depend on the extent to which particular futures encourage land management practices known to be associated with flood generation or abatement. Similarly, the impact of flooding in receptor areas, and the responses to flood risk, will vary according to dominant land use and management practices which are both scenario dependent.

The likely scenario-driven land use change characteristics and their associated flood generation impacts for the 2050s and 2080s are described in detail in Appendix D and are summarised as follows.

The World Markets scenario is characterised by outward-looking, internationally competitive, large-scale intensive farming. This is likely to exacerbate the risk of run-off and water soil-erosion in intensively farmed areas and catchments. It is likely, however, that arable production on marginal land will no longer be justified and some low-grade land will no longer be farmed. These changes could alleviate flood generation in some areas.

Under Global Sustainability, the market orientation of farming is moderated by a strong commitment to environmental protection, with a reinforcement of the agri-environment and compliance initiatives. Local-scale flood generation would generally reduce under this regime, and flood plains would be managed to provide natural storage.

The Provincial Enterprise scenario reflects a change to a productivist focus for agriculture with a comprehensive regime of direct subsidies for production and a high level of protection from external competition. The risk of flood generation at the farm scale is high, and the off-farm costs borne by third parties are significant.

By comparison, Local Stewardship involves relatively extensive, small scale farming, local area produce, and greater self sufficiency in food, with a high level of environmental protection and enhancement. Nature conservation, including managed wetlands, is a key feature, with farmers, encouraged by a mix of regulation and payment schemes, providing environmental services, including possibly flood storage on washlands. Flood management decisions will be made at local level.

Thus, differences in drivers and governance amongst the possible futures have implications for the generation of flooding from rural land as well as the type of policies, interventions and coping strategies that might be required to mitigate associated risks.

### **Likely responses to future change agricultural scenarios**

Likely agricultural responses to future change are very scenario dependent, as each scenario affects policy objectives and choice of instruments. In particular, the scenarios reflect different relative 'values' and the balance of priority given to agriculture and biodiversity.

Under the 'utilitarian' World Market and Provincial Enterprise scenarios, there will be increased risk of surface runoff in intensively farmed areas. Land managers will adopt measures to mitigate on-farm effects where these are deemed financially advantageous, but will not take measures to mitigate off-farm effects unless subject to regulation or economic penalties. In the World Market scenario, mainly economic instruments will be used to correct for external effects which are deemed unacceptable. Under Provincial Enterprise, agricultural research and extension services would encourage farmers to adopt voluntary soil and water conservation measures to reduce agricultural land degradation.

Under the more 'community' oriented scenarios of Global Responsibility and Local Stewardship, responses will reflect a commitment to sustainable land management practices and approaches to flood management. Under these scenarios, farming will be required (and in principle farmers will be more willing) to comply with 'good practice' to control runoff. In the Global Sustainability future this will be tied to income support. The multi-functionality of rural land management will receive more recognition under these scenarios, with attempts to integrate farming, landscape, wildlife and amenity. The risk of flood generation will be managed at catchment level in this broader context. In lowlands, water storage in floodplains will be integrated with biodiversity and water resource objectives. Under Local Stewardship the approach to the management of flood generation is fragmented, reflecting local priorities and preferences. In this respect there could be lack of integration at the large catchment scale.

Responses to pressures in coastal and estuarine zones will vary amongst scenarios in much the same way. The World Market scenario would encourage abandonment of unproductive coastal areas, whereas Provincial Enterprise

most likely would retain high levels of protection. Global Responsibility and Local Stewardship would seek integrated, potentially sustainable 'managed' solutions, the latter reflecting the particular interests of the local or regional community.



