Rural Land Management Impacts on Catchment Scale Flood Risk

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A Thesis Entitled

Rural Land Management Impacts on Catchment Scale Flood Risk

Submitted by

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Department of Geography

A Candidate for the Degree of Doctor of Philosophy 2010

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Abstract

Rural land management impacts on catchment scale flood risk

This thesis examines the relationship between rural land management and downstream flood risk. The recent increase in flood frequency and magnitude has been hypothesised to have been caused by either climate change or land management. The theoretical basis for why these factors might increase flood risk is well known, but showing their impact on downstream flood risk remains a challenge. Field scale studies have found that changing land management practices does affect local runoff and streamflow. Upscaling these effects to the catchment scale continues to be problematic, both conceptually and, more importantly, methodologically. Conceptually, upscaling is critical. As land management may impact upon the relative timing as well as the magnitude of runoff, any changes in land management practice may lead to changes in the synchronisation of tributaries flows, either reducing or increasing downstream flood risk. Methodologically, understanding this effect requires capturing the spatial resolution associated with field-scale hydrological processes simultaneously with the upscaling of these processes to the downstream locations where flood risk is of concern. Most approaches to this problem aim to upscale from individual grid cells to whole catchments, something that restricts the complexity of possible process representation, produces models that may not be parsimonious with the data needed to calibrate them and, faced with data uncertainties, provides computational limitations on the extent to which model uncertainty can be fully explored. Rather than upscaling to problems of concern, this thesis seeks to downscale from locations of known flood risk, as a means of identifying where land use management changes might be beneficial and then uses numerical modelling to identify the kinds of management changes required in those downscaled locations. Thus, the aim of this thesis is to test an approach to understanding the impacts of rural land management upon flood risk based upon catchment-to-source downscaling.

This thesis uses the case study of the River Eden catchment (2400 km^2) as a test case. Firstly the downstream flood risk problem was assessed using both gauged data and documentary evidence to investigate the historical flood record. This found the last decade does not differ significantly from previous flood rich periods, which were defined as 1) 1873-1904; 2) 1923-1933; and 3) 1994-present. Second, the potential causes of floods within the catchment were investigated; firstly climate variability was assessed using Lamb weather types, which found that five weather types were responsible for causing 90% of the floods in the last 30 years. Third, spatial downscaling of catchment-scale flood risk was undertaken using two methods; data-based statistical analysis; and hydraulic modelling. Both approaches consider the magnitudes and the timing of the flows from each major sub-catchment. The statistical approach involved a principal components analysis to simplify the complex sub-catchment interactions and a stepwise regression to predict downstream flood risk. The hydraulic modelling approach used iSIS-Flow to undertake a series of numerical experiments, where the input hydrographs from each tributary were shifted individually and the effect on downstream peak stage assessed. Both these approaches found that the Upper Eden and Eamont sub-catchments were the most important in explaining downstream flood risk. The Eamont sub-catchment was chosen for future analysis as: (1) it was shown to have a significant impact on downstream flood risk; and (2) it had range of data and information needed for modelling land use changes.

The second part of this thesis explored the land management scenarios that could be used to reduce flood risk at the catchment scale. The scenarios to be tested were determined through a stakeholder participation approach, whereby workshops were held to brainstorm and prioritise land management options, and then to identify specific locations within the Eamont sub-catchment where they could tested. There were two main types of land management scenarios chosen: (1) landscape-scale changes, including afforestation and compaction; and (2) channel modification and floodplain storage scenarios, including flood bank removal and wet woodland creation. The hydrological model CRUM3 was used to test the catchment scale land use changes, while the hydraulic model iSIS-Flow was used to test the channel and floodplain scenarios. It was found that through changing the whole of a small sub-catchment (Dacre Beck), the scenarios of reducing compaction and arabilisation could reduce catchment scale (2400 km^2) flood risk by up to 3.5% for a 1 in 175 year flood event (January 2005). Changing localised floodplain roughness reduced sub-catchment (Lowther) peak stage by up to 0.134 m. This impact diminished to hardly any effect on peak flow magnitudes at the sub-catchment scale (Eamont). However, these scenarios caused a delay of the flood peak by up to 5 hours at the sub-catchment scale, which has been found to reduce peak stage at Carlisle by between 0.167 m to 0.232 m, corresponding to a 5.8% decrease in peak discharge. A key conclusion is that land management practices have been shown to have an effect on catchment scale flooding, even for extreme flood events. However, the effect of land management scenarios are both spatially and temporally dependent i.e. the same land management practice has different effects depending on where it is implemented, and when implemented in the same location has different effects on different flood events.

Acknowledgements

Firstly I just want to say what an enjoyable experience doing my PhD has been. This is all because of the interesting topic it has been researching, but more importantly the people who I have worked alongside. It has been an honour to be supervised by some great supervisors who have been supportive and offered encouragement throughout. First, Stuart Lane, who has offered some great "big ideas" but still allowed me to lead the direction of the project. Richard Hardy has provided some great advice and always been there to answer the problems I have encountered. Sim Reaney has been of great support on the modelling part of the project, considering I hadn't "modelled" before my PhD. I really appreciate all the help that they have given me and feel that my thesis is far better than if it had not had their insight and guidance.

I want to thank the industrial partners; the Environment Agency and United Utilities, for funding my PhD, and also the Eden Rivers Trust for coming up with the initial questions, even if I have changed them quite a bit over the years - remember the original aim of "the effects of wetlands on high and low river flows" -, but I hope that everyone involved is happy with the broader scope work I have done. I want to thank people from these organisations who have assisted me personally through the research. Firstly, Lucy Dugdale (of ERT) who has been of great support, having been through the PhD experience herself, understood the pressures of "doing research" and stakeholders needs and questions. I would like to thank her and Joe for letting me stay with them on my many visits to Penrith, along with Linda Cook and her son Jordi, who introduced me to many new things such as squash and Indian food. Second, I would like to thank Maggie Robinson, Becky Helm, Joanne Backshall, Will Cleasby and Simon Johnson of the ERT for making me feel so welcome on my many visits to their offices. Thanks, must also be extended to the Trustees, especially Nick Lloyd, Nick Marriner and Ian Gregg, and to ART's Alistair Maltby. Third, many people from the Environment Agency have provided both advice and data; Iwan Lawton has been of great help with iSIS and been a great first call of contact; Glyn Vaughan has shown real interest and enthusiasm about the work I have done, despite his busy schedule; Jenny Clift and Dawn Matthews have been of great help providing me with the vast amounts of gauged data I required. Finally I would like to thank the "stakeholders" from the many professional partners involved in the project, who have made the findings potentially more useful. These were Tim Youngs (RSPB), Stephen Lund (Natural England) and Andrew Herbert (Lake District National Park). It has been challenging at times, but overall has been of real benefit to have them involved in the project.

I also want to thank the many students and friends who I have worked alongside during my PhD. Firstly, “Team Lane” who which I have shared an office with; Dave, who has helped with the mysteries of computer coding; Emma R, who helped with statistics; and Carly, who has made coming to work so fun, as well as providing intellectual insights. I also want to mention Peter, Emma N, Jonah, Brian, Rob, Phil, David, Katie R, and Victoria, who I have shared what must be the quietest office ever, yet make coffee times so memorable and fun, along with Emma W, Tasha, Vicky and Katie O. Thanks must also be extended to Krysia who has always been so helpful and chatty.

Finally, I want to give huge thanks to my mother, Amy; and my brother, Graham, who have always given me loads of support, encouragement and love.

As you can see, I can’t ever keep anything short, even my acknowledgements, so I hope anyone who reads this has the stamina to see it through to the end.

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Chapter 1

Introduction: Research Framework and Aims

1.1. Thesis Aim

This thesis aims to investigate the potential impact of rural land management for catchment-scale flood risk reduction. It is widely thought that flood risk has increased during the last two decades, with several hydrologists claiming we have entered a flood rich period or cluster (Werritty, 2002; Lane, 2008). Indeed, flood risk management has become a top priority within the hydrology community. There are two hypotheses for these changing patterns: (1) changes in climate, and notably the sequencing of extreme wet and dry periods, leading to a greater magnitude and/or frequency of hydrological extremes (Arnell, 2003; Huntington, 2006); and (2) the effects of land management in changing the relationship between extreme climate events and hydrological extremes (O'Connell *et al.*, 2004; Lane *et al.*, 2007). Proving these hypotheses, especially the second, remains a challenge.

This thesis is concerned with the second of these hypotheses and specifically whether or not there are situations where land management might be relevant to flood risk management at the catchment rather than the plot-scale. In relation to flood risk, much of the context for this derives from Defra (O'Connell *et al.*, 2004) and Foresight Future Flooding Study (Lane *et al.*, 2007) research that suggests we simply do not understand how, and even if, the impacts on hydrological regimes of local changes in land management scale up to the river basin scale. This upscaling is extremely difficult with data (O'Connell *et al.*, 2004) and through using numerical models due to the large scale of catchments. An alternative approach is to use data to determine which part of the catchment to focus upon. The aim of this project is the development and application of an approach based on downscaling catchment scale flooding to identify which of the upstream contributing tributaries are relevant.

1.2. The downscaling approach

The theoretical basis for why climate change and land management might impact on flood risk is well established, with climate, and especially precipitation patterns driving flood risk, and land management impacting on the way in which rainfall interacts with the land surface to generate runoff (Holman *et al.*, 2003). However proving these hypotheses still remains a challenge, with the link between land management and catchment scale flood risk proving elusive.

Field scale studies have found that changing land management practices may impact on local runoff and streamflow, but upscaling these effects to the catchment scale continues to be problematic, both conceptually and more importantly methodologically (Wheater, 2002). This is due to three main reasons. First, attenuation effects including tributary interactions may prevent land use signals from propagating downstream. Second, the nature of land use is spatially variable and not necessarily readily determined over whole catchments. Third, land management practices may either amplify or balance out the impact on flows according to where and when they are adopted (Lane *et al.*, 2007), depending on the spatio-temporal pattern of precipitation.

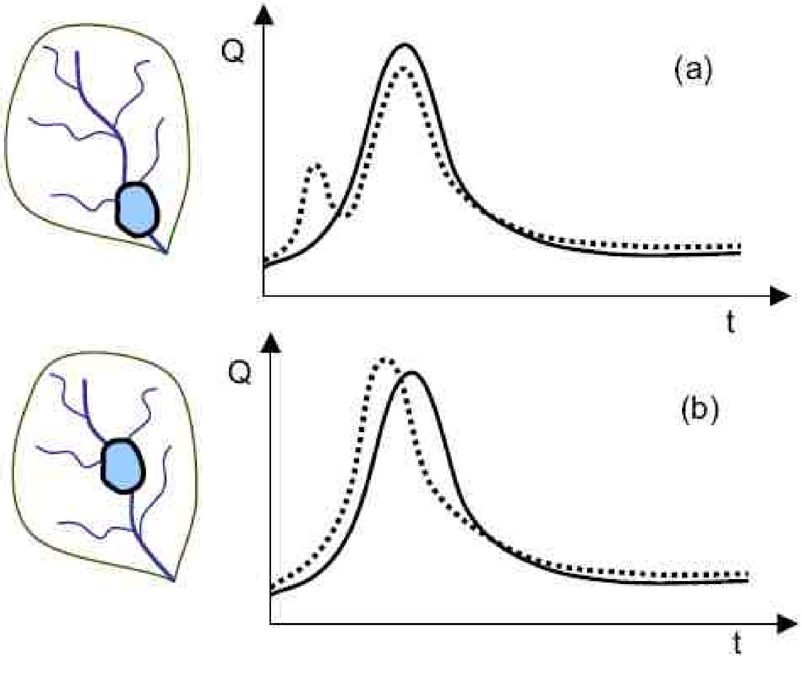


Figure 1.1 *Effect of land management change location upon the downstream flood hydrograph. (Blue area shows area of compacted soils, solid line indicates pre-change hydrograph, and dashed line shows post-change hydrograph). (O'Connell et al., 2004)*

Figure 1.1 shows how the hypothetical impact on downstream peak flows of an area of compacted agricultural land is dependent upon where in the catchment the changes occur. When the area of compacted land is downstream (Figure 1.1a), the rapid runoff caused by the less permeable surface occurs before the main peak arrives, meaning that the main peak is now preceded by a smaller peak, but the main peak flow is reduced in magnitude. If the compacted land is upstream (Figure 1.1b), then the rapid localised runoff coincides with the main flood wave, leading to a higher magnitude peak downstream. Along with highlighting the importance of spatial location of change, this example highlights the importance of the timing of runoff and flows from different parts of the whole catchment.

The importance of catchment-scale interactions creates a major challenge for the study of the effect of land use on downstream flooding. This challenge arises because catchments do not necessarily lend themselves to conventional, field-based experimental testing as natural variability can confound interpretations of specially designed land management experiments. Furthermore, there are many possible measures to test and locations to test them in. Finally, upscaling the effect to the catchment scale means data are needed from multiple locations. Thus, numerical modelling has proved to be crucial. However, catchment-scale numerical models still have limitations because: (1) the parameters in each model grid cell are rarely known, (Dunn and Lilly, 2001); and (2) as the spatial scale of analysis has to be increased, so to does the resolution of the model, requiring process representation to be simplified (Bormann *et al.*, 2009).

To address these issues, this thesis reverses the normal approach to analysis by seeking to work upstream from the known flood risk problem to focus in on the contributing sub-catchments (upstream causes), thought to be worth exploring as candidates for land management change. In other words, rather than upscaling to identify problems of concern, and then simulating impacts on these problems, this thesis downscales from known problems of concern to focus on those sub-catchments most likely to be contributing to those problems.

This approach could have several benefits over the traditional upscaling approach. First, it may be possible to detect the effect of land use changes in upstream areas on downstream flood risk, by weighting the areas of most importance in determining flood risk in hydrological models. Second, it provides an efficient method to optimise areas for land use management changes in the light of restricted resources. Third, this downscaling approach allows targets to be found for how much flows from each sub-catchment have to be changed to have the desired effects on flooding downstream. Specifically an objective for downstream flood reduction can be set, and then this downscaled to the contributing sub-catchments, where targets for hydrograph change in terms of flood peak magnitude and timing can be determined which will deliver the required downstream effect. Then, traditional hydrological modelling can be used on a smaller sub-catchment scale to try and achieve these targets, which also has advantages to whole catchment models, such as model run time reduction, reducing data demands, allowing for fuller uncertainty analysis.

Downscaling results in a smaller hydrological focus (area). This allows a second critical challenge of rural land management to be addressed: delivery. Lane *et al.* (2007) note that rural land management measures represent a very different kind of approach to reducing flood risk as they are diffuse, require many landowners to agree to them and that these landowners may not be the ones to gain from the measures. Thus, their social and economic acceptability must be secured, meaning that stakeholders must be involved in evaluating what to try where. The smaller spatial extent of focus makes this delivery more feasible.

1.3. Thesis Objectives

The overall aim of this thesis is:

To investigate the potential impact of rural land management for catchment scale flood risk reduction.

This aim will be achieved through the following objectives:

1) *To assess the problem of flood risk in the case study catchment (River Eden) including how the frequency and magnitude of flooding has changed over different spatial and temporal scales, and the potential drivers of these changes.*

It is widely believed both in public and academic domains that flood risk is increasing (Robson, 2002; Hannaford and Marsh, 2007). This thesis downscales the downstream problem (i.e. flood risk) to its upstream causes (i.e. sub-catchment flows). To do this, the flood risk problem first has to be identified and second the extent of the problem has to be assessed. Flood records can be analysed for both flood frequency, using peak over threshold series (Bayliss and Jones, 1993) and flood peak magnitude, using annual maximum flood series (Svensson *et al*., 2005). However, these analyses are particularly sensitive to the length of the record (Kundzewicz and Robson, 2004; Dixon, 2006). Most of the UK gauging station network was commissioned in the 1960s and 1970s (Lees, 1987), meaning that most records are only 30-40 years long. Before analysis proceeds data will have to be evaluated to ensure it is suitable.

A key theme in this thesis is scale, and it is important that flood risk is assessed at several spatial scales. Therefore, gauging stations from different sub-catchments will be assessed over the whole record length for statistically significant trends, if available data permits this, as smaller sub-catchments are often ungauged (Lees, 1987). Temporal trends are also crucial to determine possible causes of changes in flood risk. Robson (2002) analysed both local and UK flood series and found that there was an increasing trend over the past 30-50 years. This has important implications for the assumption of stationarity of flood frequency (Milly *et al.*, 2008). However, Robson (2002) found no significant relationship over the last 80-120 years. Grew and Werritty, (1995), MacDonald (2006) and Lane (2008) have suggested a pattern and clustering of the worst flood events rather than a random occurrence. Therefore there are two hypotheses of trends in flood frequency: (1) flood rich and flood poor periods; or (2) a unidirectional trend over time. To put the shorter gauged record into a historical context, a longer flood record will be constructed from documentary evidence, following approaches used by Grew and Werritty, (1995), Macdonald *et al.,* (2006) and McEwen, (2006). This historical flood record will be used to test the alternative hypotheses of flood clustering and flood trends.

Two hypotheses have been suggested to explain changes in flood frequency and magnitude. First changes in climate, relating to both changes in temperature and precipitation (Arnell, 2003; Huntington, 2006), and second the effects of land management in changing the process of rainfall to runoff conversion (O’Connell *et al.*, 2004; Lane *et al.*, 2007). The first of these will be assessed through looking at Lamb weather types, which characterise both the type of weather system and the direction it is coming from. The second will not be addressed explicitly but rather explored implicitly by investigating whether or not downscaled interventions have any effect at the catchment scale.

2) *To determine which areas (sub-catchments) of the catchment are the most important in explaining downstream flooding in terms of both the magnitude and timing of the flows.*

   a) *To develop methodologies that are able to achieve this*
   b) *To apply these approaches to the Eden catchment*

The hypotheses of climate change or land use change are complicated by a fundamental impact: the effects of scale. Climate change could manifest at a number of very different scales of response: these could include major synoptic shifts to produce periods of greater cyclonic rainfall; or more intense but shorter duration convective rainfall. The former are more likely to lead to more larger-scale flooding; the latter to greater local-scale flooding. Similar scale impacts are also associated with land management which tends to have impacts that are clearest at the local-scale (Bloschl *et al.*, 2007; O’Connell *et al.*, 2007). If the focus is upon larger-scales of enquiry, it is probable that the relative timing of sub-catchment response is a critical control upon downstream flooding. Indeed, both climate change (e.g. a systematic shift in the dominant direction of rain-bearing cyclones) and land management change (e.g. adoption of land use practices that lead to more rapid hydrological response) could lead to changes in the relative timing of response of sub-catchments and hence downstream flooding. The effect of relative timing on peak flows downstream has been investigated in a limited number of studies (Acreman *et al*., 2003; Lane 2003a; Thomas and Nisbet, 2007).

Often in large catchments the number of potential land use changes and locations where they could be implemented are vast. Therefore this thesis aims to develop approaches whereby the optimum areas to focus limited resources can be discovered. Saghafian and Khosroshahi (2005) identified flood source areas through a combined hydrological-hydraulic modelling approach, whereby tributary inputs were sequentially turned off and the impact downstream assessed through hydrograph change. Roughani et al., (2007) prioritised sub-catchments through changing the contribution of each tributary, also using a modelling approach.

Two methodologies are developed within this thesis, the first developing a statistical approach used by Lane (2003a), and second developing a hydraulic modelling approach. These are applied to the Eden catchment to determine which sub-catchments explain downstream flooding. Furthermore, these approaches allow targets to be found for how much the flow from certain sub-catchments need to be changed to have the desired effect downstream.

3) *To compile a list of potential land management scenarios which are both scientifically testable and practically feasible through stakeholder participation.*

There have been numerous land management practices that have been hypothesised to have an impact on flood risk (O'Connell *et al.*, 2004; Lane *et al.,* 2007) e.g. agriculture (Holman *et al*., 2003; Sullivan *et al.,* 2004), forestry (Robinson, 1998a; 1998b; Archer, 2003), land drainage (Conway and Millar, 1960), channel modification (Acreman *et al.,* 2003), wetlands (Mitsch and Gosselink, 2000). However, not all the possible land management practices are feasible in terms of implementing them in all catchments. This will be dependent upon many factors, including: (1) the current land uses; (2) the landowners acceptability of land use change in terms of its social and economic consequences; and (3) the resources available to implement changes. Furthermore, the spatial distribution of each land use is crucial in determining its effect downstream. Therefore, data and/or models need to be available to test different scenarios in different locations.

This thesis uses active stakeholder engagement to formulate a list of potential land management scenarios that are both scientifically testable and practically feasible in the area identified as the most important in explaining downstream flooding. The advantage of this approach is that local stakeholders possess knowledge that scientists do not, in the form of past flood and management experience, and therefore including local stakeholders in the research process allows knowledge to be co-produced and potentially lead to more useful outcomes.

4) *To determine the relationship between these land management practices and the different hydrological processes which influence downstream high flows, including*

    a) *Partitioning rainfall into runoff*
    b) *Hydrological Connectivity*
    c) *Storage*
    d) *Channel Conveyance*

Different land management practices impact downstream flooding due to their effect on different aspects of the hydrological cycle. Lane *et al.* (2007) suggested several mechanisms through which downstream flooding could be reduced through managing different parts of the hydrological cycle. Some land management practices influence the soil and vegetation characteristics, which affect the hydrological processes of interception, evapotranspiration and infiltration. The first hypothesis is that, by decreasing the partitioning of rainfall into runoff, flood flows can be reduced. The theory behind this suggestion is that more water will be transferred into the slower sub-surface pathway and less into more rapid overland flow (Boardman *et al.,* 2003). Other land uses affect connectivity of elements of the landscape that link the hillslopes and the river channel (Lane *et al.,* 2009). A second hypothesis is that poorly connected systems are less likely to produce flood flows. Another process by which land management can impact flood risk is through water storage (Morris *et al.,* 2002). The third hypothesis is that by retaining water close to source, or at strategic locations where flood attenuation is increased, catchment scale flooding can be mitigated. Once water reaches the channel it is conveyed downstream. The fourth hypothesis relates to slowing the passage of the flood wave downstream, through either increasing flow resistance (channel roughness), altering channel planform (e.g. meandering (Morris *et al.,* 2004) or temporary floodplain storage (Chatterjee *et al.*, 2008)). It is important that the effect of land use changes are understood in terms of general hydrological processes, so that findings can be transferred to other hydrologically similar areas.

5) *To establish the cumulative impact of different land use management practices on high flows, including the scales at which those impacts can be identified*

Once the impact of each land use scenario has been assessed on the individual hydrological processes, the overall effect of the land use change needs to be tested. This is because some land use changes may affect more than one hydrological process, and it is essential to determine which the dominant process is (Lane *et al.,* 2007). The cumulative impact can be investigated at several spatial scales; firstly at the reach scale where the change was made; secondly at the sub-catchment scale; and finally at the whole catchment scale to determine how far downstream the effect propagates (Wheater, 2002).

6) *To produce a series of recommendations for what land management practices can be used to reduce downstream flood risk, and where to implement them.*

As this research has been done in collaboration with stakeholders who manage the Eden catchment, it would be useful to feedback the study's findings to the organisations involved. Furthermore, the findings from this thesis are important to the general debate on the potential of land management to reduce downstream flood risk. There are two key aspects of this, firstly where in the large catchment would be the optimum location to focus resources; and secondly what land management scenarios deliver flood risk reduction in certain situations (i.e. in catchments with certain characteristics).

1.4. Catchment Description

The approaches used throughout this thesis are general methodologies that could be applied to any river catchment. However, for completeness and simplicity, one river system has been chosen for this research: the Eden catchment in Cumbria, North-West England. There are several reasons why this is a suitable catchment to test the approaches and substantive research questions which are the focus of this thesis. First, there was an extreme flood in January 2005 throughout the Eden catchment, with the worst effects seen downstream in the city of Carlisle. Second, the Eden catchment is 2,400 km^2, meaning that it is suitable to assess sub-catchment interactions. Third, it is dominated by rural land uses, meaning that changes to the management of the catchment have the potential to reduce flood risk. Fourth, the river system is well gauged, with a wide range of data, both spatially and temporally. Finally, local stakeholders were interested in exploring the possibility of land management as a possible flood risk management strategy and funded the research.

The Eden catchment, Cumbria, North-West England consists of six major sub-catchments (Figure 1.2); (1) Upper Eden (616 km^2); (2) Eamont (396 km$^{2)}$; (3) Irthing (335 km^2); (4) Petteril (160 km$^{2)}$; (5) Caldew (244 km^2); and (6) Lower Eden (~650 km^2). The Eden catchment is particularly diverse in terms of its climate, topography, soil types, geology, land cover and ecology.

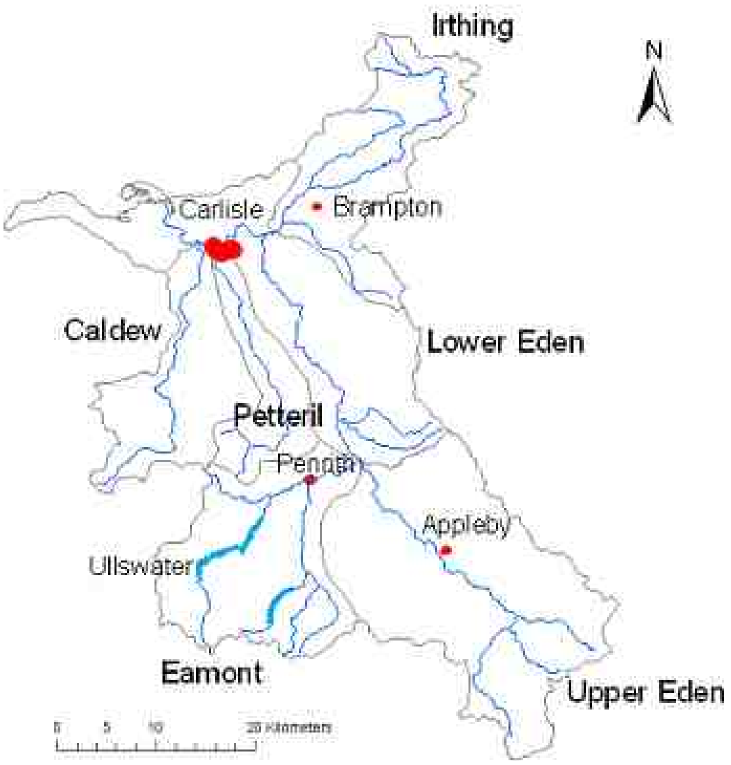


Figure 1.2 *Map of the Eden Catchment*

1.4.1. Climate

The average annual precipitation of the Eden catchment is 1,183 mm. The Eamont sub-catchment receives the highest rainfall per year with an average of 1,768 mm. The precipitation quantities in the highest altitude areas exceed 2,800 mm. The lowland Petteril experiences the lowest rainfall totals with 942 mm per year, while the Lower Eden in the city of Carlisle receives approximately 800 mm every year (Table 1.1). Figure 1.3 shows the average annual precipitation amounts for the Eden catchment.

