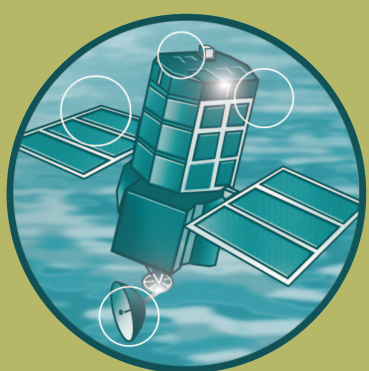
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

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

Impact study report

Appendix B: Data analysis and modelling at the catchment scale

R&D Technical Report FD2114/TR



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Appendix B: data analysis and modelling at the catchment scale

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 though specific land management practices, and those who wish to assess the impact of specific management practices on flood risk.

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Executive summary

FD2114/TR, the 'Impact study report', introduces the FD2114 project and gives a comprehensive review of the impacts of rural land use and management on flood generation. Project FD2114 is part of the Broad Scale Hydrology Modelling Programme (Calver and Wheater, 2001).

This report, which constitutes Appendix B of FD2114/TR, provides a review of (1) data analyses of catchment flow records for the identification of changes in the occurrence and magnitude of floods and (2) rainfall-runoff modelling studies assessing the impacts of land use and management practices on catchment hydrology.

The majority of the small catchment hydrological studies performed in the UK has considered the effects of afforestation/deforestation and land drainage. These studies illustrate that changes in flooding in response due to land management practices may be observed, but, due to year-to-year climatic variability, it is rarely the case that such changes can be shown to be statistically significant.

The most comprehensive statistical analysis of UK flood records for the detection of historical changes in flood magnitude and frequency was conducted as part of the Flood Estimation Handbook (Institute of Hydrology, 1999). In this study climate or land use change were not demonstrated to have changed the occurrence of flooding, 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. In addition, the majority of the catchments used in this study had not experienced major land use changes, but they may have experienced land management changes.

A number of empirical studies have been reported in the literature in which various hypotheses about land use change impacts have been made and explored using some form of data analysis. There is evidence linking autumn-sown cereal fields and local ‘muddy floods’ during the autumn in the South Downs, which is supported by studies from France and Belgium. A study on the Yorkshire Ouse catchment did not establish a significant link between land use and flooding because of data limitations and the influence of climatic variability. However, circumstantial evidence was put forward to suggest that changes in agricultural practices may have resulted in increased flood runoff.

The main conclusion from the rainfall-runoff modelling studies investigating land use and management changes on catchment hydrology was that the models used were not fit for purpose. Most of these studies have focussed on changes in land cover, since this is the most readily available indicator of land use change. Changes in land management practices within a particular land use category (e.g. arable) have received rather less attention, since these changes are rather more difficult to quantify within a rainfall-runoff model.

The basic approach taken to predicting impact has been to calibrate an existing rainfall-runoff model, then change its parameters to reflect the change in land use and management, and then to run the model with the changed parameters. However, it is not known which type of model is required for predicting impact, a problem that stems from the absence of a widely accepted hydrological theory to simulate catchment behaviour. In addition, as the predictive capabilities of the various models have not been documented, it is not known how a models parameters need to be altered to reflect a future change, and there are difficulties in quantifying the predictive uncertainty in model results.

Contents

1. Introduction

This Appendix supports the ‘FD2114/TR: Impact Study Report’, which was produced as part of the FD2114 project investigating the impacts of rural land use and management on flooding. In particular, this Appendix reviews studies in which flow records have been analysed for the detection of historical changes in the frequency and magnitude of flooding, and provides a review of the current status of rainfall-runoff modelling for predicting the impact of changes in land use and management practices on catchment hydrology. The identification of changes in flood records would aid the understanding of the effects of land use and management practices at the catchment scale, thereby helping to support policy decisions and operational methods used for assessing mitigation options. Rainfall-runoff modelling will need to be applied for estimates to be made for the change in local and downstream flooding associated farming practices and mitigation measures.

Analyses of flood records performed using statistical and empirical approaches are presented in Section 2. Statistical analyses of peak runoff records have the potential to identify changes in the nature of flooding, but not the cause. In explaining any identified change consideration must be taken of alterations to the catchment and channel properties (e.g. land use, including urbanisation, reservoirs, flood alleviation schemes) and climate change. Empirical studies that investigate the links between impacts and their perceived causes, using some form of data analysis are also reported. These studies provide circumstantial evidence, but cause effect relationships are invariably not proven.

Issues relating to the use of rainfall-runoff modelling for the prediction of the effects of changes in land use on flood generation are presented in Section 3. Firstly, background information on rainfall-runoff modelling is provided. The key modelling studies available in the literature are then summarised. Finally, model types, calibration, validation and predictive uncertainty are assessed in the context of predicting the impacts of land use and management.

2. Analyses of flood records and the occurrence of local flooding

This Section reviews analyses of data from small experimental catchments, statistical studies in which flood series have been investigated for trends and fluctuations, empirical studies in which hypotheses about land use change impacts have been explored, and analyses of the occurrence of local flooding, specifically with regard to sediment laden runoff ('muddy floods').

2.1 Analyses of small catchment experimental data

The majority of the small catchment hydrological studies performed in the UK have considered the effects of afforestation/deforestation and land drainage. The key findings from these studies are provided here. This Section supplements Appendix A, in which UK experimental studies are discussed (including those pertaining to agriculture, pasture and arable), and Appendix C, which details many agricultural studies performed at the plot and field scale.

The main focus of afforestation and deforestation experiments in the UK has been to gain a full understanding of how forests affect the water balance and, more generally, the hydrological and water quality regimes of upland catchments. The majority of these studies have been performed using a paired catchment design, in which two catchments with similar sizes, topography, soils, geology, and land use are selected. It is assumed that the two catchments will behave similarly to a given climatic event and should therefore be located in close proximity. After an initial period, in which differences in response due to local peculiarities are identified, one of the catchments is modified ('treated') and the other is left unchanged ('control'). In comparison with using of a single catchment, this approach has the major advantage that the effect of natural climatic variability can be removed.

In the UK, the major studies into the effects of afforestation have been conducted in the uplands, at Plynlimon and Llanbrynmair in mid-Wales (Hudson et al., 1997; Kirby 1991); Balquhidder in the Grampians (Johnson and Whitehead, 1993); and Coalburn in the boarders (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 paired catchment experiment at Plynlimon was established in the early 1960s to resolve the controversy created by Law's (1956) results: do upland forested catchments yield less water than grassland catchments. The experiment was located in the steep headwaters of the Severn (8.7 km^2, 70% forest), and the Wye (10.1 km^2, 100% grass) in mid-Wales. Annual precipitation in this region is high, approximately 2,400mm per year, and of low intensity. The main finding of the experiment was that the annual evaporation losses from the Severn were 200 mm greater than those from the

Wye, which represents a 15% reduction in flow. The explanations for this were:

1. The lower runoff from the forested Severn catchment compared to the grass-covered Wye was principally the result of increased interception losses from the forest. The higher interception losses are due to increased turbulence and lower aerodynamical resistance to the transport of water vapour and heat between the forest surface and the atmosphere;
2. Transpiration from the forest was typically 10% less than that from the grassland as a result of lower stomatal conductance.

These two results indicate interception losses are likely to increase with increasing vegetation height and, when soil moisture is nonlimiting, forest transpiration will be similar, but slightly less than grass. However, when soil moisture is limited, transpiration from a forest is likely to be greater than that from grass due to the deeper rooting depths. Calder (1993b) concluded, from the results of the Balquhidder experiment and other sources of UK experimental data, that forests in the wet uplands of the UK will reduce water yield irrespective of whether they replace grass or heather moorland.

The impacts of afforestation on storm runoff generation and routing in upland catchments is often difficult to decipher. In a general review of the history of forest hydrology, McCulloch and Robinson (1993) concluded that afforestation should reduce peak flows, but forest management practices (notably the introduction of drainage and forest roads) may actually cause an overall increase. Trees mitigates flooding by removing a proportion of the storm producing rainfall through canopy interception and by allowing, over periods of small rainfall events, the build up of soil moisture deficits (Calder, 1993a). However, for large storms the 'effects' of soil moisture are of less importance. The increased infiltration occurring under mature forests might be expected to lower surface runoff production for individual storms; however, rapid subsurface flow on forested hillslopes might still contribute to storm runoff hydrographs. Moreover, for large storms the ‘effects’ of soil moisture will be of less importance. In the early stages of development and planting, increases in surface runoff and a reduction in the catchment response time would be expected due to the effects of drainage ditches and forest roads on surface runoff generation and routing.

Probability plots of the annual maximum discharges for the Wye and Severn headwater catchments are shown in Figure 2.1 (expressed as discharge per unit area). From this plot, no clear evidence can be seen of a significant difference in the annual maximum discharge for the two catchments (the standard errors associated with these data are very large). Newson (1980) analysed the responses of the two catchments to two major floods and noted that, even for two small adjacent catchments, different rainstorms could account for floods of the same rank in a probability plot. This is but one aspect of the difficulty of interpreting paired catchment experiments, which have been criticised in the past because the catchments will never be identical in their rainfall, topography, soils and geological characteristics. Moreover, in describing land use, there is the problem of disaggregating the effects of local variability in land use (multiple land uses, multiple ages of tree stands, drainage patterns, fertilization, local cutting patterns etc.) on the hydrology.

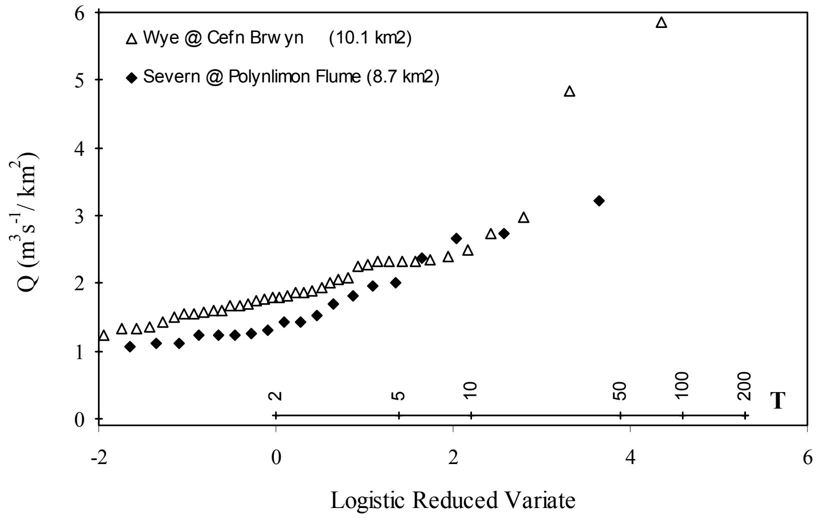

Figure 2.1 Probability of the annual maximum discharges from the Wye and Severn catchments

Robinson and Dupeyrat (2003) reported studies on the effect of logging on the annual yield, low flows and peak flows in nested catchments (~1 to 10km^2) at Plynlimon. They concluded, "*somewhat surprisingly, and in marked contrast with much of the extensive literature on the subject, there was no evidence that forest felling had a significant influence on peak flows*". They did qualify this result by saying that "*it should be noted that peak flow increases have often been attributed to soil compaction and disturbance reducing infiltration. Following modern forest management guidelines, care was generally taken during the felling to reduce soil damage and hence surface runoff by the use of brash mats*". They also reported that forest cutting increased annual flows and augmented low flows, a result that is consistent with studies reported elsewhere.

The Coalburn study, now the longest running experimental catchment in the UK, is being used to follow the pattern of change over a complete forest harvesting cycle. The catchment, located in Cumbria, has an area is 1.52 km^2, and a mean annual rainfall of 1,200mm. Monitoring started in 1967, with plough drainage performed prior to forest planting in 1972 and the harvesting of the trees is expected to start in about 2020. Robinson (1980) found that the introduction of open drainage prior to planting caused an approximate halving of the time to peak (5 to 2.2 hrs) and a 40% increase in peak flows (0.13 to 0.19 m^3/s). This was assumed to be caused by the plough drains providing impermeable surfaces and efficient flow paths for the rapid movement of surface water. A recovery to pre-drainage responses occurred after about 10 years, which was interpreted as being the result of forest growth and a decrease in the efficiency of the surface drains (Robinson et al., 1998).

Robinson (1998) also performed an analysis of the peaks over thresholds (POT; instantaneous peak flows above a selected threshold) and annual maximum (AM; the largest instantaneous flow in each hydrological year) series, which showed some evidence of an increase in the frequency of peak flows following drainage, particularly the smaller ones. The annual maximum floods increased by about 15% following drainage, but, due to the large variations between individual years, this increase was not statistically significant. Analyses of the rainfall runoff relationship using a unit hydrograph provided more statistically significant evidence of changes to the hydrological response post-drainage.

More recently, Archer and Newson (2002) have analysed the short-term flow dynamics of the Coalburn record in the context of the instream habitat impacts of upland afforestation and drainage. Using 15-minute flow data over the period 1967-98, they computed indices of flow variability based on annual number, and average and total duration of pulses (runoff events) above selected flow thresholds from which the effects of variable annual rainfall had been decoupled using regression analyses. The number of pulses increased from pre- to post drainage, but then the pulse number declined steadily and the pulse duration increased with forest growth i.e. the catchment had become more, then less 'flashy'. These results are consistent with those of Robinson (1998) and Robinson et al (1998), but demonstrate that short duration flow data may provide a valuable source of information. Archer (2003) extended this study, comparing the flow indices of the Coalburn with those for the larger River Irthing catchment (335 km^2), on which the afforested area comprised 19%. In contrast to the Coalburn, there was little evidence of change during the pre- and post drainage periods in the Irthing. However during the later forest growth period, the response of the Irthing mirrored that of the Coalburn (i.e. pulse numbers declined and pulse duration increased), but the proportional change was much smaller. Archer noted the fractional area of afforestation was much smaller in the Irthing, having a more patchwork nature and spread over a long time period, which could lead to counteracting influences. It was also noted that channel influences will be of greater importance in the larger Irthing catchment. However, this study does demonstrate the difficult in inferring a catchment scale response from a small catchment study.

The hydrological implications of performing drainage prior to conifer planting have received much attention. Davids and Ledger (1988) studied runoff generation in a peat bog in Scotland four years after it had been plough-drained for afforestation. Typically, during dry periods the runoff responses were dominated by flow generated by rain falling directly onto the ditches. Water draining into the ditches, from the strips on either side, dominated only during very wet periods. These flows consisted entirely of groundwater, and occurred at a very low rate unless the water table was within 6–7 cm of the surface. Hudson et al. (1997) quantified the hydrological effects of a land use change from moorland to forestry for a paired catchment study at

Llanbrynmair Moor in mid-Wales. Due to the disruption of the vegetation by ploughing the ground in preparation for planting the trees, actual evaporation (precipitation minus streamflow) of the treated catchment declined rapidly. The subsequent increase in evapotranspiration occurred more quickly than expected, and to greater levels than for the original moorland, since in the early stages of forest growth a dense understorey of dwarf shrubs contributed to both interception and transpiration. Calder (1993b) noted that it is difficult to generalise on the impacts of afforestation on low flows; high evaporation rates from mature, closed-canopy forest have a depressing effect on low flows, but land drainage may increase low flows in the short to medium term.

To tackle concerns about forest impacts on peak and low flows in a European context, the FOREX project (*For*estry and *Ex*treme Flows) analysed data from 28 small basins across Europe (Robinson et al., 2003). A paired catchment approach was taken, with the flow changes of the forest basins over time compared with those of benchmark or control basins. Whilst the effects of forests and forest management practices on extreme flows are often thought to be site specific, this study 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. For commercial conifer plantations on peaty soils in NW Europe it was found; (1) pre-planting forest drainage increases peak flows; (2) peak flows from a mature forest cover may be little different from unforested land; and (3) forest cutting leads to short-term increases in peak flows at the local scale, although this may not be detectable at the larger catchment scale.