## Summary and findings

Recent analyses of extreme rainfall across the UK have revealed changes that are in line with global climate change predictions. This evidence relates to an increased frequency of seasonal (autumn/winter) rainfall events in the lower return period range in the South and Midlands. Although the qualitative assessment made here of the potential impacts of climate change on land use management and flooding is little more than indicative, there is a possibility that the emerging autumn rainfall regime seen in the 90s may be linked with the increased incidence of muddy floods. An increase in the frequency of longer duration storms may lead to an increased incidence of widespread catchment saturation. The potential impacts of the changes on catchment flood risk need to be explored in future research. In the near-term future, the main instruments that will influence future land use change are Agri-environment Schemes and CAP reforms. At present, neither of the two schemes in place, Environmentally Sensitive Areas (ESAs) and the Countryside Stewardship Scheme (CSS) explicitly target runoff management, but both have features that are likely to reduce local surface runoff. New agri-environment schemes are being proposed by Defra, one of which will have a four-tiered approach, with objectives specific to each tier. It is expected that flood alleviation objectives will be met through the adoption of particular water storage options at the field and catchment level. Under the CAP reform, the commitment is to reduce direct production subsidies and to link income support payments to compliance with standards which protect the environment, health and welfare. This changing policy framework could provide opportunities to build in general measures to reduce runoff generation as part of good agricultural practice, and more specific and targeted measures in vulnerable catchments where it can be established that such interventions would be worthwhile. A range of possible long-term futures and related agricultural scenarios have been considered, together with possible responses to the risk of flood generation under these futures. Based on the Foresight Programme, four possible futures are considered (World Markets, Global Sustainability, Provincial Enterprise, Local Stewardship) which are distinguished in terms of social values and governance. Under the World Market and Provincial Enterprise scenarios which are characterised by an emphasis on private consumption, it is concluded that land managers will only adopt measures to mitigate on-farm runoff if they are deemed financially advantageous, but will not take measures to mitigate off-farm effects unless subject to regulation and economic penalties. Under the Global Responsibility and Local Stewardship scenarios, characterised by a commitment to sustainable land management, there is a requirement to control runoff, with which farmers are generally willing to comply. In the former scenario, runoff generation will be managed at the catchment scale, while, in the latter, local preferences and priorities will restrict the possibilities of integrated strategies at the large catchment scale.

## 8. Conclusions and research recommendations

One of the main purposes of this report is to support the research plan given in the companion report: 'FD2114/PR1: Research Plan'. The purpose of the plan is to map a way forward in defining and implementing best practice in flood prevention and mitigation associated with rural land use change and management practices and for operational assessment of the likely effects of prevention and mitigation measures. The research is designed to meet the needs of those involved in policy development and catchment management and also to create a sound platform for future research and development. In designing the research plan, a wide view is taken of how decisions about flood prevention and mitigation measures will be made in the future, including how an integrated whole-catchment approach to decision making will evolve. Flood prevention and mitigation will, for example, increasingly be considered alongside other functions such as water resources planning, pollution prevention, biodiversity enhancement etc, and the effect of rural land use and management on flooding will be considered in a general context alongside river engineering, flood plain management, and other aspects of flood management.

Below, recommendations are made for how to address the deficiencies in knowledge and meet the needs for policy making and operational assessments of flood impacts. These recommendations (included here for completeness) have been copied from FD2114/PR1: Research Plan, where the conclusions from this report are considered in the context of the needs of users involved in developing policy and in operational assessments of flood impacts. There are five recommendations, each relating to one of the following five needs:

- Learn what can be learned about the flood impacts of changes in rural land use and management that have taken place in the past;
- Identify catchments vulnerable to flooding as a result of changes in rural land use and management;
- Document best practice in selecting prevention and mitigation measures to meet specific needs and in promoting these measures to land managers;
- Develop decision-support tools for estimating the likely outcomes of implementing prevention and mitigation measures and the outcomes when policies and promotions are used to encourage the uptake of measures;
- Build a solid research base to support the above needs now and in the future.

**Conclusion 1** Significant changes in land use and management practices in the last fifty years have resulted in the intensification of agricultural land use. These changes have been driven to a significant degree by EC and UK agricultural policy. There is much evidence to confirm that patterns of land use and farming practices are a direct response to the incentives provided by agricultural policy, modified by local and farm factors.

**Conclusion 2** There is substantial evidence that changes in land use and

management practices affect surface runoff generation at the local scale, but the effects are complex. Field drains, for example, may either increase or decrease the surface runoff from an event, and cultivation techniques can serve to reduce surface runoff where plough lines follow contours, or increase it where wheel tramlines run downslope.