Sub-Catchment	Average Annual Rainfall (mm)
Upper Eden	1484
Eamont	1768
Irthing	1073
Petteril	942
Caldew	1216

Table 1.1 *Average annual precipitation for sub-catchments in Eden catchment (Environment Agency, Hiflows)*

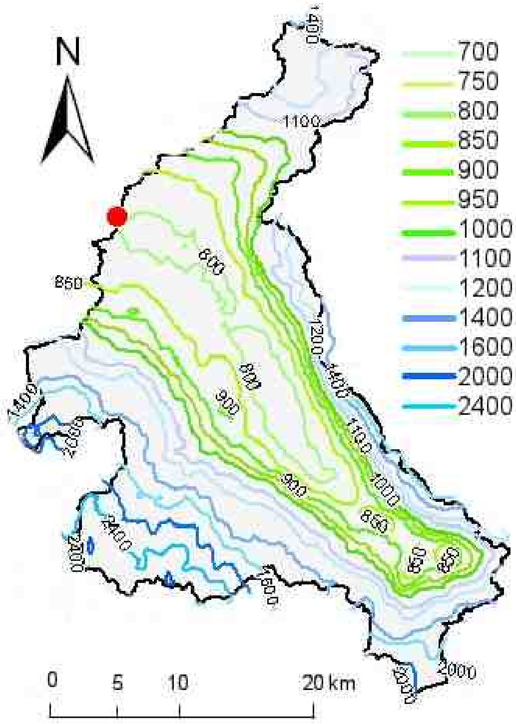


Figure 1.3 *Average annual precipitation (mm) isohyets for Eden catchment (Centre for Ecology and Hydrology, Catchment Spatial Information.*

1.4.2. Topography

The Eden catchment is surrounded by high topography, with the Pennines to the East, the Howgill Fells to the South and the Lake District to the West. The Eden rises in Black Fell Moss on Mallerstang at 690 m OD (Figure 1.4). The channel is quite steep falling to 160 m OD by Kirkby Stephen (Figure 1.5). The steepness of the Eden upstream of Kirkby Stephen means that the Upper Eden is quite flashy in nature. Downstream of Kirkby Stephen, the river valley widens and flattens at a rate of 1.8 m km^{-1} to Appleby in Westmorland (Appleby = 123 m OD, 21km downstream). The Lower Eden has a relatively flat slope, with a decrease of 1.4 m km^{-1}. The city of Carlisle is at an elevation of 9 m OD and has wide floodplains, which are utilised as storage areas during high flows. The Caldew and Eamont have the highest topography, with Skiddaw (931 m OD) and Helvellyn (950 m OD) respectively (Figure 1.4).

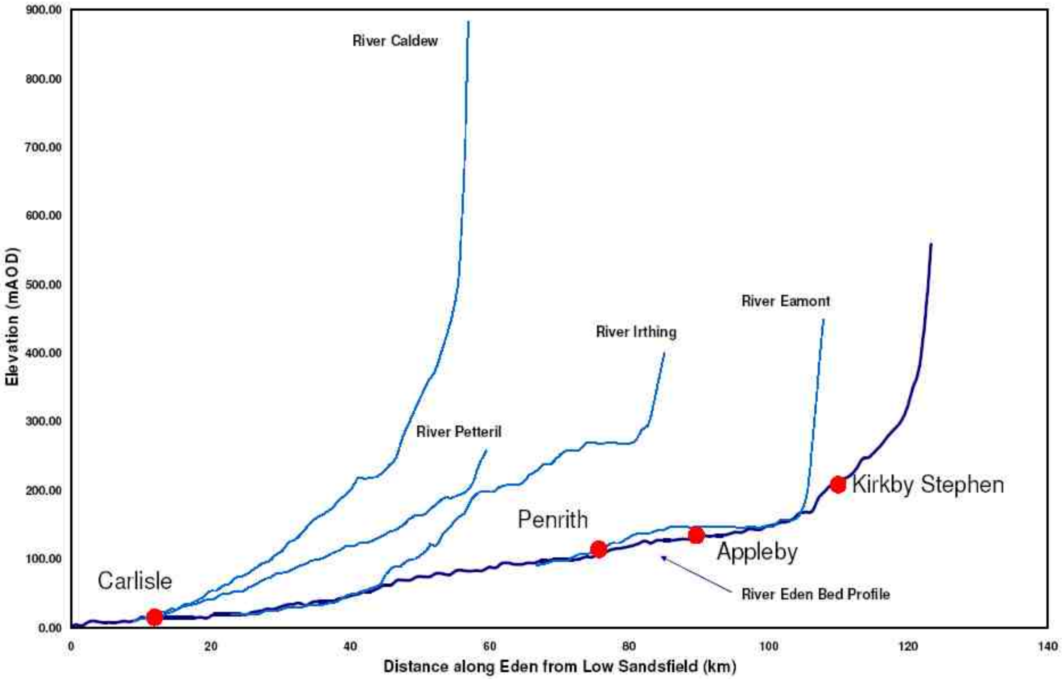


Figure 1.5 *Gradients of the River Eden and its major tributaries (Environment Agency, CFMP, 2008)*

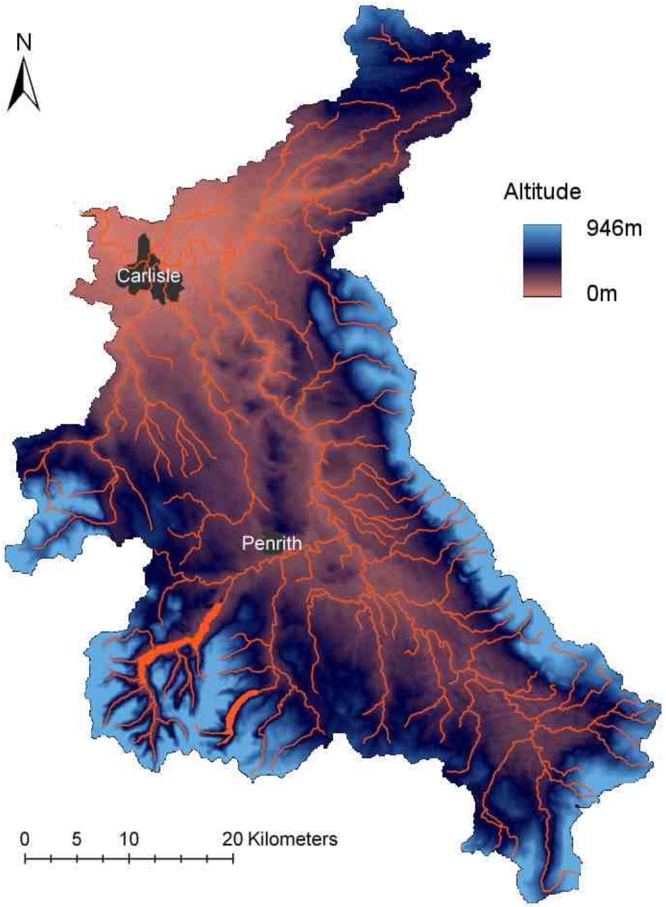


Figure 1.4 *Topographic map of the Eden Catchment (Nextmap)*

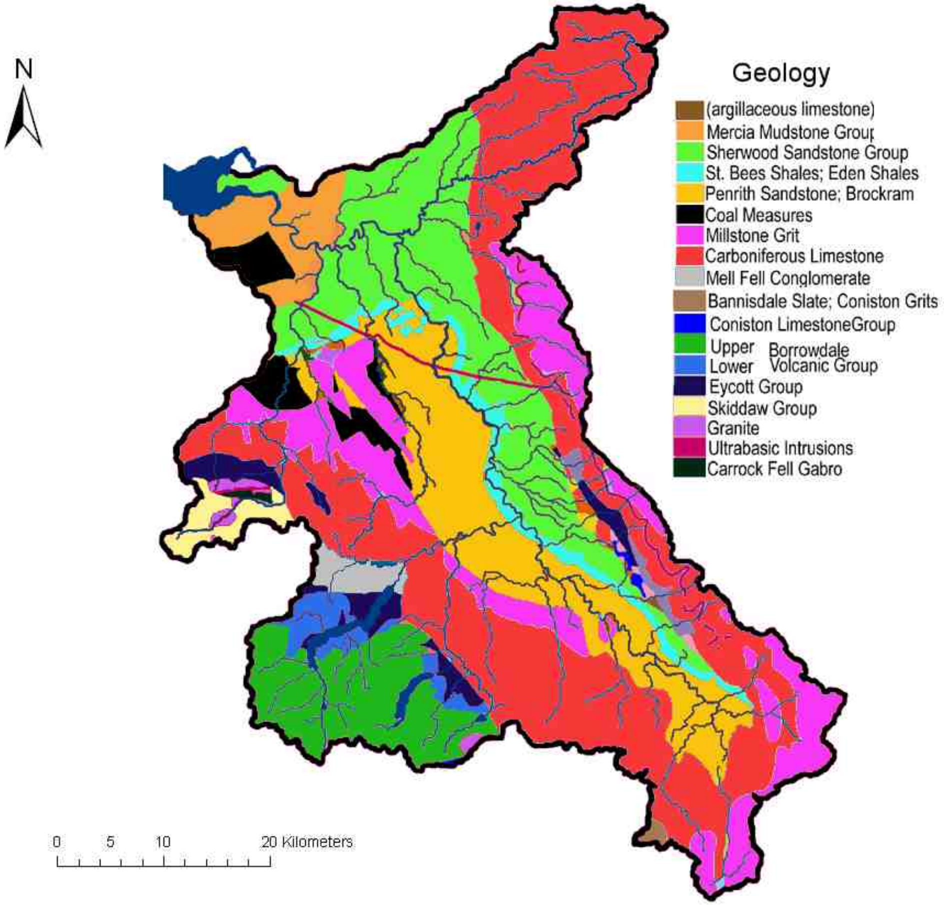
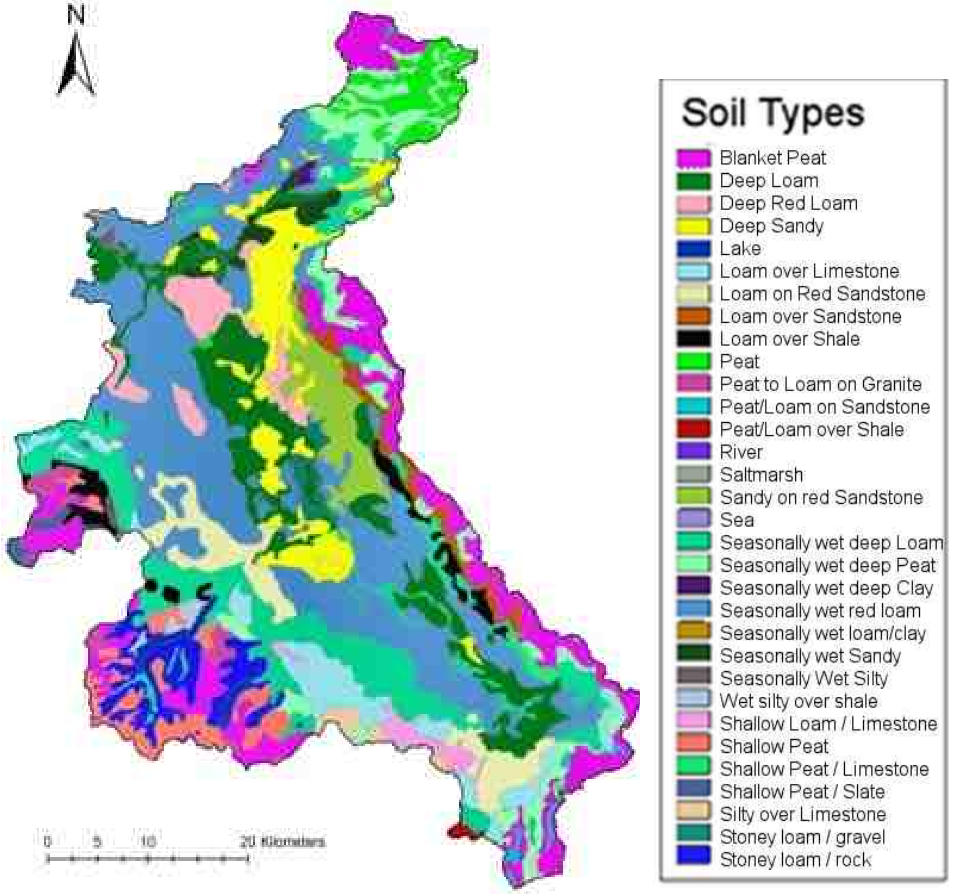


Figure 1.6 *Geology of the Eden Catchment*



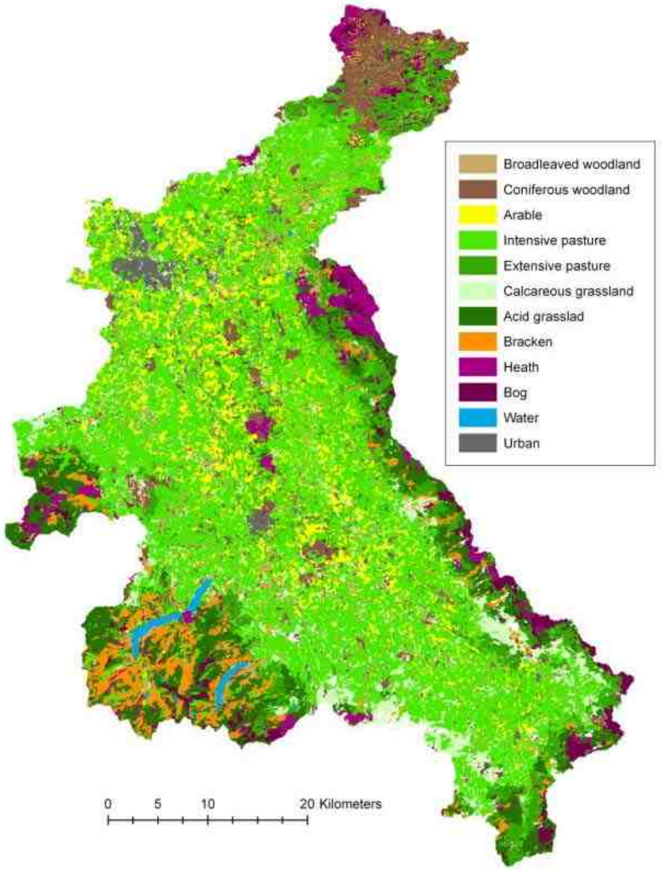


Figure 1.7 *Soil types of the Eden Catchment.*

Figure 1.8 *Land Cover Map of the Eden Catchment*

1.4.3. Geology

The geology of the Eden catchment is shown in Figure 1.6. The source of the River Eden is on carboniferous limestone in the Howgill Fells. This gives rise to mesotrophic rivers, with high chalk contents ($CaCO_3$) which sustains populations of white clawed crayfish. Many of the tributaries to the Upper Eden from the Pennines and the Howgill Fells originate on millstone grit. The main stem of the Eden overlies sandstone (Penrith Sandstone and Sherwood Sandstone). These act as aquifers, allowing groundwater stores to develop, which influence low flows. The Eamont sub-catchment consists of metamorphic volcanic rocks, which are very impermeable and lead to rapid runoff (Environment Agency, CFMP, 2008).

1.4.4. Soil Types

Figure 1.7 shows the soil types of the Eden catchment. The upland areas of the Eden catchment have blanket bog, while the Irthing catchment consists of peat which is about 0.5 m-0.3 m thick. The soil drift in the Upper Eden is dominated by a free draining sandy loam soil, which can be up to 20 m deep. In the areas with limestone geology, this drift layer is thin or non-existent. The Eamont sub-catchment is dominated by clay, or loam over clay soils, which means that the soils are quite impermeable at shallow depths, leading to high runoff rates (Environment Agency, CFMP, 2008).

1.4.5. Land Cover

Figure 1.8 shows the Land Cover Map 2000 classification of land use in the Eden catchment. The Eden catchment is dominated by agriculture, with over 90% of the area being classified as such; 4% of this land is Grade 1 or 2 (Excellent/Very Good), 36% is Grade 3 (Moderate) and 54% is Grade 4 or 5 (Poor). Approximately 11% of the population of the Eden catchment rely on agriculture for their economic income (Mackey Consultants, 2003). The types of agriculture are diverse, from hill sheep farming in the uplands, to mixed pastoral and arable farming in the lowlands. There has been a recent increase in the production of winter cereals and maize. The Upper Eden is particularly renowned for dairy production, while the lowland of the Irthing sub-catchment has extensive beef cattle agriculture.

Only 1% of the catchment is urban, with Carlisle being its largest settlement. The population of Carlisle has increased from 4,000 in 1750 to 71,773 in the 2001 census. The growth of the city has taken place on the floodplains of the Rivers Eden, Petteril and Caldew (Smith and Tobin, 1979). Other notable urban areas include; Penrith, Kirkby Stephen, Temple Sowerby and Brampton, meaning that the Eden catchment population is 167,000 (Environment Agency, 2008). The Irthing sub-catchment has more forestry than the other sub-catchments, with 19% being classified as this land use (Archer, 2003). This consists of plantations of coniferous trees, such as Sitka Spruce and Pine. Fuller *et al.* (1994) used Landsat imagery to determine that 34% of the Irthing sub-catchment is moorland.

1.4.6. Water Management

There are two aspects of water management in the Eden catchment: (1) flood risk; and (2) water resources. There have been many phases of flood management. The historical (1940s-1970s) solution was land drainage which both increased the productivity of agricultural land and was thought to decrease flood risk. This hypothesis is still under intense debate (Newson and Robinson, 1983; Robinson, 1990; Robinson and Rycroft, 1999; Holden, 2005). An example of an artificial drainage channel in the Eden catchment is Thacka Beck which links the River Eamont to the River Petteril. The 1980s were the start of a more conservationist movement, with holistic catchment management becoming popular. This initially started as a flood defence policy, whereby hard defences were built in downstream settlements to protect them from flooding. This policy has been replaced by a policy of holistic catchment scale integrated flood risk management. This encompasses soft engineering approaches such as rural land management and warning and forecasting developments.

Flood management in the Eden catchment is dominated by hard engineering flood defences. Before January 2005, there was a scheme in place to upgrade the level of protection for Carlisle. However, this would still have been exceeded during the peak of the flood. Since 2005, the flood defences have been raised to an even higher level, with embankments, walls and gates installed. However, the Environment Agency is now more open to upstream rural land management.

The management of the Eden catchment in a holistic integrated manner means that other risks such as water resources and diffuse pollution also need to be considered. The water resources network consists of 152 reservoirs, 59 river intakes, 5 lake abstractions, 170 groundwater sources and 156 water treatment works (United Utilities, 2006). Lakes Ullswater and Windermere contribute to this system, as well as Haweswater and Wet Sleddale reservoirs. Haweswater reservoir was built in the 1930s, with the water level being raised by 29 m, drowning the village of Mardale, leading to the area of the lake being tripled. Wet Sleddale was built in the early 1960s. Water is also abstracted from small tributaries of the Lowther, with Heltondale aqueduct leading from Ullswater to an intake on Heltondale Beck and Haweswater. Swindale aqueduct leads from Swindale Beck to Haweswater (Environment Agency, 2005a; 2005b). Figure 1.9 shows a schematic of this water resources system. The management of the reservoirs can also influence flood flows, for example if reservoir levels are maintained at a high level to buffer winters with low precipitation quantities, then the dam can easily be over-spilled during storms.

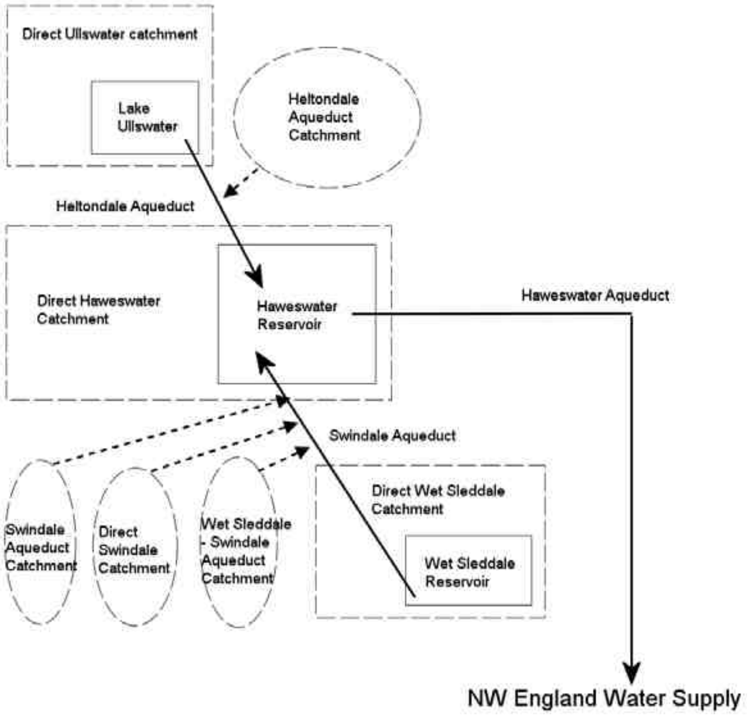


Figure 1.9 *Haweswater network system for water supply to NW England (adapted from Personal Communication, Mark Smith, United Utilities)*

1.5. Thesis Structure

This thesis is split into two parts, the first half (Chapter 3 to Chapter 6) is focussed on determining which sub-catchments are the optimum to concentrate on. The second part (Chapter 7 to Chapter 9) asks the question of which land management practices can be used in these sub-catchments to reduce downstream flood risk.

Chapter 2 provides the theoretical basis upon which this thesis is built. It discusses the impact of land use changes upon flood risk at different spatial scales. This thesis relies heavily on the use of data to both explore temporal and spatial trends of flood risk throughout the Eden catchment (Objective 1), and be used as model boundary conditions and model performance assessment (Objectives 2, 4 and 5). As no data were actually collected personally for this thesis, it is critical that the accuracy and reliability of the third party sourced data is evaluated thoroughly. This is the main aim of Chapter 3. To address Objective 1, Chapter 4 assesses trends in flooding over different spatial scale, based upon different sub-catchments of the Eden, and over different temporal scales, including seasonal, decadal and historical timescales. Potential causes of changing patterns of flood risk through time and space are hypothesised and assessed, with climate investigated through Lamb weather types. Chapter 5 outlines the two spatial downscaling methodologies: (1) the statistical data based approach; and (2) the hydraulic modelling scenario testing approach, which are used to achieve Objective 2a. Chapter 6 describes the results leading to identification the most important areas within this catchment for explaining downstream flooding, thereby achieving Objective 2b. Chapter 7 addresses the land use change scenarios that could, after testing, be used to reduce downstream flooding (Objective 3). As the sub-catchments of the Eden are still large, there are still a lot of potential locations are land use changes to be implemented, along with several different types of land management practices. Thus, stakeholder participation was used to reduce the number of scenarios and locations that had to be tested. Chapter 8 identifies how to test the chosen land management scenarios and these are implemented and tested in Chapter 9. Chapter 10 concludes the thesis.

Chapter 2

Fluvial Flood Risk and Land Management Impacts

2.1. Chapter Scope

This chapter is concerned with reviewing the causes of flooding, including meteorological conditions and flood intensifying factors, often catchment specific, such as land use, geology and soil types (Smith and Ward, 1998). This chapter consists of four main sections; (1) Section 2.2 provides a review of past issues relating to the hazard and risk of flooding in the UK; (2) a summary of studies on the effects of land use changes on flooding is given in Section 2.3, along with the different approaches and methodologies that can be used in such studies; (3) Section 2.4 reviews different conceptual frameworks that have been used to investigate the causes of floods; and (4) Section 2.5 assesses the impacts of land management on the hydrological processes that drive flooding.

2.2. Flooding issues in the UK

It is widely believed both in public and academic domains that the magnitude and frequency of river flooding is increasing (Robson, 2002; Hannaford and Marsh, 2007). It is thought that one in six homes in the UK is at risk of flooding (Environment Agency, 2009). Recent, widespread flooding in the UK has been used as evidence for this perception. Particular floods which are highlighted are the Central England floods of Easter 1998 (Horner and Walsh, 2000), the Sussex and Yorkshire floods of Autumn 2000 (Marsh and Dale, 2002; Kelman, 2001), the flash flood in Boscastle 2004 (Golding *et al.*, 2005; Roseveare and Trapmore, 2008), the Carlisle flood in January 2005 (Environment Agency, 2006), the widespread Summer 2007 floods (Marsh and Hannaford, 2007; Marsh, 2008) and the floods in Cumbria in November 2009. The apparent increase in flood events, however, needs to be evaluated to assess whether or not it represents a long term trend or shorter term variability. Robson (2002) analysed both local and UK river flood series and found that there was an increasing trend over the past 30-50 years. This means that the assumption of stationarity in flood frequency needs to be questioned (Milly *et al.,* 2008). Natural systems are assumed to fluctuate within an unchanging range of variability over time. The stationarity assumption for floods has been compromised by human disturbances such as channel and land use changes and also by natural climatic variability, but the effects of these were thought to be relatively minor. However anthropogenic climate change is believed to have caused significant change in flow regimes and Milly et *al.,* (2008) use this reason to justify the non-validity of the stationarity assumption. Furthermore, there seems to be a pattern and clustering of the worst flood events rather than a random occurrence (Wheater, 2006). However, this could be attributed to shorter term climatic variability, rather than a longer term climatic trend, as there was no significant relationship over the last 80-120 years (Robson, 2002). Others have reached the same conclusion with respect to smaller regional datasets, for example, Scotland has seen an increased river flood frequency since 1988, with new maximum discharges for many rivers, especially in the west (Black, 1995; Black and Burns, 2002; Werritty, 2002). Similar studies in Europe have found similar trends (Milly *et al.,* 2002). There has been a statistically significant increase for floods of magnitude greater than a 100 year return period in large (>200,000 km^2) catchments. This has tentatively been explained by climate change. However, for shorter return period events there has been no significant increase. This suggests that the effect of climate is the dominant control on river flood frequency. Mudelsee *et al,* (2003) reported that there was no upward trend in the frequency of flow extremes in Central Europe. For the Elbe and Oder rivers the frequency of flood occurrence in winter has decreased, while there is no trend in summer floods. This observation has been explained by changing climate, specifically that there is less freezing of the river and soil. However, this study was only for two rivers and flood records used unverified sources. Furthermore, the magnitudes of events were arbitrarily divided into categories and stage-discharge relationships introduced uncertainty.

2.3. Methods used in studies on land management and high river flows

There are two main possible approaches to use when aiming to answer the question of the impacts of land use changes on flood and drought risk at the catchment scale; (1) quasi-experimental catchment approaches, and (2) numerical modelling.

2.3.1. Quasi-experimental catchment approaches

Quasi-experiments, so-called as they do not meet all the requirements necessary for controlling the influence of extraneous variables (Campbell and Stanley, 1963), offer potential links between cause and effect in natural systems. Limitations of the approach are that experiments cannot be repeated and that results only apply to the specific case study (Block *et al.,* 2001). The traditional method to study the impacts of land use changes on hydrological regimes is to use controlled observation and measurement of catchments. There are two types of approaches (Calder, 1993a; 1993b): (a) single-catchment experiments, where the effect of a land use change is measured by comparing observations from before and after the change; and (b) paired-catchment experiments, where there is a control catchment, which has constant characteristics and a treatment catchment, where the land use is manipulated (Brown *et al.,* 2005). It is important that the catchments are hydrologically similar, preferably geographically proximate (Andreassian, 2004) and similar in terms of their area, topography, soils, geology and climate. Both catchments are monitored before any land use changes occur, known as the calibration period, and then one undergoes a change in management and the other remains the control catchment (Best *et al.,* 2003; Brown *et al.,* 2005). Monitoring catchment change over time can be attributed to either natural variability or the treatment. This type of approach has been used in three main UK situations; Plynlimon (Kirby *et al.,* 1991), Balquhidder (Johnson, 1991) and Coalburn (Robinson, 1986).