The effect of forests on catchment hydrology has been a major research topic throughout the world and there are several international studies of general relevance. Bosch and Hewlett (1982) analysed the results from 94 catchments located worldwide and found a 10% change in cover caused approximately a 40 mm change in annual water yield for coniferous forests, 25 mm for deciduous forests, and 10 mm for brush or grass cover. Andréassian (2004), in a comprehensive review of results from international paired catchment experiments, summarised (a) deforestation could definitively increase both flood volumes and flood peaks, but this effect may be inverted in some years or seasons, (b) the (rare) existing studies on reforestation show a limited effect on floods in general, and no effect on the larger ones, and (c) the deforestation studies reveal the effects of exploitation rather than that of the land cover itself. Bowling et al. (2000), in an analysis of 23 paired catchments in Western Washington, US, found an apparent increase in flood peaks for treatment (greater harvest) relative to control (lesser harvest) peaks, the mean magnitude of which decreased with increasing return interval up to about the 10-year return period. However, they noted "*owing to the small number of catchment pairs available, this analysis cannot be considered conclusive*". The results of a number of recent American studies on the effects of roads and timber harvesting on hydrologic regimes are summarised in the USDA publication, "Forest Service Roads: A Synthesis of Scientific Information"

(Gucinski et al., 2000) which states: "*Collectively, these studies suggest that this effect of roads on basin stream flow is generally smaller than the effect of forest cutting, primarily because the area occupied by roads is much smaller than that occupied by harvest operations. Generally, hydrologic recovery after road building takes much longer than after forest harvest because roads modify physical hydrologic pathways but harvesting principally affects evapotranspiration processes".*

Much less is known about water losses from broadleaf trees in lowland areas, yet this is the species/mix targeted by the proposed expansion in forestry (Robinson et al., 2000). In the lowlands of the UK, water use by transpiration generally exceeds that by interception. Tree physiology exerts a strong control over transpiration rates, depending on interactions between atmospheric demand and available soil water. Since this can result in lower or higher transpiration losses when compared with shorter crops, predicting evaporation differences becomes very uncertain (Calder, 2003a). From the few studies that have been carried out in broadleaf forests, it appears in drought years the evapotranspiration losses will be greater than for shallow rooting crops (e.g. grassland and arable), resulting in lower streamflows.

2.2 Statistical analyses of Flood Records

Background

An analysis of UK flood records would seem to be the best method of determining if there has been an historical change in the occurrence of flooding. However, the detection of a change in a flood regime (non-stationary behaviour) cannot automatically be attributed to modern agricultural practices; the cause of change would still need to be identified. Potential causes of change include (a) measurement problems (e.g. changes in rating equations, reconstruction of weirs), (b) changes within the catchment (e.g. land use change, drainage diversions, reservoirs), and (c) variations in climate (e.g. climatic variability and climate change).

Non-stationary behaviour occurs in a data series if some of the underlying statistical properties change over time. A data series is said to show a trend if, on average, the series is progressively increasing or decreasing; a fluctuation if the average changes through time, but not in any consistent direction; and a step change if there is a sudden jump in the data values. Time-series analysis of flow records is usually performed using either an annual maximum (AM) series, in which the largest flood in each water year is extracted from the series, or a peak over threshold analysis (POT), in which floods larger than a threshold are extracted. If a low POT threshold is chosen (e.g. so on average three floods are selected per year: POT3) tests for changes in medium size floods can be performed, while choosing a high threshold allows tests for changes in only the largest floods.

Climate variability is the greatest hindrance in the identification of change. Inter-annual variation is caused by the mix of weather systems the UK experiences, but there is also a tendency for flood-rich years to be interspersed by series of flood-poor years. In the UK, short-term fluctuations in climate can influence records over a period of 5-20 years and therefore trends identified in short records should be treated with caution. To investigate the length of flow record needed to statistically identify a change in the presence of climatic variability, Radziejewski and Kundzewicz (2004) imposed trends on a randomly generated synthetic river flow series. It was found that statistical tests were unable to identify weak changes and changes that have not lasted long. It was concluded that the examination of data records should be a permanent exercise, as a change not yet detected may be detected in the future.

Changes can be observed but it is rarely the case that such changes can be shown to be statistically significant. An example of already cited above is the Coalburn catchment (1.5km^2) where Robinson observed a 15% increase in peak discharges after drainage; however, this range was not found to be significant in the presence of the considerable natural year to year variability in the record. Given that the change signal might be expected to be strong for such a large change affecting the whole of the catchment, this underlines the difficulty of detecting such changes in relatively short records. The difficulty in detecting a change is compounded by the gradual return of the catchment to its original hydrological state i.e. the effect of the change is transient not permanent. However, changes such as road building associated with forestry operations are more permanent, but their detection is still subject to the difficulties outlined above.

FEH Analyses of Flood Records

An extensive study to identify non-stationary behaviour in UK flood data was conducted as part of the UK Flood Estimation Handbook (Institute of Hydrology, 1999, vol. 3) study, which has recently been updated by Robson (2002) to investigate the detection of climate change. Four statistical tests were employed to establish trends and a further four were used to detect step changes in 1000 station records. Several different flood series were analysed for each station, based on annual maxima and peaks over threshold, giving up to 40 tests for each site. For many medium- to short-length records, observed trends may prove to be linked to climatic variation during the period of record. If a trend is caused by climate, it is likely that similar patterns will be seen at other sites nearby. Therefore, comparing flood data with neighbouring sites can usually indicate whether the trend is linked to climate or other causes (unless the other causes are common). Based on a comparison with the average behaviour of the surrounding region climatically adjusted site variables (AM or POT based) were obtained which were then subjected to analysis for evidence of other changes.

From an analysis of the results from the statistical tests, 104 records were identified as exhibiting possible evidence of non-stationary behaviour. Where non-stationarity was observed, there was a tendency to more frequent flood occurrences and an increase in the annual maximum flood. Further analysis indicated that climatic variability (especially in short records) and gauging problems were the most common causes of non-stationarity. There were no obvious cases of effects from drainage diversion or other land use changes, but this finding was qualified by the following observation:

"the gauged records used in the FEH are rarely located in catchments experiencing major land use change. It is therefore not very surprising that land use change effects are not evident in the FEH data, but this may well not be representative of the wider picture (Institute of Hydrology, 1999 Vol. 3, p234)".

In making the above comment, it is not clear how the author viewed land use change. However, it is likely to be based on a land cover view, rather than a wider land use and land management perspective. It is almost certain that a considerable number of the records analysed will have been for catchments affected by changes in land use management practices, but these cannot be described by land cover information only.

An additional national analysis was performed using long data records to look specifically at the question of whether climate and/or land-use changes are increasing flooding. Data records need to be considerably longer than 40 years to allow anthropogenic changes to be distinguished from climatic variability (Robson, 2002). Two main analyses were performed, the first examining records since 1940, these providing a good spatial coverage, and the second examining records since 1880, for which fewer records were available, but for which the effects of short-term climatic variability will be reduced. Figure 2.2 shows the average number of POT3 events per year and the scaled annual maxima, together with the fitted trends and locally weighted smoothing curves. The influence of longer-term climatic variability on both flood occurrence and flood magnitude is evident. From the analyses the following conclusions were drawn:

1. Whilst there are few significant trends for the period to 1980/90, the influence of climatic variation is clear. Its confounding effect means that trends associated with land use change or climate change can neither be easily identified nor readily dismissed;
2. The analyses do not show that climate change has affected UK flood behaviour. However, neither do they prove that it has not affected flood behaviour; the possibility of climate changes affecting flood response, now or in the future, cannot be eliminated and should not be disregarded;
3. Significant year-to-year fluctuations in flooding are observed. These have important consequences for both trend analyses and flood design, especially when short records are used.

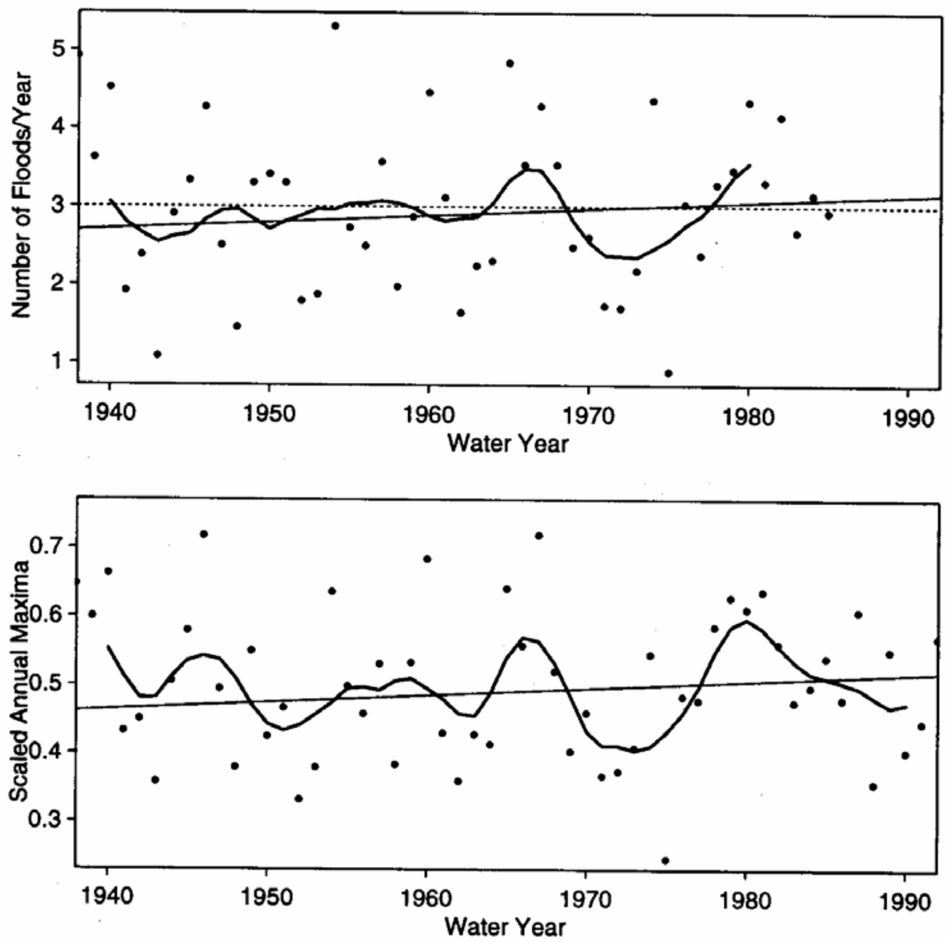

Figure 21.5 *Trends in flood occurrences and flood magnitudes since 1940. The solid line is the trend (non-significant). The upper graph shows the nationally averaged number of POT3 flood occurrences per year: the horizontal dotted line marks the average number of POT events per year for the POT3 series. The lower graph shows the nationally averaged values of the scaled annual maxima.*

Figure 2.2 Trends in flood occurrences and flood magnitudes since 1940 (Institute of Hydrology, 1999, vol. 3)

Thus in summary, the analyses of the FEH records have neither proved nor disproved that land use change has had an impact on the occurrence of flooding. The current methods used for the identification of non-stationary behaviour in runoff records cannot isolate the over-riding influence of climatic variability. Also, the analyses so far performed may have been for catchments that have not undergone major land use changes.

The FEH also contains methods for making predictions across the full frequency curve. These methods are briefly described here from the standpoint of predicting the impacts of land use and management on the flooding.

FEH statistical approach

The basis of the FEH statistical approach is that an appropriate probability distribution is used to characterise the relationship between peak discharge Q_p and its probability of exceedance. Typically, the annual maximum (AM) peak discharge 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). The theory of L-moments is 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. However, for sites where there are insufficient data and/or a flood estimate with a high return period is required, the FEH statistical approach requires a regional analysis to be conducted. This involves fitting the GL distribution to pooled regional data, standardised by an index flood. To obtain the pooled regional data, the subject site for prediction is first identified, and a homogeneous group of sites are then selected using measures of similarity based on catchment area (AREA), standard annual average rainfall (SAAR) and a soils characteristic (i.e. size-wetness-soils). The data from these sites are standardised by the index flood, which is taken to be QMED (the median annual maximum flood), and the GL distribution fitted.

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. In developing this regression, 30 explanatory variables were initially considered, representing aspects of size, wetness, soil type, slope and land use, but only AREA, SAAR, soil drainage type and storage attenuation due to reservoirs and lakes, and, where necessary, an urban adjustment factor were selected. The QMED estimate from the regression 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).

The FEH statistical approach is therefore based on the assumption that the data series are stationary over the period analysed (essentially 1940-1990). Climatic variation/change and land use changes are possible reasons why this may not be justified. Moreover, land use did not appear as significant variable in the regression of QMED on catchment characteristics, and agricultural drainage was not considered. Therefore, the FEH statistical approach cannot provide a basis for predicting the impact of land use and management on flooding.#

FEH rainfall-runoff method

The FEH rainfall-runoff method is based on the regionalisation of a rainfall depth/duration/frequency relationship, a percentage runoff (PR) equation and a triangular unit hydrograph (UH). 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 which 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.

The development and implementation of a procedure for predicting the impacts of land use and management on flooding within the FEH rainfall-runoff method is detailed in the FD2114 reports C1 and C2. This procedure involves the assessment of land use and management practices on the parameters T_p and SPR, from which the potential impacts on flood estimates can be derived. It should be noted that this is only intended as a short term improvement, and a longer term solution is required.

2.2 Empirical rainfall-runoff analyses

This section details a number of empirical studies in which various hypotheses about land use change impacts have been made and explored using some form of data analysis.

River Ouse, York

Lane (2003) observed, from a visual POT analysis of stage heights, that since the 1940s, floods at York have become more frequent and that there has also been an increase in the largest annual flood since 1900. In contrast, Robson (2002) found no statistical trend in the POT series for the River Ouse. Lane investigated three possible explanations for the apparent change in flooding at York:

1. A decrease in river conveyance, resulting in higher water levels for a given discharge. This would explain the apparent discrepancy with the findings of Robson (2002), i.e. the higher observed water levels were not associated with increased discharge;
2. A change in annual or seasonal rainfall patterns;
3. Changes in land use and management. In the upper parts of the catchment, which are predominantly moorland and pasture, land drains were introduced between 1944 and 1968, and stock densities have

increased since 1982. In the lower parts of the catchment there has been an increase in under-drainage of arable land and an increase in the cultivation of winter wheat.

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 subdaily data for the study of the intensity of individual events were not available. No firm conclusions on the role of land use and management were made, but it was stated that:

"results suggest some form of correlation between increased flood magnitude and frequency at York and landscape scale changes in land management in the upstream contributing catchments"

This view is also supported by Samson (1996), in which qualitative evidence for a link between sheep stocking densities and flooding in the upper Ouse was provided. Lane (2003) concluded that there are insufficient techniques available for the disentanglement of the land use change signal from climatic variations at the catchment scale.

River Lune, NW England

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.

2.3 Analyses of the occurrence of local flooding

Muddy flows (sediment laden runoff) are often believed to be a result of land use and agricultural practices. Boardman et al. (2003) have reported on a study of local flooding incidents resulting from muddy floods in the South Downs. This region has seen a shift in agriculture production from sheep and cattle in the pre-Second World War period to arable, which, since 1970, has been dominated by winter cereal cultivation. A case study was provided for a housing estate, constructed in 1930, for which flooding became a problem in the 1980s. The cause of the flooding was attributed to an increase in cultivation of winter cereals on the farms located upslope. With the introduction of set-aside and other measures, the flooding problem was alleviated (1993/4 to 2000).

Boardman et al. (2003) note that flooding has become a common event in the South Downs in the last few decades, with 138 incidents of damage to property by muddy runoff reported between 1976 and 2001. Almost all instances of flooding were associated with ephemeral gullies in valley floors, with most instances occurring in the wetter years between October and December, when the ground was left bare in preparation for the planting of cereals. To identify areas in the South Downs most likely to experience flooding, hazard mapping was performed. The study area was first divided into 37 small catchments (0.1 to 9.4 km^2), which were termed Elementary Catchment Areas (ECAs). A database containing 32 explanatory variables was created for the study, containing 31 flood episodes and 16 non-flood episodes over the period 1982-2000, categorised by ECA. The explanatory variables fell into three categories - geomorphology, land use and composite (based on slope/area relationships) measurements. Two regression models were created to determine, for each ECA, (1) the probability of occurrence of a muddy flood and (2) the magnitude of the predicted event. For both regressions, the composite variables had the greatest predictive power. Damage potential (vulnerability) for the ECAs was then assessed by considering the hazard in relation to the extent of flood protection measures and the locations of dwellings (e.g. valley bottom or ridge).

Evans (1996) has carried out an extensive analysis of the erosion impacts of local scale flooding. He also quantifies impacts in damage terms; this information is reviewed in Appendix D.

