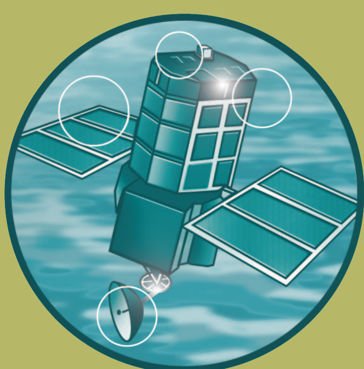
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

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

Impact study report

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

R&D Technical Report FD2114/TR



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R&D Technical Report FD2114/TR

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Produced: November 2004

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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 though 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: Runoff generation, floods, land use, land management

Research contractor: University of Newcastle upon Tyne, NE1 7RU

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www.defra.gov.uk/environ/fcd

 ISBN: 0-85521-141-5

Executive summary

This report, which constitutes Appendix A of FD2114/TR, the Impact Study Report, reviews the literature on data sources and related studies of the impacts of land use change on flood runoff generation in rural catchments. Distinguishing the effects of change are made difficult by scale effects, data uncertainties and the effects of piecemeal and gradual change at the scale of larger catchments. The difficulties of using both plot scale and catchment scale data sets to analyse the effects of changes in land management are discussed. Published studies of the effects of afforestation/deforestation, agricultural drainage, peat drainage and moorland gripping, pasture and arable land management are considered. All have been shown to have significant effects on runoff generation in some circumstances, but the effects are complex. Land drainage, for example, can both increase and decrease runoff from an event. Under wet antecedent conditions, drainage may increase the volume and velocity of runoff, but drains always serve to increase storage during periods between events that may reduce fast runoff in subsequent events. Similarly, cultivation techniques can serve to reduce surface runoff where plough lines follow contours, or increase it where wheel tramlines run downslope, while increasing infiltration and reducing surface runoff might also increase soil saturation and subsurface runoff in a series of events. Such effects have made analysis of the effects of change from the study of catchment responses difficult.

It follows that the prediction of the impacts of land use and land management effects will be subject to significant uncertainty. There are few UK studies in which a model has been applied to a catchment where change is known to have occurred and where the predictions of a model for changed conditions have been tested (either with or without an estimation of the uncertainty). There have, indeed, been very few UK studies where a model has been recalibrated for different periods of record, and the changes in the calibrated parameter values analysed. Predictions must be based on making adjustments to calibrated parameter values to account for changed conditions, but the best strategy for achieving this in the face of uncertainty is not clear.

Contents

1. Introduction

This review is limited to literature on the impacts of land use change on flood runoff generation in rural catchments, and to the identification of data sources on these impacts. In particular, it tries to assess what is known about the impacts of afforestation/deforestation; field drainage of different types; and agricultural cultivation techniques on runoff generation. Both manipulation experiments and the analysis of data from catchments subject to change are included.

In effect, every rainfall and runoff data set in the country is potentially a source of information on the impact of land use change on flood runoff production, since no catchment has been immune to land use change over historical time frames and every catchment in the country will have been subject to some form of change during the period of record. Detection of the impacts of land use change is, however, difficult; complicated by the natural variability of rainfall and weather, and by the variable, piecemeal and poorly recorded nature of change. The most important change in many catchments is that of urbanisation, which is excluded from this review but which is generally accepted as having a greater impact on catchment responses than changes in the rural landscape. Studies analysing the impacts of change in rural catchments subject to change have found that the effects can vary seasonally (e.g. Robinson and Beven, 1983), can change over time following a change and depend on patterns of rainfall within that period (e.g. Robinson, 1998; Archer and Newson, 2002) or can be difficult to distinguish at all (e.g. Hiscock et al., 2001).

The scale of land use change poses several challenges to assessing impacts. In any catchment, the impacts of different types of change will be dependent on the relative area over which they take place. On experimental catchment plots, a full 100% of the area may be subject to one particular land use strategy but the impacts will be dependent on the particular characteristics of that plot relative to other similar areas of the same scale in the same region. Larger catchment areas will integrate over a variety of plot scale characteristics but will then be subject to different local impacts taking place in different parts of the catchment. Any single type of change may then affect only a relatively small fraction of the catchment. The larger the catchment, the more variety of geology, soil and land use characteristics will be involved and the smaller the relative scale of any particular local impact will be. In addition, large catchments will be subject to routing effects, so that the effects on peak flows for example, might depend on the relative effective wave velocities with which any local impacts are propagated to the catchment outlet where measurements are made. There is also evidence of variability and long-term trends in flood producing rainfalls (Howe et al., 1967; Walsh et al., 1982; Higgs, 1987; Osborn et al., 2000) which, by nature, are sampled only relatively rarely in the record. It is therefore not surprising that it can be difficult to distinguish the impacts of change, even given long data records.

