Hydrol. Earth Syst. Sci., 11(1), 96–107, 2007
www.hydrol-earth-syst-sci.net/11/96/2007

Hydrology & Earth System Sciences

Is there a link between agricultural land-use management and flooding?

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Abstract

Over the past fifty years, significant changes in UK land use and management practices have occurred, driven by UK and EU agricultural policies. There is substantial evidence that modern land-use management practices have enhanced surface runoff generation at the local scale, frequently creating impacts through 'muddy floods'. Such local impacts can be avoided or mitigated through the adoption of better land management practices and/or small scale surface runoff control measures. There is little evidence that local scale changes in runoff generation propagate downstream to create impacts at the larger catchment scale. This does not imply that impacts do not exist, but the very few studies in which evidence has been sought have not produced any conclusive findings. Multiscale catchment experimentation, linked to new developments in modelling, is needed which can lead to a better understanding of how small scale changes to runoff generation propagate to larger catchment scales. To facilitate the tracking of changes from the local to the catchment scale, a new modelling approach is demonstrated which allows a downstream flood hydrograph to be mapped back onto its source areas, thus presenting impact information to users in a useful and comprehensible form.

Keywords: land use, land management, flooding

Introduction

When Jim McCulloch took up his duties as Head of the Hydrological Research Unit in 1964, the leading hydrological research question of the day was "Do trees use more water than grass?" In tackling this question, the Severn (forest) and Wye (grass) headwater catchments at Plynlimon were instrumented and process experimentation was used to identify the role of interception loss as a controlling factor in the catchment water balance. Underlying this key question was an important land-use policy issue: what are the consequences of large-scale afforestation of the uplands for the water yields of the affected catchments?

Over the ensuing years, the Hydrological Research Unit grew into the Institute of Hydrology to tackle a range of challenging issues, ranging from fundamental questions about process understanding to more applied hydrological prediction problems, and was widely recognised for the notable contributions made to resolving many of these issues.

One leading question which has escaped resolution is now of major concern to the UK agencies responsible for flood risk management. Tackling it presents formidable problems for catchment research, and for modelling and prediction. The question is: do spatially heterogeneous changes in local-scale runoff generation affect flooding at larger scales, and if so, how? This question is examined here, particularly for agricultural change, first by considering the physical mechanisms involved, then reviewing the evidence for local and large-scale effects and, finally, by considering the role modelling and fieldwork can play in addressing gaps in knowledge.

Before proceeding, it is necessary to clarify what is meant by the term 'impact' in this context. Flooding is generated when landscape runoff delivered to the channel network exceeds its capacity to convey 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**. The extent of floodplain inundation depends on both the peak discharge and volume of runoff associated with a flood hydrograph, so changes to the flood hydrograph provide a basis for quantifying **Impacts** associated with land use and management. 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 requires knowledge of the flood frequency curve and a damage function. The quantification of impacts in terms of flood risk lies outside the scope of this paper, and so the impacts considered here are simply effects which can contribute to flood generation.

Runoff generation and routing in changing landscapes

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 Fig. 1, and can be summarised as follows:

- accelerated loss of hedgerows and subsequent creation of larger fields;
- cultivation practices causing deeper compacted soils;
- 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;
- channelised river with no riparian buffer zone.

In this landscape, several interacting factors will have induced changes in runoff generation and its delivery to the channel network, such as the extent of soil compaction, the efficiency of land drains, and the connectivity of flow paths. A key factor is the impact that soil structure degradation (due to compaction) can have on runoff generation. By influencing the soil structural conditions that determine the inherent storage capacity within the upper soil layers, and their saturated hydraulic conductivity, land management can affect the local generation of surface and subsurface runoff significantly. 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 a result of the rapid formation of a surface crust