Advantages of this approach include the fact that these studies show the integrated effect of multiple processes at the catchment scale. However, the experiments are not focused on the specific processes, just the overall effect, meaning that results are difficult to apply to different catchments which have different characteristics. Other disadvantages include the errors involved in measuring the variables, such as precipitation, discharge etc. and particularly the need for data records to be long enough to identify trends, rather than effects caused by short term weather patterns.

2.3.2. Numerical Modelling

An alternative approach is to use numerical hydrological models to simulate the effects of land use change on flow regimes. This section aims to highlight the usefulness of models in science and particularly hydrology. It will outline the types of models used and the procedure that is taken in either model development or model application.

Modelling is used in science for three key reasons (Beven, 2001; Lane, 2003b). Firstly, it can alleviate the problems associated with empirical studies, where direct quantitative measurements are not possible to obtain for certain variables, due to technical or accessibility reasons. In these cases modelling can be used to extrapolate in both space and time. Examples of this include, in space, ungauged catchments, and in time, future scenarios of change. Secondly, modelling can be used to increase understanding of a system and identify the dominant processes involved. Models are particularly useful for identifying emergent behaviour in complex systems at different scales (Lane and Bates, 2000). Thirdly, models can be used to aid the decision making process e.g. planning flood protection, where the motivation for the research is application driven.

Types of Models

A model is an abstraction of reality (Mulligan and Wainwright, 2004). It aims to represent the complex real world system in the simplest way for the purpose of the study. This is the concept of parsimony, where a model should be no more complex than is necessary. Although, there is the problem of not knowing how much complexity is enough, known as Occam's razor. However, there are many different model typologies based upon how they are constructed. The most basic models are simply conceptual or theoretical, showing the relationship between different processes within a system. Most models originate from a conceptual model of how the system works. Simple models can be solved mathematically, although equations cannot be solved continuously in space and time, requiring discrete numerical approximation (Singh and Woolhiser, 2002).

Numerical models may be formulated using either Bottom-Up / Upward approach or the Top-Down / Downward philosophies (Sivapalen, 2003; Todini, 2007). The bottom-up approach, also known as reductionist or mechanistic, is based on the use of understanding at the local pixel scale, upscaled to the catchment scale (Klemes, 1983). This reductionist approach has received the widest acceptance in hydrology (Loague and Van der Kwaak, 2004), but several hydrologists have also raised concerns, mainly related to the relevance of small scale theory at larger scales (Beven, 1989; Bergstrom, 1991). One of the main reasons for their wide acceptance is their mechanistic or physically based nature. The equations used to represent processes are derived almost deductively from established physical laws and theories. Most physically-based models are based upon laws of Newtonian mechanics (Rouse and Ince, 1963), especially the law of mass conservation, which states that matter cannot be created or destroyed, but only transformed from one state to another. These models often have good explanatory power, as results can be explained in terms of actual physical processes, but they often have low predictive capability, as often elements of the system are not included (i.e. a realist approach) and results are not influenced by previous observations.

The alternative top-down or empirical approach downscales catchment scale data to find small scale relationships. The empirical philosophy is supported by Michel *et al*., (2006), as this focuses on the important emergent catchment scale behaviour. This means that the model focuses on recreating catchment scale observations through simulating processes that are important at the catchment scale. These data-driven (Young, 2003), empirical models are based on statistical relationships between variables to form transfer functions and their exact form is derived inductively. Problems with this approach include that the statistical relationship may be spurious and have no theoretical basis or are influenced by extreme values (Beven, 2001). This presents a specific problem to the study of floods, as empirical models have poor predictable powers beyond the range of observations on which they were based. As such they have high predictive power, but as these associations may not be causative then these models have low explanatory depth (Mulligan and Wainwright, 2004). Top-down, physically based models also exist, including Reggiani et al. (1998; 2001), which derived balance equations based on the laws of mass and momentum conservation for Representative Elementary Watersheds (REWS).

However, in reality there is more of a continuum of models than a dichotomy (Lane, 2003b). Klemes (1983) suggested combining the advantages of both approaches, with some empirical equations based on physical processes, and physically based models using empirically derived parameters or are calibrated using data. Also some parameters have a less clear practical meaning e.g. hydraulic conductivity, which is difficult to measure. Often parameters are not measured for the specific catchment under investigation and Heuvelmans *et al.* (2004) reviewed the transferability of parameters in time and space, and found that model performance declines when using regionalised parameters (Seibert, 1999). Beven (2000) noted the uniqueness of particular catchments. The issue of scale is crucial in hydrological models, especially the spatial grid resolution. Armstrong and Martz (2008) studied the effects of the scale of land cover representation and found that only extreme upscaling, resulting in near homogeneous catchments, resulted in significant changes in model output. Even in physically-based models, parameter values need to be averaged for each grid cell, which means that the overall heterogeneity of the catchment is still under-represented (Hansen *et al.,* 2007). Furthermore, the values of the parameters often have to be altered to improve the performance of the hydrological model, through calibration.

Another characteristic of hydrological models is the level at which the spatial scale is represented. At the coarsest resolution, the whole catchment is treated as a single unit – the lumped catchment model. Spatially-distributed models divide the catchment into grid cells. As the spatial scale changes (grid resolution), the input data, parameters and boundary conditions change, but more significantly the process equations used may need to be replaced (Bronstert, 1999). The spatial domain may be represented in varying dimensions, with 1D, 2D and 3D spatial models, and the possibility of variations through time. The clearest way to explain these types of model is through an example. The most complex spatial representation is three dimensional models, which model processes and change in all three x, y and z axes. An example of this type of model is a Computation Fluid Dynamics (CFD) model, which for can simulate water flow (Hardy *et al.*, 2007) and sediment transport (Hardy, 2005) over small bedform features. These models are based upon the fundamental Newtonian equations, which are simplified to create 2D and 1D forms of the equations for lower dimensional models. In 2D models the property of interest is allowed to vary in two directions. Two dimensional flood inundation models are available, which allow water to be transferred to the floodplain and flow perpendicular to the downstream channel flow. In one dimensional models the physical variable of interest is assumed to vary in only one direction. For example, in 1D flood inundation models, water is transported in a downstream direction and is not simulated to flow perpendicular to this on the floodplain. However, as the spatial dimension increases the spatial coverage is forced to decrease due to computational demands. Therefore 3D models can currently only be run at small scales, while 1D and 2D models can be run of whole catchments and river networks.

The method chosen to model time is also important, including: whether continuous simulation or discrete event based modelling is chosen; and the time-step used. Continuous simulation models allow changes over time to be studied, including the whole range of flows i.e. high and low flows. Some past studies (Cameron *et al.,* 2000, Crooks and Davies, 2001) have utilised this technique, but have concentrated on the effects on floods only.

An important aspect of model development is the method chosen to represent each process. Models are a simplified representation of reality, the extent to which models have reduced complexity of process representation relates to either *a priori* conceptualisations or model performance. Often models focus on the processes and variables which have a significant effect upon the result (Beven, 2001; Singh and Woolhiser, 2002; Beven, 2002; Wainwright and Mulligan, 2002). Sensitivity analysis can be carried out to determine which processes and parameters are important in influencing the model output. This leads to a better understanding of the hydrological system and the structure of the model. More detail will be provided on the use of numerical models for catchment scale investigations of land use changes on floods in Chapters 4 and 8.

General Modelling Procedures

The modelling process is summarised in Figure 2.1 (Beven, 2001), and includes the perceptual model, the conceptual model and the procedural model, along with the model assessment stages of verification, sensitivity analysis, calibration and validation. The following section will explain these modelling procedures and terminology. The first stage in the construction of any new model is the formulation of the perceptual model, which is an idea of how the system works, including which processes are viewed to be important. It is commonly a personal perception and different modellers' ideas may be different (Lane 2003b). It is an important stage, as the model developer/user must believe in how the model represents the real world system which of interest. The next stage is converting this theoretical description into a numerical model, which requires deciding on the equations required to represent each process: the conceptual model. This often involves simplifying the perceptual model into processes which can actually be represented using equations and making assumptions about the system (Beven, 2001). The third stage is coding the equations in programming software, forming the procedural model. Verification takes place during this stage, which makes sure the code carries out the algorithm it is designed to. This process also involves debugging the code to identify typing mistakes and mis-conceptualisations (Wainwright and Mulligan, 2004). Oreskes *et al.*, (1994) use the term benchmarking to describe this process, which can be summarised as solving the chosen equations correctly (Boehm, 1981; Blottner, 1990; Roache, 1997).

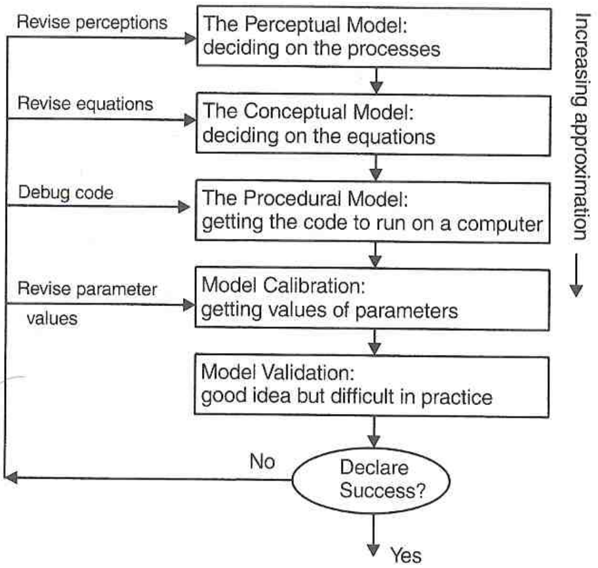


Figure 2.1 *Flow diagram of the modelling procedure (Beven, 2001).*

To explore the behaviour of the model further and to identify which processes are important in determining the results in the model, sensitivity analysis is carried out (Lane *et al.*, 1994; Wainwright and Mulligan, 2004). The model sensitivity to each parameter is assessed by varying each individual parameter value incrementally and assessing the proportional effect on model output (Hamby, 1994). Often the results of a sensitivity analysis are shown on a response surface (Harlin and Kung, 1992), where the effects of two parameters are compared. This is also done to achieve model parsimony, whereby parameters which are insensitive are removed from the model, as well as to target the calibration of the model (Young et al, 1971; Beven, 1979).

A model is assessed through the process of validation, which makes sure that the equations chosen to represent the real world system are suitable and that the parameters used are correct (Fishman and Kivat, 1968). The errors are assessed using the goodness of fit criteria which compare observations with predictions (Luis and McLaughlin, 1992; Fawcett *et al.*, 1995). The source of the observed data used to validate models can be either be analytical solutions (Horritt, 2000), laboratory scale models (Thomas and Williams, 1995), field data (Lane *et al.*, 1999) or remotely sensed data (Horritt, 2000).

Any difference between observations and model predictions is caused by conceptual misrepresentations rather than mathematical mistakes, although it is important to note that an invalid model can make the right predictions (Lane *et al.*, 2005). There is often confusion between the terms verification and validation (Rykiel, 1996) and Oreskes *et al.*, (1994) proposed the use of the term model evaluation to replace validation. Lane and Richards (2001) argue that the term “validated” is used to prevent the criticism from the public that model results are unreliable. Another approach to evaluating models is to use a benchmarking approach which compares different models for the same network or catchment (Tayefi *et al.*, 2007).

The techniques used to assess the goodness of fit between observed data and simulated results are now outlined. Firstly, a graphical comparison can yield quick and valuable insights into model performance, although this technique can be rather subjective (Haase *et al.*, 2000). Secondly, statistical functions are used to assess the accuracy of the model. Green and Stephenson (1986) produced a summary of twenty one different measures of goodness of fit between model predictions and measured observations. However, most studies have a particular objective and therefore the most suitable measure depend on the focus of the study. Johnstone and Pilgrim (1976) argue that this approach also makes use of statistical measures subjective as the decisions on which to use bias the results. Ibbitt and O’Donnell (1971) suggested examples of where particular statistical equations would suit certain research aims. In studies where the routing effects of the river network are the focus then the hydrograph shape, especially the rising and falling limbs are important. If the role of floodplain storage is the focus then the volume of water is critical, shown by the area under the hydrograph but above the defence level. For low flow studies, it is recommended that the discharges are transformed by taking the logarithm, which introduces a bias for low flows. For high flow research, like this project, it is the peak flow which is the critical aspect of the hydrograph. Some investigations have multiple aims, such as looking at both high and low flows simultaneously, and these need multi-tier criteria to be assessed with (Lichty *et al.*, 1968). Thirteen of Green and Stephenson's (1986) goodness of fit equations have been chosen, as they focus on either the peak flow or have a high flow bias, and are summarised in Table 2.1. The main measure of error between predicted and observed values is the residuals, which are calculated by subtracting the model simulation output from the corresponding measured observation. Key factors considered when deciding which measures to use are whether the statistic is dimensionless and whether the number of observations influences the output. The most commonly used measures of goodness of fit are the sum of squared residuals (equation 1), the sum of absolute residuals (equation 2), the Nash-Sutcliffe coefficient (equation 3), the root mean square error (equation 5), and the percentage error equations (equations 9, 10 and 11).

Green and Stephenson (1986) also highlight the need to assess the accuracy of the timing of flows as well as the magnitudes. This is particularly important in this study as the timing of the flows from each sub-catchment may be important. Land use changes can change the timing of peak flows as well as their magnitude. It is therefore important that the modelling approach also considers the timing of flows as well as their magnitude. Past studies have done this to varying extents, with Marsalek (1979) and Watson (1981) detecting errors in terms of timing of the flows. Haan (1975) and Constantinides (1982) accounted for errors in terms of timing by shifting the simulated hydrograph in time to achieve the best fit. Lane (2007) also explored the localisation of error at particular times through wavelet analysis. This compared the observed and simulated time series with a chosen wavelet transform. In this study, the error in terms of timing between model simulations and observed hydrographs will be assessed through an adaptation of Equation 9, focussing just on the timing of the peak flow. Equation 14 shows how the difference between the time of the peak flow of the model prediction and the actual time is divided by the actual time of the peak flow. This is thought to be the most appropriate measure of the error in terms of timing, as it is the timing of the peak flow that the statistical analysis uses and Green and Stephenson (1986) state that Equation 9 is the most suitable for studies focussing on high flows.

Green and Stephenson (1986) conclude that no single statistical goodness of fit criterion is sufficient to assess the errors between model outputs and observed measurements, but through using this suite of model assessment criteria it will hopefully yield the optimum model to use. This is because the importance of any bias in any of the measures will be reduced due to multiple criteria being analysed. However one of the problems with all the criteria cannot be solved, as it is an inherent problem with the concept of time series data, where successive time intervals are not independent of each other (Aitken, 1973). These systematic errors are autocorrelated in time and can lead to over/under-estimation of the errors between observed and predicted values. However, these are thought to be more of an issue in continuous simulation modelling, than in single event modelling. This means that the errors in hydrological models need to be interpreted with caution. As hydraulic models often study a single high flow event, the problem of time autocorrelation of errors will be less of a problem.

Model outputs rarely match measured observations, and therefore parameters are adjusted to improve the goodness of fit between the simulated and observed data. This is the process of model calibration, where model predictions are fitted to observations. Often the most sensitive parameters are used to calibrate the model, as changes in these have the impact on the output. However, the model optimisation process has to be done against particular measures of goodness of fit, which assess different aspects of the output (Dawdy and O’Donnell, 1965). This is an iterative process, where the parameters are altered, the model is re-checked by comparing observations and predictions, and then this process is repeated until the model user is satisfied with model performance. Once the model has been calibrated and assessed to find the optimum set of parameters to use, it is important to check that the model performs well using different datasets. This is an independent validation stage to check that the model is representing the real world system accurately. It is important that a different dataset is used than the one used to calibrate the model. The model has now been evaluated and is ready to use for the purpose which is intended.

	Criterion	Equation	Comments	Reference
1	Sum of Squared Residuals	$G = \sum_{i=1}^{n} [\, q_o(t) - q_s(t)]_i^2$	• Bias towards high flows, as largest residuals often occur for high flows, which are given greater weight when squared. • Assumes residuals have a normal distribution with a mean of zero. Not always the case and can lead to incorrect model interpretations • Output is dimensional; meaning comparison of models in different units is not possible.	Diskin and Simon (1977)
2	Sum of Absolute Residuals	$G = \sum_{i=1}^{n} \mid [q_o(t) - q_s(t) \mid_i$	• Output is dimensional; meaning model comparison in different units is not possible. • Output dependent upon number of observations, meaning comparison between events of different lengths is not possible.	Stephenson (1979)
3	Nash-Sutcliffe Model Efficiency	$R^2 = \frac{F_o^2 - F^2}{F_o^2}$ where $F^2 = \sum_{i=1}^{n} [q_o(t) - q_s(t)]_i^2$ $F_o^2 = \sum_{i=1}^{n} [q_o(t) - \bar{q}\ ]_i^2$	• Dimensionless • Simplicity, answer tends to unity as model fit improves. • Insensitive. Poor models give quite high values, while better models only gave slightly higher values. • Values of >0.65 are thought to be acceptable in models. (Rouhani et al, 2007; Wu and Johnston, 2008)	Nash and Sutcliffe (1970)
4	Normalised Objective Function	$P = \frac{1}{\bar{q}} \left(\frac{F^2}{n} \right)^{\frac{1}{2}}$	• Form of coefficient of Variance • Recommended by FSR (1975)	Ibbitt and O'Donnell (1971)

5	Root Mean Square Error	$RMSE = \left(\frac{1}{n}\sum_{i=1}^{n}(q_o(t) - q_s(t))_i^2\right)^{\frac{1}{2}}$	• Dimensional • Recommended by Flood Studies Report (1975)	Patry and Marino (1983)
6	Reduced Error Estimate	$REE = \left[\frac{\sum_{i=1}^{n}(q_o(t) - q_s(t))_i^2}{\sum_{i=1}^{n}(q_o(t) - \bar{q})_i^2}\right]^{\frac{1}{2}}$	• Biased towards high flows and insensitive to errors in low flows.	Manley (1978)
7	Proportional Error of Estimate	$PEE = \left[\sum_{i=1}^{n}\left(\frac{q_o(t) - q_s(t)}{q_o(t)}\right)\right]^{\frac{1}{2}}$	• Gives equal weight to equal proportional errors. Therefore, more evenly represents whole range of flows.	Manley (1978)
8	Standard Error of Estimate	$SEE = \left(\sum_{i=1}^{n}\frac{(q_o(t) - q_s(t))_i^2}{n-2}\right)^{\frac{1}{2}}$	• Dimensional • Not influenced by the number of observations in simulated and observed data.	Jewell *et al.* (1978)
9	Percentage error in Peak	$PEP = \frac{q_{ps} - q_{po}}{q_{po}} \times 100$	• Particularly valuable in peak flow studies.	
10	Percentage error in Mean	$PEM = \frac{\bar{q}_s - \bar{q}_o}{\bar{q}_o} \times 100$	• Assess whole of the hydrograph	

11	Percentage error in Volume	$PEV = \frac{v_s - v_o}{v_o} \times 100$	- Useful for studying floodplain storage - Limitation that volume might be the same, but the shape of hydrograph might be completely different. - Measures of divergence way of accounting for this problem.	
12	Variance	$S^2 = \frac{1}{n}\sum_{i=1}^{n}[q_o(t) - q_s(t)]_i^2$	- Overcomes problem of observations effecting result, as Sum of Squared Residuals divided by number of observations.	
13	Mean Deviation	$MD = \frac{1}{n}\sum_{i=1}^{n}[q_o\,(t) - q_s(t)]_i$	- Overcomes problem of observations effecting result, as Sum of Absolute errors divided by number of observations.	
14	Percentage error in Timing of Peak	$PEP_{Time} = \frac{q_{ps_{time}} - q_{po_{time}}}{q_{po_{time}}} \times 100$		

Table 2.1 *Goodness of fit statistical functions*

n = number of observations
i = observation number
$q_o(t)$ = observed discharge at time t
$q_s(t)$ = simulated discharge at time t
F^2 =

F_o^2 =
$\bar{q}$ = average discharge
$\bar{q}_s$ = average simulated discharge
$\bar{q}_o$ = average observed discharge
q_{ps} = simulated peak discharge

q_{po} = observed peak discharge
$q_{ps\ time}$ = simulated peak discharge time
$q_{po\ time}$ = observed peak discharge time
v_s = simulated volume
v_o = observed volume

2.4. Summary of results from studies investigating link between land management and flood risk.

Rural land management practices have commonly been attributed to the hypothesis that flood risk is increasing. However, firm evidence for this assertion is lacking, due to the complexities of the hydrological and fluvial systems (O'Connell *et al.*, 2004; Lane *et al.*, 2007). Many factors interact to determine a river's flow regime. These can be classified as: climatic inputs; natural catchment characteristics; and human catchment management. These variables combine to give a unique response, both temporally and spatially, meaning that every rainfall event leads to differing runoff patterns and river discharge. There have been many studies of the effects of land management on high river flows. These can be divided into categories based upon the spatial scale of the study; plot/field or catchment, and the approach used to investigate the effects of the change; observations or modelling. Table 2.2 summarises these types of studies, and gives an example of how they have been used to investigate land use change impacts on flood risk.

Spatial Scale	**Approach**	**Rationale**	**Example**
Plot/Field	Observations	Monitoring of local scale runoff rates and soil moisture in areas with different land management practices.	Compaction by machinery (Hawkins and Brown, 1963) and stock (Heathwaite *et al.*, 1989; Heathwaite *et al.*, 1990) has decreased infiltration rates and increased localised overland runoff rates.
Plot/Field	Numerical Modelling	Hillslope scale 3D physically based models (e.g. Richards equation, macropores)	Jackson *et al.*, 2008a; 2008b using SPW studied effects of shelterbelts on peak flows and found a reduction of 40%, with a 60% decrease in overland flow.
Catchment	Observations	Often Quasi-experiments based on paired catchment approaches	The Coalburn experiment investigated the hydrological impact of different forest growth stages including pre-forest, land drainage preparation, forest growth and felling. It was found that runoff increased following ploughing and the recovery to pre-ploughing levels took 20 years (Robinson, 1986, Archer and Newson, 2002)

Catchment	Numerical Modelling	Some studies have used past land use changes and compared results to observed changes in discharges, while others have used hypothetical scenarios	De Roo *et al.* (2001) investigated the effects of land use changes from 1975-1992 in the Meuse catchment on peak discharges. It was found that land use changes suggest a slight increase in peak discharge of 0.2%, although this is highly uncertain.

Table 2.2 *Summary of studies on the link between land use and flood risk*

2.5. Hydrological processes resulting in catchment scale flooding

Lane *et al.,* (2007) outlined a theoretical approach to conceptualising the link between land use and fluvial flood risk. This considered three aspects of flood generation; (1) partitioning of rainfall between surface and subsurface flow, through the process of infiltration; (2) storage of water, either on the surface or subsurface or through biomass uptake; and (3) conveyance of water both on the hillslopes and within the channel. This framework was thought to be appropriate for the aim of this thesis as it focuses on the physical hydrological processes that drive flooding at the catchment scale. These processes are discussed in detail in the following sections.

Partitioning of rainfall between surface and subsurface flow

An important factor which determines the quantity of water that enters a river is the response of the land surface to precipitation. The partitioning of rainfall between surface overland flows and subsurface pathways is significant, as it determines the speed at which water is transferred from hillslope to the river channel. Overland flows are thought to be faster routes than subsurface flows, and therefore the proportion of rainfall which takes either route determines the timings of water input into the river. This assumption is currently being questioned as well structured/drained soils may have rapid throughflow. The processes involved in conditioning the differentiation of flows are; infiltration and percolation. These depend on the soil structure and type, topography and antecedent conditions. Specifically, infiltration is the movement of water through the soil via macropores. Therefore the number, size and connectivity of these pores determine the rate of infiltration. If infiltration is limited by any of these factors then overland flow results.

There are two types of overland flow. Firstly, Hortonian Overland Flow (Horton, 1933) occurs when rainfall intensity exceeds infiltration capacity. This means that the rate of rainfall is higher than the rate at which water is infiltrated into the soil and leads to downslope sheet flow. This type of overland flow commonly occurs due to short, high intensity precipitation events, which in the UK often occur as summer convective thunderstorm events. Secondly, Saturation Overland Flow occurs when the soil profile becomes saturated with water, meaning that all the macropores are full. This results in no infiltration occurring and water ponding on the soil surface and flowing downslope. This often occurs during long duration, less intense rainfall events which often occur due to advective weather types in the UK winter (Bronstert *et al.*, 2002).

The partitioning of rainfall into runoff has importance implications for the relative timings of different pathways to the river channel. Therefore, an important factor to consider is the location in the catchment where infiltration capacity is high or low and therefore where runoff is fast or slow. If infiltration rates are low in the upper catchment and high in the lower catchment, then it is likely that the peak flow will be higher at the river's outlet, as the flood wave from the upper catchment combines with the lower catchment's delayed peak flow.

Thus, the management of the land surface may be used to reduce flood peaks, by affecting the partitioning between surface and subsurface flows and therefore the relative timings of the water input into the channel. Several land uses have been investigated in terms of their effect on infiltration, including; agricultural practices (arable, pasture), land drainage, forests, urbanisation and buffer zones.

Storage of water

Water storage within the catchment means that the runoff into rivers is reduced, leading to a lower flood risk. Furthermore, the flood peak is delayed and attenuated, meaning it is lower, but longer in duration. Examples of surface water stores include; wetlands (Mitsch and Gosselink, 2000; Zedler, 2003), washlands, ponds, impoundments and flood expansion areas (Pivot *et al.,* 2002). The exact location of these stores within the catchment is an important factor, along with their total volume. It is essential that water storage is co-ordinated at the catchment scale. The mitigation of flood risk by water storage is an established concept and has fewer uncertainties associated with it. Engineered storage in the form of reservoirs is known to reduce flood risk downstream (De Roo *et al.*, 2003). However, diffuse storage management schemes, where there are a large number of small storage systems which rely on general attenuation, are less well understood than large volume storage systems. An advantage of these type of land management practices, is that they may have multiple benefits including; biodiversity, pollution control, along with floods.

Management of Hillslope-Channel Connectivity and River channel Conveyance

Connectivity has become a popular term in recent years with it being used to describe catchment processes in hydrology (Western *et al.,* 2001), geomorphology (Brierly *et al.,* 2006) and ecology (Pringle, 2003). However, there are problems with the use of this term, including no constrained definition and the difficulty of quantifying it (Bracken and Cloke, 2007; Michaelides and Chappell, 2009). Bracken and Cloke (2007) formulated a conceptual model of hydrological connectivity, shown in Figure 2.2, which consists of five components; climate, hillslope runoff potential, landscape position, delivery pathway and lateral connectivity. Climate is important as it controls the amount of water in the system. For catchment scale hydrological connectivity to occur, prolonged, high intensity precipitation must occur, while more localised hillslope connectivity can occur quite quickly in smaller storms. Runoff potential depends on the catchment characteristics, such as soil, antecedent conditions and vegetation. Ambroise (2004) defined active areas as areas where surface runoff occurs, and contributing areas as active areas which actually connect to the river network. This has also been referred to as “effective hillslope length” (Aryal *et al.,* 2003) and “dynamic contributing areas” (Beven, 1997). Therefore, landscape position is important as areas of the landscape closer to the river channel are more likely to connect. The delivery pathway, such as incisional rills, concentrated overland flow and sub-surface flows are important in controlling connectivity. Finally lateral buffering, describes the physical connection between the hillslopes and the channel.