Ideally, therefore, impact studies would use multiple replicate sample study areas over a sufficient length of record that the distribution of flood producing rainfalls is adequately sampled. There are no studies that really meet these requirements. Even where multiple plots have been instrumented, there are rarely replicates (although see Clements et al., 2003) and the period of record tends to be limited. Longer-term records are available from some catchment experiments, but these cannot be easily replicated and are usually limited to monitoring a single changing catchment, or to a pair of catchments one of which is intended to serve as a control (but where the pair of catchments will also differ in terms of inputs, topography, soil and other characteristics).

Thus, making inferences about the impacts of change on flood runoff is fraught with difficulties, in particular because there may be mixed effects; afforestation in the uplands for example is often accompanied by the implementation of drainage schemes; deforestation by improvement of forest road networks; new cultivation techniques may be superimposed on old drainage schemes (some of which survive from the 19th Century (Trafford, 1970; Belding, 1971; Robinson, 1990); increased sheep densities may be associated by improved upland pasture or moorland gripping. In what follows, the information available about different types of change from field studies in the UK is considered. Some of these studies are not specifically designed to investigate the impacts of change, but rather the impact of land use on sediment production and water quality or other issues. The variety of field studies and catchment data sets is summarised in Appendix 1. The review does not include the impacts of arterial drainage on catchment scale responses, but flow routing considerations might be important in how local changes impact the peak response of a catchment area.

2. Afforestation / deforestation

All the experimental information on the effects of forest management in the UK is primarily in the uplands, though it is likely that the effects of the planned lowland afforestation will be mostly on evapotranspiration rates and low flows than on flood peak discharges.

The major studies in the uplands have been at Plynlimon and Llanbrynmair in mid-Wales (Kirby et al., 1991; Hudson et al., 1997); Balquhidder in the Grampians (Johnson and Whitehead, 1993); and Coalburn in the borders (Robinson, 1986; Robinson et al., 1998). All of these were carried out by the Institute of Hydrology (now Centre for Ecology and Hydrology) at Wallingford. The Plynlimon study was instigated as a result of the controversy about the effects of forests on water yield resulting from the earlier study of Law (1956) in the Forest of Bowland, Lancs. Law's work was one of the earliest examples in the UK of a paired catchment experiment, in that case comparing the Bottoms Beck catchment, that had been planted to forest, with the nearby (but not adjacent) Croasdale Beck that was left as pasture. His study was supplemented by a plot scale lysimeter study of surface runoff from a plot planted to conifers at Stock's reservoir, where daily runoff was measured over a period of several years.

The paired catchment approach was continued at Plynlimon (the 70% forested Severn catchment in comparison with the adjacent pasture covered Wye catchment) and at Balquhiddar (the 41% forested Kirkton catchment compared with the nearby pasture Monachyle catchment). The paired catchment approach for evaluating the impact of different land covers has been criticised in the past because of the fact that the catchments will never be identical in their geology, soil, topography and rainfall characteristics (particularly in extreme events for the latter, see for example the Newson, 1980, study of extreme events at Plynlimon) and the problem of disaggregating the effects of local variability in land use (multiple land uses, multiple ages of tree stands, drainage patterns, fertilisation, local cutting patterns etc) on the hydrology.

Llanbrynmair and Coalburn were not a paired catchment studies, though at Coalburn a number of nested discharge measurement sites were used during part of the period of study (and there are plans within the NERC funded CHASM project to instrument a nearby pasture catchment of similar size). It has been used to follow the pattern of change over a complete forest harvesting cycle, starting in 1967. Plough drainage prior to forest planting was carried out in 1972. Harvesting of the trees will start in about 2020. Discharge measurements have continued at the main gauging station to the present day and this is now the longest running experimental catchment in the UK. The Coalburn study 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 10 years (Robinson et al., 1998). This recovery was interpreted as being the result of forest growth and a decrease in the efficiency of the surface drains. Application of a physically-based model to a period prior to drainage, and to various scenarios following drainage, produced “acceptable prediction of flow” but the inclusion of drainage in the simulations resulted in underprediction of peak flows, the opposite of what was observed (Robinson et al., 1998). Increases in base-flow drainage following drainage were predicted more correctly by the model.

The results from these studies on the impact of forestry on flood runoff have been instructive. All of these studies have shown that there is a tendency for water yields from forested catchments to be less than for upland pastures. The conclusions in respect of flood runoff production, however, are somewhat less clear. In their general review of the history of forest hydrology, McCulloch and Robinson (1993) conclude that afforestation should reduce flood peaks, except for the effects of drainage and forest roads. In the Coalburn experiment, peak flows increased (20% in the first 5 years, decreasing to 10% after 10 years) and times to peak decreased after forest planting as a result of the effects of plough drainage and ditching (Robinson, 1986; Robinson et al., 1998).