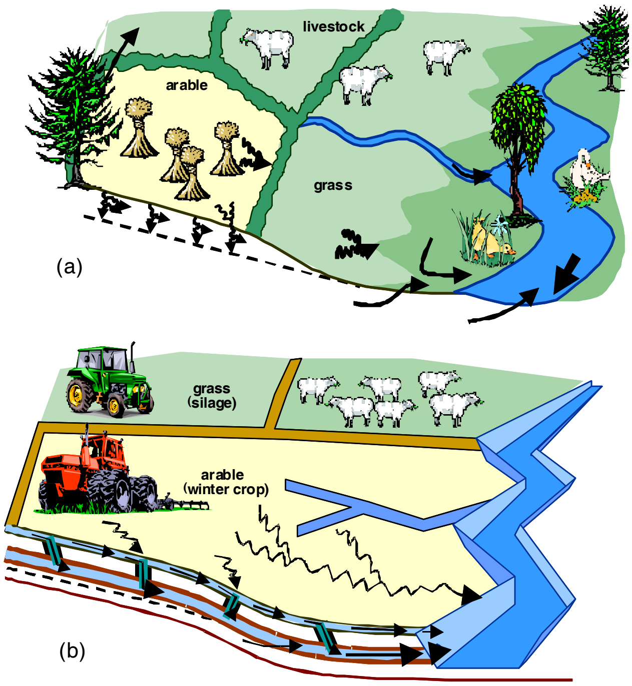

Fig. 1. *Pre-war (a) and recent (b) agricultural landscapes at the hillslope scale*

with very low moisture storage capacity and hydraulic conductivity. Practices which cause compaction at the base of a plough layer can also lead to saturation-excess surface runoff and to subsurface runoff by rapid lateral throughflow in the upper soil layers.

Apart from the soil degradation factors discussed above, 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 government subsidies ceased; many of these may have become blocked and will not function effectively. Overall, the hillslope element in Fig. 1(b) can be expected to generate more surface runoff and to deliver it more rapidly to the surface water network than that shown in Fig. 1(a). The landscape within a catchment is a complex mosaic of elements similar to those in Fig. 1, all with different responses and overlain by a range of land management practices, so the key issue is how the responses of these elements combine to generate the overall catchment response.

As runoff is routed from the local to the catchment scale, the shape of the flood hydrograph will reflect increasingly the properties of the channel network, such as its geometry, the slopes and roughnesses of individual stretches, 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 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 will depend on the spatial distribution of rainfall over the catchment.

When considering impact, therefore, the main questions are:

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?

It is possible, here, to make a pertinent observation about flood risk mitigation, based on the understanding above about mechanisms and impact. Risk is likely to be catchment specific, and dependent upon the natural catchment characteristics (topography, soils, etc.) as well as on land management practices and vulnerability to economic damage. This means that the effectiveness of mitigation measures is likely to vary from catchment to catchment.

Field evidence for impacts and mitigation

In recent years, several large floods have occurred in the UK, notably in 1996, 1998, 2000, 2004 and 2005. When such floods occur, debates arise as to the possible causal mechanisms. Soil saturation was thought to be widespread during the 2000 flooding, and this was linked with the loss of soil structure through compaction. Subsequent surveys of soils in a number of catchments did reveal some evidence of compaction (Hollis *et al*., 2003; Holman *et al*., 2003; Holman *et al*., 2001), but it was felt that a comprehensive review of the literature was needed to establish the current state of knowledge concerning any possible links between changes in land-use management practices and flooding. Consequently, a national review of the impacts of rural land use and management on flood generation was commissioned through Defra/EA R&D Project FD2114 by a consortium of experts in agriculture, soil science, hydrology, hydrogeology and socio-economic science. The summary of evidence given here is drawn mainly from the extensive review of peer-reviewed literature carried out in that project (O'Connell *et al*., 2005). This review, which considered only the literature that quantified impacts, not general observations or argued opinions, covered:

1. Field experiments, available data, models, and flood analysis and prediction methods.
2. Catchment modelling and the prediction of impacts.
3. Current state of managed land in England and Wales: arable (including cereals, oilseed rape, maize and root crops); annual feed crops; woodland; grassland; livestock; and field under-drainage.
4. Effects of current farming practices on soil structure and runoff.
5. Flood mitigation practices, including cover crops, minimum tillage, hillslope runoff control, use of machinery, retention structures and wetlands.
6. Monitoring and modelling studies (plots, fields, hillslopes and catchments).
7. Socio-economic aspects, including the response of land managers to measures and policies, categorised in terms of a Drivers-Pressure-State-Impact-Response (DPSIR) framework.
8. The future. Agri-Environmental Schemes, CAP reforms, long-term Foresight scenarios, climate change, etc.
9. Integrated runoff management at the farm scale, generating wider benefits by reducing erosion and agricultural pollution.
10. Implications for water resources.