Similar studies to that of Boardman et al. (2003) have been carried out in recent years pertaining to the occurrence of flooding and related damage in specific regions of western Europe, e.g. the Pays, the Caux in France (Papy and Douyer, 1991), Lunburg in the Netherlands (Schouten et al., 1985), central Belgium (Verstraeten and Poesen, 1999) and the Walloon region of southern Belgium (Bielders et al., 2003).

The study of Bielders et al. (2003) is of particular interest since it involved an assessment of (1) the contribution of runoff from agricultural land to flooding and (2) farmers perceptions of runoff and erosion. A questionnaire-based survey was conducted to establish the frequency and nature of flooding within the 262 municipalities of the Walloon Region of Belgium. The floods were classified as being either ARFs (Agricultural Runoff Floods), caused by runoff from agricultural land, or VBFs (Valley Bottom Floods), resulting from the overflowing of streams or rivers. The latter type may include a contribution from agricultural runoff, but in the former case the water does not pass through a permanent river network. Eighty three per cent of the municipalities were subject to at least one flooding event over the past decade. Fifty per cent of the municipalities were affected by ARF and 67% by VBF. In the silt loam/sandy loam regions of Wallonia, 66% of the municipalities were affected by ARF or combined ARF/VBF, while, in the remainder of the Walloon Region, only 28% of the municipalities were affected by ARF. The silt loam/sandy loam soils are highly sensitive to surface sealing and erosion, and the percentage of cropland was much higher for these soils (42%) than for the remaining regions (6%). These soil regions were also characterized by a much lower occurrence of VBF compared to the remainder of the Walloon region. These results do not therefore suggest that a greater incidence of ARF or ARF/VBF results in a greater incidence of VBF flooding, and raises questions as to how the impacts of local scale ARF flooding are propagated downstream into valley floors.

The local scale factors influencing the generation of farm scale runoff were explored through a survey, in which 360 farmers responded. Only 12% of farmers had no erosion or runoff problems over the last decade. The probability of observing erosion on a farm was found, perhaps not surprisingly, to be correlated to the absolute area of cropland. More specifically, the probability was found to be positively correlated with the area of row crops and, surprisingly, the area of set-aside, but negatively correlated to the area of winter cereals. The authors speculated that set-aside was more likely to be located on unproductive steep slopes. Winter cereals provide more soil protection than row crops in the spring and summer when intense erosion causing rainfall events occur. The farmers did not remain passive when confronted by erosion; the majority took runoff and erosion control measures.

In the above studies qualitative evidence that agricultural practices can cause flooding is provided. Additionally, the studies give a preliminary indication of how vulnerability mapping could be performed, information that would be useful for the identification of suitable research sites, areas where mitigation activities may be required etc.

3. Rainfall-runoff modelling

This Section firstly provides some background material on rainfall-runoff modelling, then presents the key modelling studies involving the prediction of the hydrological impacts of land use and management change, and finally discusses issues concerning model calibration, validation and predictive uncertainty in the context of predicting change.

3.1 Models

There are a number of good texts and papers on rainfall-runoff modelling, so there is little to be gained by including a substantial amount of general review material here:

- Beven (2001b) is the standard textbook on rainfall-runoff modelling, and describes the philosophy and practice in some detail;
- Singh and Frevert (2002a) describes 23 of the most popular models for ‘small’ catchments (< 250 km2 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;
- Wheater (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.

The modelling methods used in rainfall-runoff modelling tend to be generic, rather than application specific, i.e. a model code is parameterised to reflect local conditions. Nearly all the models and methods described in the general references have the potential to be applied, in some fashion or other, to modelling the impact of rural land use and management on flood generation.

Thirteen models are listed in
Table **3.1**, 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. 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.

Conceptual	Based on qualitative descriptions of the processes thought to be controlling runoff.
Continuous	The model operates over a long period, predicting the catchment response both during and between rainfall events.
Distributed	The model inputs and landscape properties are described spatially, and state variables, such as soil moisture, vary in space.
Distribution function	Function (usually for probability or topography), which defines the (usually spatial) variation of properties in a catchment or land area.
Empirical	Based directly on measured data.
Event-based	The model simulates a single flood over a period ranging from minutes to days.
Empirical	Based directly on measured data.
Hydrological response unit	Parcel of land surface defined in terms of soil, vegetation and topographic characteristics thought to be hydrologically homogenous.
Linear store	A model component in which the output is directly proportional to the current storage value.
Lumped	The model inputs and state variables, such as soil moisture, are catchment averages, so do not vary in space.
Physically-based	The model parameters are based on small scale physics (such as hydraulic conductivities, defined in terms of Darcy's law).
Quasi-physical	Partly physically-based or some elements physically-based or some clear link to physical properties or information.
SCS-CN	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.
Semi-distributed	Lying somewhere between lumped and distributed; the spatial representation is typically based on sub-catchments.
Unit hydrograph	Storm runoff hydrograph from a unit volume of effective rainfall.

From a traditional hydrologist's perspective, success in modelling the effect of change in land use equates to success in predicting the magnitude of the resulting change in the downstream river flow rate. Here, it is assumed that flow downstream can be represented by a hydrological model incorporating an algorithm for flow routing, so engineering hydraulic models are not reviewed. Several types of routing components that are commonly used in hydrological models are described briefly below.

Advection-diffusion	Diffusion wave approximation to St. Venant equations, solved analytically (linear) or numerically (non-linear) on a grid or network.
Kinematic wave	Kinematic wave approximation to St. Venant equation.
Geomorphological Instantaneous Unit Hydrograph (GIUH)	A unit hydrograph derived from structural relationships describing the catchment geomorphology, in particular the branching structure of the channel network.
Network width function	Histogram of number of reaches in the channel network at a given distance from the outlet. Used in conjunction with advection-diffusion routing.

Model	Agric. or Hydr.	Type	Style	Runoff generation	Infiltration equation	Routing
FEH (Institute of Hydrology, 1999)	H	Percentage runoff / unit hydrograph	Lumped	Storm runoff based on HOST & other factors.	Infiltration not modelled, effective rainfall used	Unit hydrograph
EPIC (Williams, 1995)	A	Empirical lumped	Lumped	Infiltration excess (SCS)	SCS	None
PDM (Moore and Clark, 1981)	H	Conceptual probability distribution function	Lumped	Fast surface & slow subsurface drainage	Probability distribution	Exponential decay of routing storage
CLASSIC (Crooks and Davies, 2001)	H	Conceptual	Semi-distributed	Saturation excess	Conceptual stores	Network response function
ARNO (Todini, 1996)	H	Conceptual distribution function	Semi-distributed	Saturation excess & slow subsurface drainage	Probability distribution	Advection-diffusion network
TOPMODEL (Beven, 1997)	H	Quasi-physical topographic distribution function	Semi-distributed	Saturation excess, infiltration excess & groundwater exfiltration	Green-Ampt based model	Network width function (and others)
UP (Ewen, 1997)	H	Upscaled physically-based	Hydrological response units	Parameterised based on physically-based modelling	Does not explicitly define an equation, but should be physically-based	Advection-diffusion network
SWATCATCH (Hollis et al., 1996)	A	Empirical distributed	2D grid	Rapid, intermediate & base flow (HOST)	HOST based method	None
ANSWERS	A	Quasi-physical	2D grid	Infiltration excess	Modified	Stage-

(Beasley et al., 1977)		distributed		& saturation excess	version of the empirical Holtan model	discharge relationship
WaSiM-ETH (Gurtz et al., 2003)	H	Physically-based, distributed	2D grid	Infiltration excess, saturation excess & slow subsurface drainage	Green-Ampt	Muskingum
LISFLOOD (De Roo et al., 2000)	H	GIS physically-based distributed	2D GIS grid	Infiltration excess & saturation excess	Smith-Parlange equation	Kinematic wave
MIKE-SHE (Refsgaard and Storm, 1995)	H	Physically-based distributed	1D / 3D finite-difference grid	Infiltration excess, saturation excess & groundwater exfiltration	Richards equation	Uses the MIKE11 hydraulic model
SHETRAN (Ewen et al., 2000)	H	Physically-based distributed	3D finite-difference grid	Infiltration excess, saturation excess, groundwater exfiltration & subsurface drainage	Richards equation	Diffusion wave

Table 3.1 Models and classification

In the above table the models have been separated into hydrological and agricultural models. The modelling approaches of these two disciplines differ:

In terms of issues and goals, hydrologists, in general, seeks to trace the evolution of flow from the rainfall through the land and aquifers and through the river network, while specialists in agriculture and soil modelling are usually more concerned with the stability and productivity of the soil and landscape for the purpose of sustainable agronomic production.

In terms of location, hydrologists have tended to concentrate on upland natural and semi-natural catchments, seeking fundamental insights to the runoff mechanisms, while specialists in agricultural and soil modelling often work in the lowlands, studying moisture and nutrient management, the interaction of soil water with local land drains and ditches, and so forth.

In terms of scale, hydrologist try to work across scale by studying processes from the point to the catchment scale, while specialists in agricultural and soil modelling tend to focus on the point scale, supported by laboratory and plot experiments.

Both sets of specialists would claim to be able to represent each others' subjects in some way. A hydrologist can parameterise crops and land drains. Equally, point scale soil, crop and water use models can be link to catchment data to give results at the catchment scale.

Before providing details of studies in which the impacts of land use and management change on catchment hydrology were assessed, a brief review of three models is provided; the SCS method, PDM and SHETRAN. These models were chosen as they represent a range of complexities, each is a representative from a wider category of model and all have been proposed or are used for modelling the impacts of land use change on catchment hydrology.

<u>SCS</u>

The USDA developed the Soil Conservation Service (SCS) method for the estimation of direct runoff from storm rainfall in agricultural catchments. This is an event-based lumped model, which has gained popularity as it is easy to understand and use. The method has also been extended to allow it's incorporation into continuous hydrological models, including EPIC (Williams, 1995) and SWAT (Arnold et al., 1998).

The SCS method has its origins in empirical analyses of rainfall-runoff data obtained from a small number of hillslope plots and small catchments in the US (Mockus, 1949). It is usually interpreted as an infiltration excess equation, but a sufficient view of the method is that it incorporates some empirical knowledge of fast runoff generation (see Beven, 2001b for discussion of background and other interpretations of the SCS equation). The equation for runoff from an event is:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

where Q is runoff, P is rainfall, S is potential maximum storage retention and I_a is the initial abstraction (all in inches). The initial abstraction is the amount of water required for runoff to start, which, in a physical interpretation, should be dependent on interception storage, infiltration and surface storage. As can be seen from the above equation, the model has two parameters, the initial abstraction and the maximum storage retention. The SCS recommends that the initial abstraction I_a should be set to $0.2S$. This leaves a single parameter, the maximum storage potential, which is defined as:

$$S = \left(\frac{1000}{CN} - 10 \right)$$

where the dimensionless curve number CN has a value between 0, representing a catchment with unlimited storage ($Q=0$), and 100, representing an impervious surface ($Q=P-I_a$). Tables are available for relating CN to (1) hydrologic soil group, defined in terms of infiltration rate; (2) land use/treatment class, defined for various types of vegetations, crops and urban environments; and (3) surface condition, which indicates the effect of cover type on infiltration, usually estimated from plant density and residue cover. The value of CN can then be adjusted to account for the antecedent soil moisture using one of three defined classes: dry, average and wet.

The above method provides only total storm runoff, which must then be routed to provide a hydrograph. The SCS method uses a triangular unit hydrograph, in which the time to peak and the peak flow are estimated from empirical equations, derived from unpublished data collected from a large number of catchments and locations in the US (Pilgrim and Cordery, 1993).

In their definitive review of the SCS method, Ponce and Hawkins (1996) stated the advantages of the method as:

- It is simple, predictable and stable;
- It relies on one parameter, *CN*, which can be related to catchment properties;
- It is well documented, with readily available *CN* tables;
- It is well established, both within the US and other countries.

The perceived disadvantages are:

- It was developed using data from mostly small rural basins located in the Midwestern US, and local studies are required to establish *CN* values elsewhere;
- It is very sensitive to the choice of *CN*, which is often based on visual inspection, not on infiltration measurements (Smith and Eggert, 1978). Additionally, for a considerable range of rainfall values, accurate curve numbers are more important than accurate rainfall estimates.
- The method performs best in agricultural sites in which it was developed, with fair performance in rangeland areas and poor performance in forested areas.
- There is no explicit provision for the effects of spatial scale.
- The choice of the initial abstraction rate is usually fixed to 0.2S, but more research is required to identify the sensitivity of this parameter with regard to geology and climate.

In regard to disadvantage (1), it is now recognised that a single value of *CN* may not be applicable to similar conditions over the entire US (Pilgrim and Cordery, 1993), which implies that US derived *CN* values should not be used under UK conditions.

<u>Probability-Distributed Model (PDM)</u>
The PDM is a simple conceptual lumped model that attempts to represent the spatial nature of runoff generation in a simple way (Moore, 1985). The soil moisture storage capacity within a catchment may vary significantly, often being greater in the valley bottoms than on the ridges. During a rainfall event, areas with shallow soils may be expected to saturate more rapidly than areas with deep soils. Therefore, rather than using a single bucket to represent the average storage capacity of the catchment, a more realistic representation would be to use many buckets of varying sizes. In the PDM approach, a catchment is considered to consist of a very large number of soil columns, defined in terms of their storage capacities, which vary in length. If all of the columns were arranged in descending size order, with their tops at the same horizontal level, then a wedge shape would be formed, similar to that

illustrated in Figure 3.1 (left-hand side). The curvature of the wedge reflects the distribution of the different sizes of storage. In practice discrete columns are not modelled, instead the length of the stores is described using a continuous function.

In the example in Figure 3.1, the full soil columns are those with a storage capacity less than C*, and the shaded area represents the rainfall stored within the soil. Rain falling on the full columns becomes direct runoff (i.e. it cannot infiltrate) and is routed through a fast flow store (storm runoff). The columns are emptied by evapotranspiration (ET) and via drainage (recharge), which is then routed through a slow flow reservoir (baseflow).

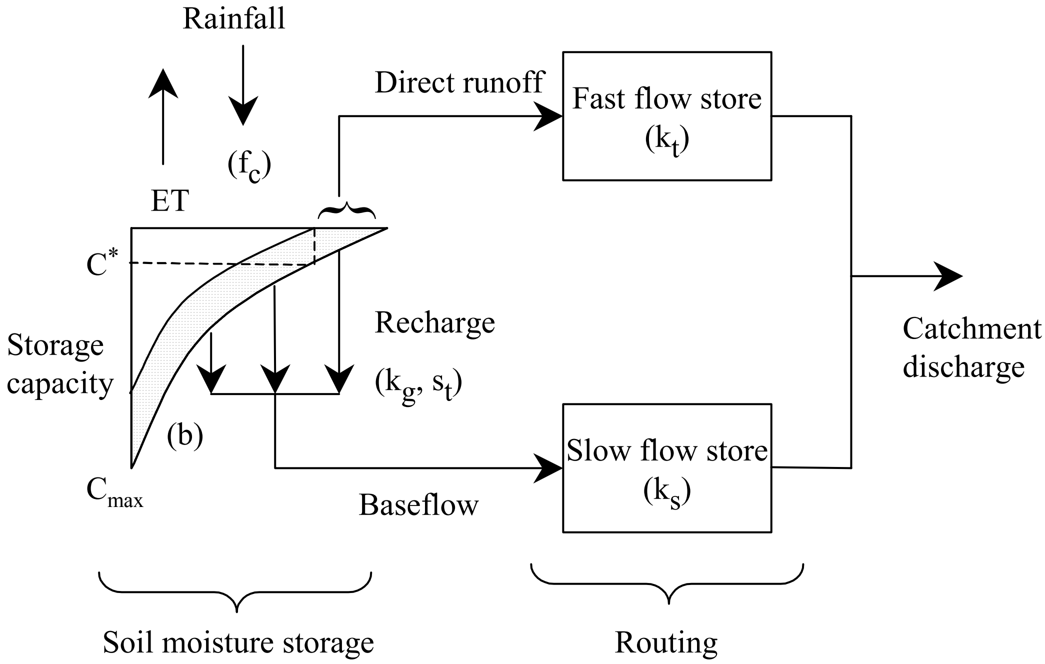

Figure 3.1 Structure of PDM (from Lamb, 1999). The model parameters are shown in parentheses.