3. Agricultural drainage

The question of the impacts of agricultural drainage on runoff production and flood peaks has been of interest for a considerable period of time. Nicholson (1953) reviews the discussion of a paper given at the Institution of Civil Engineers in 1861 by J. Bailey Denton in which it was suggested that underdrainage in the catchment area upstream during the preceding 20 or 30 years (1830-1860) had greatly reduced the time to peak in the Thames near Abingdon. Note that this is some 130 years before the peak of the grant-aid supported drainage schemes of the 1960s and 1970s. A recent summary of the areas affected by agricultural drainage in the UK is provided by ADAS (2003).

Nicholson (1953) concludes that field drainage should in general reduce peak flows by increasing the available storage between events. A similar conclusion was reached by Rycroft and Massey (1973) who argued that, particularly in clay soils, drainage is effective in increasing antecedent storage capacity prior to an event and reducing the likelihood of saturation causing fast runoff. They suggested that there was no evidence that under-drainage increased flooding. In essence they were arguing that the increase in antecedent storage capacities prior to an event would dominate the potential impact of increased flow velocities of runoff through drains and ditches during an event. This can only be the case, however, up to a point. The effect will be greatest in small to moderate storms. In large storms, when the antecedent storage deficit is small relative to the storm volume, the effect on runoff volume will be relatively smaller and the faster routing velocities may be important.

However, drainage schemes are implemented at the field scale. At large scales more complexities arise because of the effects of routing of the outputs from individual fields, with or without drainage, to a site at risk of flooding. The relative timing of different runoff sources to the stream channel will then be important. It could well be that a drainage scheme, by speeding up runoff from an area that before drainage had contributed water directly to the hydrograph peak, would have the effect of reducing the flood peak. Conversely, speeding up runoff from an area that prior to drainage had lagged behind the hydrograph peak, could act to increase the flood peak.

The Grendon Underwood experiment, carried out by the Institute of Hydrology (Beven, 1980; Robinson and Beven, 1993, Robinson, 1990) reveals some of these complexities. This experiment, in the River Ray catchment, Oxfordshire, was based on a pair of field plots (2500 m^2) on heavy clay Denchworth series soil and under permanent pasture. The plots had a 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.

Other experiments on drained plots have been carried out by the former ADAS Field Drainage Experimental Unit at Brooksby Hall (Trafford and Rycroft, 1973); Brimstone Farm (Cannell et al., 1984; Harris et al., 1984, 1993; Harris and Catt, 1999) and by the Institute of Grassland and Environment Research at North Wyke, Devon (Sholefield et al., 1993;

Armstrong and Garwood, 1991) (See Appendix 1). There are also a number of small rural catchment experiments where there has been significant agricultural drainage, for example at the Catchwater catchment (Tang and Ward, 1982, Robinson et al., 1985); and Rosemaund (Williams et al., 1996).

Robinson (1990) summarising the results from many different studies suggests that drainage tends to reduce peak flows from clay catchments, by increasing antecedent storage deficits, but that drainage may increase peak flows for more permeable soils. He notes that the type of drainage scheme might also be important, with moling and subsoiling giving higher peaks than pipe drains alone, and open ditches giving higher peaks than subsurface drains. Ground condition, due to both agricultural practices and cracking in heavy clay soil may also be important in controlling the responses, but in general drainage tended to modify the timing of runoff and the peak flow rather than the volume of runoff from a given storm.

4. Peat drainage and moorland gripping

There is much less 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 (1985, 1998) has 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., 1987; 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.

5. Pasture

5.1 Cattle

A major study of the effects of different types of grass management for cattle has been carried out on twelve 1 ha plots at Rowden Moor, North Wyke, Devon (see Armstrong and Garwood, 1991; Scholefield et al., 1993). The plots were in 2 blocks of six, with 2 drainage treatments (moled and undrained) being combined with three agronomic treatments (different levels of fertiliser additions, with and without reseeding). All the plots were grazed by beef cattle. The results showed that rapid subsurface drainage from the sites was dependent on the efficiency of the mole drain system. On the undrained plots the water table remained close to the surface, with generation of surface or near-surface lateral flow to the collector drains, even though infiltration capacities of the soil were generally less than the measured rainfall intensities. The drained plots, however, gave generally higher runoff peaks, even though little surface runoff was collected (Armstrong and Garwood, 1991).

5.2 Sheep

There is no doubt that the numbers and stocking densities of sheep in the British uplands has increased dramatically in the last 50 years. This increase has been encouraged by the policies of the European Common Agricultural Policy. In some parts of the country, particularly Yorkshire and Cumbria, this increase was halted by the foot and mouth disease epidemic of 2001, but restocking of many farms took place soon after the outbreak was declared over. In many areas the sheep are grazed in the open throughout the year.