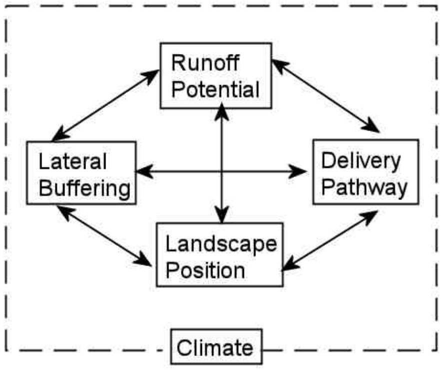


Figure 2.2 *Components of Hydrological Connectivity (Bracken and Croke, 2007)*

Lane *et al.*, (2009) developed a methodology for predicting the sources of fine sediment and nutrients based upon the probability that a potential source area in the catchment will be hydrologically connected to the river channel, using a digital elevation model. Management of the pathways of water transport can reduce flooding in two aspects; firstly the amount of runoff that enters the channel can be controlled; and secondly the speed at which water enters the channel and is transported downstream can be managed. The extent to which the channel and floodplain are linked and the exact spatial and temporal patterns of this linkage are important in controlling the amount of water entering the channel. Furthermore, the rate of hillslope connectivity can be controlled by the surfaces over which the water flows. Hillslope connectivity can be reduced by increasing the flow resistance due to rougher land surfaces.

Traditional flood management solutions consisted of structural defences, which disconnected the river's floodplain from the river's channel. This meant that water was constrained by the channel and that flow attenuation may decrease leading to flood magnitudes increasing downstream. However, when the peak water levels were high enough to overtop the flood defences flow attenuation increases due to the offline water storage on the disconnected floodplain.

Channel conveyance can also be altered to affect the relative timings of when tributaries peak flows join the main channel. Channel conveyance can be increased through reducing flow resistance by channel straightening or in-channel vegetation removal. Conversely, channel conveyance can be reduced through transferring water to the floodplain, where water is stored and conveyance is slower. However, changes upstream cause downstream impacts due to how different sub-catchments interact. For example, if a downstream tributary's flow is delayed due to attenuation of the flood peak, then it may become coincident with the flow from the upstream main channel, generating a higher magnitude flow downstream. Before the flow from the downstream tributary was delayed, the tributary flood wave would have passed through before the upstream main channel peak flow arrived. This approach requires areas to be defined as either flood acceptable or flood protected. For example, downstream urban areas need flood protection, so the flood wave could be conveyed through these areas more quickly. However, upstream reaches could be used to delay flows through the storage of water on agricultural fields. This would attenuate the flood peak from these sub-catchments and if done in the right locations could reduce flows through downstream settlements. The critical aspect of this management approach is that it must be focussed at the catchment scale, so that any upstream and tributary changes do not have negative impacts on areas downstream.

2.6 Impact of Land Management on hydrological processes and flood risk

This section discusses the impact of several land management practices on both localised and catchment scale flood risk. The types of land uses and management practices that are included are; (1) arable agriculture; (2) pastoral agriculture; (3) buffer strips; (4) forestry; (5) land drainage; (6) wetlands; and (7) channel modification. The effect of these land management practices will be discussed using the hydrological process conceptual framework outlined in Section 2.4. Some management practices effect more than one process and therefore they will be discussed in multiple sections.

2.6.1. Partitioning of rainfall between surface and subsurface flow

Arable Agriculture

The intensification of agriculture over the past 15-20 years has coincided with a rise in flood risk (Kenyon *et al.*, 2008). It has been hypothesised that the two events are linked, through the reduction of infiltration, leading to increased runoff. The main cause of this is the degradation of soil structure, caused through compaction by heavy machinery (Holman *et al.*, 2003). A common trend is that the proportion of the catchment under arable land use increased up until the late 1990s. This was initiated by the World War 2 policy of the "Plough up campaign" (Crooks and Davies, 2001). This means that runoff from arable fields, which have low infiltration rates has increased. A case study which shows this effect is the River Camel, Cornwall (Sullivan *et al.*, 2004). Cultivation increased from 1969 to 1997 from 14.9 km^2 to 25.3 km^2 (8% of catchment area), although it has decreased slightly since then. Five out of the six largest flood events (64-150 cumecs) occurred in the 1990s, which coincides with a large proportion of arable fields within the catchment. However, a causative link between these factors has not been proved and other causes, such as the higher rainfall totals or other land management practices, are just as likely.

There has been a shift in the crop species which are grown in the UK, with an increase in maize from 1979. This is sown in winter, meaning that plant cover is low during the period of highest rainfall. The high proportion of bare ground means low interception losses, and leads to soil surface sealing and crusting, and siltation of the macropores within the soil structure. These processes reduce water infiltration rates and increase runoff (Sullivan *et al.*, 2004). A good example of flooding that has most likely been caused by bare ground in agricultural fields is in the South Downs (Boardman *et al.*, 1994; Boardman, 1995; Boardman *et al.*, 2003; Butler, 2005). Land use in the period 1900-1950 was grassland for sheep and cattle grazing. Pasture to arable conversion occurred during the second world war due to the "Plough up campaign" and then spring crops were replaced by winter crops, such as wheat in the 1970s. These crops were high yielding and had a guaranteed sale price, making then the most economically viable type of agriculture. Prior to the 1970s there was practically no flooding in this area (Boardman, 1995). However, in the period 1976-2000 there have been 138 separate, so called "muddy floods". This terminology arises from the content of the flood water, which originates from farmers fields. The area under winter crop production has increased over time, with 15% in 1975, 35% in 1981 and 60% in 1988 and 1991 (Boardman *et al.,* 2003). It has been found that soil erosion is most intense where the land cover is less than 30% (Evans, 1990). Rates of erosion in this area have reached 200 m^{3}ha^{-1} in individual fields, where rills and gullies have formed which transport water much faster than overland flow. Furthermore, field boundaries in critical locations have been removed, increasing hydrological connectivity. In the Autumn of 2000 2.5-3 times the normal amount of rainfall occurred in the South

Downs, with a return period of 1:100 years (Marsh, 2001). However, the flooding which resulted from this rainfall was less extreme than the floods of 1987, when there was less rainfall (Butler, 2005). This has been explained by the small decline in winter cereal cropping, which has been initiated by set-aside schemes and an Environmentally Sensitive Area (ESA) scheme (Boardman *et al.*, 2003).

Set-aside and fallow periods are recommended “best practices” as they have aimed to reduce the intensity at which land is managed. Set-aside areas are fields or parts of fields planted with cover crops and are thought to increase the infiltration capacity of the soil and reduce overland runoff (Auserwald, 1998). Bormann *et al.* (1999) studied the effects of fallow periods on flood risk. Three types of land use were investigated; bare fallow, intermittent fallow and reduced cultivation. Bare ground fallow was found to increase the rate of runoff due to surface capping caused by raindrop effects (Niehoff *et al.* (2002) and reduced roughness of the surface due to no vegetation cover. Intermittent fallow was found to reduce runoff, but was highly dependent on the location within the catchment where this was implemented. The optimum land management was found to be reduced cultivation which consisted of less ploughing and resulted in a reduced peak discharge due to lower runoff rates caused by higher infiltration capacities. Another suggestion has been to use cover crops (Schafer, 1986; Dabney, 1998; Clements and Donaldson, 2002), to protect the soil surface during periods of no cultivation. Lane *et al.*, (2007) supports this practice as it reduces runoff, although Geelen *et al.*, (1995) believes this practice has no effect on the hydrological regime.

Ploughing is thought to increase the rate of surface runoff (Kwaad and Mulligen, 1991; Martyn *et al.*, 2000; Clements and Donaldson, 2002), due to the compaction of soil, thus reducing the infiltration capacity of the soil. Heavy machinery is used in this agricultural practice, which leads to wheel tracks being compacted. Figure 2.3 shows how the infiltration capacity of compacted soils (b) is lower than uncompacted soils (a). It was found that the hydraulic conductivity of soil decreased by 40% in the wheelings compared to the areas between the tracks (Coutadeur *et al.*, 2002). The timing of ploughing has an important effect on runoff generation. It was found that ploughing in the spring and autumn and not in winter lead to a 30-100% reduction in runoff (Kwaad and Mulligan, 1991). Tillage has been recommended as a management practice to improve soil structure and allow cultivation with minimal soil disturbance (CIWEM, 2006). Lane *et al.* (2007) highlighted that the timing and type of tillage regime is critical to its impact on hydrological processes such as infiltration and runoff. The direction, angle and depth of the wheel tracks have been found to be important in determining the runoff rates at the local scale (Duley and Russel, 1939; Schwab *et al.,* 1993).

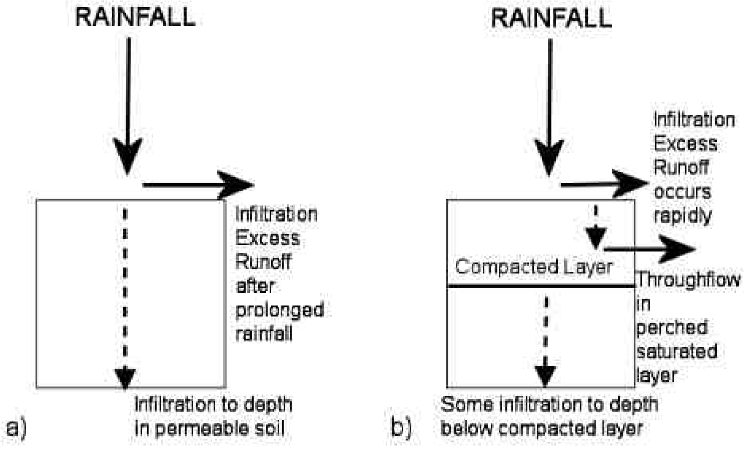


Figure 2.3 *Schematic showing the effects of compaction on soil infiltration (adapted from O'Connell et al., 2004)*

Finally conversion of arable fields to grassland or forest is thought to impact on the water balance of the catchment. However the effects are difficult to predict (Burt and Slattery, 1996) due to the various variables involved and how changes in one balance effect another. Lahmer *et al.,* (2001) states that arable reversion has only a small impact on surface runoff, but affects other processes, such as evapotranspiration and interception more, while Fohrer *et al.,* (2001) believes runoff is most susceptible to changes due to land management. Naef *et al.,* (2002) proposed three approaches to delay runoff which are; improved tillage, plant species with high root densities and permanent surface cover. Figure 2.4 shows the hypothetical response of a hillslope to a storm event, with (a) being a pre-war landscape and (b) being a recent landscape. The modern catchment has a flashier regime, with a higher peak flow and a steeper rising and falling limb.

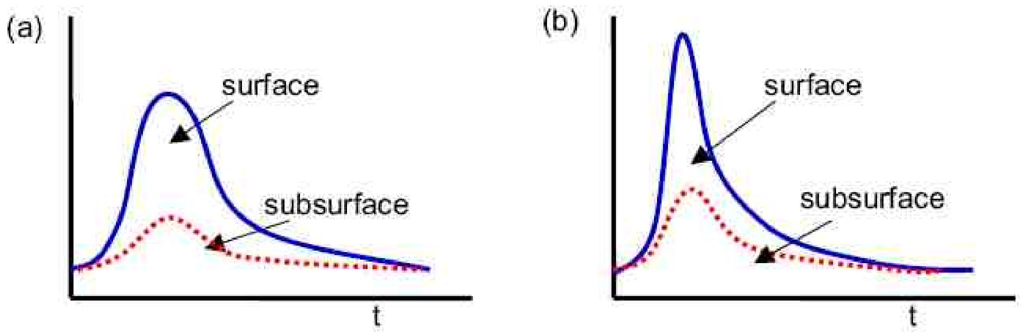


Figure 2.4 *Response of a hillslope to the same storm for a (a) pre-war landscape and (b) modern landscape, showing the partitioning of precipitation into surface and subsurface flows. (O'Connell et al., 2004)*

Buffer Strips

Buffer zones are known for their beneficial impacts on both water quality issues (Vought *et al.*, 1995; Burt *et al.*, 1999) and soil erosion. However, the impact upon flood risk is highly uncertain due to the lack of research focussed on this function. Buffer zones are areas of uncultivated land; usually they consist of permanent grassland and are normally formed within the riparian zone. These grass strips increase the infiltration capacity of the soil, due to the lack of cultivation processes, such as ploughing or harvesting. This means that more water is stored within the soil profile and delays input into the channel. However, this is a finite process, because once the soil is saturated, surface runoff begins. This highlights the importance of antecedent soil conditions upon the effectiveness of buffer zones (Lane *et al.*, 2007). Therefore a small, narrow strip of grassland between the hillslope and the channel is unlikely to increase infiltration of runoff, due to the low slope and high upslope contributing area, meaning the soil is easily saturated. However, Auerswald (1998) found that runoff from field edges reduced by 10 times when a buffer strip decoupled hillslope from channel, which could be accounted for by dry antecedent conditions

Pastoral Agriculture

Marsh and Dale (2002) highlighted the different effects of upland and lowland land use changes on flood risk. Pastoral fields are commonly found in the uplands of catchments, which are known as "less favoured areas" (Sansom, 1999) and are more susceptible to soil degradation and erosion. The major trend concerning pastoral agriculture is the exponential increase in stocking numbers and densities. Sheep numbers in the UK in the 1860s were about 8 million. The population of sheep in the UK has increased from 19.7 million in 1950 to 40.2 million in 1990 (Fuller and Gough, 1999)

Case studies which show the effect of stocking density on runoff and flow regimes include the River Derwent (Evans, 1996) where sheep numbers doubled between 1944 and 1975, which coincided with an increased runoff rate of 25%. Also Orr and Carling (2006) showed the importance of upland land use on flow regime. There was no trend in the rainfall data, but flow peaks increased in the upper catchment of the River Lune, while they decreased in the lower catchment. A study of the River Ouse, Yorkshire (Lane, 2003a), where sheep numbers have increased in the catchment since the 1970's, found a correlation with flood frequency and magnitude which have also been increasing. Two main explanations were proposed for this possible relationship. Firstly, increased sheep densities caused overgrazing of pasture fields, reducing the biomass, which meant that evapotranspiration losses declined. Jones (1967) found that when sheep are excluded from heathland, there is a 30% increase in heather (biomass by weight) in 2 years and a 88% increase 15 years later. However when sheep were re-introduced there was a 10% reduction over a 12 year period. Furthermore root depths decreased, which meant a reduction in infiltration rates. Secondly it has been found that sheep follow particular pathways, concentrating the hoof pressures on a small area of the fields (Sheath and Carlson, 1998; Gilman, 2002). This causes compaction and a reduction in soil bulk density, meaning the infiltration capacity of the soil declines. This relationship has been shown by Langlands and Bennett (1973), which found a positive correlation between soil bulk density and sheep density and a negative relationship between soil pore space and stocking density. Furthermore the compaction of the soil degrades the ecological status of the soil, reducing the number of earthworms which improve drainage (Guild, 1955; Hills, 1971). These processes lead to an increased runoff rate, as less water is lost to the atmosphere (evapotranspiration) or is partitioned into the slower subsurface throughflow pathway (Owens *et al.*, 1997). Within the Ouse catchment over 40% sites investigated had high soil degradation, which led to an increased runoff rate of between 0.8% and 9.4% (Holman *et al.*, 2003). Overgrazing is the cause of 23% of soil degradation in Europe (Royal Society for Nature Conservation, 1996). A recent study at Pontbren (Jackson *et* *al.,* 2008a; 2008b; Marshall *et al.,* 2009) found that small tree strips on hillslopes have the potential to reduce peak flows by 40%, as the land is no longer trampled by livestock. Figure 2.5 demonstrates the impacts of heavy grazing on the soil structure and the hydrological cycle.

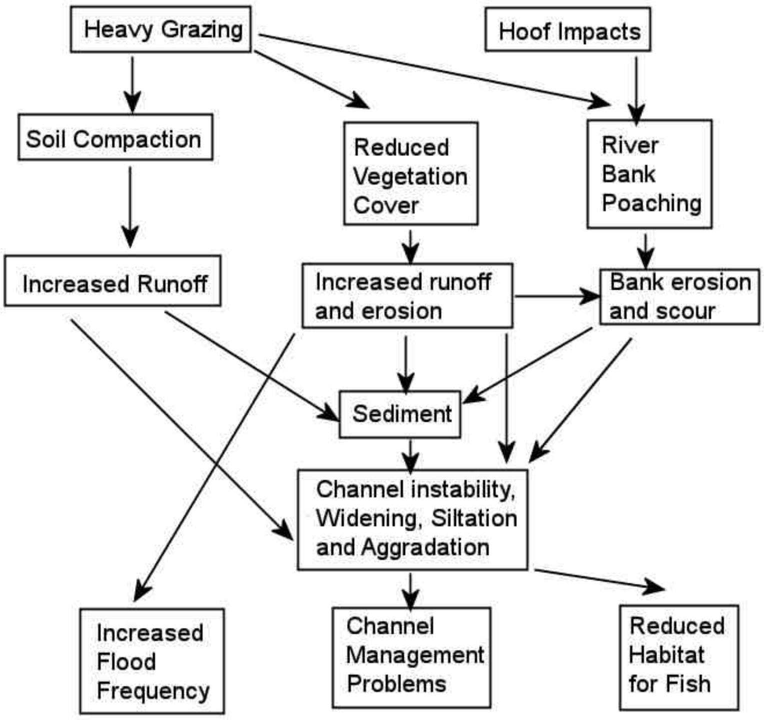


Figure 2.5 *Impacts of overgrazing on runoff and soil erosion (Orr and Carling, 2006).*

Variations occur spatially within the catchment and how these field scale effects propagate downstream is uncertain. An example of how pasture effects vary between fields is the type of animals. Cattle have been found to have a smaller effect on soil structure than sheep. This is due to cattle causing a vertical movement of soil disturbance, while sheep cause surface compaction. Therefore a shift from sheep to cattle could potentially reduce flood risk (Betteridge *et al.,* 1999). Also runoff under pastoral fields is lower than arable land management (Sibbersen *et al.,* 1994).

Forestry – Deforestation / Afforestation

The effects of mature woodland on the hydrological regime have been debated for decades and are still uncertain. The two opposing schools of thought are that forests increase peak flows (Robinson, 1986) or lower peak flows (Binns, 1979). The uncertainty arises over the different stages in the forests life cycle and establishment. There have been periods of widespread deforestation in the UK, including during World War 1 (Crooks and Davies, 2001). This caused an immediate increase in runoff (Law, 1956). Since 1919, a policy of afforestation has been supported and has seen the area of the UK classified as woodland increase to 11%. Recently the growth of woodland area has increased further and saw an increase of 29% since 1980 (O'Connell *et al.*, 2004). Afforestation is thought to decrease overland flow runoff by increasing the interception and evapotranspiration losses and partitioning a greater proportion of the rainfall into the subsurface flow pathways. Evaporation losses from the intercepted water within the forest canopy have been calculated to be 25-30% of the precipitation (Johnson, 1991), although the precise effects are dependent upon climate and tree species (Hall and Kinniburgh, 1994). This is due to changing vegetation cover, specifically the leaf area index, which influences the rate of evapotranspiration (De Roo *et al.*, 2001). Fohrer *et al.*, (2001) believe that the most important affect of afforestation is the increase in water storage, due to the process of interception, meaning that runoff is both reduced and delayed. Also a greater proportion of precipitation is partitioned into the subsurface, as the infiltration rate is increased. This effect can be relatively quick, with effects over 2-6 years (Carroll *et al.*, 2004). Afforestation is often preceded by land preparation, including gripping, which will be discussed in the next couple of sections.

Land Drainage – Gripping

Land drainage measures were commonly introduced in Britain in the 1960s/70s, but have declined since 1985. Land drainage schemes such as moorland gripping have two opposing effects on runoff, whereby they can either increase or decrease peak flows (Robinson, 1990). Firstly, they can lead to peak flows decreasing by increasing the infiltration capacity of the soil, allowing water to be stored within the soil and travel through the slower subsurface pathway. This decreases the peak flow, increases the lag time between peak precipitation and the flood event and increases the duration of the peak flow due to multiple sources of runoff arriving at different times. However this argument is dependent upon whether or not the subsurface flow is slower than overland flow, and whether processes such as pipeflow mean that it is faster than initially thought. Furthermore, there is a national division of effect, whereby the peak flows are increased in the drier east and south of the UK, while in the west and north, peak flows are decreased. This is due to the effect of the antecedent conditions (water saturation/deficit) on the partitioning of rainfall between the surface and the subsurface (Arnell, 2003). Also the extent and exact locations of the drains within the catchment are important considerations, as different areas have different characteristics. The impact of storm drains is thought to be dependent upon the soil type, whereby drainage increases the peak flow for permeable soils, but decreases the runoff for clay soils (Gilman, 2002). Secondly, peak flows can be increased by the land drains increasing the connectivity between the hillslope and the channel, which is discussed further in the next section.

2.6.2. Management of Hillslope-Channel Connectivity

Land Drainage – Gripping

Land drainage increases the drainage density of the catchment, making it more efficient in discharging water to the outlet. Water flows faster in channels than as overland flow or as throughflow. Therefore gripping increases the hydrological connectivity between the hillslope and the channels. This process is thought to be more important in the uplands than the lowlands, as runoff rates are affected more in the uplands due to the steep slopes, which mean the flood wave is conveyed downstream faster. Evidence for this comes from a study in the Upper River Tees catchment in the North Pennines by Conway and Millar (1960), in which peak flows increased by 85% and took a shorter time to peak by 1.6 hours (46% reduction).

Land drainage affects both the processes of infiltration and hydrological connectivity. The main debate in the literature concerns which of these processes dominates and what the resultant effect of grips on flood risk is at both local and catchment scales. The general consensus on the effect of land drainage is that it reduces peak flows (Robinson, 1990). A study in Plynlimon, Wales found that after the installation of grips, the peak flow decreased by 40-45%. This study also found that the time to peak increased by 25% (Newson and Robinson, 1983). However, they emphasise the importance of local factors upon the effect of grips on flooding, such as soil type and the location within the river network. Gilman (2002) believes that the effect of increased infiltration is overrated and is negated by compaction due to overgrazing. Lane *et al.*, (2003) criticises past research on the effect of grips, stating that it has focussed too much on empirical studies of individual drains or small networks, rather than furthering our understanding of hydrological connectivity at the catchment scale. The effects of land drainage on flood risk are contingent, with the impact unable to be generalised without considering the spatial context.

<u>Forestry – Deforestation / Afforestation</u>

As mentioned in an earlier section, the change in land use management to forestry requires land preparation, which includes ploughing and land drainage. These two actions are known to increase surface runoff by disturbing the soil structure and increasing hydrological connectivity between the hillslope and the river channel. The most extensive study into catchment scale effects of the life cycle of forest plantations is Coalburn, in the River Eden catchment in Cumbria (Robinson, 1998; Archer, 2003). The Coalburn catchment is a headwater sub-catchment of the River Irthing and has been monitored for over 40 years. Four periods of hydrological change have been proposed by Archer (2003), which are outlined below:-

1967-1971	Pre-draiange
1974-1982	Immediately following afforestation
1983-1990	Intermediate stage
1992-1999	Canopy closure

The difference between the pre-drainage state and the 5 years following afforestation indicate a rapid increase of 20% in the surface runoff. This decreased to an increase of 10% on the pre-drainage levels after 10 years of forest growth. Currently, rates are similar to pre-drainage levels. The flow regime of the River Irthing became more variable and flashier after afforestation. However, the effects were more evident in the Coalburn tributary, due to over 90% of the catchment by area being affected by afforestation, while only 19% of the River Irthing catchment was changed. It is thought that the proportion of the catchment changed has to be greater than 20% to see any change at the catchment scale, and preferably more than 40% to clearly see the effect of afforestation (Sahin and Hall, 1996). Similar conclusions were found in another study of the Cedar River in America (Wissmar *et al.,* 2004). A two stage model has been suggested, whereby initially after land preparation and afforestaion flood peaks increase, while as the forest matures and canopy closure occurs, flooding decreases. However, a factor under debate is the period over which the ploughing affects the runoff rate. It was thought that this could be as long as 30 years (Howe *et al.,* 1967), although MacDonald (1973) believes 15-20 years is more likely. It is thought that mixed age forests may balance out the hydrological effects and lead to flooding decreasing (Robinson, 1998).

Due to the complex hydrological impacts of afforestation, the potential for forests to reduce flooding is likely to be lower than widely claimed (O’Connell *et al.,* 2004). Therefore, afforestation is probably only going to have a small mitigating effect on regional flood risk (Robinson *et al.,* 2003). Although, afforestation is thought to have the greatest effect on moderate magnitude floods (Blackie and Newson, 1986). However, the multiple factors that influence flood generation which include; storm size, location in catchment, and catchment characteristics (geology, soil, vegetation etc.) it is difficult to predict the impacts of afforestation (Calder and Aylward, 2006).

Buffer Strips

In addition to the effect on the process of infiltration, buffer strips influence the hydrological connectivity between the hillslope and the channel (Lane *et al.,* 2003). The buffer zones disconnect the river from the runoff from the hillslope, as these strips have higher infiltration rates and therefore the pathway from hillslope to channel is broken. Therefore it is really the effect of buffer strips on the process of infiltration that drives the connectivity or disconnection. To be successful, land management needs to be at the landscape scale, as buffer zones need to intercept pathways of concentrated runoff and flow convergence. Also buffer zones help reduce overland flow, and increase the proportion of runoff partitioned into the subsurface (Buttle, 2002).

Another change in agricultural practices in the post World War 2 era is the increase in field sizes. There has been a 50% reduction in hedgerows since 1945 (Robinson and Sutherland, 2002), which increases the connectivity between hillslopes and the river channel. Ghazavi *et al.,* (2008) studied the hydrological effects of hedgerows in terms of interception, soil moisture dynamics and groundwater transfer. Hedgerows were found to intercept 28% precipitation for the leafed period and 12% for the leafless period. They were also found to delay the rewetting phase of the soil in autumn. Furthermore, it was found that the soil water potential in the area 9 m upslope and 6 m downslope of the hedgerow was affected. However, the affect of hedgerows at the catchment scale has not been assessed but is believed to be minor due to the small percentage of the catchment covered by them.

2.6.3. Storage of water

Wetlands

The use of wetlands in mitigating flood risk is well documented (Mitsch and Gosselink, 2000; Zedler, 2003; Mitsch *et al.*, 2005; Zedler and Kercher, 2005), although they have not been widely adopted as a flood abatement approach. Wetlands have been degraded and lost over the last century, meaning that their effectiveness in reducing flood risk has diminished. By the 1930s, a quarter of the historical wetlands in England had been lost (English Nature *et al.*, 2003). However, there is a recent trend of wetland restoration which is known to have multiple benefits, including water quality improvement, increased biodiversity, carbon storage, and flood control.