PDM requires the specification of few parameters; one is needed to describe the storage capacity curve (i.e. the shape of the wedge), two for the recharge rate and one for each of the storages
Table **3.1**; see Lamb, 1999 for equation descriptions). A reader unfamiliar with hydrological models may be surprised to find no parameters describing soil characteristics (e.g. saturated hydraulic conductivity), vegetation types (which are accounted for externally in the estimation of ET), topography etc. However, C_{max} reflects soil storage while the shape of the storage capacity curve controls infiltration. During calibration, Moore and Clarke (1981) found this model to be capable of providing daily estimates of discharge of similar quality to that provided by a 19-parameter conceptual model.

Parameter	Description
b [-]	Controls the variability of the storage capacity (i.e. the shape of the wedge)
fc [-]	Rainfall correction factor
k_g [T]	Time constant
s_t [L]	Threshold storage, below which no drainage occurs
k_f [T]	Time constant
k_s [T]	Decay parameter

Table 3.2 Parameters of the PDM model

Distribution functions are used within many models; ARNO, which has been widely used in flood forecasting applications, uses a similar storage capacity function to PDM and the distributed TOPMODEL uses an index derived from topography to identify locations that exhibit similar hydrological behaviour. The main advantage of this approach is that nonlinearities in runoff generation can be reflected without the need to introduce a large number of parameters, which simplifies calibration and also deals with spatial variability in an implicit way.

<u>SHETRAN</u>
Physically based distributed models (PBDMs), so called because the equations are derived from physics based equations, represent the upper end of model complexity in terms of process descriptions. Much of the following description of SHETRAN is also of relevance to MIKE-SHE (Refsgaard and Storm, 1995), as both models are derived from the original Système Hydrologique Européen (SHE). The SHE was inspired by the 'blueprint' for a modelling system described by Freeze and Harlan (1969), in which it was proposed that the available good quality physically-based equations for describing water flow could be integrated to create a catchment model.

SHETRAN is a grid-based model in which the main computational structures are channel links, used to represent the river network, and columns, used to represent the catchment landscape. The hydrological processes in each column, or link, are modelled using finite difference representations of physics-based equations. A column is comprised of many stacked finite-difference cells, each of which may be associated with a different soil or rock type, characterised by hydraulic properties (porosity, saturated hydraulic conductivity, etc). Lateral transport can occur between cells in adjacent columns, allowing the representation of 3D flow processes under both unsaturated and saturated conditions. Each column is also associated with a land cover, characterised by its leaf area, resistances to evaporation, canopy height, etc. One of the strengths of SHETRAN is that the subsurface and surface are coupled, giving groundwater flows that are controlled by realistic surface saturation and infiltration, and surface conditions that are controlled by realistic groundwater levels and discharges. The main processes, associated equations and data requirements are provided in Table 3.3 (see Ewen et al., 2000 for more details). Data requirements for physically-based models are high. In normal use, SHETRAN requires data from many hard and soft sources, including weather station and river gauge records, maps of topography, geology and land use, channel surveys, soil permeametry and borehole pumping records and geophysical logs.

Process	Equation	Data
Canopy interception	Rutter model	Canopy drainage parameters and storage capacities
Evapotranspiration	Penman-Monteith	Canopy resistances and aerodynamical resistances, vegetation root density
Snowpack development and snowmelt	Accumulation equation energy budget melt equation	Snow density, zero-plane displacement height, roughness height
Storage and 3D flow in variably saturated media (including infiltration, groundwater seepage discharge, well abstractions, and combinations of confined, unconfined and perched aquifers)	Variably saturated equation	Matric potential functions, saturated hydraulic conductivity, porosity and specific storage for rocks/soils
Channel flow (and channel aquifer transfers, river augmentation and abstraction)	Saint-Venant equations, diffusion approximation	Roughness coefficients, channel cross section dimensions, elevation
Overland flow	Saint-Venant equations, diffusion approximation	Roughness coefficients, elevation

Table 3.3 Main processes and equations represented in SHETRAN

It is often argued that this class of model, in which spatially varying estimates of hydrological fluxes and storages are calculated, is necessary to predict erosion and non-point pollution transport, and also the impacts of land use and climate change. However, the complexity of these models means their application requires a significant amount of user knowledge and effort in data collection.

In the above discussion, a critique was provided only for the SCS method. The relative merits of conceptual and physically based models, of which PDM and SHETRAN are examples, have been subject to great debate in the literature; these are discussed in detail later in this report (Section 0).

3.5 Modelling studies

The key studies that have employed modelling to assess the impacts of land use and management change on catchment hydrology are summarised below. These studies are ordered in approximate increasing level of complexity in terms of the model used, and are identified by the model, the authors of the study, and the location.

In the majority of the impact studies a split-sample validation approach is performed, in which the model is firstly calibrated on one segment of the available discharge record and then tested (validated) by assessing its capability to reproduce the other segment. The models goodness of fit is typically reported as a Nash and Sutcliffe (1970) efficiency (N&S), which is based on the error variance:

$$E = \left[1 - \frac{\sum(O_i - M_i)^2}{\sum(O_i - \overline{O})^2}\right]$$

where O_i is the observed flow, M_i is the modelled flow and $\bar{O}$ is the average observed flow over the time period. A value of 1 indicates a perfect fit; a value of 0 indicates the model is no better than using the mean observed discharge for all time steps; and a negative value indicates the model performance is worse than using the mean. It is generally thought that a model capable of achieving an efficiency of greater than 0.7 provides an adequate description of the observed discharge, but this is purely subjective.

The amount of detail provided by the authors varies between the modelling studies. However, to aid comparison between studies, each description has been split into a number of sections; (1) purpose (as designated by the author), (2) the location of the application, (3) model description, (4) data requirements to set-up and run the model, (5) calibration/validation details or methodology, (6) scenario of change, and (7) the authors' conclusions.

IHACRES (Sefton and Howarth, 1998); England and Wales.

Purpose: To develop a methodology for the estimation of the model parameter values from catchment characteristics, thereby allowing the application of the model without direct calibration (e.g. for the prediction of flow in ungauged catchments). A preliminary investigation was undertaken to assess the potential for using the methodology to predict the impacts of land cover change.

Application area: Several catchments in the UK were modelled.

Model description: IHACRES is a lumped, conceptual rainfall-runoff model, in which rainfall is filtered (as a function of temperature) to produce an effective rainfall that contributes directly to stream flow. Routing is then performed using a unit hydrograph approach, with fast and slow components.

The model contains six parameters, representing streamflow recession, catchment loss and water balance characteristics.

Data requirements/set-up: For general application, rainfall and evaporation are the only data requirements; no catchment property data are needed.

Methodology: The methodology for estimating the models parameters required (1) the model to be calibrated to a number of catchments (the models parameters were termed Dynamic Response Characteristics; DRCs); (2) the selection of the bio-geophysical catchment properties that were thought to control the runoff within the selected catchments (termed Physical Catchment Descriptors; PCDs); and (3) the development of multiple regression equations to relate the catchment properties to the calibrated parameter values (DRC-PCD relationships).

In step (1), 60 catchments (<1,000km^2) in the UK were selected, each of which was thought to be watertight, and largely unaffected by abstractions, impoundment and snow. For each catchment, the model was calibrated over a 3 year period and then validated using another 6 years of data. The average of the N&S efficiencies for the 60 catchments was 0.77 during calibration and 0.69 during validation

In step (2), the chosen bio-geophysical catchment properties (PCDs) consisted of measures of topography, soils, land use and climate.
In step (3), for each DRC, statistical methods and knowledge of hydrological processes were used to identify the PCDs that had the highest explanatory power.

Validation: To assess the effectiveness of the methodology, two gauged catchments were treated as ungauged, and the parameter values for each were estimated using the DRP-PCD relationships. The results from the simulations were then compared to those obtained by direct calibration. It was found, as expected, that direct calibration produced superior results (the calibrated N&S efficiencies for the two catchments were 0.72 and 0.56), but the DRC-PCD relationships compared satisfactorily (N&S efficiencies of 0.61 and 0.53).

The authors proposed that the DRC-PCD relationships could be used in the estimation of land use change. This of course requires that the DRP-PCD regression equations include the necessary information to represent the effects of both land use and agricultural practices on key hydrological processes; only the fractional areas of upland, arable, deciduous and urban were found to be important in the selection of the PCDs. A simplistic land use scenario was conducted for a catchment in which the area of grassland (33%) was replaced by deciduous woodland, resulting in a reduction in low flows (as expected). In another scenario, the grassland was replaced by crops, which resulted in an unanticipated increase in flow volume.

Conclusions: The authors noted that a more detailed analysis of the interdependencies of the PCDs was required, and noted that the parameter representing the drying rate of the catchment did not include any climatic variables.

This study is useful, in that it provides a practical method for relating the model parameters to catchment characteristics. However, there are obvious limitations; the model is lumped so the spatial nature of change cannot be represented, it is not known if the overall model structure is adequate for the task of predicting impact and the standard errors of the coefficients used in the regression equations were very large. With regard to the last point, the authors commented, "*the relationships produced, in common with other studies of this type, are limited in terms of statistical accuracy.*" This type of approach is widely used for the estimation of flows in ungauged catchments, but usually the equations are developed over homogenous areas (usually defined in terms of climatological and/or terrain attributes) (e.g. Croke et al., 2004; Kokkonen et al., 2003; Post and Jakeman, 1996).

CLASSIC (Crooks and Davies, 2001); Thames, UK.

Purpose: To explore the effect of historical land use changes (1961-1990) on flood frequency.

Application area: Thames catchment at Kingston (area ~10,000km^2)

Model description: CLASSIC (Climate and LAnd use Scenario Simulation In Catchments) is a (grid-based) semi-distributed, daily rainfall-runoff model, developed at CEH Wallingford, to investigate the impacts of land use and climate change on flood frequency in large catchments (Reynard et al., 2001). The model incorporates three components; a soil water balance module to determine the effective rainfall (i.e. rainfall less evapotranspiration) for each grid square, accounting for the percentage of each land cover; a drainage module based on the unit hydrograph method, with two linear stores for semi-permeable areas, a single store for groundwater dominated areas and a simple urban representation for paved areas; and a channel routing module, which routes the outputs from the drainage module to the catchment outlet using a network width function that represents the spatial configuration of the drainage paths within the catchment. Multiple land covers and drainage types can be assigned to an individual grid square.

Data requirements/set-up: The model requires rainfall, potential evapotranspiration (PE) and land cover data. Soils data are not used directly; instead the response is described as being groundwater dominated, semi-permeable or urban. The model was run using a daily time step, with the catchment discretised into 20 x 20 km grid cells (42 in total).
To map 1990 land use conditions, the ITE automated classification of Land Thematic Mapper data (Fuller, 1993) was used (50m grid resolution). The available 25 land use classes were combined into six types (grassland, arable, upland, urban, coniferous and deciduous woodland). To represent land use conditions in 1961, the 1990 land use grid cell fractions were rescaled using county level land use survey data. Between 1960 and 1990, the catchment fractional area under urban development increased by almost

40%, to 18.5%, grassland increased by 24% to 34.3%, arable declined by 30% to 32.1% and woodland and upland remained reasonably constant at approximately 12% and 3% respectively. Changes in land cover in the Thames catchment over the last 120 years were also determined from a variety of sources, but were not included in the rainfall-runoff modelling.

Scenarios: To determine the impact of land use change, two 30-year simulations were performed, one using the 1961 land use data and the other the 1990.

Calibration/validation: The model was calibrated, using daily flows, over the period 1980 to 1991, with an N&S efficiency of 0.93, and validated over 1961 to 1990 with an efficiency of 0.91. It is believed that the calibration and validation were performed using the 1990 land use data set.

Conclusions: A POT analysis was used to determine the flood frequency curves for the two modelled flow series. It was found that the two flood frequency curves were similar, indicating that the impact of historical land use change on the flood frequency was small "*compared with the predominant factor controlling the generation and severity of flood events, rainfall*". The authors observed that the effects of earlier changes, particularly during the period 1939-45 when a 110% increase in arable land took place, accompanied by extensive land drainage measures, might have had a more significant effect, and that this would need to be explored.

Essentially, this is a macroscale hydrological model, which is reflected in the simplistic representations of soils and land cover types. Although each grid cell can contain multiple land cover types, the precise locations of these within the grid are not specified. Impact at a given location will be dependent not only on the changes in magnitude of upstream runoff, but also the timing. Given the imprecise specification of the land cover distribution, it is doubtful whether this model structure is capable of representing the distributed nature of change. Additionally, it is not obvious how land management practices can be incorporated into the simple soil representation. However, the prediction of a flood frequency curve is important, allowing the assessment of impact across a wide range of flows.

Dominant runoff processes, (Naef et al., 2002), Sulzbach, Gemany.

Purpose: The authors developed a decision support scheme to identify the likely dominant runoff processes (DRPs) within a given temperate catchment. It was argued by the authors that a knowledge of runoff processes could help in the identification of appropriate mitigation strategies.

Application area: The scheme was initially developed from data collected from sprinkler experiments conducted on 60 m^2 plots at a number of grassland sites in Switzerland (Scherrer and Naef, 2003) and then tested in the Sulzbach catchment, Germany (8.4 km^2).

Model description: The structure of the scheme corresponds to a soil column, comprising of vegetation, topsoil, subsoil and bedrock. Using a binary decision tree, the path of rainfall impacting at the surface is traced vertically and horizontally through the soil, taking into account the soil structure, stratification, depth, macroporosity, matrix characteristics and slope. The tree identifies the likely runoff generation mechanism (e.g. infiltration excess, saturation excess, lateral flow and vertical flow) for a given soil profile.

Data requirements/set-up: A soil classification map is required to delineate the spatial extent of the soil types within the catchment, and textural information is required to describe the soil hydraulic properties (permeability, storage capacity, texture) in each of the major soil horizons. Maps of topography, land use and geology are also required to characterise the column.

Calibration/validation: This scheme does not produce a discharge hydrograph, it only identifies the runoff generation mechanisms, and therefore validation in a traditional sense cannot be performed.

Scenarios: No scenarios of change were conducted.

Results and conclusions: For the application to the Sulzbach catchment, 24 soil profiles were analysed, and sprinkler and tracer experiments were performed at 7 sites to observe the actual infiltration behaviour. The contributions of the different runoff mechanisms to total runoff were then calculated across the catchment using the scheme. The authors stated, "*land use change can only significantly reduce flood flows in catchments where most of the runoff is generated on areas with rapid runoff production.*" It was concluded that as most of the runoff in this catchment was produced in slowly reacting areas, the potential for mitigation was low.

The approach taken is similar to the HOST system (Borman et al., 1995), which also infers hydrological response from soil properties and profiles, but HOST does not take direct account of the actual runoff generation processes. The authors argue that knowledge of processes is required for the identification of appropriate mitigation strategies. However, this is a conceptual profile/patch model, and does not quantify local runoff generation or predict a catchment hydrograph.

<u>HYDROLOG (Monash) (Nandakumar and Mein, 1997); Australia.</u>

Purpose: This study quantifies the levels of uncertainty in rainfall-runoff model predictions due to errors in hydrological and meteorological data, and considers the implications for the prediction of the hydrologic effect of land use change.

Application area: The model was applied to five temperate catchments in Australia, ranging in size from 1.6 to 150 ha.

Model description: HYDROLOG is a daily version of Monash, a semi-distributed conceptual rainfall-runoff model. Five compartments are used to represent interception, depression, soil, groundwater and channel storage. The model area is dived into a number of subcatchments, each of which must have a similar size due to limitations in the simple storage delay time function used to represent channel flow routing. The infiltration model represents the infiltration excess mechanism. There are 13 key model parameters, representing depression storage, infiltration, vegetation characteristics, groundwater recharge, soil characteristics and interflow.

Data requirements/set-up: The model requires daily rainfall, evapotranspiration and land cover data.

Calibration/validation: All of the available data were used in calibration, which was performed using an automated procedure, "*to increase the chance of exposing rarely activated processes*".

Scenarios: For the purpose of error analysis, HYDROLOG was assumed to be perfect in simulating hydrologic processes. The model was firstly calibrated to each catchment to provide a baseline against which simulations with systematic and random errors in the forcing data could be compared.

Conclusions: Accurate rainfall measurements were found to be essential; a 10% bias in rainfall resulted in a 35% bias in predicted runoff (annual yield). Potential evaporation errors had a lesser impact; a 10% bias resulted in a bias of up to 10% in predicted runoff.