Samson (1996) points to the "well documented" evidence that sheep damage the uplands by overgrazing leading to loss of heather, poaching of the soil surface, degradation of river banks, and accelerated erosion. She suggests that "sheep may be causing enough loss of vegetative cover and serious poaching of the soil surface to lead to increased runoff rates and thus to an increase in the likelihood of serious floods, such as the four major floods experienced [in the Ure and Swale catchments of the Yorkshire Dales] in the last 13 years [1982, 1986, 1991, 1995]" (p2). She notes that the 1995 flood was the highest ever recorded on both the Ure and the Swale, and that the 1986 flood was unusual in being a summer (August) event, resulting from the remains of the Hurricane Charlie storm. She also notes that at Mickley Weir on the Ure, the highest recorded floods (since 1982) have increased in [almost] chronological order and cites qualitative evidence that the time scale of spates in the Dales rivers has become much shorter. She gives more weight to the effects of sheep rather than of drainage because "the main period of drainage was earlier during the 1960s and 1970s" (p2), and calls for more investigations into whether there is a link between sheep and floods.

The analysis presented by Samson (1996) makes a reasonable case for stocking densities of sheep to have an effect on flood runoff production but is not backed up by a quantitative analysis of the occurrences of extreme rainfalls in the Dales, a full frequency analysis of the flow records, nor of other impacts such as drainage, river training etc. There are ongoing studies of upper Wharfedale at Leeds University which also suggest a significant impact of sheep on runoff production (Lane, pers. comm.) but no citable publications as yet. No controlled experimental studies of the effects of stocking densities on runoff production in the UK have been found.

6. Cultivation techniques

There are very many studies of the effects of different cultivation techniques on productivity, but relatively few have been related to runoff studies (but see some of the studies of the impacts of drainage that have included replicate plots using different cultivation techniques, such as at Rowden and at Brimstone Farm). Where there have been associated runoff studies, this has primarily been concerned with measures for controlling erosion, sediment production and associated nutrient losses. One example is the study of surface runoff under maize at North Wyke, Frithlestock and Long Ashton by Clements et al., 2003). Maize is of particular interest in this respect because, for a large part of the year, the soil surface has little or no vegetation cover. The results showed that techniques such as chisel ploughing (even where this was implemented up and down rather than across the slope) could have a very significant effect on runoff by roughening the surface and creating cracks that increase the infiltration capacity of the soil. They suggest that only part of the area might need to be treated in this way and that planting with a rye grass understory might reduce runoff and erosion further still. The difficulties of predicting the impacts of cultivation on runoff and erosion are also discussed by Burt and Slattery (1997), in relation to a field study of the River Stour in Oxfordshire.

7. Groundwater flooding

Flooding from extreme groundwater levels was a problem in the floods of both 2000 and 2002, although generally thought to be relatively rare in occurrence since it requires enhanced recharge rates over a prolonged period. Land use change that enhances infiltration to reduce surface runoff and erosion might increase the potential for local soil saturation, subsurface stormflow and groundwater flooding in a series of events if there is not a compensating increase in rates of evapotranspiration. Lowland afforestation, for example, might reduce surface runoff and increase recharge, but will also tend to increase evapotranspiration relative to arable or pasture uses (although most recharge below the root zone will tend to take place in discrete events in winter when the soil is at “field capacity” and evapotranspiration rates are low). The balance of increased infiltration to increased evapotranspiration might, however, be sensitive to small changes in soil or land use characteristics and to the sequence of rainfall events over a prolonged period. No studies have been found of the effects of land use on groundwater flooding, although the modelling studies of Crooks and Davies (2001) have looked at deterministic model responses to changing fractions of land use in different parts of the modelled Thames basin.

8. Other plot and small catchment studies

There are many other small plot and small catchment studies that have been carried out in the UK or that are ongoing, that could serve as data sources for responses for specific land uses under specific geology, soil, topography conditions. Many of these experiments have been designed with other purposes in mind (e.g. water quality rather than flood runoff production, such as at the Llyn Briane catchment experiments, e.g. Soulsby, 1995, or the C2 catchment at Plynlimon, Chapman et al., 1993; Muscatt et al., 1993) but a study of the availability and utility of such data sets would be valuable.