LOCAL-SCALE IMPACTS

Local surface runoff can increase as a result of modern farm management practices such as increased stocking densities on grassland (Heathwaite *et al*., 1989; Heathwaite *et al*., 1990), the prevalence of autumn sown cereals (Sibbesen *et al*., 1994), the increase in maize crops, the production of fine seedbeds (Speirs and Frost, 1985), and trafficking on wet soils (Davies *et al*., 1973; Young and Voorhees, 1982). 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. Reduced infiltration and increased surface runoff associated with modern practices is quite widespread (Hollis *et al*., 2003; Palmer, 2002; Palmer, 2003a; Palmer, 2003b; Souchere *et al*., 1998).

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 (Armstrong and Harris, 1996; Leeds-Harrison *et al*., 1982; Robinson and Rycroft, 1999).

Enhanced surface runoff generation in consequence of some of the above modern farming practices can generate local-scale flooding. For example, long-term studies in small catchments in the South Downs of South-East England show that there is a significant relationship between the presence of autumn-sown cereal fields and local 'muddy floods' in autumn (Boardman *et al*., 2003). The frequency of these floods can be reduced by appropriate arable land management practices (Evans and Boardman, 2003), as has also been observed in France (Papy and Douyer, 1991; Souchere *et al*., 1998) and Belgium (Bielders *et al*., 2003; Verstraeten and Poesen, 1999). Moreover, Evans (1996) has found that muddy floods, and the erosion and subsequent deposition of substantial amounts of eroded soil, generate substantial economic damages each year, most of which occurs off-farm.

There is, in contrast, very little direct evidence on how such changes affect the flow in surface water networks and such evidence as is available is for small catchments, (<10 km^2). The effect of forestry is beyond the scope of this paper but, in their general review of the history of forest hydrology, McCulloch and Robinson (1993) concluded that forests should reduce flood peaks, except for the effects of pre-planting drainage and forest roads. In the Coalburn experiment, however, peak flows actually increased by 20% in the first five 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. The evidence on the effects of field drainage is also difficult to interpret. 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' flooding downstream are oversimplifications of the complex processes involved; this research found that river channel improvements had a much greater effect on peak flows than field drainage, so it is essential to distinguish between in-field drainage and downstream main channel improvements.

CATCHMENT SCALE IMPACTS

National analyses of flooding trends (Institute of Hydrology, 1999; Robson *et al*., 1998) have shown no 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. The UK Flood Estimation Handbook (FEH) (Institute of Hydrology, 1999) is based on two methods of flood estimation, the statistical approach and the rainfall–runoff approach. Regression relationships linking flood statistics (e.g. the median annual flood) or rainfall runoff method parameters (e.g. the time to peak of the unit hydrograph) with catchment characteristics did not reveal any significant relationship with land cover. However, the records used in the analysis were mainly from catchments not experiencing major land-use change (see p 234 in FEH Vol. 3), and land cover data alone cannot reflect land-use management practices.

UK river channels have also undergone substantial modifications over the past 70 years as a result of land drainage schemes and flood protection works for urban and rural floodplain areas (Newson and Robinson, 1983; Robinson, 1990; Robinson and Rycroft, 1999; Sears *et al*., 2000). Channels have been subject to a number of different modifications, depending on the circumstances, e.g. straightening, re-sectioning, embanking, culverting and the construction of weirs and sluices. More recently, there has been a move towards the restoration of channels and floodplains to their natural states and functions, as part of biodiversity and natural flood mitigation schemes. It is clear that such modifications will have changed the natural routing processes in many UK catchments and so would have to be taken into account (a formidable challenge) when assessing evidence that changes to local runoff generation processes have affected flooding at the catchment scale.

MITIGATION OF IMPACTS

Interventions can mitigate or avoid the impacts of land-use management on local flooding. Most of these interventions are aimed at source control of on-farm runoff through the use of good land-use management practices. For example, for maize cropping, particularly in free-draining loamy, silty and sandy soils, ploughing in the autumn and spring can reduce field plot runoff by between 30 and 100% compared to conventional management (Clements and Donaldson, 2002; Kwaad and Mulligen, 1991; Martyn *et al*., 2000). 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 in surface runoff using winter cover crops (Schafer, 1986) to no significant difference using under-sown rye grass or winter cover crops (Clements and Donaldson, 2002). At some sites, direct drilling or reduced cultivations can significantly reduce in-field runoff by 17% to 48% for a range of arable crops (Charman, 1985; Tullberg, 1996), and carefully targeted use of grass strips in arable systems can reduce edge-of-field runoff by 90% (Auerswald, 1998; Melville and Morgan, 2001).