The percentage of forest that needed to be removed to produce an increase in flow detectable in the presence of a 10% error in either the rainfall or evapotranspiration data was then calculated. Errors in rainfall were found to be of greater importance than those associated with evapotranspiration. The percentage of forest cover that needed to be removed to produce a detectable change at the 10% significant level was 12 to 43% for a 10% underestimate in rainfall (the sensitivity varying between the 5 selected catchments), compared to 3 to 16% for a 10% error in evapotranspiration.

The authors concluded that small changes in catchment land-use may cause changes in runoff which cannot be detected statistically from data errors.

This is one of the few land use impact studies that has attempted to tackle problems associated with uncertainty. However, no account was taken of the potential impact of model structural errors.
The model itself is not suitable for application under UK conditions; in the application to one of the catchments, the authors speculated that runoff was generated by the partial area runoff mechanism, which the model does not represent. The infiltration parameters were instead set artificially low to generate runoff by infiltration excess. Obviously, such a model will not posses the correct sensitivity for the simulation of change.

WBM and FEST98 and SHETRAN (Polytechnic of Milan, 2001), Europe.

Purpose: This study formed part of the EC-FRAMEWORK project, the aim of which was to evaluate the sensitivity of flood risk in flashy river systems to anthropogenic influences including man-induced changes to the runoff generating and propagating mechanisms and climate fluctuations. A sensitivity analysis was also performed to identify the factors controlling the flood frequency curve.

Application area: Three catchments were simulated, the Murg in Switzerland (8 km^2), the Modau in Germany (204 km^2) and Bisagno in Italy (92 km^2). Results from the Bisagno are not given here as the effects of land use change were not quantified.

Model description: This study used the WBM, FEST98 and SHETRAN models. WBM is a spatially distributed catchment model, with the capability of representing reservoirs and urban systems, based on empirical and conceptual modules (Lempert and Ostrowski, 1997). Within each grid element vertical moisture fluxes are calculated, and routing performed using a cascade of linear reservoirs. FEST98 combines conceptual and physically-based methods within a spatially distributed approach based on topography (Rulli and Rosso, 2002). There are two major modules, the first identifies the river network from topography, and the second provides the hydrological computation for each cell. The SCS method is used to calculate the effective rainfall, which is routed using a dynamic wave approximation. SHETRAN has been described in Section 0. A stochastic rainfall generator was linked to the models to allow the simulation of the impacts of land use changes on the flood frequency curve.

Data requirements/set-up: FEST98 and WBM require a DEM, a land cover map and a soil map. SHETRAN requirements are summarised in Section 0.

Calibration/validation: A wide variety of measures were used to test the models goodness of fit including coefficient of correlation and mass balance error. The reported N&S efficiency for SHETRAN for the Murg was 0.64, and for WBM for the Modau the efficiency was 0.65. (No other N&S values were provided.)

Scenarios: For each catchment, historical data pertaining to changes in land cover and river engineering works were obtained. For the Modau, land use data were collected for four years between 1935 and 1997, inclusive. Over this period the area of urbanisation increased from 3% to 15%, arable declined from 64% to 49%, with the remainder of the catchment under forest. Changes in the types of arable crops were not represented. For the Murg catchment, land use was obtained for 1883 and 1992, and a scenario was generated for 2005. The major changes in land use were an increase in urbanisation from 1.5% to 13.5%, a decline in arable from 65% to 53%, with the remainder arable. Land use data for the Bisagno were collected for the period 1805-2000.

Conclusions: For the Modau catchment it was found that urbanisation had no impact on the flood peaks of large events (50 year return period), but the runoff volume did increase. During large events, the majority of the runoff was produced in rural areas, which were found to show little sensitivity to land use changes. The rapid runoff from urban areas did not coincide with the main hydrograph peak, and therefore the historical increase in urbanisation did not exacerbate flooding. At the outlet of the Murg, there was no significant change in the hydrograph, and the authors concluded, "*changing agricultural land into areas rich in settlement and infrastructure does not produce a significant increase in runoff production*". The authors speculated that the runoff generation from agricultural land and urban areas are similar, and larger impacts would be expected with the conversion of forested areas to one of these land cover types.

In summary, the authors concluded (1) land cover changes had not had a significant impact on flood formation, but urbanisation and engineering works were of major importance; (2) the location of urbanisation was particularly important as it alters the timing of the tributary flow peaks relative to the main channel peak, which may either increase or decrease flooding; and (3) it is difficult to generalize results as each river basin has its individual characteristics, which must be considered in a suitable model.

As almost all UK catchments contain an urban area, any change in the historical nature of flooding will need to consider a change in urbanisation as a cause. An increase in urban area would be expected to be accompanied by larger flood events as a result of impermeable areas, but this study has demonstrated that changes in timing rather than magnitude may be of primary importance.

HBV-D (HR Wallingford, 2001); Elbe.

Purpose: The principle aims of this study, undertaken as part of the EUROTAS project (HR Wallingford, 2001), were to explore the impacts of (a) climate change (not reported here) and (b) land use change on the hydrological regime of the River Elbe, including flooding.

Application area: The Elbe river basin was modelled between the river's tidal limit at Nan Derchau and the Czech-German border (80,000km^2).

Model description: HBV-D is semi-distributed conceptual model running at a daily time step (Bergstrom, 1995). It uses subcatchments as the primary hydrological units, which may be further divided into zones, based on elevation, soil type and land use. Simple conceptual models are used to represent snowmelt (degree-day index), infiltration, evapotranspiration (as a function of temperature and PE) and routing (fast nonlinear reservoir and slow linear reservoir). Infiltration is represented using a statistical distribution of storage capacities, similar to that used in the PDM model.

Data requirements/set-up: HBV-D requires air temperature, precipitation and potential evapotranspiration data as forcings, and elevation, soil and land use data for the characterisation of the subcatchments. For this application, the land use data were derived from the CORINE database and the catchment was divided into 44 sub-catchments.

Scenarios: Two scenarios were performed to evaluate the effect of land use changes on flooding; firstly, the urban area was increased by 10%, with a related decrease in agricultural land; and secondly, agricultural land was decreased by 10% in favour of urban, forest and grassland. The spatial distribution of land use change was generated using the LADEMO land use model. LADEMO (Menzel and Blongewicz, 2001) uses a priority system, based on biophysical conditions (slope, soil quality etc.) and neighbourhood relationships, to identify those areas most likely to change under a given user defined scenario.

Calibration/validation: The model was calibrated at 4 river locations over 3 years, and then validated by extending the runs for an additional 5 years. The N&S efficiencies over the calibration and validation periods ranged from 0.78 to 0.83.

Conclusions: The results of the investigations were summarised by the authors as follows: (1) the effect of the land use changes on runoff decreased with increasing catchment size; (2) there was no clear link between land use and flood peaks; (3) urbanisation was found to increase mean discharge, but not flooding; and (4) an increase in forested area resulted in a reduction in runoff, but no general conclusions could be drawn regarding flooding.

HBV was designed for hydrological forecasting, for which the prediction of peak flows is of primary importance, but it has also been for other applications, including water balance mapping and design flood estimation. The treatment of soils and evapotranspiration is very simplistic, and the lumped structure makes the model unsuitable for application to areas smaller than the mesoscale (~10^3 km^2). However, the use of the LADEMO illustrates a method for generating realistic spatial changes in land use in response to policy.

<u>HYLUC (Hydrological Land Use Change)(Calder et al., 2003), Nottingham.</u>

Purpose: This paper presents results of field study investigations of the water use of several vegetation types, which were used to calibrate the HYLUC water use model and derive predictions of the impact of different vegetation types on recharge. The work was instigated as a response to the UK Government’s proposed doubling of the area of woodland within England by 2045. Although the study does not deal directly with flood runoff, it is included as it is one of the few studies to examine the impacts of broadleaf forests on catchment hydrology.

Application area: Clipstone Forest, Nottinghamshire.

Model description: HYLUC is a physically based daily water balance model for the estimation of the impacts of afforestation on the water balance (Calder, 2003b). The model contains no routing algorithm and therefore cannot be used directly in flood estimation, but it does have the potential to be incorporated as a module into a catchment scale hydrological model. HYLUC was developed from knowledge of the underlying biophysical processes that govern evaporation from different land uses (advection, radiation, physiology and soil moisture), while maintaining a parsimonious approach in terms of parameter requirements. It is based on the Penman equation, but with modifications to account for the effects of tall vegetation, for which interception losses may form a significant component of the hydrological mass balance. Infiltration is simulated using the 1D Richards equation.

Data requirements/set-up: Requires daily rainfall, daily potential evapotranspiration and land cover and soil data.

Scenarios: The recharge values at several sites possessing different land cover types were predicted. This information could be extrapolated to determine the effects of changes in land cover fractions on local recharge rates.

Calibration/validation: Field study observations of the water use of grass, heath, oak and pine at Clipstone Forest, Nottinghamshire, were used to calibrate HYLUC. In total 6 parameters (representing soil and vegetation properties) were modified during the calibration, in which model predictions of soil moisture were fit to neutron probe measurements.

Conclusions: Predictions of the impact of different vegetations on recharge were performed. Clipstone Forest is drought prone, with rainfall not greatly exceeding potential evapotranspiration. It was found that the flows (recharge plus runoff) beneath pine forest was approximately one quarter of that under grass and essentially only occurs in years of above average rainfall. Oak woodland reduced flows by almost one half when compared to grassland.

Accurate predictions of evaporation are essential for the estimation of soil moisture conditions, which in turn have a major control on runoff generation. Although not a catchment model, this study provides an initial indication of how the introduction of broadleaf forests may be expected to change catchment hydrology in the UK lowlands.

SWATmod (Fohrer et al., 2001); Dietzholzer, Germany.

Purpose: This study explored the effect that land use changes, resulting from European market policy, could have on the discharge hydrograph.

Application area: Dietzholzer catchment, Germany (area 82 km^2).

Model description: SWATmod is a derivative of the Soil Water Assessment Tool (SWAT: Arnold et al., 1998; Srinivasan et al., 1998), which was developed to predict the impact of land management practices in meso- to macroscale catchments. The model, which is essentially a semi-distributed daily water balance model, consists of components describing the major processes associated with water movement, sediment transport, plant growth, nutrients, pesticides and land management. The catchment is firstly divided into sub-catchments, which in turn are divided into Hydrological Response Units (HRUs), each of which is assumed to be homogenous in terms of land use and soils. Surface runoff is calculated using the SCS method as an infiltration equation (described in Section 0) and peak discharge is predicted using the Rational equation. Other hydrological processes represented include return flow, percolation, evapotranspiration, channel transmission losses, pond and reservoir storage, and groundwater flow.

Data requirements/set-up: The model was parameterised using a 40m DEM, a 1:50,000 digital soil map, land use derived from a Landsat satellite image, four rainfall gauges, and a meteorological station. The catchment was divided into 35 subbasins, collectively comprising 218 HRUs.

Scenarios: The spatial changes in land cover were generated using the raster based Proland (Moller et al., 1999) land use model. Proland assumes the main driver for change is economic; it is assumed that farmers will maximise profit for any parcel of land. Site specific information such as soil type and temperature are used to calculate crop potential yield, and costs are calculated using a standard database modified to account for site conditions (e.g. slope and clay content).

The initial land use within the catchment consisted of 55% forest, 28% fallow, 10% grassland, 6% urban and less than 1% arable. Two land use change scenarios were performed. In the first, a financial bonus was introduced for grassland areas. ProLand predicted an increase in the area of grassland, in response to the financial incentive, from 10% to 45%. In the second scenario, unfavourable conditions were introduced for animal husbandry, resulting in an increase in the forested area to 82% and also an increase in arable.

Calibration/validation: During calibration the saturated hydraulic conductivity and available water capacity were adapted within their physical ranges. The model was calibrated using daily data for 1991-1992, with an N&S efficiency of 0.84, and validated over 1993-1994, with an efficiency of 0.87.

Conclusions: Results were presented for the different land use scenarios in terms of changes to the water balance. An increase in grassland at the expense of forest was found to significantly increase surface runoff (+75%), but as baseflow and interflow were the main runoff processes, the overall increase in discharge was much smaller (9%). The no-husbandry scenario had little effect on the catchment mass balance as the predicted increase in forest evaporation was countered by the opposite effect under arable. Under both scenarios an increase in flood peaks occurred, but this was not quantified.

SWATmod is typical of the type of model used by the USDA (other examples are given in Beasley et al., 1977; Knisel and Williams, 1995; Williams, 1995).

These models seem to offer a great deal, but given very large number of parameters they contain (most of which are multiplying factors), calibration is problematic and there is great uncertainty in the predictions. However, the models do contain many of the hydrological mechanisms that can be changed as a result of farming, and there are numerous plot experiments to back up the values used. It's also worth noting these models were originally designed for the prediction of water yield rather than for the purposes of flood prediction.

SIMULAT and KINEROS (Bormann et al., 1999); Neuenkirchen, Germany.

Purpose: This study investigated the effects of land use changes, due to EC policy, on runoff. Additionally the re-establishment of channels was considered.

Application area: Neuenkirchen, northern Germany (16 km^2)

Model description: A coupled modelling approach was performed using the physically based SIMULAT and KINEROS models. SIMULAT (Diekkrüger and Arning, 1995) is a continuous 1D soil-vegetation-atmospheric-transfer (SVAT) model, capable of simulating vertical fluxes (channel routing is not performed). Evapotranspiration is simulated using the Penman-Monteith equation, soil water flow and infiltration are based on Richards equation, interflow on Darcy's law and snow melt on a degree-day index. KINEROS (Woolhiser et al., 1990) is a physically based distributed model, which represents only infiltration, using the Smith-Parlange equation, and surface and channel routing, using the kinematic wave and time of concentration approach. KINEROS is an event-based model and therefore requires the specification of an antecedent soil moisture.

Data requirements/set-up: The premise taken was that only (generally available) standard data sets should be used in the modelling exercise in order to guarantee the transferability of the system to other regions. For the calculation of evapotranspiration, SIMULAT requires land use, rainfall, temperature, global radiation and windspeed data. Both models require soil data. For the application of SIMULAT, the area was divided into a number of homogenous areas, defined by their topography, land use and soil types. For the application of KINEROS, the area was divided into 122 slopes, each connected to a channel.

Scenarios: The study focussed in particular on the impact of the introduction of fallow fields, in response to EC policy, and the effects of modifications to the river channel on routing.

Calibration/validation: Not performed – model results from the various scenarios were compared.

Conclusions: SIMULAT was used to assess the impacts of land use on the catchment's water balance (i.e. runoff, evapotranspiration and recharge), using an 8-year record of historical meteorological data. Firstly, the effects of historical changes in land use between 1979 and 1995 were assessed. Over this period there was an increase in grassland (3 to 6%) and winter wheat (41 to 56%) and a decrease in winter barley (23 to 11%). This was predicted to have had no significant effect on the catchment's annual mass balance. However, a scenario in which the area of fallow land was increased to 15%, in line with EC policy, resulted in a 200% increase in annual groundwater recharge if the land was left bare, but only 55% if a cover crop was used. The effects of the seasonal development of crops on peak discharge were simulated by altering the surface roughness parameters in the KINEROS model and then applying a design storm. Results from SIMULAT were used to set the antecedent soil moisture conditions for these simulations. Introducing a 12% area of bare fallow at the expense of cereals during the winter increased the peak discharge by between 0% and 30% – the size of the change depended on the location of the land use change within the catchment. In March, a 12% change in land cover from cereal to plant-covered fallow had almost no effect on flows, irrespective of the location of land use change. Minimum tillage practices lowered peak discharge by between 8 and 34%, and also retarded the hydrograph. Re-establishing the river channel to the more meandering 1815 conditions reduced peak discharge by 63%, which was further lowered with the introduction of channel plant growth.

This study is interesting in that it is one of the few in which the effects of the location of change within the catchment, the influence of land management practices and the importance of the channel network were evaluated. However, as with all of these studies, caution should be exercised when interpreting the results. As the model was not validated, the catchment should be considered synthetic. Also, as KINEROS is an event-based model, the results are strongly dependent on the antecedent soil moistures provided by the 1D SVAT model, which obviously cannot account for hillslope processes. Also, the effects of changes in land use on storm runoff were parameterised by changing only the overland flow resistances.

LISFLOOD (De Roo et al., 2001; De Roo et al., 2003); Oder.

Purpose: This study investigated the causes of flooding and the influence of land use, soil characteristics and antecedent catchment moisture conditions.