There have been some summaries of catchment research in the UK, listing data sets collected by a variety of Institutes, Universities and other groups (e.g. NERC, 1970; 1975, 1986; British Hydrological Society 1999). These are, however, incomplete summaries. Annual reports of the ADAS Field Drainage Experimental Unit, the Road Research Laboratory, the Institute of Hydrology and other research bodies can also provide information about ongoing plot and catchment experiments. Plot experiments have usually been designed to study one specific land use management strategy (such as the effects of improving upland pasture in the Wye catchment at Plynlimon reported by Roberts et al., 1986a,b). The smallest catchment experiments might provide information about the hydrological responses of "single" land use management strategies (e.g. the ongoing IGER/Lancaster catchment experiments at Drewston and Den Brook, near North Wyke, Devon, Haygarth et al., in prep), though even small headwater catchments can encompass a variety of (changing) land uses (e.g. the mixture of market gardening, cereals, ley pasture and permanent pasture in the 1 km^2 Slapton Wood catchment, Devon, see Roberts, 1993).

9. Making use of plot data sets

In that any catchment data sets will almost inevitably involve a variety of land uses and land management strategies, plot scale data sets which concentrate on single land uses and single land management strategies, would appear to have some advantages. The studies reviewed above show that such plot scale experiments are undoubtedly useful in understanding the hydrological responses to land management, including sediment production and water quality impacts.

There are, however, a number of difficulties in making use of plot scale data sets in predicting the impacts of change at large scales.

Each plot has its own unique characteristics, and responses of adjacent plots can be significantly different. This can make the responses of individual plots difficult to model in detail (see for example Koide and Wheater, 1992).
Each plot experiment is often set up with a particular mechanism in mind (e.g. to measure surface runoff) when other mechanisms (e.g. subsurface stormflow) might also play a role in flood runoff production.

The position of plot experiments on hillslopes might be important in controlling their response, both in respect of the boundary conditions for the plot (it can be difficult to completely isolate a field plot without major disturbance and if it not isolated then mass exchanges with the surrounding soil will be poorly characterised) and in terms of how well the plot is representative of runoff production in a larger catchment (they are often chosen on straight hillslope segments and may therefore miss the runoff production in hillslope hollows).
Extrapolation of plot results to the larger catchment requires consideration of the variability of soil and topographic characteristics and the scaling effects associated with the connectivity of plot scale units of the landscape within the catchment. In general, this will require a modelling strategy but results will be subject to poor knowledge of such variability and its effects on downslope flows e.g. the importance of percolines (Bunting, 1961) or depth to bedrock (Freer et al. 2002); the effects of roads and drains on connectivity etc

10. Making use of catchment data sets

It has already been noted that any catchment data set in the UK has the potential to provide information about the nature of changing responses to land use change. However, there are a number of difficulties in using such data sets.

- Availability of the data. There are many data sets that might have been useful in this respect that would now be difficult to access due to loss, change of storage media, staff retirements etc;
- Even when the data are available, it might also be difficult to control for quality due to loss of field notes, lack of resources in maintaining gauges, sedimentation problems etc;
- Many catchment studies only ran for a limited period of time, and may not have sampled major flood runoff producing events;
- There is a problem of interpretation of catchment data sets, even at small (1km^2 or less) scales, since the catchment area may include different land uses or management strategies;
- At any larger scales, the impacts of local change will also depend on the effects of routing through the hillslope and stream network. Increasing peak runoff locally, for example, might not increase peak runoff in an area at risk of flooding if the timing of that local peak is such that it contributes only to the rising or falling limb of the hydrograph;
- Also at larger scales, the impacts of change to the rural landscape may be obscured by the effects of urbanisation.

Analysis of the impacts of change is an interesting problem since it is possible that the changes might have both positive and negative impacts on peak flows depending on the volume of storm rainfall, and the antecedent conditions. Robinson (1990) reviews a number of studies of change at the catchment scale and presents a number of studies of catchment data (Ray, Catchwater, Llanbrynmaier) using an approach based on deriving the unit hydrograph for different periods in the available records. Robinson demonstrates changes (increases in the peak) in the unit hydrograph with increasing drainage, using the Flood Studies Report methodology to separate the storm runoff for individual storms. It is not clear whether the magnitude of the changes are within the limits of uncertainty of the analysis. At larger scales, a similar unit hydrograph analysis of the response of the River Severn was used by Gilman (2002).

A good example of the difficulties of catchment scale analysis is given by the continuing studies of the impact of forest operations in the Pacific North West. Jones and Grant (1996) attempted to deal with the potential for different types of impact by analysing changes for different classes of events. Their conclusions were, however, queried by Thomas and Megahan (1998) who, working with the same data set came to differing conclusions. The debate was continued by an exchange of comments (Jones and Grant, 2001; Thomas and

Megahan, 2001) and by the analysis of additional data sets by Bowling et al. (2000). The latter revealed both positive and negative trends in peak flows in both annual maximum and peaks-over-threshold series, but suggest that no strong conclusions could be drawn because the magnitude of the trends were generally less than a minimum detectable difference. Stronger trends were found in the residuals from predictions of a model calibrated for a constant forest cover condition. A similar type of residual analysis was used by Letcher et al. (2001), in the Macquarie Basin, Australia to examine changes in response to land use and the construction of small scale farm dams. However, neither of these studies took account of uncertainties in either modelled or observed peak discharges.