Wetlands reduce flood risk by acting as a store for water, which would have potentially connected to the river channel, causing increased flow discharges and stages. This is done by intercepting runoff and either absorbing water, through infiltration or retaining water. Another important process by which runoff is reduced is through evaporative losses from wetland surfaces (Lahmer *et al.*, 2001). Wetlands act as temporary stores and delay runoff to the river channel. This is done by either natural or designed controls which manage the conveyance of water runoff on the hillslope and attenuates water input into the channel. The wetland buffers the runoff process, meaning that water supply to the river is spread out over a longer period of time, resulting in lower, but longer flow peaks. Other factors which may influence the function of wetlands are; its size and storage capacity, and the level of control over inflow and outflow. However, probably the most important variable is the distribution within the catchment due to the interaction of different sub-catchments. Various studies have proposed recommendations for wetland creation, including Loucks (1989) who believes that lots of small wetlands in the uplands are better than fewer, large wetlands in the lowlands. Ogawa and Male (1986) think that the opposite distribution is best. However, there is some generally accepted advice for wetland restoration projects. This highlights the need for catchment-scale planning and recommends that 3-7% of the catchment consists of wetlands (Mitsch and Gosselink, 2000). There are few hydrological models which integrate wetlands into them, but Hatterman *et al.*, (2006) derived a numerical representation of the surface-groundwater coupling, as well as the climatological processes which affect wetland sustainability.

The most effective type of storage is controlled, often by structures which either control the opening/closing of gates or are levees which control the water level which storage starts at (Jaffe and Sanders, 2001). This means that water is only stored temporarily and can be managed to reduce the rising limb and peak flow and then release water on the falling limb (Forster *et al.*, 2008; Chatterjee *et al.*, 2008). If the storage area is utilised too early then the detained volume is taken from the rising limb and is full by the time the peak flow arrives. If the gates are opened too late then the volume is just taken from the falling limb. Neither of these two scenarios reduces the peak flow considerably (Silva *et al.*, 2004). Figure 2.6 shows how a flood embankment can be used to increase the effectiveness of water storage on the floodplain. The presence of a levee (Figure 2.6a) between the river channel and the floodplain delays the time from which water is stored, meaning that it is the peak of the flood wave that is stored meaning less water flows downstream. Without a levee storage would occur during the rising limb, meaning that by the time the peak flow arrived the floodplain would be at capacity and therefore the peak would just travel downstream without being attenuated.

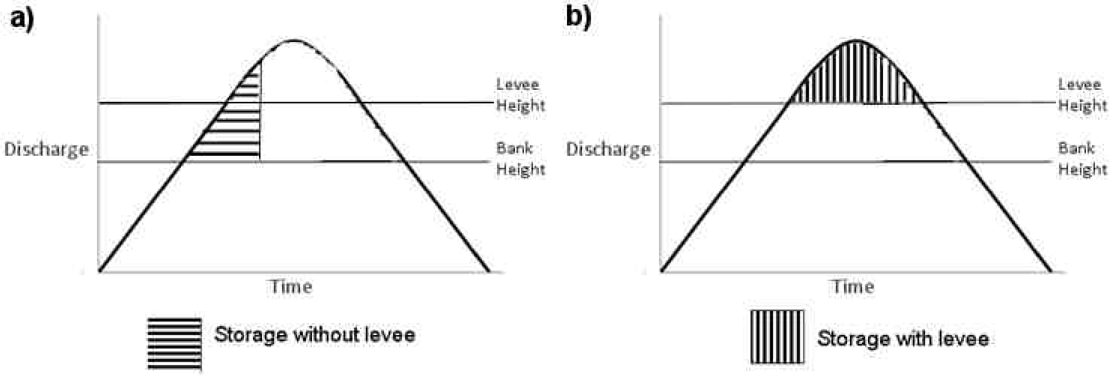


Figure 2.6 *Mechanism by which flood embankments reduce peak flow magnitudes a) without levee; b) with levee*

The specific location of a flood defence is critical in evaluating its effect on a flood peak. Flood defences close to the settlement are beneficial, as they take the top of the peak of the flood. Flood defences further away from the settlement contain the water within the channel, conveying more water downstream, potentially causing a higher peak flow downstream. Therefore it is beneficial to have no flood defences upstream, so that water is transferred to the floodplain, reducing the amount of water travelling downstream and attenuating the flood peak.

The storage structure should be emptied as soon as possible after the river water levels decrease, so that maximum storage capacity is available for future high flow events (Hall *et al.*, 1993). The Elbe flood in August 2002 was lowered by 40cm due to a temporary detention area at the confluence of the Havel and Elbe rivers. Furthermore dike failures in another location led to floodplain storage which reduced the river stage by 11cm (220 m^3s^{-1}) in Wittenberg (Forster *et al.*, 2008).

Other surface storage features, such as ponds, ditches and impoundments function in similar ways, although there is more uncertainty associated with there ability to reduce flood risk. Floodplain restoration schemes are thought to reduce flood risk as they reconnect the channel to its floodplain (Acreman *et al.*, 2007), allowing water storage on the floodplain in flood expansion areas, which are commonly agricultural fields (Pivot *et al.*, 2002). Interception ponds have been used at Nafferton Farm in the Tyne valley to store road runoff to benefit water quality (Jonczyk *et al.*, 2008), but has also been shown how they have water quantity advantages at Belford in Northumberland (Wilkinson *et al.,* 2008).

2.6.4. Management of River channel Conveyance

Channel Modification / Floodplain Restoration

Channel modifications can consist of hard engineering works including channel straightening and bank/bed changes. Furthermore, the connectivity between hillslope and channel can be changed by the introduction of levees/embankments, although recently there has been a trend of restoration of natural channel and floodplain structure and function.

A good example of the effects of channel modification on flood risk is Acreman *et al.,* (2003). Several model runs were carried out to show the effect of several scenarios on flood risk for the River Cherwell, UK. It was found that by embanking the river, flood peaks were increased by 50-150% and were flashier. This structural approach led to the return period of floods decreasing, meaning floods of a certain magnitude was found to occur more frequently. This is because the river channel is disconnected from its floodplain, meaning that water cannot be temporary stored and channel conveyance is increased.

Another scenario involved restoring the channel configuration to pre-1900 conditions, which meant making the channel narrower and raising the bed. This approach was found to reduce and attenuate the peak flow downstream by 10-15%, as water could be stored on the floodplain where restoration had occurred. Also, the return period of floods was found to decrease, meaning that overall flood risk declined.

Bormann *et al.,* (1999) found that restoring the original river planform to a meandering pattern reduced the peak discharges downstream, as the length of the flow pathway was increased and the slope decreased, meaning that the conveyance decreased. Another finding was that increasing the amount of in-channel vegetation decreased the flood hazard downstream, as the flow was attenuated due to the resistance on the flow increased, as channel roughness increased.

2.7. Chapter Summary

From this review it is clear that the link between rural land management and flood risk represents a fundamental challenge (O'Connell et al., 2004), which needs to be assessed at multiple scales and by suitable approaches. Over the past 50 years many changes in land use have occurred in UK catchments, including agricultural practices, afforestation/deforestation, channel engineering and urbanisation.

This chapter has raised three major problems in establishing a link between land management and flooding; (1) the effects of scale; (2) the uniqueness of catchments; and (3) the land use effects are not mutually exclusive from climate change impacts. Land management has been studied, in terms of its effect on flood risk, but often only at the local scale (O'Connell *et al.*, 2004). However, the catchment scale the impacts are highly uncertain. It is important to understand how the local effects of land management on runoff are propagated through the drainage network to downstream settlements. Additionally, this review has highlighted the importance of the spatial distribution of land management changes, as land uses affect both the quantity of runoff and its timing. Therefore it is the relative timings of each sub-catchments contribution to the main channel, which influences the volume of water at a given location at a given time. Tributaries peak flow phasing with respect to the main channel is a key control on how local scale runoff changes are upscaled to the catchment outlet.

The second reason why there are uncertainties over the hydrological effect of land use changes is due to the specificity of meteorological events and the unique nature of catchments (Beven, 2000). Bronstert *et al.,* (2002) state that land use changes are more significant for convective thunderstorm events than advective, frontal rainfall. This is probably because convective storms occur in Summer when rates of interception, evapotranspiration and storage are highest (Archer, 2007). Also catchments are often driest in summer, and Bronstert *et al.,* (2007) stated that when the antecedent conditions are dry, the effects of land cover are highest. Furthermore convective storms are localised in nature and therefore affect small catchments the most where the effects of land use changes are greatest (Gilman, 2002). O'Connell *et al.,* (2004) believe that land use changes have a greater impact on small/moderate floods. Also some catchments are more sensitive to land use changes than others (JBA Consulting, 2007; Environment Agency, 2008). The Environment Agency, (2008) study ranked the Eden catchment as the 24th most sensitive CFMP catchment to land use changes in England and Wales out of a total of 77 CFMP catchments. Often a high proportion of the catchment needs to be changed for any impact to be detectable downstream.

The third important area relates to the issue that the land management effects are not mutually exclusive from the climatic effects in the flood record. This is one of the main reasons why proving the land use link to flooding has proved so difficult as this impact has to be disentangled from the climatic change effect. At present it is thought that land use change effects are of second order importance behind natural climatic variability (O'Connell *et al.*, 2004). It is likely that land use changes are amplifying the effect of climatic variability, and this does not mean that land management policies cannot be used to mitigate the effect that climate variability has on increasing flood risk. Bloschl *et al.*, (2007) looked at the effects of climate change on both high and low river flows and produced Figure 2.7 as a summary. Climate change occurs at quite large spatial scales and is likely to affect the same catchment in a similar way, independent of the part or scale of the investigation. However, land use changes are localised in nature and the impact of the change will be lower as the catchment size increases. The crossover point will be catchment specific depending on how sensitive the catchment is to change.

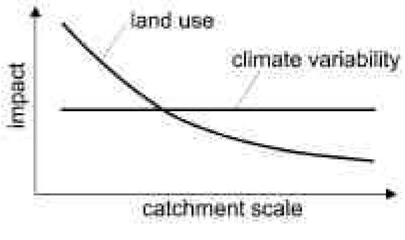


Figure 2.7 *Hypothesised impact of land use and climate change on hydrological response as a function of spatial scale. (Bloschl et al., 2007).*

The complexity of the controls on flood risk mean that several methods have been used to quantify their effects, namely quasi field-experiments and numerical modelling. Quasi-experiments offer the ability to determine the real effects of land management changes, although there are concerns over the lack of “control” in these investigations. The use of rainfall-runoff models to predict the impacts of certain climatic/land use changes is in its infancy and therefore there is considerable debate over the best type of model to use and what the best data to input into it are. Furthermore, there are inherent uncertainties involved in using models, such as how the model is defined and the quality of the input data. A problem with predicting the impact of future events is that there are multiple future scenarios, depending on the driving factors. A major question which is important in assessing future flood risk, is determining possible future land use and climatic scenarios.

In addition to the methods used to investigate the link between land use and flooding, this review has reported on different conceptual approaches to the problem. A hydrological process based conceptualisation proposed by Lane *et al.* (2007) has been used to show the theoretical link between local scale changes in runoff and changes in flood risk at the catchment scale. This is summarised in the following three suggestions on how to reduce flood risk: (1) to increase the proportion of precipitation partitioned into sub-surface flows; (2) to increase the amount of water storage within the catchment; and (3) to decrease the speed of conveyance of runoff and channel flow (Lane *et al.*, 2007).

In conclusion this review has highlighted the potential for land management practices to reduce flood risk, although they are yet to be proven as generic tools, and there are still uncertainties over the precise effects at the catchment scale. This is partly because catchments consist of a mosaic of different land uses and are dynamic in both space and time. Fohrer *et al.* (2001) believes that the complexity of the land uses within the catchment may lead to a compensating effect, whereby some land use changes cause increases in flood risk, while others decrease peak flows, leading to land use having a minor effect on flood frequency and magnitude. However, Sullivan *et al.* (2004) thinks that small scale land use changes can have a significant hydrological impact, although it is only due to the cumulative nature of the same change throughout the catchment and different land management changes, that a land use signal can be found in the river flow record.

To resolve these uncertainties more catchment scale research needs to be carried out on the individual and cumulative effects of the various land management practices. This is essential as flood risk management needs to be planned at the catchment scale. It is important that the phasing of different tributaries and the main channel are separated, meaning that flood waves do not combine and amplify the flood risk. However, it is thought that management at the source of the problem is better than controlling the effects downstream. Therefore, a upstream, diffuse management policy to mitigate flood risk is supported (Lane *et al.*, 2003; Lane *et al.*, 2007), especially as potential climatic effects may increase precipitation levels within the UK. In summary, no strong evidence has been produced to prove that land management can reduce flooding at the catchment scale; however, this does not mean that it doesn't have a role to play in flood risk reduction. The reasons why evidence has proved so elusive are that modelling and field based studies are in their infancy (O'Connell *et al.*, 2007) and that it is difficult to distinguish the effects using sparse catchment scale and time limited data (DEFRA, 2008), especially as the effects of climate change and land use change are not mutually exclusive. The literature review outlined in this chapter will be used in Chapter 7, along with stakeholder participation to decide which land management scenarios will be tested in this thesis.

Chapter 3

Methodology: Data related elements

3.1. Chapter Scope

The approaches used within this thesis combine data analysis with numerical modelling. This chapter focuses on the data related aspects of the methods used, while the numerical modelling methodologies are outlined in Chapter 5 and 8. Data are an essential component of the approach taken in this study, as part of both (1) the downscaling methodology used to prioritise sub-catchments (Chapter 6); and (2) the numerical modelling methodology used to assess future land management impacts on downstream flows (Chapter 9). This chapter addresses the types of data used (Section 3.2) and how these data were prepared for analysis and model input (Section 3.3). This chapter also evaluates the raw data to assess its validity for analysis throughout the thesis. This is done for data on two different timescales: (1) instrumented (1976-present); and (2) historical (1770-present). Section 3.4 outlines how the data were used to assess trends in both flood frequency and magnitude.

3.2. Data Types and Availability

A data trawling exercise was carried out, whereby the data needed for data analysis and modelling were defined and then sourced through the different organisations involved in the project. Instrumentation of the catchment as part of this study was not an option as; (1) the duration of the study might not capture flood events; and (2) the large area covered by the study would not be covered by available instrumentation resources. The types of data which were needed are summarised in Table 3.1 and are; (a) discharge; (b) stage; (c) precipitation; (d) temperature; (e) channel cross sections; (f) a land cover map; (g) a soil type map; and (h) topography. Discharge and stage data are needed for assessing trends within the catchment. Furthermore, these data are needed as inputs into hydraulic models and also for assessing the outputs of hydrological and hydraulic models. Precipitation and temperature data are needed for input to hydrological models. Channel cross sections and information on channel roughness are also needed for hydraulic models. In addition, spatially distributed hydrological models require a land cover map, soil type map and topography data. Data availability and limitations are described in the following sections.

Data Type	Need / Use	Summary	Source
Discharge	- Trend assessment - Statistical downscaling Methodology - Hydraulic model boundary Conditions - Hydrological model validation	Monitored data at a 15 minute resolution at gauging stations with a rating relationship	Environment Agency
Stage	- Hydraulic model validation	Monitored data at a 15 minute resolution	Environment Agency
Precipitation	- Hydrological model input	Monitored data at a 15 minute resolution	- Environment Agency - Met Office - BADC
Temperature	- Hydrological model input	Monitored data at a daily resolution (maximum and minimum)	BADC
Channel Cross sections	- Hydraulic model boundary conditions	Channel shape and elevation along river network	Environment Agency models
Land Cover map	- Hydrological model input	Land uses and cover for catchment	Land Cover Map 2000
Soil Type map	- Hydrological model input	Soil type over catchment	
Topography	- Hydrological model input - Hydraulic model construction	Elevation of land surface in catchment	- NEXTMap - Environment LIDAR data

Table 3.1 *Summary of data needs and availability*

3.2.1. Discharge

Most of the data used within this thesis is gauged discharge series. Figure 3.1 shows the spatial distribution of the gauging stations within the Eden catchment. These provide continuous measurements of river stage (h) which are converted to discharge (Q) using a stage-discharge rating relationship. Rating relationships take the following form:

$Q = K (h + a)^{p}$ where a is the stage at zero flow (Datum corrected) and K and p are constants

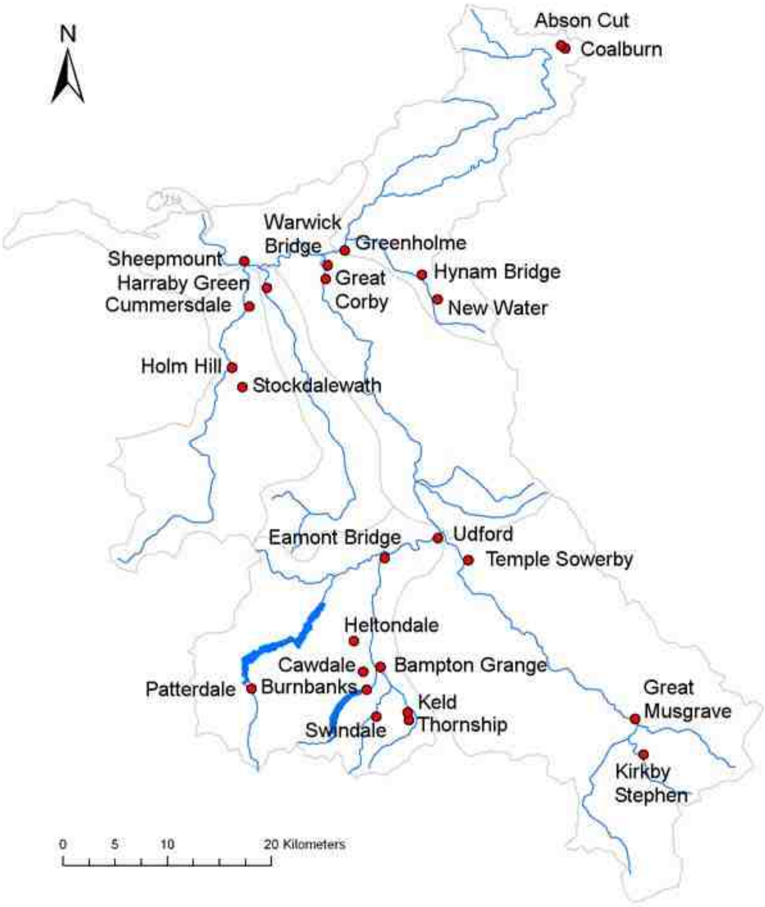


Figure 3.1 *Map of gauging stations in the Eden Catchment monitoring stage and with stage-discharge rating curve.*

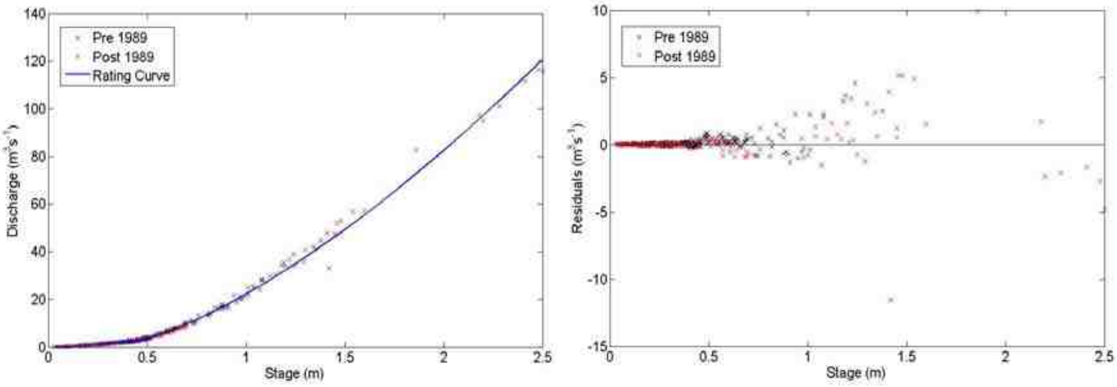
In order to assess trends in the high flow record in the Eden catchment, a discharge gauging station from each of the major sub-catchments was chosen to be representative of flows contributing to the main Eden from each tributary. The criteria used to assess the gauging stations were three-fold. First, a gauging station on each main tributary (highest order stream) (Strahler, 1952) nearest the confluence with the River Eden that would be most representative of flows from each sub-catchment was needed. Second, the quality of the data at each station needs to be high. Problems with gauging station records include transcription errors, unrecorded/missing data, datum changes, rating equation changes and relocation or rebuilding of structures e.g. weirs. A critical consideration is the stage-discharge relationship for overbank flows. Babaeyan-Koopaei (2001) states that there is no recognised method for deriving an out of bank rating and that the common extrapolation of the in-channel curve is incorrect, as the slope of the curve above bankfull is different. The quality of the rating equation for the highest flows is often poor, due to floods occurring infrequently and their short duration especially in responsive catchments, meaning that measurement campaigns may miss them. Furthermore, access to sites for gauging is made more difficult during out-of-bank flows. Backwater effects also complicate the conversion of stage to discharge, as water stored on the floodplain is returned to the channel. Modern techniques such as acoustic doppler instruments can provide accurate velocity and discharge measurements in locations where conventional methods have problems such as unsteady and bi-directional flows (Yorke and Oberg, 2002). Also some stations are designed to measure either high or low flows but not both. Each gauging station was assessed for this criterion through communication with the Environment Agency (2006) and through comparing spot gaugings to the model predictions (Cox *et al*., 2006). Third, a gauging station with a minimum record length is needed to assess temporal trends. There have been several recommendations on what the minimum record length needs to be to make sure the results are statistically valid. This is because what can appear to be a trend in a short duration record could be viewed as a fluctuation in a longer data record (Robson, 2002). Robson (2002) states that the shorter the record length, the more susceptible it is to so called edge effects, when periods which have several floods or few floods at the beginning and end of the record influence the strength of the trend. Kundzewicz and Robson (2000; 2004) stated that a record of at least 50 years is needed to detect the possible climate change impacts on streamflow. However, although the longest period possible is desirable, few records in the UK longer than 30-40 years exist. This is because the UK gauging station network was commissioned in the 1960s and 1970s (Lees, 1987). In fact when using the 890 gauging stations in the Institute of Hydrology’s Peak over Threshold database, the average record length was only 18 years (Robson *et al.,* 1998). The recommended range of record length is from 10 to 40 years.

The Interagency Advisory Committee on Water Data (1982) suggested that 10 years was enough to define the frequency of flooding, although Konrad and Booth (2002) found that such short records could lead to spurious trends. A minimum record length of 20 years led to the range of streamflow parameters narrowing significantly according to study by Richter *et al*., (1997). Most investigations of streamflow trends have been carried out on data records of at least 30 years (Lettenmaier *et al*., 1994; Lins and Slack, 1999; Douglas *et al*., 2000). Gan *et al*., (1991) suggested that at least 40 year records are needed to ensure robust assessment of discharge trends over time. Huh *et al*., (2005) found that to be able to detect step changes in flooding frequency, record lengths needed to be at least 40 years for flood frequency to be assessed and 60 years for low flow trends to be tested. A benchmark network of gauging stations collated by Hannaford and Marsh (2006) had an average length of 33.7 years. However, the record length needed to accurately assess flood frequency depends both upon whether flood events are clustered and the temporal resolution of the data used. What is clear from this is that the longer the record the better, but also there needs to be a compromise between temporal and spatial coverage (Burn and Hag Elnur, 2002). It was also stated that a common period of data record is best, so that comparisons between stations can be made. Hannaford and Marsh (2006) argued that using a fixed period for relatively short records is problematic, as trend analysis is sensitive to the chosen period. This is illustrated by a study by Hisdal *et al*. (2001), where for a single station, using different 30 year periods, both positive and negative significant trends were found. From this review of the literature, it has been decided that the minimum length of the record needs to be 30 years, as there are numerous stations with this length, but few much longer.

The following section outlines which gauging station was chosen to represent each sub-catchment, by systematically assessing the stations by the three criteria outlined above.

Upper Eden

As this sub-catchment has the largest area (616 km^2), it was decided to use multiple gauging stations to assess its flow characteristics. First, Kirkby Stephen, draining an area of 70 km^2 was assessed. This station has a record extending back to 1976, but is incomplete with 1979 and 1980 missing from the record. For this station to be meet the 30 year record length criteria, this gap in the data would have to be filled by some method. However, there is no appropriate gauging station to do this as the nearest gauging station, Great Musgrave, only starts in 2000. However, as this is only a gap of two years, the Environment Agency were contacted to use the microfiche to extract the flood peaks for the specific events from the undigitised original data, which were converted to discharge using the rating curve. The weir at this station is a non-standard compound broad crested weir. The Environment Agency (2006) states that this gauging station has a reliable record for both high and low flows, although the high flow record pre-1989 is likely to be overestimated by as much as 40% at bank full (2.5 m). The rating curve used at this station was improved in 1989. Prior to this year, the rating equation was only based on spot gaugings up to 1.42 m and above this stage extrapolation resulted in overestimation of discharges (Figure 3.2a). It is clear that the current rating equation, starting from 1989, fits the data well up to bankfull at 2.5 m. Figure 3.2b shows the residuals of the observed spot gaugings compared to the rating equation prediction. Residuals are quite small, with most being within ±11.6 m^3s^{-1} of the monitored discharge for the corresponding measured stage. There is more uncertainty above bankfull as about 10% of the flow bypasses the gauge (Environment Agency, Hiflows). It has been decided that the gauging station of Kirkby Stephen will be used in further analysis, as the data quantity and quality meet the criteria outlined.

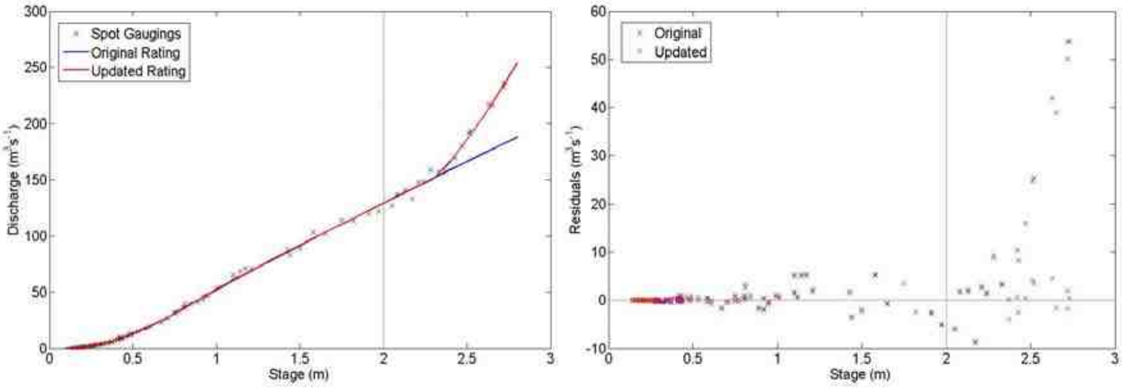


a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.2 *Assessment of the Kirkby Stephen rating curve*

The second gauging station in the Upper Eden catchment is Great Musgrave, which has an upstream contributing area of 223.4 km^2, but only has a gauging record since 2000, meaning it does not meet the 30 year criterion. The data quality is good with the rating equation fitting observed data for the gauged range (< 2.7 m) (Figure

3.3a). The original rating was derived for spot gaugings up to 2.4 m, with extrapolation to higher values. Later measurements found that discharge increased faster beyond this stage than the extrapolation suggested and therefore an updated rating was proposed. The measurements of the fit between rating curve prediction to spot gauging observations highlight the improvement of the updated curve. The range of the residuals for the original curve is from 53.8 m^3s^{-1} to -8.8 m^3s^{-1}, suggesting that this rating underpredicts the highest flows significantly. This is improved in the updated equation which has a far smaller range from 9.3 m^3s^{-1} to -8.5 m^3s^{-1} (Figure 3.3b). The Sum of the Squared Residuals (SSR) for the original rating is 13687.2 m^6s^{-2}, while the RMSE is ±10.2 m^3s^{-1}. The SSR for the updated equation is 513.3 m^6s^{-2} and the RMSE is ±2.0 m^3s^{-1}. There are problems with the gauging of flows at this site due to upstream sedimentation on a mid-channel island and also above bankfull complex floodplain interactions make out of bank flows difficult to gauge. It has been decided that the gauging station of Great Musgrave does not meet the criteria outlined, due to a record length of significantly less than 30 years and concerns over data quality, especially for high flows.