Application area: The upper Oder (59,162km^2)

Model description: LISFLOOD is a distributed model that employs a mixture of (more or less) physically based and conceptual representations of hydrological processes. The model was developed to simulate runoff and flooding in large European catchments, in which the flood events last for durations in the order of 6 weeks (Bates and De Roo, 2000; De Roo et al., 2000). There are three model components; a daily water balance module, an hourly catchment-scale module and a floodplain module running at a resolution of several seconds. The water balance module is started one year before a flood, and provides the initial hydrological conditions for the catchment module, which is started several days prior to the flood. The main difference between the water balance and catchment modules is the time step used, which is smaller in the latter to improve the river routing. Physically based equations are used to calculate evapotranspiration (Penman-Monteith & Priestly-Taylor), infiltration (Smith-Parlange), vertical soil moisture movement (Richards equation), percolation to the groundwater store (Dary's law), and overland flow (kinematic wave). Degree-day indices are used to model soil freezing and snowmelt. Channel routing is performed using either a kinematic wave or dynamic wave approximation, depending on the river channel bed gradient and the occurrence of backwater effects. The flood plain module is used to provide flood extent/depth maps.

Data requirements/set-up: Data requirements for LISFLOOD are similar to those of SHETRAN (described in Section 0). The data used in this study comprised of digital elevation data, CORINE land cover data, soil parameters from the European Soils Database and meteorological data from the MARS database. Following a review of the data available in the literature to parameterise the model, the authors commented that, "*it is clear that the number of field and laboratory measurements on the parameterization of the effects of land use changes on floods is currently insufficient.*" The catchment was represented by pixels of 1 km.

Scenarios: Land cover data for 1975 were derived from a Landsat image, and historical maps were used to establish 1780 conditions. In 1975, approximately one-third of the catchment was forested, one-half under agriculture, 5% urban, and pasture and other land uses contributing the remainder (precise figures were not provided). Over the period 1780 to 1975, it was found that the area of urban and forest increased, arable decreased and grassland remained stable (none of the changes were greater than 10% of the total catchment area). Using the CORINE database, it was also noted that the land cover had not changed significantly over the period 1975 to 1995.

Calibration/validation: The model was calibrated manually for three events using visual inspection of the simulated and observed hydrographs.

Conclusions: For the single event analysed, the change in land use between 1975 and the present increased peak flows by only 0.2% (De Roo et al., 2001). Changes since 1780 were not quantified, but it was stated that the expansion of urban area had caused an increase in flows (De Roo et al., 2003).

This study demonstrates that physically based modelling can be applied at large scales. The usual approach to modelling a catchment of this size would be to resort to a less computationally demanding semi-distributed or lumped structure, e.g. a 1D SVAT model similar to SIMULAT or CLASSIC. Of the models used in the land use change studies, this model also incorporates the most physically detailed representation of the channel network and floodplain. However, the size of the application area means the results of this study are of little relevance to UK conditions.

DHSVM (LaMarche and Lettenmaier, 1998); Deschutes River Basin, US.

Purpose: To examine the effect of forest harvest on flooding in maritime mountainous environments, with particular attention to the role of forest roads. The study used a combination of field observations and rainfall-runoff modelling.

Application area: Deschutes River, Washington, USA (149 km^2).

Model description: The Distributed Hydrologic Soil Vegetation Model (DHSVM) is a grid-based physically based hydrology model (Wigmosta et al., 2002). It consists of a two-layer canopy representation for evapotranspiration, a two-layer energy balance model for snow accumulation and melt, a multilayer unsaturated soil model and a saturated subsurface flow model. Runoff is generated by saturation excess, and routing is perfomed using slope information from a digital elevation model.

Data requirements/set-up: Model forcing data consists of precipitation, temperature, humidity, incoming long- and shortwave radiation, and wind speed. The catchment is characterised using the soil, vegetation and terrain data.

Scenarios: To evaluate the effects of forest roads and harvest on peak streamflows, catchment-wide simulations with and without roads were performed.

Calibration/validation: During calibration, the snow–rain threshold temperature, lateral hydraulic conductivity, exponential decrease in hydraulic conductivity with depth, cutslope height, wilting point, and leaf area index (LAI) were modified. Calibration/validation graphs were shown, but N&S efficiencies were not given.

Conclusions: Through the use of a calibrated model, it was shown that at this experimental catchment scale, forest removal (without introducing any road effects) would increase the mean annual flood by about 10%. For floods of greater magnitude (longer return period) the model predictions indicated a decreasing (percentage) effect. The effects of forest roads (without any forest removal), which effectively increase the density of the stream network, were predicted to increase the mean annual flood by a similar amount (~10%). But, unlike the forest removal effect, the ‘road’ effect was shown to increase with increasing flood magnitude. While the effects of forests in flood amelioration decreases as the size of the storm event increases, the road is a permanent fixture that contributes to the runoff directly as the storm input increases.

The results from this study are of limited relevance to UK conditions; snow processes were of greater importance than under typical UK conditions and in the US clear cut logging is performed over much larger areas. However, this study helps disentangle the ‘road’ and ‘forest removal’ effects associated with logging.

WaSiM-ETH (Niehoff et al., 2002); Lein catchment, the Rhine.

Purpose: This study evaluated the impact of land use changes on flooding, taking into account the spatial and temporal dynamics of rainfall events.

Application area: The Lein catchment (115 km^2).

Model description: WaSiM-ETH is essentially a distributed physically-based hydrological model, into which mechanisms have been incorporated to achieve an improved representation of land use related runoff generation mechanisms, specifically, a macropore module to account for fast infiltration processes; a siltation module that allows soil hydraulic conductivity to decrease as a result of soil aggregate breakdown under intense rainfall; and an urban module to reflect the impervious and sealed portion of a grid cell. The model also represents infiltration (Green-Ampt), vertical flow in the unsaturated zone (Richards equation), interflow, baseflow (a linear reservoir), evapotranspiration (Monteith), snow processes (energy balance), and flow routing (time concentration) (Schulla, 1997).

Data requirements/set-up: The model was parameterised using CORINE land use database, a general soil map (1:20,000), a digital elevation model. Rainfall and evaporation data were used to force the model. The grid size used was not quoted.

Scenarios: Scenarios were developed using the LUCK toolkit, a grid based scenario generator in which the potential for change considers both the biophysical characteristics of the grid cells and neighbourhood relationships (Fritsch et al., 2000). Three land use types are considered by LUCK; urban, agriculture and forest. Urbanisation was given the highest economic priority, and the potential for change to this type considered structural constraints (topography) and legal constraints (conservation areas). In determining conversion to arable or set-aside, the potential yield of a grid square was considered in terms of soil fertility and suitability for mechanised farming. Forestation is given the lowest priority.

Two scenarios were generated using the LUCK toolkit. Firstly, the area of urbanisation was increased by 50% to 11.1%. Secondly, 10% of agricultural land was set-aside, in line with an EU resolution. At present 60% of the area is under agricultural land use.

Two storm events were simulated, one convective and one advective, both with return periods in the order of 3 years. The convective event was characterized by low antecedent soil moisture and high rainfall intensities (summer conditions) while the advective event had much lower intensities and high antecedent soil moisture (winter conditions).

Calibration/validation: Details of calibration and validation were not provided.

Conclusions: For the urbanisation scenario, the flood volume and peak increased for each of the two storm events, but the change was much more distinct for the convective storm. The explanations for the lower impact for the advective event were; (a) agricultural and urban areas produce similar amounts of runoff under near saturated soil moisture conditions and (b) the main hydrological effect of urbanisation is to lower infiltration capacities, but the low precipitation intensities did not cause infiltration excess.
The simulated hydrographs under the scenario of increased set-aside showed a minor increase in runoff for the convective event, due to a reduction in infiltration capacity caused by siltation, while virtually no change in runoff was simulated for the advective event.

The authors concluded; "*The influence of land-use on storm-runoff generation is stronger for convective storm events with high precipitation intensities than for long advective storm events with low precipitation intensities, because only storm events originated by high rainfall intensities are at least partially controlled by the conditions of the land-cover and/or the soil-surface.*" It was also noted; "*Convective storm events, however, are of very minor relevance for the formation of floods in the large river basins of Central Europe because the extent of convective rainstorms is usually restricted to local occurrence.*" The authors acknowledge the limitations of their modelling approach, since land use change and hydrological modelling predictions are accompanied by a high degree of uncertainty, particularly for distributed process-based models. However they argue that, on the other hand, they have represented the influences of land-cover characteristics on storm runoff generation in a comprehensive way, allowing complex interactions to be tracked which otherwise would not be obvious.

This is one of the few studies that directly addresses the link between land cover and soil properties. The representation of macropores and siltation used conceptual process descriptions, and it is not obvious how such modules can be calibrated. This is perhaps reflected in the authors' statement about the high levels of uncertainty. In the parameterisation of the module describing siltation, the authors commented, "*the empirical evidence obtained for siltation at the plot scale cannot simply be adopted in order to describe runoff generation at the catchment scale.*" This was attributed to spatial heterogeneity in soil properties, with infiltration-excess generated locally re-infiltrates in areas not affected by siltation.

<u>SHETRAN (Lukey et al., 2000); France.</u>

Purpose: Primarily, this study was concerned with sediment transport. However, a study of the impacts of afforestation on streamflow was also performed as part of this work.

Application area: Draix catchment (86 ha) located near the Mediterranean coast of France.

Model description: The study used SHETRAN, described in Section 0.

Data requirements/set-up: The land use coverage was obtained from aerial photos and the associated vegetation parameters were selected on the basis of previous modelling experience. Hourly precipitation and evapotranspiration were used as model forcings. The catchment was represented by 50 m by 50m grid squares.

Scenarios: The entire catchment was reforested to its former condition.

Calibration/validation: The model was parameterised using a variation of the 'blind' methodology proposed by Ewen and Parkin (1996). The philosophy behind this validation approach is that the modelling should be performed under similar conditions to those for which it is to be used, which in the case of modelling a future change means that no discharge data will be available. Thus, to parameterise the model, field data may be collected but observations of the catchment response must not be viewed until after the predictions have been made.

The blind validation was performed under present conditions (i.e. pre-afforestation) so that observed discharge data could be used to evaluate the 'blind' predictions. Only two soil samples were available to characterise the subsurface properties and it was recognised that these data were subject to great uncertainty. Additionally, there was insufficient information to specify a resistance for overland flow. Based on field measurements and the modellers' experience, baseline, maximum and minimum estimates were specified for three soil parameters and the resistance parameter. Simulations were carried out using all combinations of the four parameters with their three estimates, i.e. 3^4 or 81 simulations. (Due to computational requirements a Monte Carlo analysis could not be performed.) Taking the largest and smallest simulated discharge value from the 81 simulations at each time step, an envelope of simulated discharges (bounds) was produced. It was found that the prediction bounds encompassed 64% of the observed flows, with the authors concluding, "*there is significant uncertainty in the parameter values that has not been satisfactorily represented*". It was also stated "*predictive capabilities can therefore best be enhanced through a combination of process studies and further test applications aimed at reducing uncertainty in model parameter evaluation.*" From the 81 simulations, the highest N&S efficiency was 0.32 (the 'best estimate' simulation).

Scenario: A simulation was then performed to establish the impact of afforestation on streamflow. This involved re-parameterising the best estimate simulation; assigning forest vegetation to all grid cells and increasing the flow resistance to reflect the change in land cover characteristics. No further uncertainty analysis was conducted. It was found that annual runoff following reforestation decreased by approximately 60%.

This study gives some indication of how difficult it may be to apply a model for the prediction of land use change using a priori estimates of catchment parameters, and it also provides information on the uncertainty in predictions of land use change when no data are available to calibrate.

From the above summary, it can be seen that a wide variety of models and modelling techniques have been used to simulate the effects of land use change on catchment hydrology. (Table 3.4 summarises studies in which hydrographs were simulated.) Given the differences in the catchment sizes, climate, land uses, geophysical properties and hydrological features of interest, it difficult to draw any general conclusions on the hydrological impacts of land use changes from these modelling studies. Also, the majority of these studies only involved changes in the fractional areas of broad land cover types (woodland, grassland, arable etc). From the plot scale experiments detailed in Appendices A and C, it was established that local runoff generation can vary significantly between different types of crops, and is particularly influenced by the seasonal variations in the protection that the vegetation coverage provides. Additionally, the management practices associated with a land use are of great importance; the density of livestock on grassland, the use of cover crops and buffer strips, the extent and type of field drainage, tillage practices, and so forth. Niehoff et al. (2002) did include processes to represent a reduction in infiltration resulting from the removal of a protective vegetation coverage, but none of the other studies considered the effects of management practices on soil physical properties, infiltration and runoff generation. The majority of the studies also did not represent any associated changes to the flow routing.

For a rigorous assessment of the effects of land use and management changes on flood risk, it is not sufficient to predict possible impacts on individual floods; the full flood frequency curve must also be considered. Only in the studies performed by Crooks and Davies (2001), for the large Thames basin, and the Polytechnic of Milan (2001), for several European catchments, was the flood frequency curve considered. In the former study long records of rainfall were available, but often the data series will need to be generated using a stochastic rainfall model. This method is illustrated in the study of O'Connell et al. (2003), in which a stochastic rainfall model and a simplified version of the ARNO model were used to show possible sensitivities of the flood frequency curve to land use changes for a synthetic catchment. Continuous models provide a complete representation of the hydrological cycle at the catchment scale, while event-based models only consider runoff generation processes. As event-based models require the use of a water balance model for the specification of antecedent soil moisture conditions (e.g. Bormann et al. (1999) coupled SIMULAT and KINEROS), continuous modelling is the preferred option for flood frequency analysis.

Modelling results are invariably characterised by a degree of uncertainty. These include uncertainty in the modelling structure and in the field measurements used to force, test and calibrate the model. Ideally, the predictions made should be in the form of narrow, accurate error bounds, giving prediction ranges that accurately reflect the combined effect of the uncertainties. In the above modelling studies, uncertainty was only considered in the study of Nandakumar and Mein (1997), and this was limited to user imposed errors in the forcing data and no account was taken of model structural errors; and in the study of Lukey et al., (2000), in the estimation of the parameter values. Uncertainty in predictions will need to be quantified for the operational use of hydrological modelling in impact assessment.

In general, it can be concluded that the models or modelling approach used in the above studies are not suitable for use in operational assessments of impact (Table 3.4). It is probably reasonable to say that the use of rainfall-runoff modelling to predict land use management impacts on flooding is in its infancy, and the available modelling studies provide only a preliminary indication of how rainfall-runoff modelling could be used to predict impact. In particular, the following issues remain unresolved:

1. What is the most appropriate type of model for the prediction of change (e.g. a conceptual or physically-based model)?
2. Which hydrological processes need to be incorporated into a model, and in how much detail (e.g. macropore flow, soil structure degradation etc.)?
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?

Below, the modelling process, the types of models available for impact assessment and problems in calibration, validation and predictive uncertainty are discussed.

Table 3.4 Summary of the key modelling studies land use change studies

Model	Catchment	Land use change impact study	Fitness for purpose
CLASSIC (Crooks and Davies, 2001) Distributed conceptual model	Thames at Kingston ($10,000 km^2$)	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^2), 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 ($80,000 km^2$).	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^2).	A 35% increase in grassland resulted in a 9% increase in annual flow. The peak flows also increased (not	Model derived from SWAT, which was originally designed for the prediction of monthly

		quantified).	water yield.
SIMULAT / KINEROS (Bormann et al., 1999) A coupled 1D SVAT and physically based modelling approach)	Neuenkirchen catchment (16km^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. 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^2) 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^2)	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.