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

There have been a variety of other modelling studies that have attempted to predict the change in response due to change in land use. In general, these have been based on models calibrated to a particular catchment, followed by a comparison of predictions under calibrated and changed conditions. Example UK studies of this type include Binley et al. (1991) using the IHDM model and Dunn and Mackay (1995, 1966) using the SHETRAN model. These are both examples of “physically-based” rainfall-runoff models. The argument for using such models for these types of predictions is that the parameters will be able to reflect the characteristics of a catchment and its land use in a more direct way than more conceptual models. Thus, it should be possible to reflect changes in land use to changes in the appropriate parameter values. This argument is, however, subject to the limitations of current physically-based model structures in representing the complexity and heterogeneity of the hydrological processes in a catchment (Beven, 2000, 2001). The study of Binley et al. (1991) demonstrated how uncertainty in parameter values could be estimated during model calibration, in a way that might allow for effective parameter values to compensate for deficiencies in model structure, and how those uncertain effective parameter values might then be used in estimating responses during scenarios of model change.

11. Non-UK studies

There are a variety of other data sources that might be relevant to UK conditions. This includes, for example, the drainage plot experiments from Ballinamore, Ireland (see Robinson et al., 1987; Robinson, 1990) and from Chiemsee, Germany (see Robinson et al., 1991). Robinson and Rycroft (1999) review a variety of sources of data on drainage impacts, including non-UK sources. Bosch and Hewlett (1982) review 94 different studies from around the globe of the impact of forestry on catchment responses.

Catchment scale model predictions of the impacts of change are also being reported. Examples include Bronstert et al., 2002; Niehoff et al. (2002), Storck et al. (1998), van Rompaey et al. (2002) and Wooldridge et al. (2001). In most studies just two model runs are made: one for each land use scenario. Exceptions are Nandakumar and Mein (1997) and Eckhardt et al. (2003). Both of these studies examine uncertainty in the predictions before and after change by using Monte Carlo simulation based on prior assumptions about uncertainty in the model parameter values. No account is taken of the potential impact of model structural error in representing the flow processes.

12. Discussion

The summary table of Appendix 1 essentially reveals how little information is available from experimental studies with which to assess the impacts of different types of change in any particular location or catchment in the UK. The review above, also reveals some of the difficulties of using the information that is available for both the analysis of the impacts of change for those sites where data are available; and the extrapolation to other sites where predictions of the potential impacts of future change might be required. Both will require a modelling strategy, but all modelling strategies to date, included those that are “physically-based”, have not proven to be totally reliable in prediction of the observed responses of gauged plots and catchments, even after some calibration of parameter values. The choice of model structure is still an issue in a proper assessment of such uncertainty (see, for example, the application of different model structures to Balquhidder in Robson et al., 1993; Eeles and Blackie, 1993; and Jakeman et al., 1993).

Thus, any modelling methodology is going to be subject to significant uncertainty and one of the important issues in assessing the impact of land use change is going to be how to best estimate the major sources and magnitude of that uncertainty (Binley et al., 1991; Ewen and Parkin, 1997; Beven, 2002). This needs to be the subject of further research. It is a common assumption of deterministic modelling studies that the parameter values for changed conditions can be specified *a priori* but there are few UK studies in which a model has been applied to a catchment where change is known to have occurred and where the predictions of a model for changed conditions have been tested (either with or without an estimation of the uncertainty). There have, indeed, been very few UK studies where a model has been recalibrated for different periods of record, and the changes in the calibrated parameter values analysed.

With parameter uncertainty, the problem is more difficult: estimating a change in the value of one or more parameter values then becomes a matter of “drifting” a cloud of parameter sets representing calibrated conditions through the model space to a new (more diffuse) cloud to represent the changed conditions (Beven, 2002). This suggests that there could be a valid argument to keep the number of parameters to be changed as small as possible. The best strategy in this respect is still unclear: there is an obvious tension between using a model that represents as many aspects of the processes thought to be important as possible (and which consequently will involve many parameter dimensions), with one that represents the dominant modes of response of the catchment with only a small number of parameters (but which may be sensitive to a change in mode of response that is not adequately represented by the simpler representation). The problem of predicting the different responses of mole drained and undrained plots are a good example in this respect.

This would not be such a problem if we could be sure that the parameters of the more complex models could be estimated more easily because of the way in which the detail of individual processes is represented. This, however, is difficult because of the problem of matching measurement and model scales in heterogeneous and poorly characterised flow domains (Beven, 2000). The problems that this poses are still poorly understood but they clearly add to the uncertainties that are necessarily associated with any predictions of the impact of change.