**Conclusion 3** There is only very limited evidence that local changes in runoff are transferred to the surface water network and propagate downstream. This may be because there have been very few studies in which evidence has been sought, or because such studies (of, for example, afforestation or land drainage) have produced inconsistent or uncertain conclusions. However, in comparison with natural climatic variability, it would appear that land use management effects are of second order importance.

**Conclusion 4** Analyses of peak runoff records has so far produced very little firm evidence of catchment scale impacts of land use management. However, such analyses have not focussed on areas where changes in land cover or management practices are likely to have been greatest (other than in forested headwater catchments) and have not considered the possible effects on the storm-to-storm variability or seasonality of flooding events.

The recommendations related to these conclusions are as follows:

**Recommendation 1** There is a need to learn what can be learned about the flood impacts of changes in rural land use and management that have taken place in the past. In particular, there is a need to apply modern modelling and statistical techniques to examine existing rainfall-runoff records and isolate and quantify flood impacts. Also, there is a need for multiscale monitoring in catchments to build up the knowledge base related to how catchments function and in particular how the effects of changes in land use and management propagate downstream.

**Recommendation 2** For general use in research and in impact assessment and policy making, there is a need for an electronic map identifying the catchments that are vulnerable to local and downstream flooding as a result of changes in rural land use and management.

The following conclusions and recommendations relate to flood prevention and mitigation practices.

**Conclusion 5** There are many measures that can be taken to mitigate local flooding by delaying runoff, such as using grass buffers, temporary ponds, and appropriate ditching. An integrated approach is needed in applying these measures so that the maximum overall benefit is gained for flood and pollution mitigation and erosion reduction.

**Conclusion 6** There is considerable uncertainty about how effectively land managers will respond to any promotions or policies related to particular flood prevention or mitigation measures. There is evidence, however, to suggest that

the effectiveness can be increased if compliance with specified flood prevention and mitigation measures is used as a condition of support to farm incomes.

**Recommendation 3** There is need for field trials of flood mitigation measures, to build up the knowledge base. There is also a need for best practice to be established, both for selecting which flood prevention and mitigation measures should be used to meet local needs and how these measures should be promoted.

The next conclusions and recommendation relate to modelling the flood impacts of land use change and management practices.

**Conclusion 7** Rainfall-runoff modelling to predict the effects of changes in rural land use and management on flood generation is in its infancy: there is no generally-accepted theoretical basis for the design of a suitable model, it is not known which data have the most value, and there are limitations in the methods available for estimating the uncertainty in predictions. The modelling should be distributed and be capable of running continuous simulations. It should also be partly or wholly physically based so that the properties of local landscapes, soils and vegetation can be represented, and it should include detailed modelling of surface water flow so that the effects of changes can be tracked downstream. A considerable amount of high-quality field data on runoff generation, the local effects of change, and the way that changes propagate downstream will be needed to support the development of robust modelling and the use of this modelling in predicting flood impacts.

**Conclusion 8** The uncertainty in the response of land managers noted in Conclusion 6 needs to be accounted for when modelling the overall outcomes when flood prevention and mitigation practices are promoted.

**Recommendation 4** A coherent approach is needed in modelling the flood impacts of changes in land use and management. Ideally, this would represent socio-economic, agricultural and hydrological effects and responses. It would be in the form of a decision-support tool for estimating the likely outcome of implementing flood prevention and mitigation measures and the outcomes when policies and promotions are used to encourage the uptake of measures. The tool would take account of uncertainty, could be used to examine future scenarios for climate, land use and management, and would give a basis for rigorously testing rainfall-runoff modelling so that issues related to the theoretical basis of modelling and the value of data can be addressed.

The reviews and assessments cover several disciplines, including economics, agriculture and hydrology, and a wide range of skills from these disciplines, in both fieldwork and modelling, must be applied together if progress is to be made in understanding and representing the likely outcomes when flood prevention and mitigation measures are promoted. A further recommendation can therefore be made.

**Recommendation 5** A solid research base must be established and maintained if real progress is to be made in assessing the flood impacts of changes in rural

land use and management and in establishing best practice for flood prevention and mitigation. It is essential therefore that the research work in the research plan should be designed to leave a high-quality, useful and comprehensive legacy in the form of project reports, specification documents, datasets, open-source software, user manuals, and guidance.

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