2.4 Elements of Modelling

What many hydrologists would consider to be the idealised procedure for conducting a rainfall-runoff study is shown in Figure 3.2 (Refsgaard and Henriksen, 2004). The inner arrows represent how the procedures relate to one another, and the outer circle refers to the procedures that evaluate the credibility of this process. The hydrologist should firstly analyse the catchment (‘reality’), creating a qualitative and quantitative description of the hydrological processes thought to be controlling the response (the ‘conceptual’ model; this should not be confused with a conceptual rainfall-runoff model). The conceptual model must then be translated into a model code, usually in the form of a generic mathematical formulation, which requires testing to ensure that it works as the user intended (‘code verification’). As the majority of current model codes are generic, it is not necessary to create a new code for each application – one of the existing codes that can provide a representation of the user’s conceptual model may suffice (e.g. see
Table **3.1**). The code must then be parameterised to provide a site-specific description (‘set-up’), with the parameter values either estimated and/or measured in the field. These parameter values may, for example, represent

the size of the stores in a conceptual rainfall-runoff model, or the soil characteristics (e.g. porosity, saturated hydraulic conductivity) in a physically-based model. The parameter values initially selected are typically adjusted to increase the quality of match between predicted and observed catchment response ('calibration'). Simulations are then performed (with data not used in calibration) to substantiate that the model accuracy is consistent with the intended application ('validation'). Finally, simulations are conducted to obtain predictions for use, e.g. by water resource managers or in flood forecasting. Model confirmation involves determining whether the conceptual model is an adequate reflection of reality (fit for purpose), which requires consideration of the results from calibration and validation and the assessment of field data.

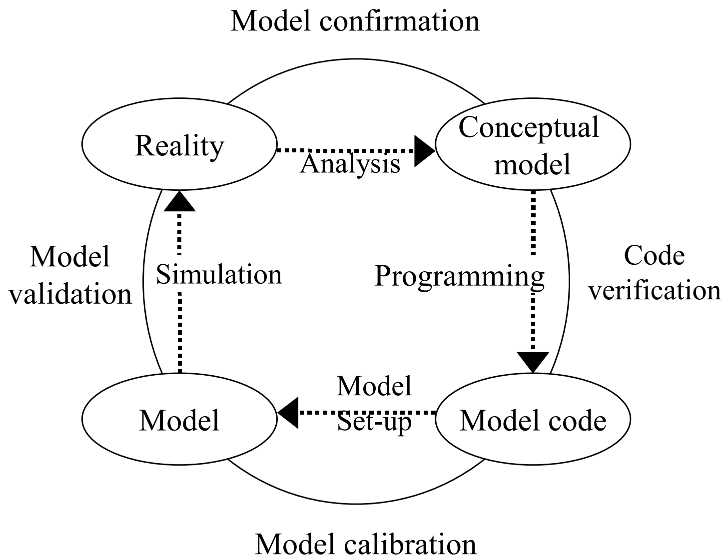

Figure 3.2 Elements of modelling (Refsgaard and Henriksen, 2004)

An additional step in the above procedure is required when modelling change; the parameter values of the validated model must be modified to represent the altered state of the catchment and the simulations rerun. The impact will then be given as the difference between the 'unchanged' and 'changed' simulations. As the assessment of impact requires the calculation of 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.

The procedure described above would appear to possess a degree of scientific rigor and be relatively straightforward to implement. However in practice this is rarely the case, with subjective decisions made throughout the modelling process.

Model Selection

As there is no widely accepted hydrological theory to simulate catchment behaviour, the selection, or development, of an appropriate model code for a particular application is a difficult task. The choice of model is often made on the basis of subjective and non-scientific criteria, such as the users' past experience and knowledge, economic constraints and data availability.

The selection of a model is especially difficult when attempting to simulate the hydrological effects of land use and management practices. The chosen model code must have the ability to reflect the user's conceptual model of both present and future conditions. However, knowledge of how land use and management practices affect catchment hydrology is incomplete. Soils partition rainfall into surface flow, subsurface flow, and transpiration loss, yet little is known of the effects of management practices, such as tillage and different cropping practices, on soil hydrology. (The evidence that is available tends to be empirical rather than process based.) Additionally, hydrological knowledge of how changes in local scale runoff propagate to the catchment scale is largely absent. It may appear that a more complete understanding of the influence of farming practices on runoff would allow the selection of an appropriate model for the prediction of change. However, analysis of the current modelling philosophies and techniques indicates that even in the absence of change hydrological modelling is a difficult task.

To represent the impact of land use change on catchment hydrology, a reductionist approach is often viewed as being appropriate. Hydrological behaviour is considered as the aggregate of many small-scale processes, each represented by a physics based equation whose parameter values spatially vary over the modelling domain. SHETRAN, a physically based distributed model (PBDM), is an example of the reductionist approach. This methodology provides conceptual clarity; the individual hydrological processes are represented by deterministic models (e.g. Richards equation for infiltration, Saint Venant equations for channel flow) for which the parameters have a clear physical meaning and can, in theory, be measured.

It is often argued that PBD modelling has not lived up to its early promise, in which it was envisaged the physical basis, and measurable parameters, would allow the prediction of flows in ungauged basins, the effects of land use and climate changes on flow regimes etc. Although this criticism has some substance, rigorous testing has never been widely performed to establish the true capabilities of physically based models. This 'overselling' of potential is not unique to physically based modelling. Refsgaard and Henriksen (2004) argue there is a lack of credibility and transparency associated with hydrological modelling in general, resulting from insufficient attention being given to the documentation of the predictive capabilities of models.

Another common criticism of physically based modelling concerns the treatment of scale. The area to be modelled is divided into a number of computational elements such as hillslopes, grid squares, land patches, or agricultural fields. However, the equations used to describe the hydrological processes have typically been developed at the point scale. There is therefore a discrepancy in scale between the application of the equations and the point scale theory. In this context, there are two questions that need to be addressed: (1) can point scale equations be used to describe processes at the macroscale (i.e. the computational elements of a PBDM)? and (2) if so, what are the aggregation rules to obtain the model parameters at the macroscale (i.e. parameter values that represent the properties of the computational elements) (Beven, 1989; Blöschl and Sivapalan, 1995).

To provide an example, consider the modelling of infiltration using a point scale model of infiltration, for example Richards equation. The spatially heterogeneous area corresponding to a single computational element (which could be as large as 1 km^2 in a catchment application) is usually simplified to a homogenous area with a single soil profile. To obtain the infiltration model parameter values (saturated hydraulic conductivity, porosity etc.) for the element, it is not possible to simply take the average of measurements from the field due to the nonlinear nature of unsaturated zone processes. There is a need for an 'effective parameter' value – that is, a single parameter value, that when assigned at the grid scale yields the same output as that from a model based on the heterogeneous field. Unfortunately, with the exception of some cases of saturated flow, rules for obtaining effective parameters do not exist (Blöschl and Sivapalan, 1995). In the absence of aggregation rules several other approaches have been forwarded. Spatial heterogeneity could possibly be accounted for using distribution functions (similar to that previously described for the PDM model) or bulk equations (i.e. by not explicitly resorting to local equations). A good example of the later case is the work of Moore and Burch (1986), in which a power law was used to represent the aggregate effect of many rills, thereby avoiding the need to characterise each individual rill. Despite the practicalities of these methods they are not truly physically based and are therefore diversions away from the original modelling philosophy.

While the equations used in PBD modelling have a physical basis, they do not necessarily incorporate all of the processes operating at the point scale. Consider again the case of infiltration. There are many models with some degree of physical basis that could be used to represent infiltration, but none of these is capable of properly describing the natural complexity of water flow in soils and the way it is affected by factors such as soil mineralogy, soil water chemistry, preferential flow, crusting, diurnal and seasonal thermal cycling, stress cycling by farm animals and vehicles and rainfall impact. The question arises as to how much point scale complexity is actually required to perform PBD modelling. It has been argued that the individual small-scale processes are selected (or not) based on the subjective judgement of which are thought to be important (Sivaplan et al., 2003), and on the ability to mathematically describe them, rather than determining which processes are actually important in a given environment.

Two further criticisms levelled at PBD models are the high data requirements, which can rarely be met, even in experimental settings, and the large computational demands. Remotely sensed data has been forwarded as a solution to the data problem, but there are few cases in which the practical benefits have been demonstrated. One potential avenue of research is the exploitation of hydrological similarity, that is, developing methods to allow data collected from one site to be extended or adapted for use at another. The computational problem is becoming less of an issue due to advances in computer hardware and the use of distributed software design (Beven, 2003). However, there is also the potential of using hydrological similarity for this problem. Rather than explicitly modelling the entire catchment, results from one area could be suitably adapted to represent another.

Because of the high data requirements, the need for effective parameters and deficiencies in the process equations, physically based models are usually calibrated to some extent. Calibration is difficult due to the inherent interaction between the parameters, and equally good results may often be obtained with different sets of parameter values (this is termed 'equifinality'; Beven and Freer, 2001). This problem of parameter identifiably means that PBD models are over-parameterised in a systems sense. Physically based models share many of the calibration problems that are experienced in the parameterisation of simpler conceptual models; this issue is discussed in more detail below.

There have been attempts to extend physically based models to include land management interventions. For example Dunn and Mackay (1996) incorporated field drains into a SHETRAN model of the River Tyne catchment, and MIKE-SHE has been coupled to DAISY (Hansen et al., 1990), a soil-plant-atmosphere system model which simulates crop production as well as water and nutrient dynamics in the root zone. While these approaches are attractive, there is the obvious danger of introducing additional unidentifiable model parameters into the already complex model structures.

There is still ongoing debate on the merits of PBD modelling (e.g. Beven and Feyen, 2002; Beven, 2002; Ewen et al., 2000; Grayson et al., 1992; O'Connell and Todini, 1996; Refsgaard, 1997; Woolhiser, 1996), and many of the criticisms levelled at PBD modelling apply equally to the alternate modelling philosophies. However, there is also a strong consensus, even among critics, that distributed models with some form of physical basis are needed for the practical prediction of the effects of land use change, non-point source pollution, impacts of erosion etc. Two routes for the advancement of physically based modelling have been proposed: (1) the development of improved scaling theory and process representations (Blöschl and Sivapalan, 1995) and (2) detailed evaluation of modelling applications (Beven, 2001a). While issue (1) remains unresolved, there are several practical approaches that could be performed in relation to issue (2). Ewen and Parkin (1996) developed the blind validation technique to evaluate the true predictive capability of physically based models in applications such as land use change. Beven (2002) argues that there is a need to apply models over long time periods to specific catchments, increasing potential for model evaluation, post-simulation audits and learning about where the model does and does not work.

A simpler approach to the representation of hydrological processes is taken in conceptual rainfall-runoff (CRR) modelling. The hydrological sub-processes occurring within a catchment are aggregated into several key responses which are represented by a number of linked storage compartments (Wagener et al., 2003a). The model parameters describe the sizes of the storage compartments and control the rates at which fluxes may move between them. There are a large number of conceptual models available, differing in the degree of detail described, the manner in which the processes are conceptualised, the input requirements, the hydrological variables predicted, and the treatment of spatial and temporal resolution (Wagener et al., 2003a). Most operational CRRs have 10 or more parameters, for example the Sacramento Soil Moisture Accounting model, used by the US National Weather Service for flood forecasting throughout the US, has 17 parameters.

As aggregate process descriptions are used in CRR models, the parameters have no direct physically measurable identity and consequently calibration is necessary (Wheater, 2002). However, it is assumed that, even though the parameters cannot be measured, they are constants and represent inherent properties of the catchment. During calibration, it is often found that many parameter sets are equally able to describe the measured response (non uniqueness) and different conceptualisations of the catchment may provide equally good results. These issues have serious implications when attempting to model future conditions for which no catchment response data are available.

Consider for example how soil compaction could be parameterised in a very simple conceptual model, in which the soil is represented by a bucket and a linear reservoir is used to represent drainage (e.g. a similar structure to that used by the PDM model). Compaction affects the soil porosity, the connectivity of the soil pores and the microscopic sub-pore interactions between the soil water and the soil solids. A reduction in porosity could, for example, be represented by decreasing the size of the bucket, with all other processes represented by a change in the drainage parameter. However, as the individual processes are not represented, it is not obvious how the parameter values can be altered to reflect the change without resorting to calibration, for which there would be no data when predicting future change. Even if auxiliary information could be obtained to link the parameters to compaction, this 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 similar to those previously described in relation to PBD modelling.

To tackle the problem of non-unique parameter sets, parsimonious model structures have been proposed, in which the minimum number of parameters required to produce an acceptable simulation are specified. This is based on the commonly accepted fact that the information contained within a rainfall-runoff record is only able to support a model of very limited complexity. For example, Jakeman and Hornberger (1993) demonstrated that a model may only require between three and five parameters to simulate daily runoff, and that introducing additional model structure, and associated parameters, leads to no improvement in fit, yet introduces poorly identified parameters. Perrin et al. (2001) investigated the link between model complexity (i.e. the number of model parameters) and model performance through the calibration of 19 daily lumped models on 419 catchments. It was found that the more complex models outperformed the simpler ones during calibration but not during validation. However, increasing parameter identifiability at the expense of a reduction in the number of processes modelled may lead to an over simplistic model that is unreliable when extrapolated for the purpose of modelling change (Reichert and Omlin, 1997; Wagener et al., 2003b). Because a process cannot be identified in the observed records does not necessarily imply that it will not be of importance under conditions of land use and management change. Alternatively, complex models may have the potential to make meaningful extrapolative predictions, but because of information constraints may be unable to realise it (Kuczera and Mroczkowski, 1998)

An interesting hybrid approach is the Upscaled Physically based (UP) system of Ewen (1997). A set of physically based distributed models is applied at the small scale, and the results are then used to parameterise a simpler model at the large scale. It is argued that the underlying physical basis means that the large model will possess the correct sensitivities to changes in physical properties. The difficulty for impact assessment would be in deciding the structure of the large scale model, as this depends on the modelling aims, and is not uniquely defined within the UP system. However, UP does provide a method for linking detailed process-based modelling with simpler conceptual representations.

The final class of hydrological models considered here is termed ‘metric’ models (Beck, 1991). These models are strongly observation-oriented, and are constructed with little or no consideration of the features and processes involved in runoff production; they usually have very simple structures and low computational demands. The use of metric models is widespread in hydrology; examples include the unit hydrograph, the Rational method and the SCS method. The study of Sefton and Howarth (1998) can be considered a metric-conceptual approach, i.e. metric models, in the form of regression equations relating model parameters values to catchment characteristics, used to parameterise a conceptual model. This method is attractive, but in terms of representing modern farming practices only land cover was incorporated and the statistical accuracy of the relations is often poor. Additionally, the location of change will be of importance, but again it is not known how to incorporate such information into the regressions. A distributed model will probably be required to simulate the changes in the timing and magnitude of local runoff resulting from the piecemeal nature of agricultural practices. To integrate these changes to the downstream point of impact, it is also likely that the model will need an explicit routing scheme, or at least, a method for generating a distribution function which takes into account the locations of the land areas undergoing changes in land use and management.

An extension to the metric approach is data-based mechanistic (DBM) modelling, in which statistical tools are first applied to the observational series for the identification of parsimonious modelling structures, which are then interpreted in physically meaningful terms (Young, 1998; Young, 2001; Young et al., 2004). This is often termed ‘top-down’ modelling, as the model structure is developed from an understanding of the data, rather than being imposed a priori (i.e. as in the ‘bottom-up’ PBDMs). Due to a lack of high quality field data, it is not obvious how the metric or DBM modelling approaches could be utilised in the modelling of land use change on flooding. However, a DBM approach, in which the parameter estimates are allowed to vary over time, could be used as a way of detecting change and learning empirically about the impacts of change on the catchment response. It is not clear that this would lead to more certain predictions of the impact of change than trying to change multiple (interacting) uncertain parameters in a PBDM where there is also the need to learn about how to change the parameters in a meaningful way.

Calibration and Validation

Whether a CRR or PBD model is chosen for the modelling of the impacts of land use and management change on flooding, it is likely that some form of calibration will be required. Calibration would appear a relatively straightforward procedure, but in reality it has proved to be a challenging and subtle task, and a general methodology has still not been accepted (examples of the current state-of-the-art methods are given in Duan et al., 2003). In part, this reflects the diverse range of applications for which models are being utilised, but there are more fundamental problems e.g. the parameters of a model are often highly correlated and there are multiple parameter sets that are equally capable of describing the observational data.

Calibration is usually performed using either a manual or an automated procedure. Manual calibration involves the alteration of the model parameters by the user on a semi-intuitive trial-and-error basis (Boyle et al., 2000). The measures for the closeness of fit between the observed and simulated catchment response (usually a hydrograph) may be subjective, based on a visual comparison, coupled with more objective statistical measures of the differences between the observed and simulated response (e.g. the Nash and Sutcliffe efficiency). Automated calibration techniques use a search algorithm to identify the model parameters that minimise the chosen objective measure. The automation of the calibration process eliminates the subjective human judgements associated with the manual approach and is also less labour intensive. However, the automated procedure is very dependent upon the choice of objective function, and it has been argued that the hydrographs produced by such methods are often not considered acceptable by hydrologists (Boyle et al., 2000).