Desirable management practices for mitigating field-scale runoff generation are depicted in Fig. 2. Most require careful

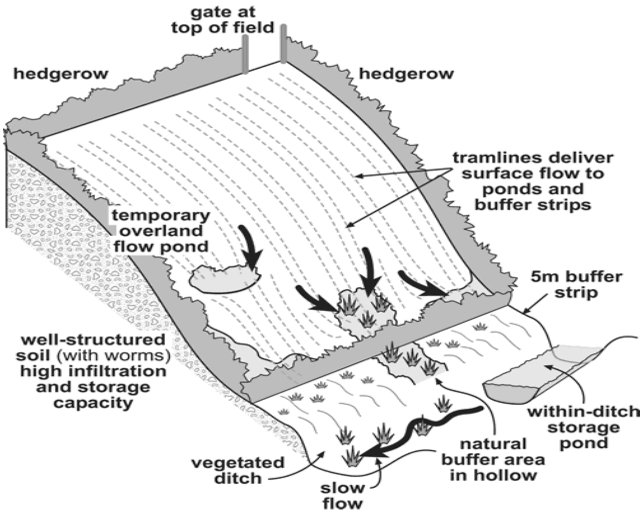

Fig. 2. *Potential for integrated runoff control to reduce flood risk, pollution and erosion*

targeting with respect to specific topographic, soil, cropping and climatic conditions. Moreover, such measures can also control nutrient pollution and sediment transport, thus generating multiple benefits for the water environment.

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).

Modelling and predicting impacts

Modelling has a role to play in encapsulating knowledge and in the decision-making process when changes are proposed. The most straightforward way to make predictions of impact is:

(1) Select an appropriate model which can represent the changes in hydrological functioning that might be associated with the proposed change in land use and management.
(2) Calibrate the model and run simulations of the catchment in its state prior to change.
(3) Alter the model's parameters to reflect the change.
(4) Run simulations using the altered parameters.
(5) Estimate the effects of the change on the discharge hydrograph, based on the differences between the runoff responses in the step 4 'changed' simulations and the step 2 'unchanged' simulations.
6. Estimate uncertainty bounds, with a stated reliability level, for the predicted effects.

There is a wide choice of model. Based on recent books and reviews (Beven, 2001; Singh and Frevert, 2002a, b; Singh and Woolhiser, 2002), well in excess of 100 rainfall–runoff models are currently being used worldwide, not counting many of the models used by soil and agriculture scientists. There are, though, serious problems with predicting impacts using models, to the extent that O'Connell *et al*. (2005) concluded that the existing models and the six-step approach above are not reliable. The problems include the well-known general problems associated with rainfall–runoff modelling (e.g. see Beven, 2001) but also particular problems related to predicting change using the six steps listed above (e.g. Ewen *et al*., 2006), and to representing the fundamental mechanisms that affect runoff generation. For example, a full understanding of the effects of the land-use management practices represented in Fig. 3 would need to consider several of the following (which is well beyond the capabilities of any current catchment rainfall-runoff model):

- 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;

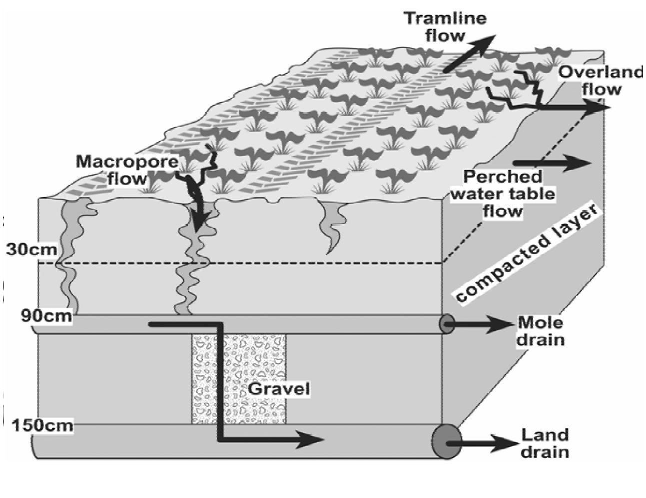

Fig. 3. *Microscale mechanisms of runoff generation*

- rainfall impact and crust formation and degradation;
- various forms of artificial drainage.