13. Conclusions

This report has reviewed the UK data sources that might provide evidence for the effects of land use and land management on runoff generation and flooding. It is evident from the published work that the data sources are inadequate, in terms of both the number of catchments studied and, in most cases, the length of the studies, to provide firm conclusions about the general nature of such effects. The difficulties of using both plot scale and catchment scale datasets for analysing the effects of change have been discussed. Small-scale studies have shown that the effects of land management on runoff can be important, but this has not always been evident in studies at larger catchment scales. This situation is complicated by the uncertainties associated with hydrological data (in the measurements of both inputs and discharges, especially flood discharges), the expectation that the effects of change may only be significant under some hydrological conditions and not under others, and the fact that at larger scales, the effects of change will be spatially piecemeal and gradual. However, the catchment-scale analysis carried out to date has been relatively unsophisticated and more research needs to be carried out on the potential for distinguishing the effects of change for different hydrological circumstances.

Any predictions of the impacts of change will require a modelling strategy that must take account of these scale and uncertainty issues. There are few UK studies in which a model has been applied to a catchment where change is known to have occurred and where the predictions of a model for changed conditions have been tested (either with or without an estimation of the uncertainty). There have, indeed, been very few UK studies where a model has been recalibrated for different periods of record, and the changes in the calibrated parameter values analysed. Predictions must be based on making adjustments to calibrated parameter values to account for changed conditions, but the best strategy for achieving this in the face of uncertainty is not clear.

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Appendix 1: Summary of field studies

Land Use Category	Land Management Factor	Site	Soil	Drains	Period	Reference
Plot Experiments	Arable	Boxworth, Cambs 1.5 ha plots	Hanslope	Yes	89-	FDEU/ADAS
	Arable	Brimstone, Oxon 1875 m^2 plots various cultivations inc. minimum tillage winter cereals some now grass	Denchworth	Yes	78-	FDEU/ADAS Cannell et al., 1984; Harris et al., 1984, 1993; Harris and Catt, 1999
	Arable	Rickworth Arable plots	Prickwillow/ Downholland/A dventurers	Yes	93-96	FDEU/ADAS
	Arable	Drayton, Warks Arable plots	Denchworth	??	70-71 78-83 90-93	FDEU/ADAS
	Arable	Layer Breton, Essex Plots	Windsor	Pipes 22m	71-78	FDEU/ADAS
	Cereals/grass	Cockle Park, Northumberland 0.25 ha plots drained/undrained	Dunkeswick	Mole/ subslng	83-92	FDEU/ADAS Armstrong (1984), Robinson (1990)

	Maize	North Wyke, Devon 4.5*10m plots 4 tillages/5replicates	Crediton	No	1999/2001	IGER, North Wyke Clements et al., 2002
		Frithelstock 4.5*10m plots 4 tillages/3 replicates	Neath	No	2000/2001	IGER, North Wyke Clements et al. 2002
		Long Ashton RS 12*6m plots 8 tillages/2replicates	Holdnet	No	1998	IGER, North Wyke Clements et al. 2002
		Long Ashton RS 12*6m plots 4 tillages/2 rpelicates	Holdnet	No	1999	IGER, North Wyke Clements et al. 2002
	Peas	Birds Eye Walls		Yes		FDEU/ADAS
	Potatoes					
	Wheat					
	Rye					
	Barley					
	Oats					
	Mixed Corn					
	OSR					
	Autumn sown crops	Rectory Farm, Enfield Chase	Windsor	Mole/ Tile		Reid and Parkinson, 1984a,b; Reid et al., 1990
	Spring sown crops					
	Cereals/Grass rotation	Withernwick Field 2/3			74-76	Robinson, 1990
	Cereals	Withernwick Field 4			74-76	Robinson, 1990

	Field vegetables					
Horticulture	Horticultural crops					
Set-aside						
Grass	Pasture	Wytham, Oxford	?	Mole Drains		Haigh and White, 1986
	Pasture	??		Mole Drains		Haliard and Armstrong, 1992
	Pasture	??		Mole Drains		Trafford and Rycroft, 1973
Managed Grass	Sheep	Plynlimon (Severn)				CEH Wallingford Roberts et al., 1986a,b
	Dairy					
	Beef	Rowden Moor, North Wyke, Devon 1 ha plots	Hallsworth	Some plots moled and tiled		IGER North Wyke Scholefield et al., 1993; Armstrong and Garwood, 1991
	Grass	Hayes Oakes, Purton, Wilts Grass plots	[clay]	Mole	80-84	FDEU/ADAS Arrowsmith, 1983; Arrowsmith et al. 1989
Extensive Grass	Sheep	Staylittle			75-78	CEH Wallingford Newson and Robinson, 1983; Robinson, 1990
		Tylwch			75-77	Robinson, 1990
	Beef	Grendon Underwood, Bucks	Denchworth	Mole drains		CEH Wallinford Beven (1980); Robinson and Beven (1983); Robinson, 1990