Once calibrated, the model must be shown to provide a good representation of the hydrological system. There is some debate and confusion about the appropriate use of terminology for this procedure, which is typically termed validation (to denote an establishment of legitimacy). Oreskes et al. (1994) argue that validation is impossible in natural systems as they are never closed and model results are always nonunique, and that ‘confirmation’ is a more appropriate term, indicating that the model results corroborate the hypothesis, i.e. the chosen model structure is a satisfactory representation of the catchment. In the following discussion the term ‘validation’ is used to indicate whether a predictive hydrological model is acceptable for the intended use (see Refsgaard and Henriksen, 2004; Rykiel, 1996). This is usually performed by testing a model’s ability to reproduce some catchment response data that were not used for the calibration of the model.

Before model calibration/validation is undertaken, the purpose of the modelling exercise, the criteria that must be met for the model to be declared acceptable for use, and the context in which the model is intended to operate all require specification (Rykiel, 1996). Purpose is usually implicitly defined from the modelling application. However, there appear to be few examples in the literature in which the criteria and context are specified before the modelling is performed. The criterion should tightly define the validation tests that need to be 'passed' before the model is accepted as fit for purpose. These tests, which will be dependent on the intended application of the model, are needed to convey the level of confidence in the predictions to the non-specialist user. Context embodies all of the assumptions made, and will therefore preclude operation under certain conditions. It is essential that non-specialist users be informed of the context of a hydrological model, especially given the widespread belief that modelling can bring an increased amount of confidence into the decision making process.

The credibility of the validation step depends on the power of the methods used to challenge the model hypothesis (Mroczkowski et al., 1997). Klemes (1986) proposed a hierarchical scheme for model validation:

1. Split-sample test, in which the model is calibrated over one time period of data and validated against another. This tests a model's ability to predict flows under similar conditions for which it was calibrated;
2. Differential split-sample test, in which calibration is performed with certain environmental conditions (e.g. climatic or land use) and then validated in periods with different conditions. This tests a model's ability to predict flows outside the conditions for which it was calibrated;
3. Proxy-basin test, with calibration performed in one or more catchments, and then validated in another catchment with similar characteristics. Parameters may be modified for use in the validation catchment using expert knowledge, but calibration may not be performed. This tests the transferability of a model;
4. Proxy-basin differential split-sample test, which combines (2) and (3), tests the transferability of a model to an independent catchment.

The majority of hydrological studies available in the literature, including the majority of the land use change studies presented above, perform a split-sample test (1), which Klemes (1986) argues is the minimum requirement for evaluating model performance for operational application. Tests (2), (3) and (4) have particular relevance for the simulation of land use change, but there are few high quality data sets available for performing differential tests. The study of Sefton and Howarth (1998) can be regarded as a proxy-basin test (3), in which regressions equations were developed relating a models parameter values to catchment properties. Proxy data is widely used for the estimation of flows in ungauged basins. For example, the FEH method for obtaining the median annual flood (QMED) uses regression equations based on information derived from HOST.

‘Multi-response’ calibration is an extension to split-sample testing, in which hydrological measurements in addition to discharge are used to assess model performance (e.g. groundwater levels). Mroczkowski et al. (1997) modelled a catchment in which clear-felling occurred 3 years after the commencement of monitoring. Under forested conditions the streamflow was ephemeral, but deforestation led to a rise in the groundwater table and the development of a groundwater discharge zone in the riparian region. Two model conceptualisations were devised, a ‘correct’ one with a discharge zone and an ‘incorrect’ one without. In a split-sample validation test, it was found that both model formulations were capable of adequately describing the observed streamflow record, indicating that streamflow alone was an inadequate test of model structure. It was only with the introduction of an additional model component to simulate stream chloride concentrations, which depend on the flowpath, that the ‘incorrect’ model formulation could be rejected. Franks et al. (1998) used remotely sensed saturated area data to reject parameter sets derived under a Monte Carlo framework (GLUE: Beven and Binley, 1992) that were previously accepted on the basis of streamflow alone.

Boyle et al. (2000) suggested the use of multicriteria calibration, in which several user-defined performance criteria are selected for the representation of the closeness of fit between the model output and an observed series. In comparison to using a single criterion, it was argued that a multicriteria formulation can more closely replicate the strategies used in manual calibration, but with the advantages a computerised search algorithm gives in terms of reducing user time and effort. It was acknowledged that there are still outstanding research themes associated with this approach, including the selection of the criteria and the evaluation of the sensitivity of the results to the number of criteria.

It has been argued that ‘soft’ qualitative data obtained from field studies (e.g. knowledge of the dominant runoff processes) is not utilised by the modeller, who requires hard information (e.g. streamflow records) for calibration (Seibert and McDonnell, 2002). Fuzzy measures, which reflect imperfect knowledge, offer the potential to incorporate discontinuous, numerically approximate values into an automated calibration, thereby improving the internal representation of the model. Seibert and McDonnell (2002) used a three reservoir, 16 parameter, conceptual model, formulated from knowledge gained in field experiments, for the simulation of a head water research catchment. Firstly, the model was calibrated using only hard data (runoff and two groundwater level series). A very good fit was achieved between the simulated and observed streamflows. Secondly, soft data were introduced into the calibration procedure (new water contribution, groundwater information and parameter value ranges). Perhaps unsurprisingly, the efficiency of the streamflow predictions decreased, but it was concluded that the internal catchment dynamics were simulated more realistically. The realistic representation of overall catchment functioning should provide a more robust model for the extrapolation of predictions beyond historical conditions. However, using multi-response data in calibration does have limitations, particularly as there are no theoretical guidelines for the selection of the weighting factors needed to combine the measures of the model’s quality of fit to the different response data (Kavetski et al., 2002). The study of Franks et al. (1998) was also an application of fuzzy calibration, as the saturated area information was very ‘soft’.

The ‘blind’ validation methodology (Ewen and Parkin, 1996) is suitable for assessing a model’s ability to make predictions in applications for which there are no measured hydrological data available (e.g. ungauged catchments, land use and climate change). Essentially, a series of tests is defined for the hydrological features of interest. Without viewing the observed catchment response data (i.e. ‘blind’), the modeller then performs an ensemble of simulations, with the chosen parameter values reflecting uncertainty, from which prediction bounds are derived. Data collected in the field, literature values and any other sources of information not derived from the catchment response data may be used to assist in the selection of the model parameter values. A limited number of feasible parameter sets are selected on the basis of this information and a simulation is performed for each. The prediction bounds are then calculated for each feature in a simple fashion, e.g. when predicting stream discharge, the minimum and maximum bound values are simply taken as the minimum and maximum seen in any of the simulations. The observations are then compared against the prediction bounds, and a pass or fail criterion is used to assess success. One potential draw back of this technique is the central role that the hydrologist plays in the derivation of the bounds. The tests incorporate modelling skills, which are built up over time, and consequently the level of skill is dependent upon those who perform the work. However, it is also argued that this method forces the hydrologist to understand how the catchment functions to a greater extent than the automated calibration approach. The results from any method that includes subjective steps will be to some degree dependent on the hydrologist.

Several calibration and validation techniques for the evaluation of model performance have been discussed. For the study of impact, there is a need to simulate good predictions of ‘unchanged’ and ‘changed’ conditions. The above methods may be used to perform a rigorous assessment of model performance under unchanged conditions, but only the blind method attempts to directly address how accurate a rainfall-runoff model might be for the prediction of the changed conditions, for which calibration data will not be available. Also there are few attempts to ascertain which types of site specific data (field observations, maps, etc.) are of most use in constraining a model’s parameters. This may reflect the wide use of semi-lumped and lumped conceptual models in catchment scale modelling, for which field observations of soil and other catchment properties are of limited use. It may possibly be advantageous if the model possessed some physical basis, allowing a more direct link between modern agriculture practices and the model process descriptions, and thereby data measurements and the models parameter values. Whichever approach is taken, the uncertainty in the resulting predictions will need to be considered.

Uncertainty

Uncertainty in rainfall-runoff modelling simulations originates from uncertainty in the forcing data (e.g. rainfall), uncertainty in the model parameters (e.g. saturated hydraulic conductivities), and uncertainty derived from errors in the structure of the rainfall-runoff model (e.g. limitations in the way that infiltration is represented). In the studies of land use change presented above, a rigorous evaluation of the uncertainty in the predictions was not performed. Nandakumar and Mein (1997) did analyse errors in forcing data and model parameters, but other sources of uncertainty were not considered. Lukey et al. (2000) considered uncertainty in the selection of the parameter values.

The most established method for handling uncertainty in rainfall-runoff modelling is the Generalised Likelihood Uncertainty Estimate (GLUE) method (Beven and Binley, 1992; Beven and Freer, 2001; Binley and Beven, 2003; Blazkova et al., 2001; Cameron et al., 2000; Feyen et al., 2001; Peters et al., 2003). GLUE, introduced by Beven and Binley (1992), rejects the concept of a unique optimal parameter set (and model structure) and instead recognises that there are many models of a catchment that are acceptably consistent with the observations ('equifinality'). A Monte Carlo analysis is performed, in which thousands of model runs are typically made using parameter values selected from pre-specified ranges. The acceptability of each model run is assessed by comparing the simulated catchment response data against the observational data using some chosen quantitative measure of performance, which is interpreted as a likelihood measure. Those model runs in which the likelihood is less than a selected threshold are rejected as not being representative of the catchment hydrology ('nonbehavioural'). The likelihoods of those runs not rejected are then rescaled so that their distribution integrates to 1.0. At each timestep, the outputs from the retained model runs are weighted by their likelihood values and ranked to form a cumulative distribution, from which bounds (quantiles) are chosen to represent model uncertainty. To estimate the uncertainty associated with a change, the above procedure could then be performed using parameter sets drawn from new feasible parameter ranges that reflect the altered catchment properties. Impact is assessed by comparing the changed and unchanged cumulative distributions of the predicted variables. However, since in calibration it is the parameter set that produces a behavioural simulation, there will be difficulty in properly reflecting the interactions between different parameters that might provide parameter sets that could be behavioural under the changed conditions. Beven (2000) has noted that this requires 'drifting' the cloud of parameter sets through the model space to represent the changed conditions.

A disadvantage of the GLUE approach is the number of subjective decisions required (the choice of parameters to be included in the analysis, feasible parameter ranges, a sampling strategy to select parameter sets, the likelihood function and a threshold for model rejection), but it is argued that the explicit nature of these decisions allows discussion and evaluation by others (Beven, 2001b). Also, the high computational requirements associated with Monte Carlo simulation mean that it is often not possible to perform this technique using PBD models.

GLUE treats the error series associated with a parameter set in calibration implicitly, weighting the predictions as if the error structures might be expected to be ‘similar’ in prediction. In this way any complex error structures due to input error, model structural error, observation errors etc. should be treated without having to make explicit assumptions. An extension of GLUE to try to take more explicit account of different sources of error is presently being investigated (Beven, 2004). For progress to be made in predicting impacts there is a need to understand the sources of uncertainty, identifying the errors associated with the model structure and the uncertainty in the parameter sets.

An alternative approach to uncertainty evaluation is blind validation, but this also requires subjective decisions to be made and does not attempt to quantify the individual sources of error. However, the GLUE approach employs response data in evaluating the uncertainty whereas the blind validation approach does not; for the latter the response data are only used to evaluate the predicted bounds. They are therefore addressing different problems; GLUE is providing estimates of uncertainty conditioned by the available response data, whereas blind validation predicts uncertainty bounds without using any response data.

4. Conclusions

The most comprehensive statistical analysis of UK flood records for the identification of historical changes in flood magnitude and frequency was conducted as part of the Flood Estimation Handbook (Institute of Hydrology, 1999). In this study significant impacts due to climate or land use change were not demonstrated, 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. In addition, the majority of the records used within this study were not from catchments experiencing major land cover change, but land management change was apparently not considered. However, even in small catchment scale experimental studies where major land use changes are known to have taken place, the observed changes in flooding are rarely found to be statistically significant due to climatic variability.

A number of empirical studies have been reported in the literature in which various hypotheses about land use change impacts have been made and explored using some form of data analysis. There is evidence linking autumn-sown cereal fields and local ‘muddy floods’ during the autumn in the South Downs (Boardman et al., 2003), which is supported by studies from France and Belgium (Bielders et al., 2003; Papy and Douyer, 1991; Verstraeten and Poesen, 1999). A study on the Yorkshire Ouse catchment did not establish a significant link between land use and flooding because of data limitations and the influence of climatic variability (Lane, 2003). However, circumstantial evidence was put forward to suggest that changes in agricultural practices may have resulted in increased flood runoff (Samson, 1996).

From a review of the literature, no clear consensus emerges on the type of rainfall-runoff model required for the prediction of the impacts of land use and management change on flooding. This reflects the absence of a widely accepted hydrological theory on which simulations of catchment behaviour can be based.

Physically based models are often thought to be the most suitable choice for simulating the hydrological effects of land use change. The parameter values of these models relate directly to catchment characteristics, so can, in theory, be modified in a direct way to reflect change. Several examples of impact studies in which this type of model has been used are available in the literature (e.g. De Roo et al., 2001; Fritsch et al., 2000). However, in practice, the application of the current generation of physically based models has proved difficult. Many of the problems stem from difficulties in applying their physics-based equations, derived from small-scale observations, to the often large computational grids used in modelling applications. In particular, it is not generally possible to account for sub-grid heterogeneity in geophysical properties and some hydrological processes are not represented. To overcome these deficiencies ‘effective’ parameter values are required, which may differ from those measured in the field.

The main alternate to the physically based approach is conceptual rainfall-runoff modelling, in which the hydrological sub-processes occurring within a catchment are aggregated into several key responses. These models have few parameters so are easy to work with and their mathematical performance can be analysed in depth. However, the use of aggregate process descriptions means that there is no direct link between measurable catchment properties and the parameter values. One technique to overcome this is to develop mathematical relationships between the parameter values obtained from calibration exercises and the catchment properties (e.g. Sefton and Howarth, 1998). Note that results using such methods have generally been poor to date, in part because of the effects of errors in model inputs and structures in the calibration process. Also, only the fractional areas of broad land cover categories are incorporated into the relationships, and it is not known how to represent the more subtle effects of management practices.

At the catchment scale the implementation of change will be spatially piecemeal. The importance of the location of change on peak flows was demonstrated in the modelling study of Bormann et al. (1999). Whichever type of model is chosen for impact assessment, it will probably need to be distributed to allow the changes at different locations within the catchment to be represented. Land use and management change affects not only the magnitude of local scale runoff, but also the timing. To represent changes in timing at locations across the catchment, the chosen model will also probably need to explicitly represent the channel network. This will also allow the effects of alterations in the properties of channel and floodplain attributes to be incorporated, which were also found to be of importance for the attenuation of flow in the study of Bormann et al. (1999).

The standard approach to assessing impact involves (1) calibrating a rainfall-runoff model and running simulations of the catchment in its state prior to land use and management changes being made; (2) changing the model's parameters to reflect the changes in land use and management; (3) running simulations using the changed parameters; and (4) estimating the effects of the changes, based on the differences between the runoff responses in the step 3 and step 1 simulations. In the majority of the land use change studies available in the literature, calibration was performed using only discharge data, this being the most readily available catchment response data. However, the wider literature indicates that the ability to reproduce streamflow is not a rigorous test of a model's structure. Given that a poorly formulated model of the present is unlikely to be robust in predicting the future, more attention should be paid to the validation of catchment models.

After calibration, the model is assumed fit for the purpose and the parameters are modified using expert knowledge, or some other method, to represent change. Unfortunately, the literature provides little guidance on how the parameters of a model can be suitably modified to represent a given change. Usually only the fractional coverages of land cover types are altered, and no consideration is given to associated changes in land management practices and soil properties. The one exception to this is the study of Niehoff et al. (2002), in which additional processes were added to a physically based model to represent the impacts of soil aggregate breakdown and macropores on infiltration. The use of only land cover probably reflects reliance in catchment scale modelling on regional GIS datasets, which is due, in part, to the limited availability of field scale measurements.

The need to specify model parameters for future changed conditions is an obvious source of uncertainty in impact assessment. However, even when simulating current conditions, there are sources of uncertainty deriving from errors; in the input data, the model parameter values and the model structure. A better understanding of the sources and effects of uncertainty is needed if progress is to be made in predicting impacts.

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