Some of the very few modelling studies of change which have been published are listed in Table 1, in approximate order of the complexity of the model used in the studies. These are mostly for changes in land cover.

Some of the studies focussed on changes to individual hydrographs. However, simulating changes to individual hydrographs, or to a time series of discharge, does not constitute a rigorous approach to the assessment of impact. This requires changes in the flood frequency curve to be simulated, as a basis for estimating changes in flood hazard and flood risk. For the studies listed in Table 1, only in Crooks and Davies (2001) was the flood frequency curve considered.

Modelling results are invariably characterised by a degree of uncertainty. These include uncertainty in the model structure and in the field measurements used to force, calibrate and validate the model. Ideally, the predictions should be in the form of narrow, accurate error bounds, giving prediction ranges that accurately reflect the combined effect of the uncertainties. In Table 1, uncertainty was considered in two studies only: Nakumar and Mein (1997), which had user-imposed errors in the forcing data, but no allowance for model structural errors; and Lukey *et al*.

Table 1. Some land-use modelling studies

Reference	*Model*	*Catchment*	*Land-use change impact study*	*Comments*
Crooks and Davies (2001)	CLASSIC	Thames at Kingston ($10,000 km^2$)	Estimated changes to the flood frequency curve for alterations in land use between 1961 and 1990. Changes found to be very small.	Macroscale model with coarse grid squares (20 km), and a simplistic soil representation.
Nakumar and Mein (1997)	HYDROLOG	Five temperate catchments in Australia (1.6- 520 ha)	Estimated the area of forest that would need to be cleared before a change in mean annual runoff could be detected in the presence of errors in precipitation and potential evaporation. For 10% underestimation of rainfall, 43% of forest would need to be cleared.	Limited representation of runoff generation mechanisms.Channel network not explicitly considered.
HR Wallingford (2001)	HBV-D	Mulde tributary of River Elbe, ($6,100 km^2$)	No clear link between land use and flooding could be found for a 10% increase in urban (or in a combination of urban, forest and grass), with a related decrease in agriculture.	Model designed for hydrological forecasting.
Fohrer *et al*. (2001)	SWATmod	Dietzholze catchment, Germany (area $82 km^2$)	Predicted changes in annual flow associated with changes in grassland area and animal husbandry.	Model derived from SWAT, which was designed for predicting monthly water yield.
Bormann *et al*. (1999)	SIMULAT / KINEROS	Neuenkirchen catchment ($16 km^2$) 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.Reduced soil cultivation reduced peak discharge by 8 to 34%.	No validation performed. Effects of land-use change represented by changes in antecedent soil moisture and surface roughness.
Niehoff *et al*. (2002)	WaSiM-ETH	Lein catchment ($115 km^2$) in south west Germany	Studied a convective and an advective rainfall event (both having return period of 2 to 3 years).If 10% of land is left bare, there is a marginal increase in runoff for the convective event and no increase for the advective event.	Details of validation not provided. Effects of land use on soil structure considered, but difficulties encountered with parameterisation.
DeRoo *et al*. (2003)	LISFLOOD	Oder catchment ($60,000 km^2$)	Peak discharges slightly increased from 1780-1995, attributed to urbanisation.	Land use for 1780 reconstructed from maps.
Lukey *et al*. (2000)	SHETRAN	Draix catchment (86 ha)	Reforestation of catchment resulted in 36% decrease in annual water yield.	Significant uncertainty in parameter estimates.

(2000), in which uncertainty in the parameter values was quantified and the output presented as an envelope of responses.

Current modelling capacity and research needs

In general, it can be concluded that the prediction models and approaches described above are not suitable for use in operational assessments of flood impact, and it is probably reasonable to say that the use of rainfall–runoff modelling to predict land-use management impacts on flooding is relatively undeveloped. In particular, neglecting for the moment problems associated with data, the following questions remain unanswered:

1. What is the most appropriate type of model for the prediction of change?
2. Which hydrological processes need to be incorporated into a model, and in how much detail?
3. Which model parameters need to be altered to reflect a change in land use and management conditions (and how can their values be specified *a priori*)?
4. How can the uncertainty in the results be quantified?
5. How can a model be validated for predicting impacts?