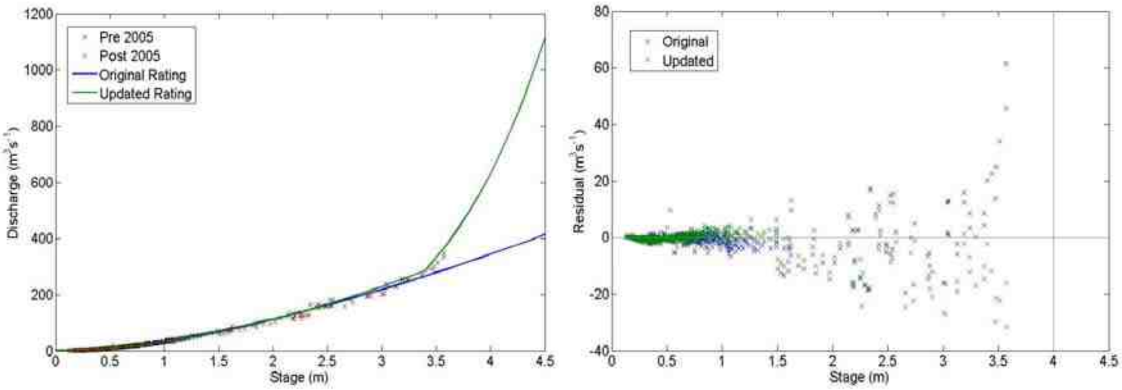


a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.3 *Assessment of the Great Musgrave rating curve*

Temple Sowerby, which is on the edge of the Upper Eden sub-catchment before the confluence of the River Eamont with the River Eden, drains an area of 616.4 km^2. This station has a record extending back to 1964, although there are missing data early in the record. However, the completeness of the gauging record improves from 1976 to the present day. Furthermore, the data before 1970 are suspect for both high and low flows (Environment Agency, 2006). The quality of the original stage-discharge rating curve is good up to 3.2 m, but higher flows are significantly underestimated

(Figure 3.4a). This is because the bankfull height changed in 1995 due to construction of a flood bank which retains flows up to 4 m within channel. Flows with a stage greater than 3.2 m before and after 1995 should have different rating relationships, but there were too few gaugings pre-1995 to quantify these differences (Environment Agency, 2006). A review of the gauging data led to a revised rating which fitted better with the spot gaugings at high flows. In 2002, the rock bar control was replaced by a non-standard shallow flat-V weir, which may have changed the relationship between stage and discharge, but this was never quantified, although it is thought to be insignificant at high flows (Environment Agency, 2006). The extreme January 2005 flood event is thought to be underestimated by 20% (Morriss, 2006). Further modelling was undertaken to improve the quality of the rating equation for high flows (Morriss, 2006). This applied the coupled 1D-2D hydraulic model, iSIS-TUFLOW, to simulate past flood events and predict the peak discharge for the January 2005 flood. It was recommended that the original rating curve was suitable up to 3.4 m, but beyond this a new rating equation was proposed. However, there are only spot gaugings up to 3.57 m, so model extrapolation beyond this up to 4.5 m has not been confirmed by gaugings. Figure 3.4b shows the residuals of the spot gaugings from the original and updated rating curves. The original rating under predicted flows above 3.4 m by up to 60.0 m^3s^{-1}. The updated rating may overpredict high flows but the error is smaller, with the largest residual being -31.6 m^3s^{-1}. The sum of the squared residuals for the original equation was 17803.6 m^6s^{-2}, compared to the updated rating with a SSR of 14023.0 m^6s^{-2}. Furthermore the root mean squared error is lower for the updated equation at ±4.4 m^3s^{-1}, compared to the original rating RMSE of ±5.0 m^3s^{-1}. Overall, the quality of the rating relationship at Temple Sowerby is thought be good for the whole range of flows. This station fits all three criteria fully, with the flow being representative of the discharge from this sub-catchment, a long record of at least 30 years and good data quality, so will be used in further analysis.

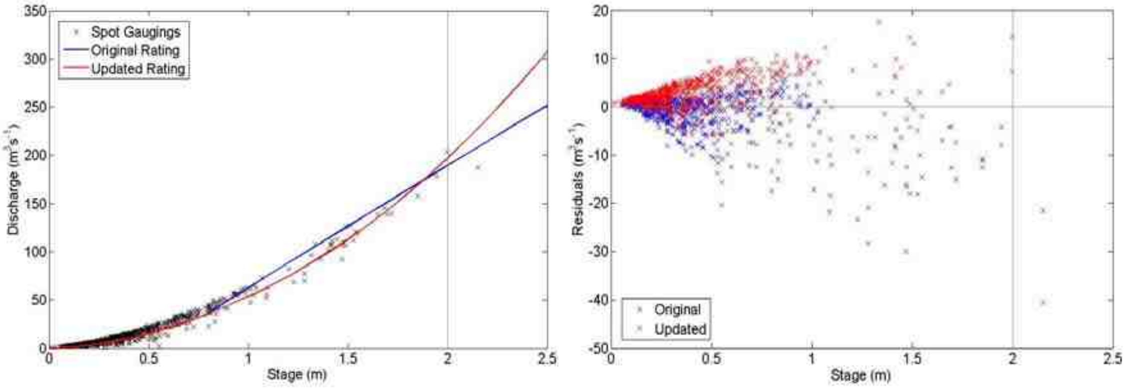


a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.4 *Assessment of the Temple Sowerby rating curve*

<u>Eamont</u>

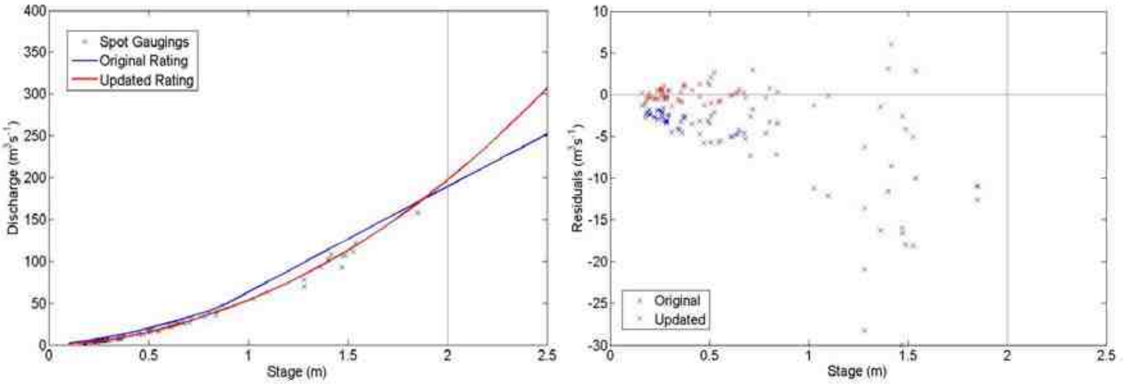
Udford gauging station is on the main River Eamont downstream of any tributary inputs (highest stream order) (Strahler, 1952) and the upstream contributing area is 396.2 km^2. The discharge record starts in 1976, but there are some major gaps (August 1979-November 1979, December 1979-May 1980, June 1980-January 1981). The quality of low flow data is thought to be poor pre-1989 and very poor since 1989, due to the frequent channel movements and weed growth (Environment Agency, 2006, 2006). The high flow records are reasonable for the whole record according to the Environment Agency (2006). From the 735 spot gaugings taken from 1968 to 2009 shown in Figure 3.5a, it is clear that there is considerable scatter around either side of the rating curve. Both the original and updated ratings are shown on this graph. Figure 3.5b shows the residuals of each spot gauging from the prediction made by both rating equations. For low flows, the original rating overpredicts discharge, while the updated equation underpredicts low flows. For higher flows, the original equation generally overpredicts, while the updated rating curve underpredicts to a lesser extent. The sum of squared errors (SSE) for the original rating is 13954.8 m^{6}s^{-2}, with a Root Mean Square Error (RMSE) of ±4.4 m^{3}s^{-1}, while the assessment of updated rating equation gives a SSE of 15195.3 m^{6}s^{-2} and a RMSE of ±4.6 m^{3}s^{-1}. This means that the original rating equation is the best equation to use for the whole range of flow over the whole time period.



a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.5 *Assessment of the Udford rating curve (1968-2009)*

However, the updated curve only starts from 2005, as the rating was updated after the extreme January flood event. This is because the original rating was worst at predicting the highest flows. Figure 3.6a shows the 76 spot gaugings taken since this event. It is clear that the updated curve fits the observed data a lot better than the original rating equation. This is further shown by the magnitude of the residuals in Figure 3.6b, smaller than the residuals using all the data in Figure 3.5b. Table 3.2 shows that the updated rating curve is particularly good at predicting the whole range of flows since 2005. The SSE of the original rating is 5037.3 m^6s^{-2}, compared to 890.8 m^6s^{-2} for the updated rating equation. The RMSE is ±8.2 m^3s^{-1} for the original equation and only ±3.5 m^3s^{-1} for the updated equation. Udford gauging station will be used to represent the Eamont as it is fit for the purpose.



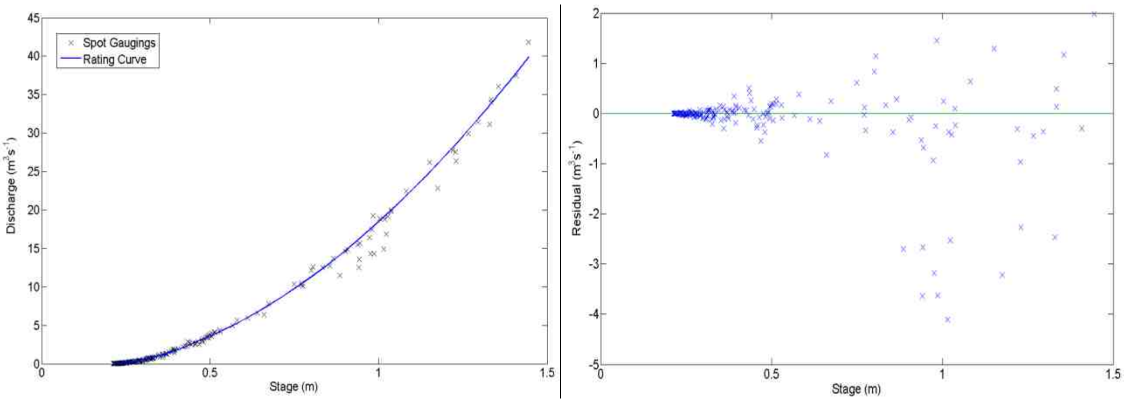
a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.6 *Assessment of the Udford rating curve (post 2005)*

	Original Range	Updated Range
All Data	44.4 (-29.9 to 14.5)	58.2 (-40.7 to 17.5)
Post 2005	28.6 (-29.9 to -1.3)	19.0 (-15.9 to 3.1)

Table 3.2 *Assessment of range of residuals for different rating curves and spot gauging for Udford*

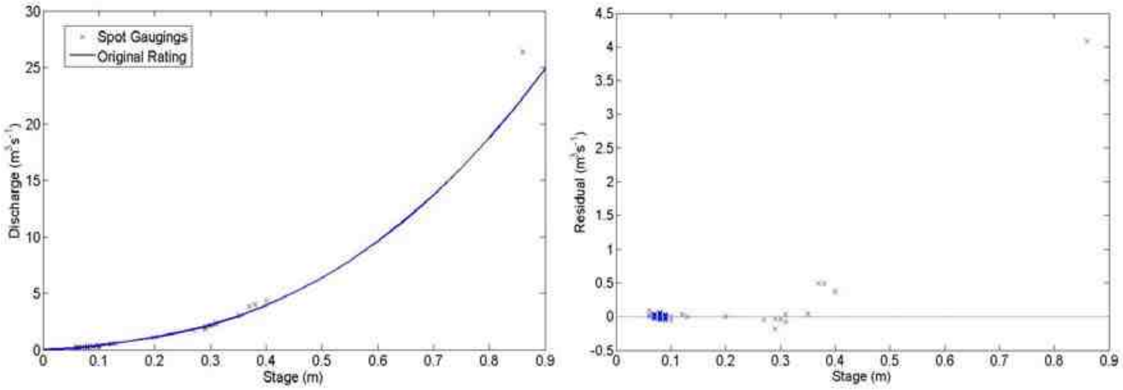
Other gauging stations in the Eamont sub-catchment have been rejected from further investigation. Most of the stations only had record extending from 1997 (Thornship US, Thornship, Keld, Swindale Fish Pass, Swindale US Intake, Cawdale US, Cawdale V Notch, Heltondale US and Side Farm) Furthermore, these stations are on rivers that have the added complication of abstraction and compensation flows. Many of these gauging stations are not intended to measure river flow, but only the water released from structures upstream (Environment Agency and United Utilities). The Bampton station was installed in 2000, so only has a short record. The gauging station on Dacre Beck at Dacre Bridge was only installed in 1997. Figure 3.7 shows the errors associated with the rating curve for Dacre Bridge. It is clear that residuals are higher for higher stages, but are still low (2 > residuals > -5).



a) Rating curve and spot gauging b) Residuals of the spot gauging from curve

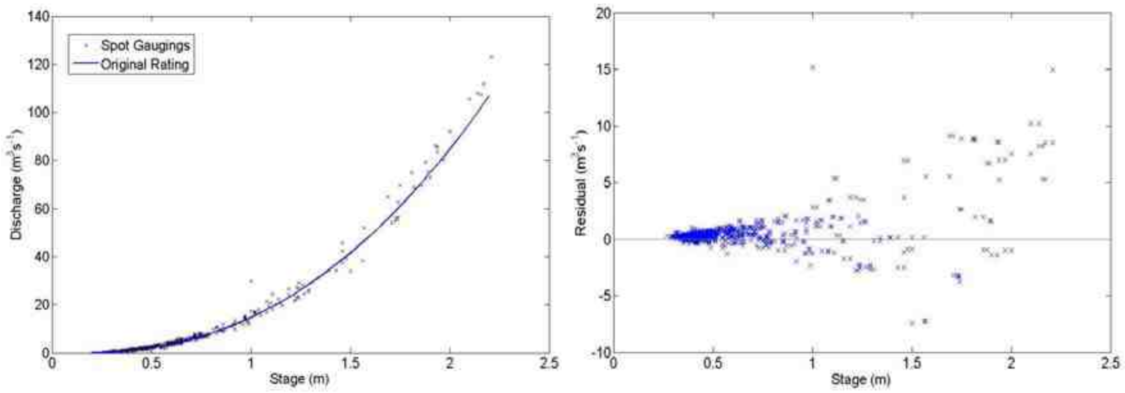
Figure 3.7 *Assessment of the Dacre Bridge rating curve*

The only stations with a record length that meets the 30 year criteria are Burnbanks (1978) and Eamont Bridge (1964). Burnbanks, is a gauging station just downstream of Haweswater dam on Haweswater Beck, draining an area of 33 km^2. It consists of a compound crump weir, but there are no high flow spot gaugings to assess the accuracy of the extrapolated rating curve. Figure 3.8a shows how all but one of the spot gaugings are below 0.4 m. The residuals are small but increase for higher flows (Figure 3.8b). This station will not be used, as it does not represent the total flows from the Eamont sub-catchment and there are concerns over data quality. Eamont Bridge has a 45 year record (1964-2009) and the rating curve is thought to be accurate, although spot gauging only extends to 2.15 m (Figure 3.9a). The rating equation fits the spot gaugings quite well, with residuals being below 20.0 m^3s^{-1}, although there does seem to be a trend that the rating underpredicts higher flows (Figure 3.9b). However, flows are contained within the channel and therefore rating curve extrapolation is thought to be suitable. The rating curve has more problems at low flows due to frequent channel migration and vegetation growth (Environment Agency, 2006). The reason why Eamont Bridge gauging station will not be used in further analysis is that it is on the major tributary of the Eamont, the Lowther, and therefore only represents 40% of the catchment area.



a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.8 *Assessment of the Burnbanks rating curve*

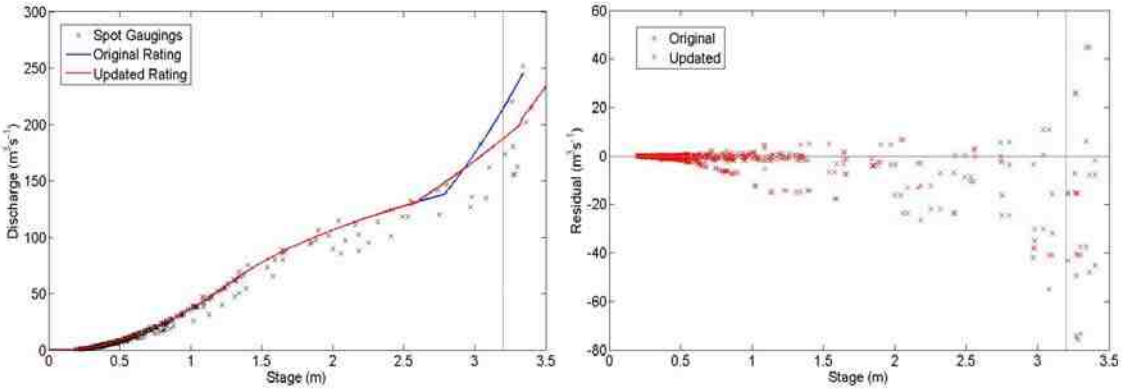


a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.9 *Assessment of the Eamont Bridge rating curve*

Irthing

Greenholme gauging station is the furthest downstream on the River Irthing and therefore may be most representative of the total flows from this sub-catchment. This station has a complete record from 1975 to the present, with only minor gaps. A problem with the reliability of the discharge data from this station arises from flows backing up from the River Eden. High flows recorded at Greenholme are worst affected, as it is likely that the Eden is also high at these times, meaning that high flows at Greenholme can be overestimated by up to 30% (Environment Agency, 2006). However, as can be seen in Figure 3.10a, there is considerable scatter in the spot gaugings, probably caused by the interaction of the Irthing tributary with the main River Eden. Therefore it is particularly difficult to derive a reliable rating equation for this station. The original rating was evaluated and a new one proposed by a modelling investigation (Morriss 2006b). This study found that the original rating was suitable up to a stage of 2.6 m. The original rating overpredicts the highest flows, as shown by a maximum residual of -75.5 m^3s^{-1} (Figure 3.10b), while the updated rating equation is closer to the majority of high flow spot gaugings, so overpredicts to a lesser extent (residual = -40.9 m^3s^{-1}). The original rating had a sum of squared errors value of 38276.9 m^6s^{-2}, while the updated rating has a SSR of 18509.1 m^6s^{-2}, less than half the original error. The root mean square error is ±7.3 $m^3s^{-1}$for the original rating and ±5.1 m^3s^{-1} for the updated equation. Also there is out of bank flow above a stage of 3.2 m, which is not accounted for in rating relationships meaning that flow estimates for higher stages should not be used. This is because the range of spot gaugings above this bankfull stage is about 100 m^3s^{-1}. There are no major problems with low flow records. Greenholme gauging station has been chosen to represent the Irthing sub-catchment, as it has a long representative record, although there are problems with the rating curves. The other stations in this sub-catchment; Coalburn, Abson Cut, Brampton Beck, New Water and Hynam Bridge are not suitable for use, as they are only on minor tributaries and have relatively short records.

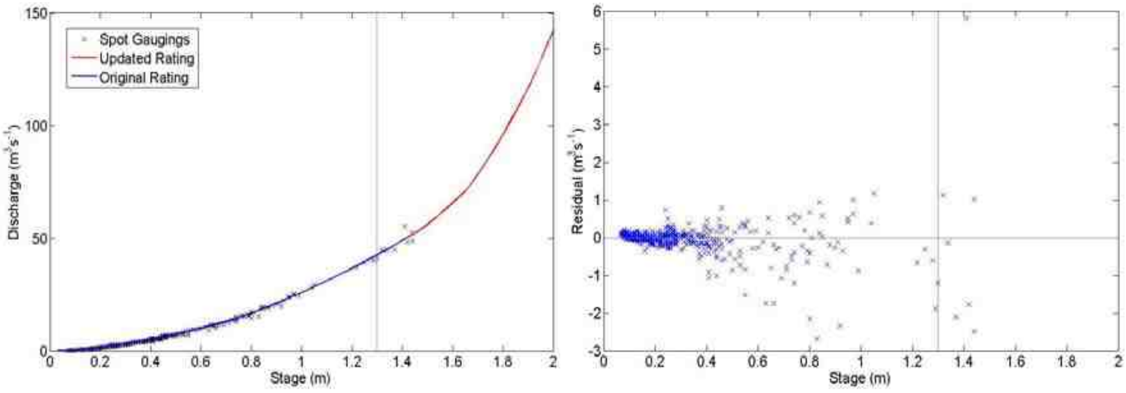


a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.10 *Assessment of the Greenholme rating curve*

<u>Petteril</u>

There is only one gauging station in the Petteril sub-catchment, at Harraby Green, which has a stage-discharge rating curve. This station is on the main Petteril tributary near the confluence with the River Eden in Carlisle. The record at this station extends back to 1975. There are some problems with the gauging of both high and low flows, where low flows may be overestimated by up to 10% since 2001 and out of bank (>1.5 m) high flows should not be used (Environment Agency, 2006). Figure 3.11a illustrates why flows above 1.5 m should be used with caution, as there are no spot gaugings above this to evaluate the extrapolated rating curve, although this was derived from a modelling study (Halcrow, 2006a), which found that the blockage of Harraby Bridge had little effect on flows and proposed an extended rating curve. The reliability of the rating curve below bankfull seems to be good, with small residuals (Figure 3.11b).

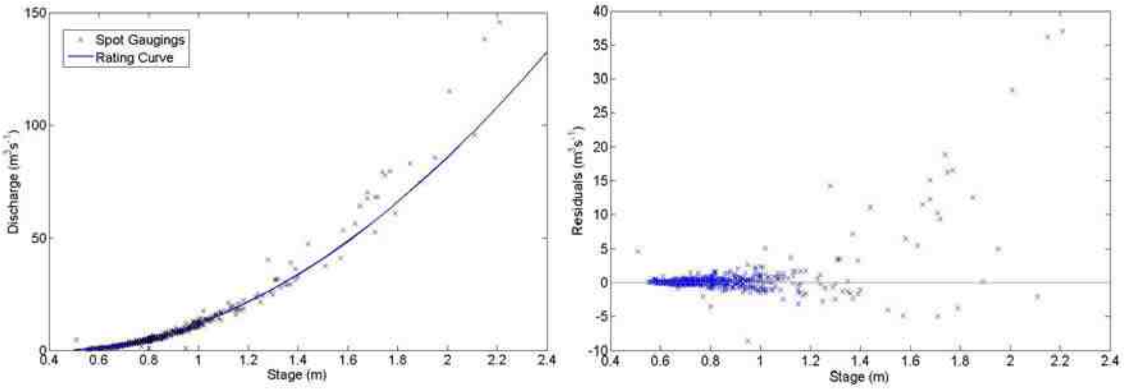


a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.11 *Assessment of the Harraby Green rating curve*

Caldew

The gauging station on the Caldew is at Cummersdale, but this record only starts in 1997. The Cummersdale station replaced the Holm Hill gauging station which was 10km upstream. The Holm Hill station covers the period 1976-2000, although all flows are considered to be unreliable, with some large differences between spot gaugings and the rating curve (Figure 3.12a). Specifically, the rating curve underpredicts the high flows by up to 40 m^{3}s^{-1} (Figure 3.12b).

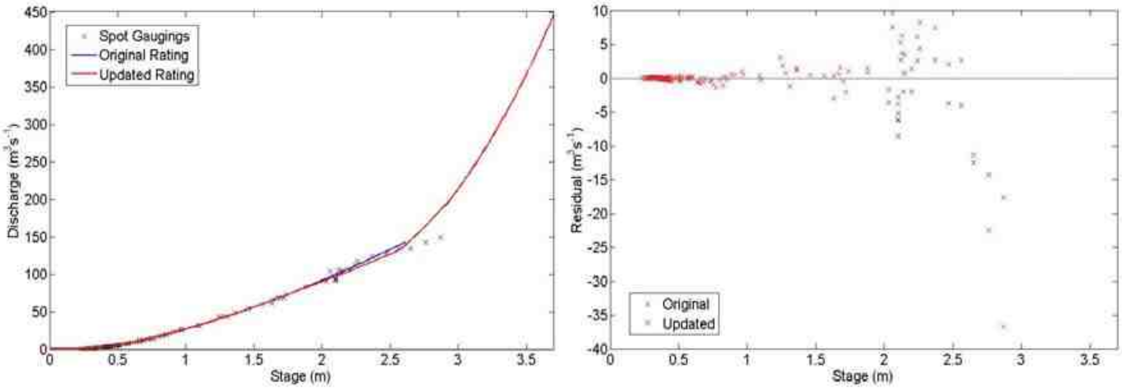


a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.12 *Assessment of the Holm Hill rating curve*

At Cummersdale, the gauging of both high and low flows is good, although becomes unreliable for over bank flows (>3.0 m), as there are no spot gaugings to confirm the extrapolated rating curve (Figure 3.13a). The original rating curve seemed to match the spot gaugings better than the updated equation, which was derived through a modelling study (Halcrow, 2006b). The SSR of the original rating was 1325.6 m^{6}s^{-2} compared to the updated equation which had a SSR of 3794.3 m^{6}s^{-2}. The RMSE values of the original and updated ratings were ±3.1 m^{3}s^{-1} and ±5.2 m^{3}s^{-1} respectively. Both ratings overpredict the highest flows by approximately 20 m^{3}s^{-1} for the original rating and 40 m^{3}s^{-1} for the updated equation (Figure 3.13b). Horritt *et al.* (2010) found that the original rating underpredicted the January 2005 event by 25%. Sensitivity analysis of the rating curve found that water stage was more sensitive to channel roughness than floodplain roughness (Horritt *et al.*, 2010).

These gaugings stations combined would cover the 30 year criteria set and are representative of flows on the main Caldew tributary, although there are issues relating to the data quality and the accuracy of the rating equations. These stations will be used in further analysis, but the rating curve errors will be considered in any analysis and interpretations. The other discharge gauging station in the Caldew sub-catchment is Stockdalewath on the River Roe, which is a tributary, so is less representative of flows and therefore will not be used in further analysis.