	Dairy	Withernwick Field 1			74-76	Robinson, 1990
	Pigs					
Moorland/ Rough Pasture	Sheep					
Orchards						
Other Land	Open cast coal site	Butterwell old/new sites		Yes	82-86/ 91-94/ 91-95	FDEU/ADAS
	Open cast coal site	Gamblethorpe		Yes	88-91	FDEU/ADAS
	Open cast coal site	Godkin		??	94-96	FDEU/ADAS
	Open cast coal sites	Outgang		??	84-86 92-94	FDEU/ADAS
Catchment experiments	Arable	Boxworth, Cambs 40 ha catchment	Hanslope	Yes, various spacings	94-	FDEU/ADAS
	Arable	Cherwell, Oxon Drain/stream study	[clay]	Yes	98-	FDEU/ADAS
	Arable	Colworth, ?? Drain/stream study		Yes	99-	FDEU/ADAS
	Arable	Rosemaund, Hereford.	Bromyard/ Middleton/	Yes (20m)		CEH Williams et al., 1996

		176 ha Catchment with gauged subcatchments grass/cereals/mixed	Compoton		89-	
	Arable	Trent, ?? Lower Smisby Catch. 250 ha			89-	FDEU/ADAS Harris and Rose, 1992
	Cereals	Stour, Oxfordshire (6.2 km2)				Burt and Slattery, 1996
	Forest	Bottoms Beck		Forest		Law, 1956
	Forest	Plynlimon (Severn)		Forest Drains		CEH Walingford
	Forest	Coalburn		Forest drains		CEH Wallingford Robinson, 1986, 1998, Robinson and Blyth, 1982; Robinson et al., 1998, Archer and Newson, 2002.
	Forest	Balqhuiddar		Forest		Johnson and Whitehead, 1993
	Forest	Llanbrynmair		Forest drains		CEH Wallingford Robinson, 1990; Hudson et al., 1997
	Forest	Llyn Biranne				Whitehead et al., 1988; Soulsby and Reynolds, 1992; Soulsby, 1995
	Woodland	Olney, Beds	[clay]		90-92	CEH Wallingford
	Mixed	Swavesey, Cambs.	Earith /	Underdrains	90-91	FDEU/ADAS

		1 km^2	Mildeney / Denchworth	/ pumped drainage		Harris and Parish 1992
	Mixed	Severn		Forest drains		Higgs, 1987; Gilman, 2002
	Mixed	New Cliftonthorpe Notts. 90ha 50% arable/50%grass	Salop / Rivington			ADAS Withers et al., 1999
	Mixed	Jubilee, Herefords. 31ha 70%arable/30%grass	Bromyard			ADAS Withers et al., 1999
	Mixed	Slapton Wood 1 km^2, 46 km^2	Denbigh/ Manod	Single drains	70-	Burt et al., 1988 Heathwaite et al. 1990; Heathwaite and Johnes, 1996; Fisher and Beven, 1996
	Grass	Ray, Bucks		Mole Drains		CEH Wallingford Beven, 1980; Robinson and Beven, 1983; Robinson, 1990
	Grass/Arable	Catchwater Drain, Humberside		Mole/Tile drains		Tang and Ward, 1982; Robinson et al., 1985; Robinson, 1990
	Grass	Croasdale Beck				Law, 1956
	Grass	Den Brook, N. Wyke		Single Drains		IGER North Wyke Haygarth et al., in prep;
	Grass	Drewston, N Wyke				IGER, North Wyke
	Setaside Effects	Conington, Cambs 50 ha	Denchworth	??	89-94	FDEA/ADAS Williams et al., 1995

	Upland Grass	C2,Plynlimon				Chapman et al., 1993; Muscatt et al., 1993.
	Upland grass	Pwllpeiran acid grass	[acid podzol?]	??		90-92
	Upland improved pasture	Redesdale, Northumb. 90ha 90% grass/10%wood	Wilcocks	Surface	94-98	ADAS Withers et al.1999
	Blanket peat	Moor House				Robinson, 1985; Evans et al., 1999
Plot Exp. in Scotland	Upland grass	Blacklaw Moss			59-64	Robertson et al., 1968; Robinson, 1990
	Upland Grass	Allt A'Marchaidh 5 plots				Wheater et al., 1991
	Upland grass	Leadburn		Plough drains		David and Ledger, 1988

PB10493

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ISBN 0-85521-141-5

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