The plethora of hydrological models that can be found in the literature, and the lack of agreement about how to use them in prediction, is worrying, as it has contributed to a failure to provide important useful answers about the impacts of land use and management change on the flow, sediment and water quality regimes of catchments worldwide. It is also worrying because many non-hydrologists will see this failure as a reflection of the progress and health of the science of hydrology. There is a pressing need to bring some coherence and direction to hydrological modelling research and to define some proper standards which can be used to assess the fitness of a model for a particular application. Question No. 5 in the list above is, therefore, probably the one that deserves the most immediate attention.

Question 4 (uncertainty) is related to question 5 (validation), but in many regards they are independent questions. For example, the 'blind' validation method (Bathurst *et al*., 2004; Ewen and Parkin, 1996; Parkin *et al*., 1996) can be used with any uncertainty-handling method that gives uncertainty envelopes for predictions, and was specifically designed for use in problems associated with changes in land use and management and climate. The main quality required for the uncertainty-handling method is that it is robust. For example, it should not be heavily dependent on restrictive *a priori* assumptions (e.g. about error properties) that are unlikely to be fulfilled by messy real-world data. The method, therefore, does not need to be statistically elegant; the assumptions made in many formal statistical methods are frequently violated in practice, so statistical rigour does not guarantee 'fitness for purpose'. This 'blind' method is not advocated alone: there may well be better approaches. What is advocated is the development of standards for validation for change effects, and that a more pragmatic approach be taken to uncertainty-handling (at least in the short term, so that research effort is spent on hydrology, modelling and testing fitness for purpose, rather than on statistical techniques). After all, what hydrologists want to be able to tell flood risk management practitioners is that their predictions use a method that has been tested and found to be reliable, rather than saying only that their predictions use an elegant or up-to-date model or form of statistical analysis. Reliable uncertainty bounds, in this context, are simply bounds created in a way that has been repeatedly and successfully used and tested, and which is consistent with the problem of predicting the impacts of land use and management change. The testing can, for example, involve checking that the bounds comply with the stated non-exceedence level, e.g. that they are correct 90% of the time, and will normally require 'new' response (validation) data which were not used when the bounds were created. In the 'blind' validation method, the validation data are not seen by the modellers until after they have created their bounds, and so the modellers work 'blind'. The underlying logic is that if modellers can simulate historically observed responses reliably when forced to work 'blind', then they are probably well equipped to predict future responses, including the future effects of changes in land use and management.

Towards understanding and predicting hydrological response as a function of scale

The review has established that there is substantial evidence in the UK of increased surface runoff generation resulting from modern land-use management practices, and evidence that such enhanced surface runoff generation and local scale flooding can be mitigated or avoided by a range of source runoff control measures. This answers the first and third questions raised earlier in this paper. It is not possible, however, to answer the second question: 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? This will require an understanding of how the hydrological response changes with scale, and how runoff aggregates and propagates through the river channel network, moderated by processes which affect flood generation at larger scales, such as exchanges with groundwater, flow through confluences with higher order streams, and flood plain inundation. New multiscale monitoring and modelling are both necessary if scientific evidence is to be assembled to address this pressing question. It is pressing because decisions concerning the mitigating potential of source runoff-control measures are being made now, and there is a strong desire among those organisations who favour 'natural' interventions in the landscape, to replace more traditional flood defence measures, such as channel re-alignment and embankments, with more natural control measures, some of which can be implemented at source.

The importance of understanding scale effects, particularly the need to understand the factors controlling the variability in response both within and between catchments, was recognised in 1998 when a consortium of universities and research institutes was formed to develop the Catchment Hydrology And Sustainable Management (CHASM) programme of integrated multiscale experimentation, modelling and prediction.

In CHASM, the instrumentation of mesoscale catchments (~100 km^2) was given high priority (historically, this is a neglected scale in hydrological field research), and hydrological response is being monitored across a range of increasing scales, from the hillslope to the mesoscale. Funding of £2M was obtained from the Natural Environment Research Council under the JIF (Joint Infrastructure Fund) initiative to instrument four mesoscale catchments (Fig. 4). The catchments were selected to take advantage of existing instrumentation associated with previous small-scale catchment experiments, including the Plynlimon and Coalburn catchments, and that deployed by the UK Environment Agency.