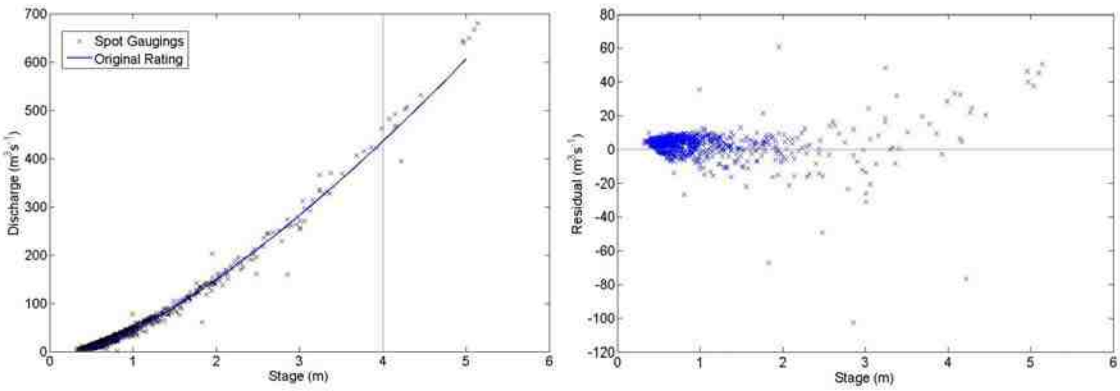


a) Rating curve and spot gaugings b) Residuals of spot gauging from curve

Figure 3.13 *Assessment of the Cummersdale rating curve*

<u>*Lower Eden*</u>

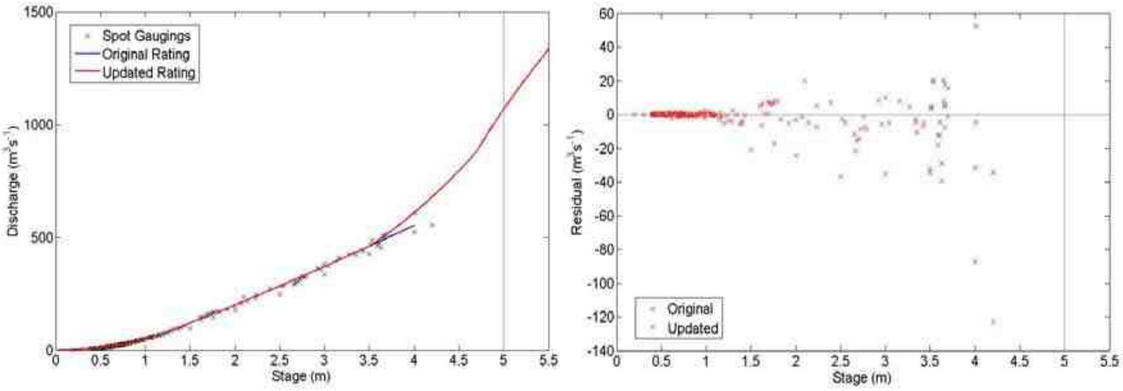
As with the Upper Eden multiple gauging stations have been used to characterise flows in the Lower Eden. First, Warwick Bridge is used to assess flows upstream of the confluence of the Eden with the Irthing, Petteril and Caldew. This station also has the oldest record, starting in 1959, although this station closed in 1998. However, there are some major problems with the reliability and accuracy of the gauging record. For low flows, gaugings are good pre-1988 when there were lots of spot gaugings, but should not be used after this time, due to weed growth affecting flow and there only being a single rating curve for this period (Environment Agency, 2006). Also, high flow discharges are underpredicted by a maximum of 60.8 m^{3}s^{-1} (Figure 3.14a/b).



a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.14 *Assessment of the Warwick Bridge rating curve*

Warwick Bridge gauging station was replaced in 1996 by one at Great Corby, slightly upstream. The whole range of flows at this new station is believed to be accurate, although extrapolated high flows (above 4.2 m) (Figure 3.15a) should be used with caution, as there are no spot gaugings to confirm whether the curve is accurate. The original rating curve follows the lower spot gaugings, while the updated rating follows the higher spot gaugings. The range of the residuals range from 52.6 m^{3}s^{-1} to -36.7 m^{3}s^{-1} for the original rating, and from 19.8 m^{3}s^{-1} to -122.6 m^{3}s^{-1} for the updated rating (Figure 3.15b). The SSR of the original equation is 15461.3 m^{6}s^{-2}, while the updated rating has a SSR of 33182.6 m^{6}s^{-2}. The RMSE of the original rating is ±9.6 m^{3}s^{-1}, while the updated equation has an RMSE of ±14.0 m^{3}s^{-1}.

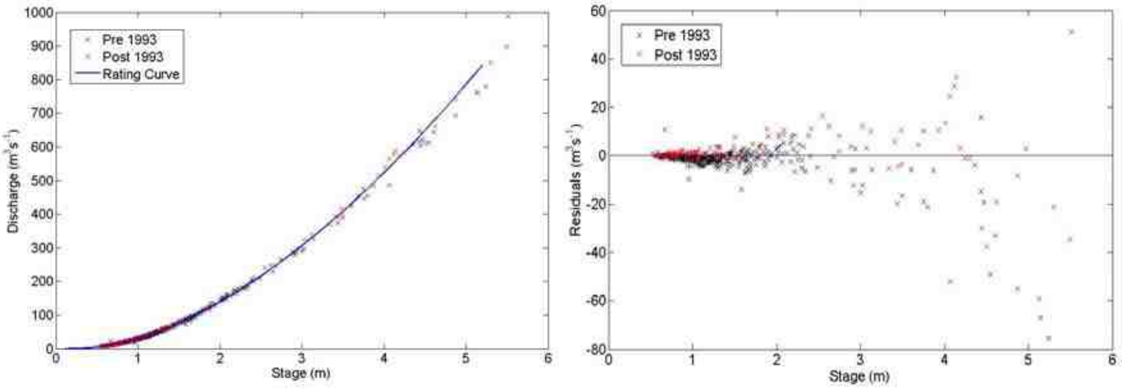


a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.15 *Assessment of the Great Corby rating curve*

Using the combination of the Warwick Bridge and the Great Corby gauging stations, which are only about 3 km apart, will form a 30 year record representing the flow of the Eden before the tributary inputs of the Irthing, Petteril and Caldew. Therefore these stations will be used in further analysis.

The third gauging station used in the Lower Eden is Sheepmount. There are no major problems with the data for this site for either low or high river flows. However there are a few causes of small errors, including siltation and bypassing of the gauge at bank full flows. Figure 3.16a shows the spot gaugings taken at Sheepmount since 1975, of which 132 were after 1993 and 352 were before 1993, when the current rating curve is meant to start. The rating fits the post 1993 data better than the whole period, with an RMSE of ±9.1 m^3s^{-1} for all the data and an RMSE of ±7.8 m^3s^{-1} for the data post 1993 only. This is also shown by the range of the residuals (Figure 3.16b), with all the data having a range of 122.4 m^3s^{-1} (75.3 m^3s^{-1} to -51.1 m^3s^{-1}) and the post 1993 data having a range of 69.7 m^3s^{-1} (37.4 m^3s^{-1} to -32.3 m^3s^{-1}). However, the largest residuals occur for the high flows which are mainly overestimated. Horritt et al. (2010) concluded that the rating curve at Sheepmount was a good fit to both stage and discharge measurements up to 1000 m^3s^{-1} and the January 2005 flood event. This is a really important gauging station, as it is the furthest downstream on the River Eden, so will be used as the dependent variable in further analysis. The data for this station meet the three criterion, with a record beginning in 1975, the flows being representative of the flows through Carlisle and the data being of high quality due to the well constrained rating curve.



a) Rating curve and spot gaugings *b) Residuals of spot gauging from curve*

Figure 3.16 *Assessment of the Sheepmount rating curve*

Section 3.2.1 has evaluated the gauging stations in each sub-catchment to determine which station fits the three criteria that were set. The most limiting factor was the minimum record length of 30 years. This is achieved by only a few stations in the whole Eden catchment, although there is often one in each sub-catchment. Where there is not, then separate records will need to be inter-related to form a single record extending back to 1976. This approach is outlined in Section 3.3. There are data quality issues for all gauging stations, but the errors introduced by the rating curves have been quantified. The chosen gauging stations are summarised in Table 3.3 and Figure 3.17, which give details on the criteria considered.

Sub-catchment	Gauging stations to be used	Record Length	Largest residual from Rating equation	Normalised residual (by magnitude of flow)
Upper Eden	Kirkby Stephen	1976 - Present (1979-1980 missing, filled using undigitised data)	+ 11 m^3s^{-1}	34%
Upper Eden	Temple Sowerby	1976 - Present	+ 60 m^3s^{-1}	17%
Eamont	Udford	1967 - Present (several months missing in 1979 and 1980, filled using Eamont Bridge cross correlation)	- 40 m^3s^{-1}	21%
Irthing	Greenholme	1975 - Present	-75 m^3s^{-1}	48%
Petteril	Harraby Green	1975 - Present	+ 6 m^3s^{-1}	11%
Caldew	Cummersdale	1997 - Present (Holm Hill cross correlation from 1976)	+ 40 m^3s^{-1}	24%
Lower Eden	Warwick Bridge	1959 - 1998 (Great Corby cross correlation from 1996-Present)	+ 60 m^3s^{-1}	30%
Lower Eden	Sheepmount	1975 - Present	-75 m^3s^{-1}	10%

Table 3.3 *Summary of chosen gauging stations assessed against criteria*

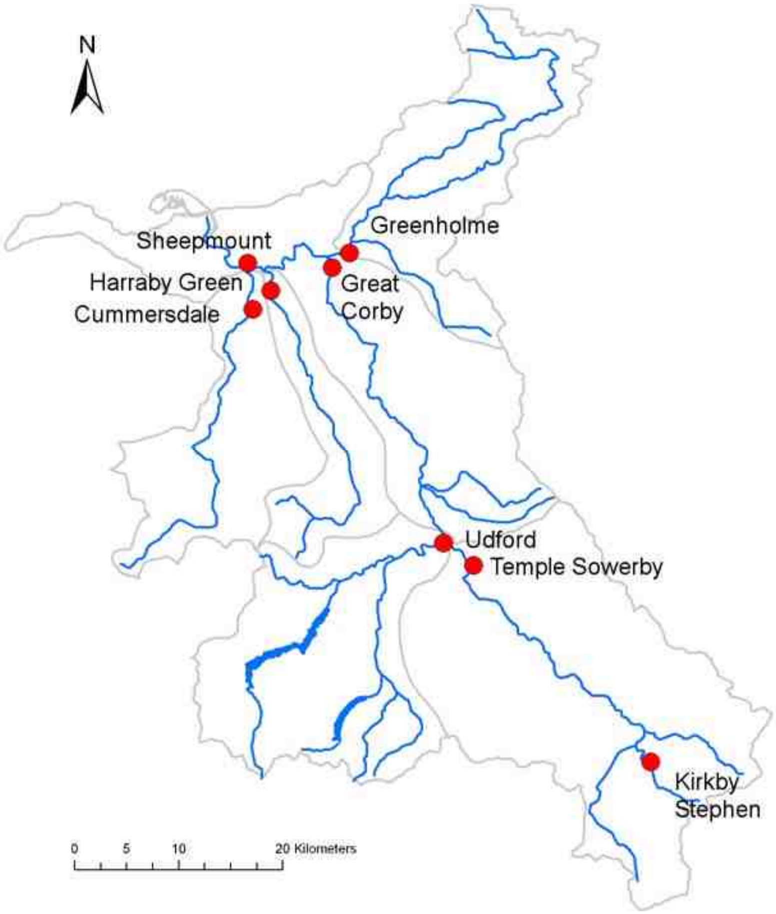


Figure 3.17 *Map of chosen discharge gauging stations which will used through rest of thesis.*

3.2.2. Stage

Figure 3.18 shows the spatial distribution of the stage only gauging stations. There are no rating curves available to convert these stage measurements to estimates of discharge. Stage is also available for all the stations outlined in Section 3.2.1, as at these stations stage is measured and then converted to discharge through the rating curve.

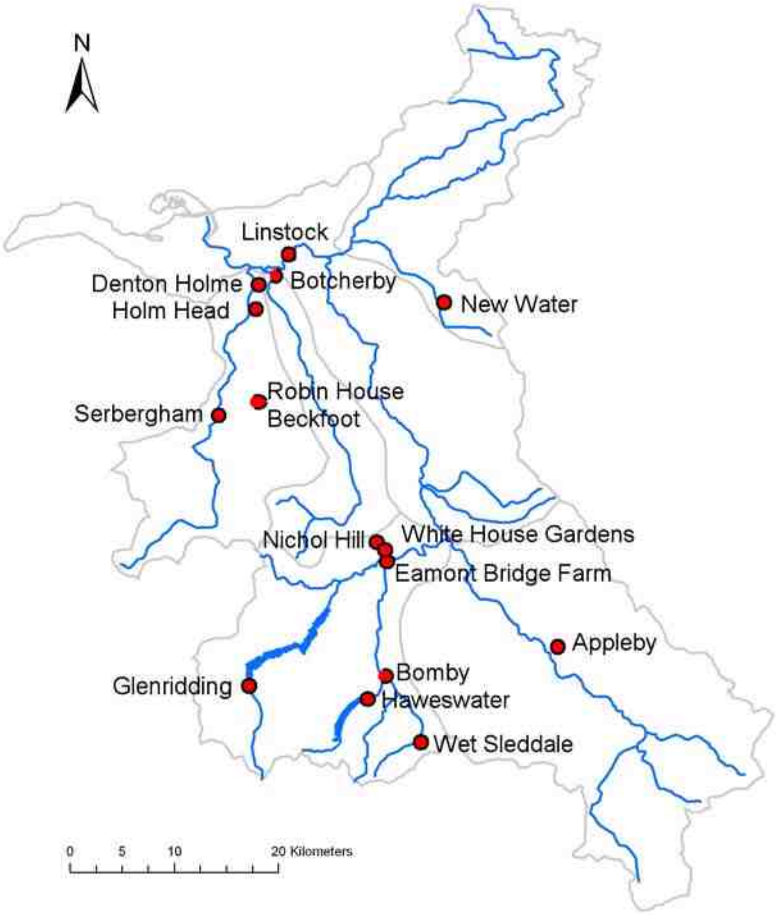


Figure 3.18 *Map of the stage gauging stations in the Eden catchment. Stage is also available for gauges shown in Figure 3.1.*

Stage is an important variable when assessing data quantity, as it is the water level compared to the bank height that determines whether there is flooding or not. However, stage measurements are site specific to the gauging station's cross section, meaning that the information is not transferable up or down stream.

Stage data is therefore less essential for the statistical methodology, but is needed for the modelling approach, both outlined in Chapter 5. This is because assessment of hydraulic models is more accurate if stage is used, as the error introduced by the uncertainty of the rating curve conversion is eliminated.

3.2.3. Precipitation

Figure 3.19 shows the spatial distribution of the rain gauges in the Eden catchment. Precipitation is an important driver in causing flooding, and a lack of rainfall causes hydrological drought. Rain gauges measure the depth of precipitation, but often underestimate the precipitation quantity due to wind, exposure and evaporation effects. Localised eddies and turbulence at the top of the gauge causes the pattern of rainfall to be disrupted and a deficiency in measured rainfall (Weiss and Wilson, 1957; Larson and Peck, 1974). The positioning of the rain gauge is also an important factor, as structures such as buildings and trees can change the exposure and catch area of the gauge to precipitation (Brakensiek *et al.*, 1979). Other issues are evaporation of the stored water (Sevruk, 1982) and splash in/out (Shaw, 1988). In total it is thought that rain gauges can underestimate precipitation by between 5-15% in the long term and up to 75% for the individual storm event (Winter, 1981).

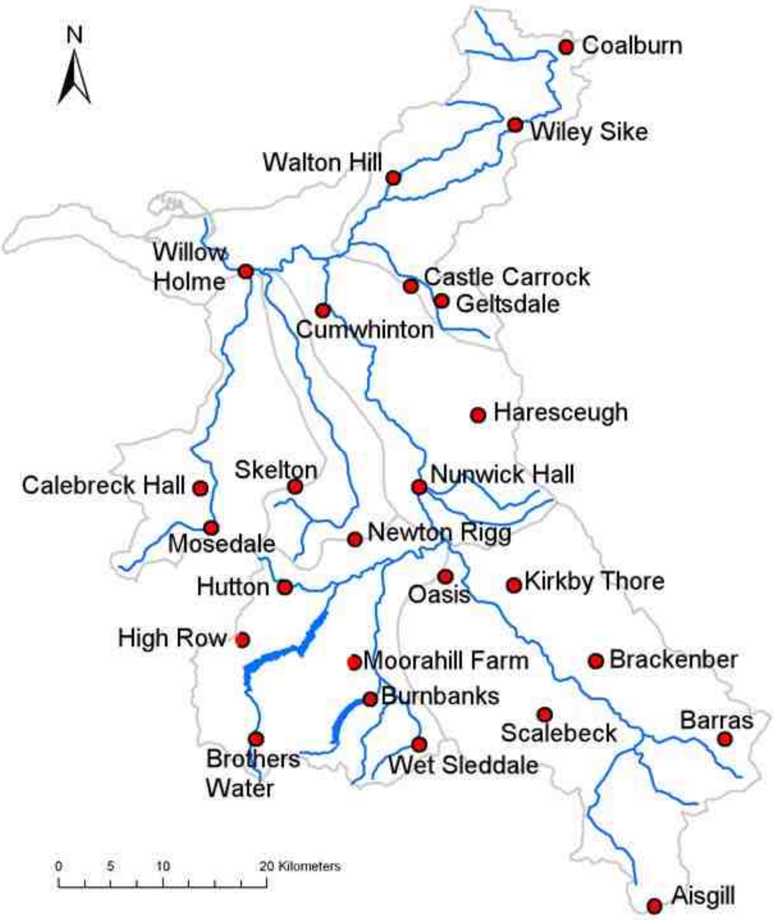
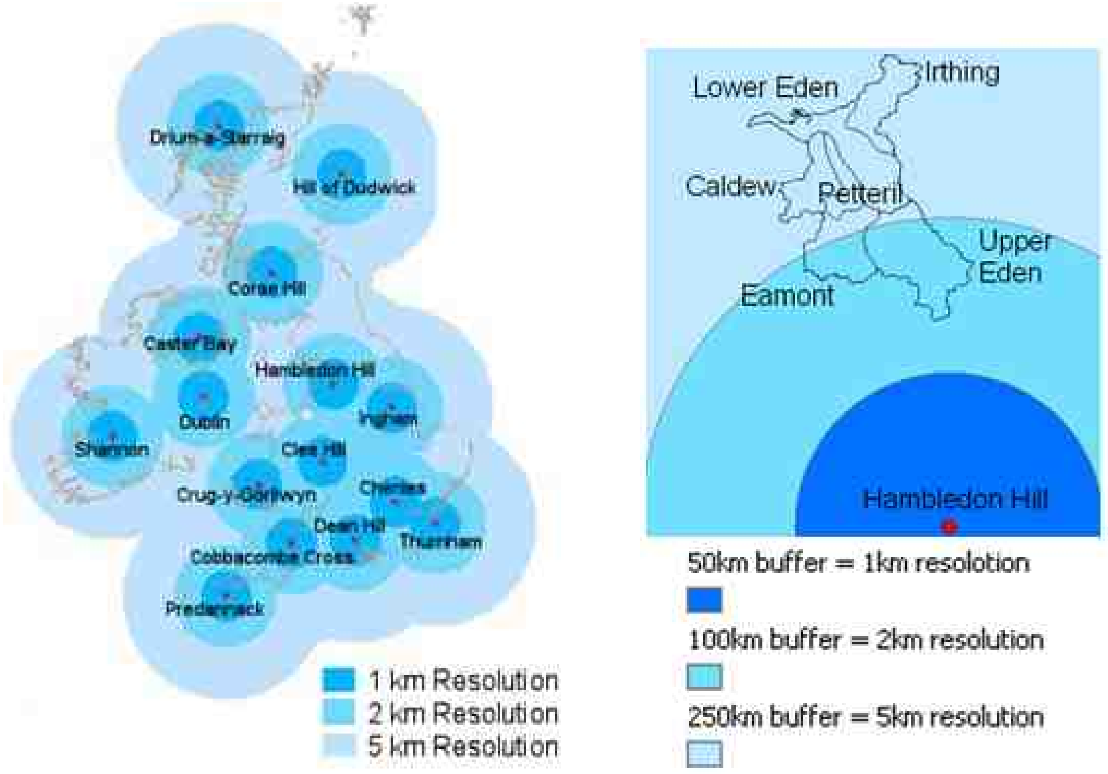


Figure 3.19 *Map of the rainfall gauging stations in the Eden catchment.*

Another method used to collect data on precipitation patterns and quantities is radar. This works by short pulses of electro-magnetic waves being transmitted from the station and then the returning (reflected by clouds) pulse is detected. The distance of the target from the location of transmission is calculated by the time it takes for the pulse to travel there and back. Figure 3.20a shows the radar coverage of the United Kingdom, which is nearly complete at a 5km resolution. The resolution of the radar stations is 1km to a range of 50km, 2km to a range of 100km and 5km resolution to a range of 250km from the radar station. 85% of England and Wales are covered to a 2km resolution (Met Office, 2007). Figure 3.20b focuses on Cumbria, which is covered by the Hambledon Hill radar station in Lancashire. It is clear from these maps that the radar coverage of the Eden catchment is not ideal for it to be used in hydrological modelling studies. The Hambledon Hill radar station provides a 2km resolution for southern Cumbria, but most of the Eden catchment has only a 5km resolution, which will not capture the most intense precipitation on smaller spatial scales.



a) UK Radar coverage *b) Radar coverage of Eden catchment*

Figure 3.20 *Radar coverage at different resolutions of UK and Eden catchment*

Harrison *et al.* (2000) discussed the limitations of radar for determining rainfall quantities, with errors associated with the measurement of reflectivity of the radar beam and then relating this to rainfall amounts. First, the radar station needs to be accurately calibrated to detect rainfall quantities, which is done through rain gauge - radar comparison. However, a problem with this is that the two methods have different sampling characteristics, whereby rain gauges measure precipitation at a point over a specified time interval, while radar measures average instantaneous precipitation over a large specific area. Second, the waves reflected by clouds detected may be contaminated by echoes from other surface obstacles such as mountains and buildings. This problem is known as occultation and can be overcome by mapping the area on a cloudless day, so only the obstacles are detected, which can be subtracted from the monitored data. A third problem is that radar beams often can’t detect low level rainfall, and cannot account for low level evaporation or orographic enhancement (Hill *et al.*, 1981, Lewis and Harrison, 2007). Fourthly, and relating to the conversion of reflected energy to rainfall quantities, is the size of the precipitation droplets in the cloud. Often an average size is used for different cloud types, but error is introduced in the process (Collier, 1996).

As stated above the radar data for the Eden catchment is mainly at the 5km scale, which is not ideal for hydrological modelling, but it is clear from Figure 3.18 that the rain gauge coverage of the catchment is at a much coarser scale than this. Roberts *et al.* (2009) noted that the radar data generally had lower rainfall amounts than the gauged network. This study was of the January 2005 Carlisle event, which will be focussed upon within this thesis, and concluded that the rain gauge data provided the most accurate measurements. It has therefore been decided that monitored data from rain gauges will be used, as the hydrological model input is not spatially distributed so this level of accuracy is thought to be sufficient.

3.2.4. Other Types of Data

The other data types needed for this project were required for both the input to, and calibration of, the hydraulic and hydrological models. To build catchment scale hydraulic models, river cross sections and floodplain storage areas are needed. The Environment Agency has an existing model containing these data, so these have been adapted for use within this project.

Temperature data are needed on the same time resolution as the precipitation data, for input into the hydrological model. This will be sourced from the British Atmospheric Data Centre (BADC) for representative stations in the chosen areas. More detail on the data used in the modelling is provided in Chapter 5 and 8.

As the focus of this thesis is the impact of land use upon extreme river flows, it is essential that land cover is well defined. This has been a major problem in past studies, as the data are not available on the spatial scales that modelling work is done at. The best data source for land cover information is the Land Cover Map 2000.

3.3. Data Pre-treatment

To achieve the first objective of this thesis, which is to assess trends in flood frequency and magnitude over different spatial and temporal scales, a continuous record of flood events are needed. This was undertaken on two temporal scales. Firstly, using the continuous discharge records from 1976 to 2007, flooding trends will be assessed throughout the whole catchment using the gauging stations outlined in the above sections. Secondly, a historical flood record will be constructed for the downstream city of Carlisle to put the shorter record into a longer timescale context.

Section 3.3.1 outlines the 1976-2007 period approach where some of the chosen gauging stations have incomplete discharge records. Observations may be missing for several reasons including where recording equipment failed to record a river stage, the effects of extreme river flows and the loss of data due to downloading or computer storage problems (Salas, 1993). The approach used for record augmentation (Matalas and Jacobs, 1964) in this research is outlined below and is based on the techniques recommended by the Flood Estimation Handbook (FSR, 1975; FEH, 1999).

3.3.1. 1976 - 2007 record augmentation approach

Minor gaps were filled in through the writing of a macro, which interpolated between the known discharges with the average of the previous and next recorded measurements. This is thought to be accurate, as long as the missing data period is not too long (< day), although flood peaks are probably still missed due to this process. This time period is dependent upon the catchment size, and the response time of each catchment was investigated to determine this threshold. The threshold of a day was decided as flood events in this catchment are on a sub-daily timescale, so the whole event would be missed through interpolation.

Missing Period (Hours)	**Kirkby Stephen**	**Temple Sowerby**	**Sheepmount**	**Udford**	**Greenholme**	**Harraby Green**
0.5	293537	381500	393299	281089	330687	227700
0.75	21406	29289	28339	30871	26808	23804
1	3535	4221	3883	4760	4203	4561
1.25	5039	6962	5904	6922	6538	7075
1.5	5455	6070	5333	6792	6640	8016
1.75	1233	1159	1010	1410	1366	1926
2	1807	2070	1786	2183	2453	3184
2 to 3	5411	3351	4108	9909	6385	9009
3 to 4	1891	2317	1169	1745	2375	3778
4 to 5	800	686	478	666	1005	1713
5 to 10	1878	829	780	1275	2242	4199
10 to 15	383	97	85	140	376	884
15 to 20	142	20	29	46	97	297
20 to 24	75	26	8	38	27	117
24 to 48	67	17	9	19	26	197
48 to 72	8	1	5	2	4	31
>72	9	2	2	7	0	13

	Cummersdale	**Holm Hill**	**Holm Hill**	**Warwick Bridge**	**Warwick Bridge**	**Great Corby**
Missing Period (Hours)	**1997-2007**	**1976-2000**	**1976-1997**	**1959-1998**	**1959-1996**	**1996-2007**
0.5	106034	199670	185915	479907	470041	107599
0.75	6705	21140	18617	35164	33156	8845
1	537	3514	2993	5231	4804	1224
1.25	383	6082	5675	11568	11241	918
1.5	439	5958	5202	8916	8401	1182
1.75	67	1337	1148	1763	1616	200
2	57	2344	2208	4235	4113	210
2 to 3	123	6791	6146	9014	8575	490
3 to 4	16	2447	2231	2865	2724	94
4 to 5	7	1164	1059	1170	1120	23
5 to 10	3	2818	2588	2530	2435	39
10 to 15	0	632	601	363	359	0
15 to 20	0	228	224	109	107	0
20 to 24	0	124	121	57	57	0
24 to 48	0	139	138	53	53	0
48 to 72	0	31	31	9	9	0
>72	0	17	16	16	16	0

Table 3.4 *Number of missing periods of different lengths in original discharge data for chosen gauging stations*

Table 3.4 show the number of gaps of different lengths in the time series of discharge for each of the gauging stations chosen to represent each sub-catchment. Table 3.4 shows stations which have a record since 1976 to 2007, and therefore the number of gaps can be compared between stations. It is evident that all the stations have a large number of small gaps (<5 hours), while they have significantly fewer longer periods (>5 hours) of missing data. Sheepmount and Temple Sowerby have the most gaps less than 1 hour, while Harraby Green has the most medium (1 to 5 hours) and large (5 to 24 hours, more than a day). Greenholme has no gaps longer than three days, while Sheepmount and Temple Sowerby have 2 periods missing larger than 3 days, the longest of which is 6 days 0.25 hours and 27 days 7.5 hours respectively. Harraby Green has 241 periods longer than a day missing from the dataset, of which 13 are longer than 3 days and the longest is 6 days 15.5 hours. Kirkby Stephen has 9 missing periods between 12 days and 884 days, the longest of which starts in May 1978 and lasts until the beginning of 1981. Udford has 7 missing periods, ranging from 5 days to 287 days. A common feature of all the extended periods missing from the record is that they occur early in the record. This is illustrated by the Cummersdale and Great Corby gauging station records, which started in the late 1990s and which have no periods of missing data longer than 10 hours. Holm Hill, the original station on the Caldew, has 187 periods longer than a day, while Warwick Bridge has 78 missing periods longer than a day.