Instrumenting mesoscale catchments is difficult and expensive, so a custom-designed approach was developed, in which mobile and permanant instrumentation is used to optimal effect. In the case of the Eden Catchment, the investigators have been particularly fortunate in capturing multiscale data for some major floods in 2004 and 2005 (Mayes *et al*., 2006); the 2005 flood inundated the city of Carlisle.

There is huge variability in processes and problems from catchment to catchment, so more field programmes of this intensity and quality will be required

TRACKING IMPACT INFORMATION THROUGH THE LANDSCAPE

It is difficult to know in which direction rainfall–runoff modelling should now proceed, given the conclusions above. One area where there are immediate opportunities is in describing the landscape in GIS systems and getting a better understanding of the development of floods by tracking flow information from the source (e.g. 50 m pixels) to the site of inundation.

Figure 5 shows the type of result that can be obtained. The runoff map shows the source area depths of runoff for the shaded area under the hydrograph peak. It can be seen that, for this storm peak, most of the water came from the central and northern parts of the catchment. This result can be explained as a combination of the effects of the spatial patterns for several variables and properties, including: rainfall, soil properties, soil wetness and the properties of the drainage network.

The model used to generate the figure could be called a

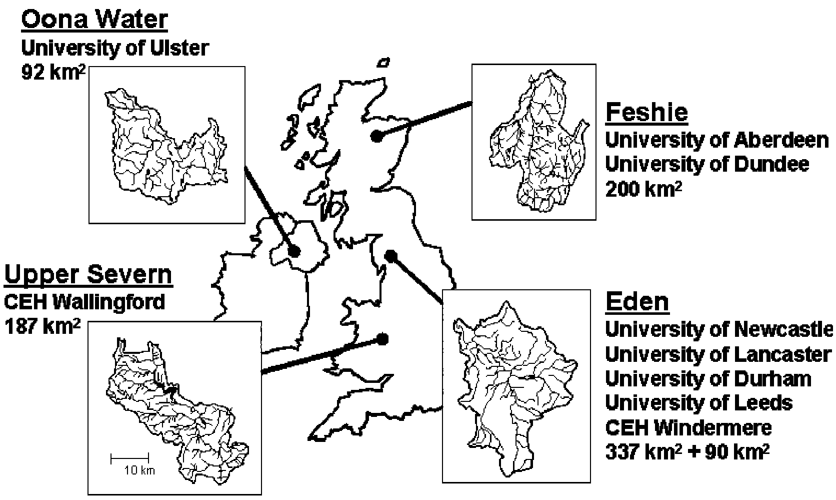

Fig. 4. *CHASM mesoscale catchments*

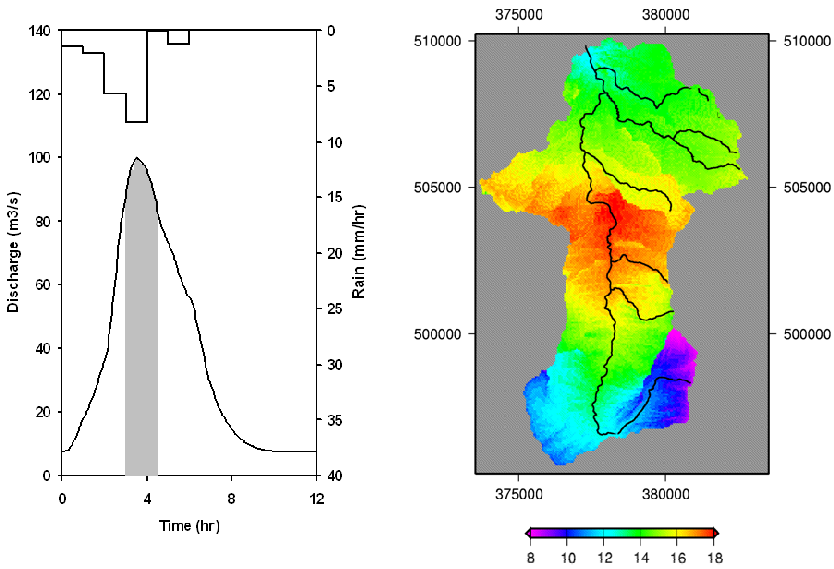

Fig. 5. *Information tracking for the River Eden at Kirby Stephen (68 km²)*

Source–Pathway–Receptor model, adopting the name sometimes used in pollution modelling. It tracks packets of water from the pixels (the source) to the site of flooding (the receptor), through the channel network, using a numerical solution for the non-inertial form of the de St Venant equations, which is designed to give accurate representation of flow at confluences. This packet model, in effect, uses a simplified form of the moving packet method, previously used to model unsaturated flow (Ewen, 2000). The further development of this method is the subject of ongoing research by the present authors.

There is a basic need for new models and approaches like this, which will allow predictions of observable space–time flood responses at multiple scales of a drainage network from fundamentally unobservable pixel-scale runoff dynamics. Many similar multi-scale problems arise in the physical, biological and social sciences (Turcotte and Rundle, 2002). For catchment hydrology, it constitutes a grand scientific challenge, many aspects of which are being addressed by the IAHS decade on 'Prediction in Ungauged Basins (PUB)' (Sivapalan *et al*., 2003)

Discussion and conclustions

In 2003, an editorial in the leading science journal *Nature* (Nature editorial, 2003) proclaimed that human activity has created an Anthropogenic Earth, and that we now lived in the Anthropocene! The main context for this assertion is global warming and its impacts, but the evidence presented in this paper demonstrates that the era of the Anthropogenic Catchment is also upon us. As a consequence, the text book descriptions of hydrological functioning, runoff generation and routing that relate primarily to 'natural catchments' may not apply to a large part of the UK landscape. In both the uplands and lowlands, a range of practices associated with intensive agriculture has altered the landscape visibly. Such anthropogenic interventions tend to generate the perception that the natural hydrological functioning of catchments has also been altered, usually adversely.

This paper has tested this perception against the available evidence, to answer the question posed in the title: is there a link between agricultural land-use management and flooding? There is field evidence that agricultural change may cause local flooding, but an almost complete lack of evidence that local-scale effects aggregate, causing impacts at larger scales downstream. Note that lack of evidence in this case does not necessary equate to a lack of effect. In theory, modelling could help fill the gaps in knowledge, but the available models, and the procedures used to validate them, have serious limitations.

There is only one way in which the necessary evidence can be generated to investigate the actual, rather than perceived, impacts, and to inform policy properly, and that is to undertake catchment experimentation. The paired catchment experiments undertaken by Jim McCulloch and colleagues in Kenya and the UK many years ago were milestones in demonstrating how to provide the evidence, and they have been replicated in many parts of the world. It is argued here that intensive multi-scale catchment monitoring programmes extending to the mesoscale, such as CHASM, are basic to the provision of sound scientific evidence for answering fundamental questions about the flood impact of changes in land-use management and for developing and testing sorely-needed methods for validating predictions when changes are proposed.

A wider, more holistic view must be taken of anthropogenic impacts in catchments, and of how to manage them. A Driver–Pressure-State-Impact-Response (DPSIR) framework for this (Turner *et al*., 1998) was adopted by O'Connell *et al*. (2005), and a programme of future research has been cast within this framework (O'Connell *et al*., 2004). Heretofore, human activity in catchments has been viewed passively in hydrological research, but there is a need to recognise and understand the drivers and pressures that create impacts from human activity and, in particular, to predict what the impacts of future changes in the drivers and pressures can be. Here a wider view needs to be taken of impacts to encompass socio-economic research. This broader view would help to anticipate future impacts resulting from changes in the drivers and pressures, and to identify the responses needed to mitigate or avoid the impacts. Indeed, this wider view is reflected in UNESCO's HELP programme (www.unesco.org/water/ihp/help <https://owa.ncl.ac.uk/exchweb/bin/redir.asp?URL=http://www.unesco.org/water/ihp/help>) which is establishing a global network of catchments to foster the integration of science with policy-making. CHASM catchments form part of this network.

Jim McCulloch's quest to unravel the complex interactions between land use and catchment hydrology is still being pursued today and catchment experimentation is part of it! As an epilogue from the first author, the development of SHE, and all that has flowed from it, could never have been achieved without his courage and support in backing such an initiative. This is but one small facet of what he has quietly achieved in his lifetime by enabling the dreams and aspirations of those who were fortunate enough to work under his guidance. The McCulloch family motto aptly describes how he did it: "By Strength and Courage".

Acknowledgements

The authors acknowledge the contributions of colleagues who worked with them on the Defra/EA FD2114 project, particularly John Hollis (NSRI, Cranfield University) who compiled the evidence for local scale agricultural impacts.

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