However, some gauging stations had periods too long (> day) to have reasonable results created through interpolation. The reliability of the interpolation is dependent upon both the length of the missing period and the catchment size, as smaller catchments have shorter response times. This threshold was defined as the hydrological events of interest i.e. floods, in this catchment have a sub-daily timescale. Therefore a systematic approach to transform the gauging record from the known record (Q_A) to an estimate of the unknown but used gauging station that has been chosen in Section 3.2.1 to represent the sub-catchment (Q_B). This will be done through using time series analysis and modelling (Pong-Wai, 1979). Recommendations by the Flood Estimation Handbook (1999) suggest that a short gauging record can be extended by using a nearby longer record. Often the relationship between the two stations takes one of the following forms:- $Q_B = a + b\,Q_A$ or $\ln Q_B = c + d \ln Q_A$

where all coefficients are empirical constants

The FEH suggests that if the regression can explain 90% of the flow variance then the model can be used.

Time series analysis is commonly used in hydrology for several purposes including: (1) to generate synthetic hydrologic records; (2) to fill in missing data (Beauchamp *et al.*, 1989); (3) to extend gauged records (Salas, 1993); (4) to forecast future hydrologic events; and (5) to detect trends and shifts in hydrologic records. The purpose of using time series analysis in this study is to extend the gauging records where the chosen station to represent a sub-catchment is less than the 30 year criteria and to make all the sub-catchments have records of the same length. Discharge records are often auto-correlated, meaning that the current discharge is dependent upon previous discharge values (Potter, 1979). Furthermore, gauging stations that are in close proximity on the same river are often cross correlated, but with some lag effects.

Therefore the general model used to relate Q_A to Q_B involved: (1) correcting for any travel time effects between the two gauging stations (lag) and (2) correcting for the differences in magnitude which may be caused by a different upstream contributing area or tributary input between the two stations. The statistical approach to achieve these corrections is outlined in the following general approach:

1) If $Q_B = f(Q_A^{t-n})$, then use time series analysis to determine the lag (n).
2) Model $Q_B = f(Q_A^{t-n})$ to determine the nature of the function that best fits the differences in magnitude between the two stations.
3) If there is hysteresis in the record then consider adding dummy variables to represent the rising and falling limbs in the discharge record and use a stepwise regression framework to determine a single equation that links the two records.

The use of dummy variables is to incorporate more information into the regression, especially information that is not measured on a continuous scale (Suits, 1957). Dummy variables are often binary, with values of 0 and 1, representing two categorical variables, often absence and presence. In this case the dummy variable would represent the rising and falling limb and separate out the hysteresis effect in the data. The use of dummy variables often improves the goodness of fit, but also reduces the generality of a model's application and interpretation.

It is important to know which flood events and gauging stations were actually recorded and which ones were estimated through the above approach, as this will have implications for how these data are used in future analysis. Therefore in Appendix A, a full list of all the data used in the future analysis is provided, showing which data have been estimated.

The following section outlines the process of preparing the datasets to form a complete discharge record for each of the gauging stations chosen to represent flows from each sub-catchment.

Caldew

The original station on the Caldew was Holm Hill (1975-2000) and the existing station is at Cummersdale (1997-2007). Cummersdale is downstream of Holm Hill and between the two stations is the confluence of the River Caldew and the River Roe. The aim of this section is to apply the general model to extend the Cummersdale record back to 1977 using the gauged record at Holm Hill. As Cummersdale is downstream of Holm Hill, it is expected that there will be a time lag between the peak flow at Holm Hill (Q_{HH}) and Cummersdale (Q_C). The two records overlap for the following period (16/9/1997-10/4/2000). However, there is a large gap (134 days) of missing data in the middle of this period for Holm Hill (Figure 3.21). To use time-series analysis a continuous record is needed. Therefore, Period 2 has been chosen to be used to develop the rating curve between Holm Hill and Cummersdale. The reasons why period 2 was chosen to be used in the analysis were twofold; (1) it is a longer period, as period 1 is 262 days, while period 2 is approximately 1½ years; and (2) it is more representative of greater range of flows, as period 1 has a range of 0.8 m^3s^{-1} to 151.3 m^3s^{-1}, while period 1 only has a minimum flow of 1.1 m^3s^{-1} and a maximum discharge of 77.9 m^3s^{-1}.

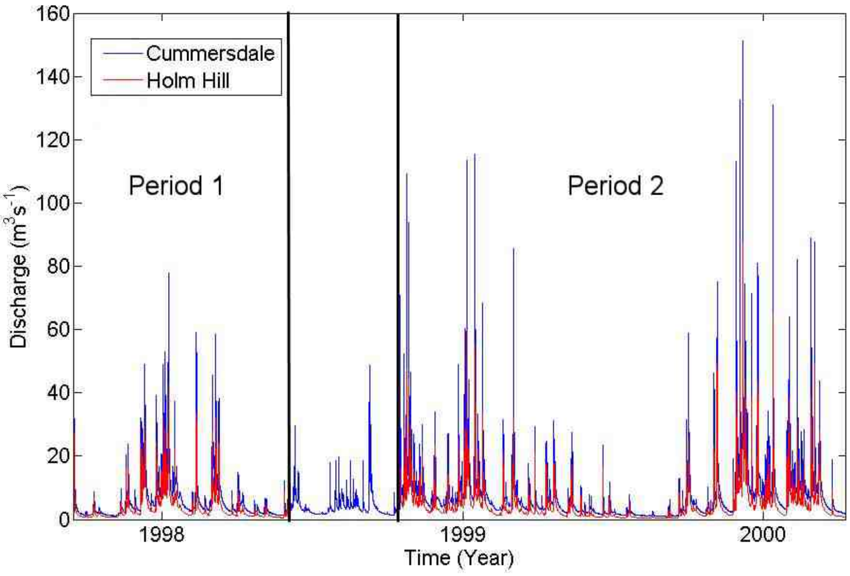


Figure 3.21 *Discharge Hydrograph for Holm Hill and Cummersdale gauging stations divided into two periods either side of missing data.*

Firstly, the time lag between the upstream station at Holm Hill to the downstream station at Cummersdale had to be quantified. This was done by cross correlation, whereby the discharge at Cummersdale is correlated with previous and subsequent discharges at Holm Hill. Figure 3.22 shows the cross correlations, and the discharge at Cummersdale is best correlated with Q_{HH}^{t-2}. This indicates that the discharge half an hour earlier at Holm Hill correlates best with the discharge at Cummersdale. Therefore the ½ hour travel time effect will be accounted for the relationship between the discharge at the two stations. However, the simple regression between the lagged Holm Hill discharge and the Cummersdale discharge exhibits hysteresis (Figure 3.23). A dummy variable, representing the rising and falling limb of the hydrograph was introduced to eliminate this error in the equation. Table 3.5 compares the original regression, with the regression with the dummy variable included. The dummy variable regression has a slightly higher r^2 value, a lower RMSE and a lower sum of the residuals. The third and fourth equations show the same approach, but using the natural logarithm of the discharge variables. These improve the r^2 and RMSE statistics, but due to the statistical bias that is introduced through the process of taking the logarithm and then transforming the predictions back to discharge, the sum of the residuals increases. This error was highlighted by Ferguson (1986), to the hydrology and geomorphological community, but had been widely known to statisticians (Miller, 1984) and ecologists (Sprugel, 1983) before this. As the actual discharge values are going to be used in further analysis, it was decided not to use the transformed regressions. Therefore Equation 2 in Table 3.5 is the regression that will be used to convert the discharge at Holm Hill to a discharge at Cummersdale to form a single record for Cummersdale starting in 1976. This has a predictive uncertainty error of 5.6 m^3s^{-1} at the 95% level. This means that 95% of future observations are expected to be enclosed by these prediction bands. Predictive uncertainty accounts for both the uncertainty in the position of the curve and the scatter of observations around the curve.

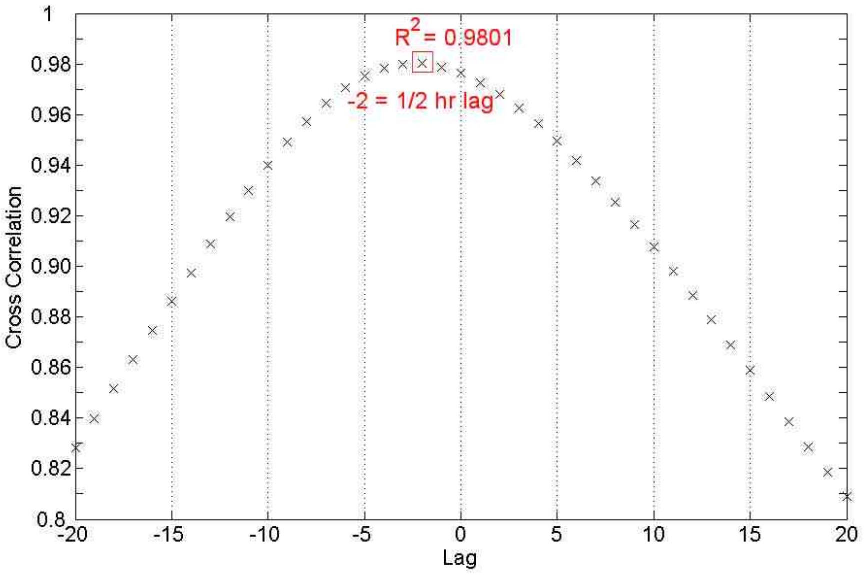


Figure 3.22 *Cross correlation plot between Holm Hill and Cummersdale gauging stations. Lag refers to the data point number, which have a time step of 15 minutes. Therefore when lag = -2 = -2 * 15 = - 30 minutes.*

		R^2	RMSE	Sum Square Residuals
1	$Q_C = 1.65\, Q_{HH}^{t-2} + 0.53$	0.93	±2.8	420888.9
2	$\mathbf{Q_C = 1.68\, Q_{HH}^{t-2} - 1.69\, D + 0.59}$	**0.96**	**±2.4**	**390461.3**
3	$\ln Q_C = 0.89 \ln Q_{HH}^{t-2} + 0.76$	0.98	±0.1	567312.6
4	$\ln Q_C = 0.90 \ln Q_{HH}^{t-2} - 0.18\, D + 0.77$	0.98	±0.1	510430.3

Table 3.5 *Regression equations relating Holm Hill to Cummersdale (chosen equation in bold) t = data point representing time at Cummersdale*

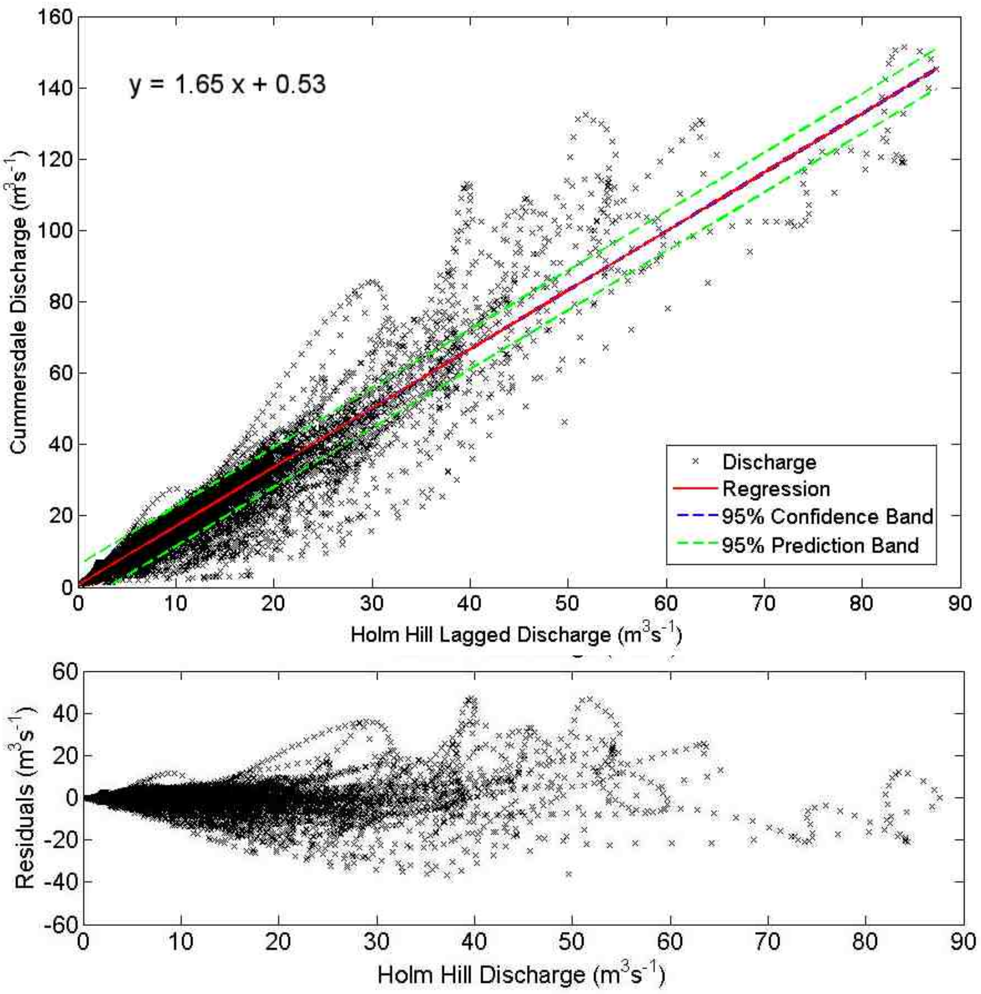


Figure 3.23 *Scatter plot (a) showing relation between delayed Holm Hill and Cummersdale discharges, with the residuals shown in (b).*

Eamont

As Table 3.4 showed, the Udford time series has several major gaps in it, pre-1981. These need to be predicted through the application of a rating curve or through cross correlation with another gauging station. There are several gauging stations in the Eamont sub-catchment. The other station on the Eamont itself is at Pooley Bridge, but this is unsuitable for relation to Udford, as it is affected considerably by the attenuating effect of Lake Ullswater. Another gauging station is on the Lowther tributary, at Eamont Bridge, which is near the Eamont-Lowther confluence. This station has been chosen to form a cross correlation with Udford. Firstly the time lag between the two stations was found through time series analysis, using the overlapping period of 1981 to 2002. Figure 3.24 shows that the discharge at Udford is most highly correlated with the discharge at Eamont Bridge one hour previously.

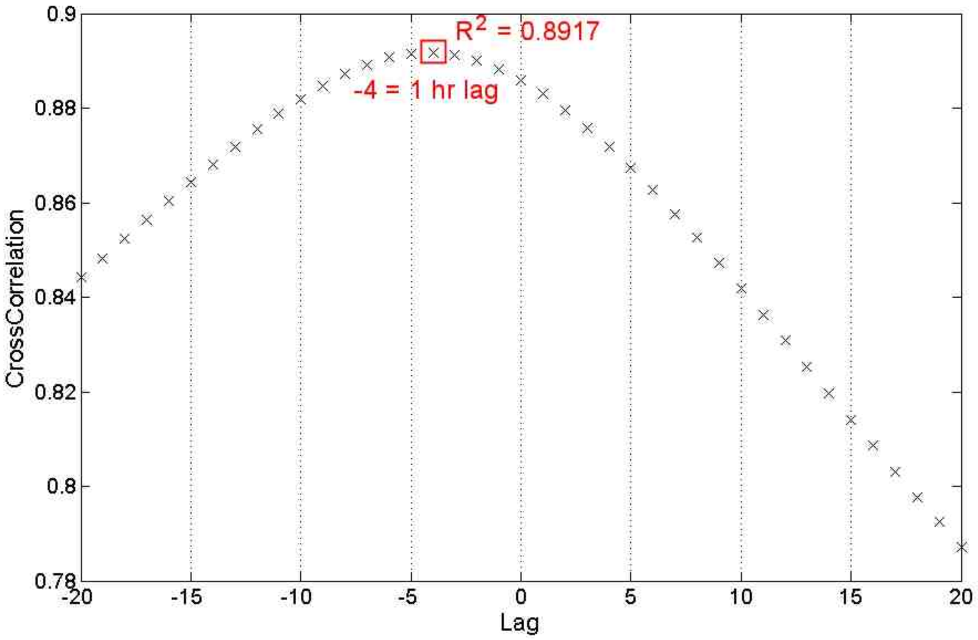


Figure 3.24 *Cross correlation plot between Eamont Bridge and Udford gauging stations. Lag refers to the data point number, which have a time step of 15 minutes. Therefore when lag = -4 = -4 * 15 = - 1 hour.*

The relationship between the discharge magnitude at Eamont Bridge (Q_{EB}) and Udford (Q_U) is not linear (Figure 3.25). However, no simple curves (linear, quadratic, cubic, logarithmic, exponential, power) would fit the data, due to the high proportion of the dataset being low flows, while only a small number of observations are high flows. This is shown by a Q5 value of 49.2 m^3s^{-1} and a Q10 value of 34.9 m^3s^{-1} (Section 4.2). This is also shown by the high norm of the residuals, which is a measure of the goodness of fit, where a smaller value indicates a better fit than a larger value. The linear relationship has a value of 7625.1 m^3s^{-1}, the quadratic curve has a goodness of fit of 6599.0 and the cubic line has a value of 6121.8 m^3s^{-1}. Therefore it was decided to remove the low flows, as the focus of this research is high flows. From looking at the dataset of POT threshold floods for Carlisle, it was found that the lowest discharge contribution to the POT series at Carlisle was 30.7 m^3s^{-1} at Eamont Bridge. Therefore it was decided to use only the values greater than 30 m^3s^{-1} to form the relationship between Eamont Bridge and Udford, as this was the range of values needed to extend the Udford record for the POT Carlisle (Sheepmount) analysis. Figure 3.26 shows the relationship between the two gauging stations. The quadratic relationship has an RMSE of ±17.7 m^3s^{-1} and a norm of the residuals value of 1830.6 m^3s^{-1}, while the linear relationship had a higher RMSE of ±17.9 m^3s^{-1} and norm of the residuals value of 1951.5 m^3s^{-1}. Figure 3.26 shows hysteresis in the relationship. This was addressed through the use of a dummy variable, where 1 = rising limb, and 0 = falling limb. Using this dummy variable improved the relationship to a RMSE of ±17.6 m^3s^{-1}. Therefore it is Equation 4 in Table 3.6 that will be used to relate the discharge at Eamont Bridge to Udford. This equation has a ±34.7 m^3s^{-1} predictive uncertainty error at the 95% level.

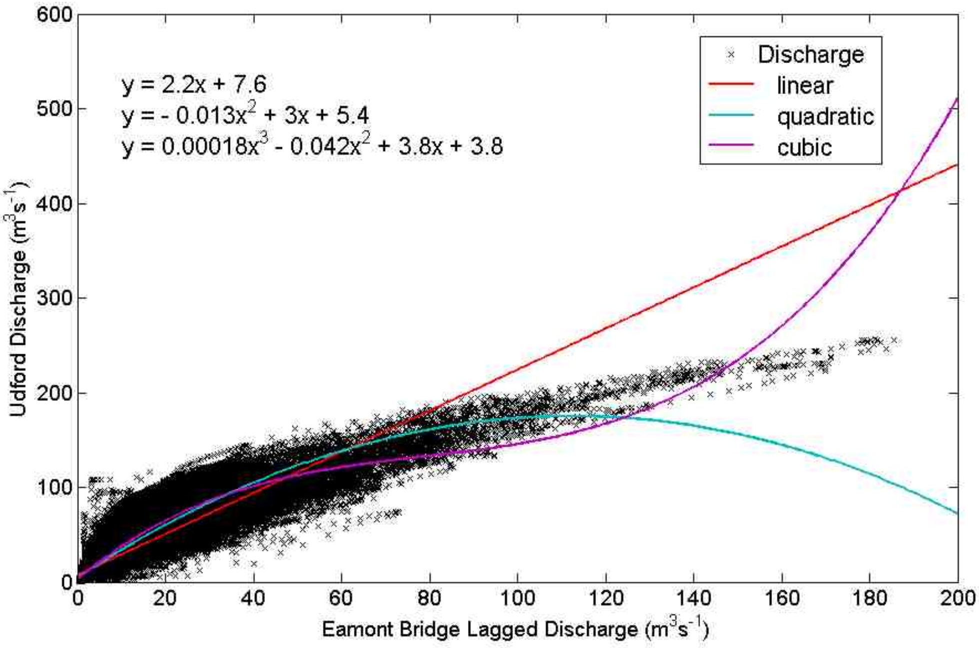
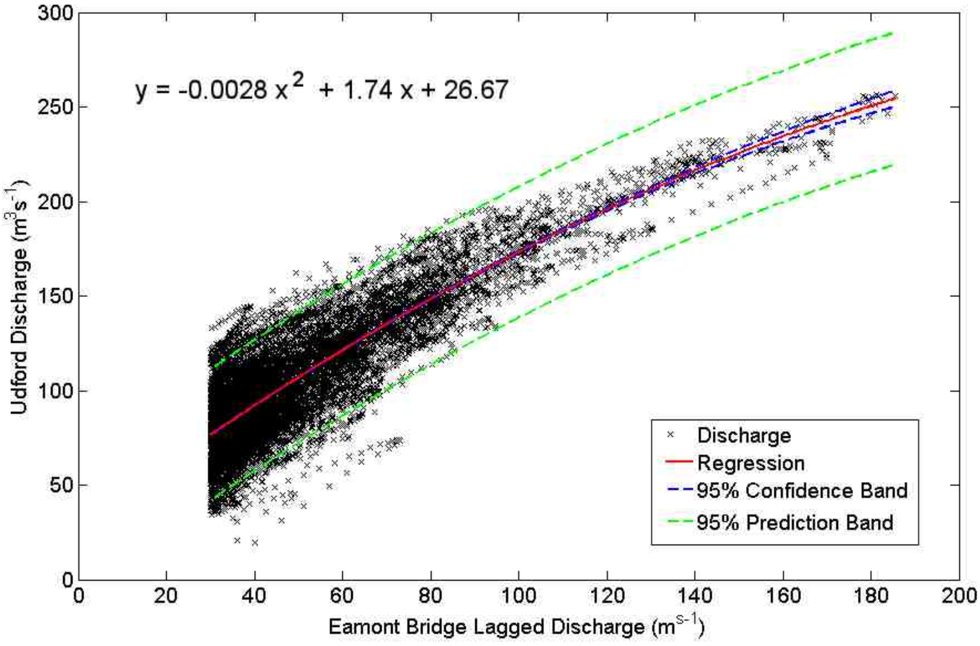


Figure 3.25 *Scatter plot showing relation between delayed Eamont Bridge and Udford discharges.*



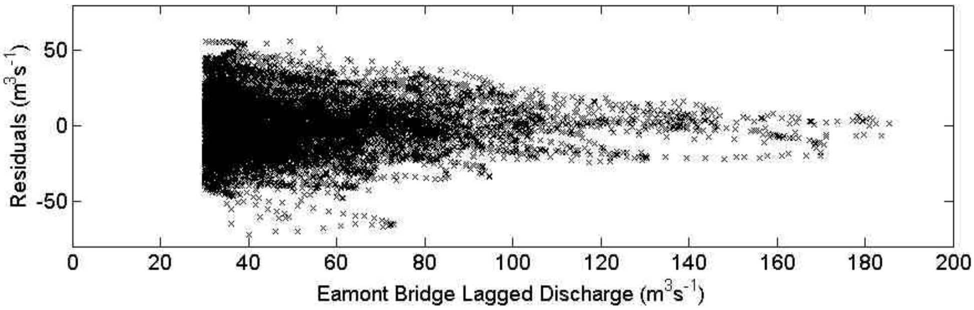


Figure 3.26 *Scatter plot showing relation between delayed Eamont Bridge and Udford discharges for discharges above 30 m^3s^{-1}, with residuals shown in (b)*

		R^2	RMSE
1	$Q_U = 1.33\ Q_{EB}^{t-4} + 39.1$	0.74	±17.9
2	$Q_U = -0.0028\ (Q_{EB}^{t-4})^2 + 1.74\ Q_{EB}^{t-4} + 26.67$		±17.7
3	$Q_U = 1.34\ Q_{EB}^{t-4} - 3.08\ D + 39.99$	0.75	±17.8
4	$\mathbf{Q_U = -0.0029\ (Q_{EB}^{t-4})^2 + 1.77\ Q_{EB}^{t-4} - 3.54\ D + 27.07}$		**±17.6**

Table 3.6. *Regression equations relating Eamont Bridge to Udford (chosen equation in bold). t = data point representing time at Udford*

Lower Eden

The Warwick Bridge gauging station is situated on the Lower Eden before the confluence with the River Irthing. However, this station was replaced by Great Corby in 1996. There is only 1.6 km between the two stations and there are no tributary inputs between them. Therefore, the Great Corby (Q_{GC}) station will be used to extend the Warwick Bridge (Q_{WB}) discharge time series to the present day. The overlapping period, 1996-1998, between the two stations can be used to create a transfer relationship. As Warwick Bridge is downstream of Great Corby, it is expected that there will be a time lag between the peak flow at Great Corby and Warwick Bridge. Firstly, this time lag has to quantified, which was done by cross correlating the Warwick Bridge discharge with lagged Great Corby discharges. Figure 3.27 shows that a half hour lag (Q_{GC}^{t-2}) exists between these two stations. Therefore the discharge at Warwick Bridge was regressed against the Corby Bridge discharge half an hour beforehand, shown in Figure 3.28. There does not seem to be much evidence of hysteresis in the time series, but a dummy variable was added to represent rising and falling limbs in a stepwise approach (95% Significance Level) to see if this improved the predictability of the equation. The results are shown in Table 3.7, indicating that the regression with the dummy variable improved the predictability of the equation slightly and therefore Equation 2 will be used to extend the Warwick Bridge time series using the modern Great Corby time series. This equation has a 4.9 m^3s^{-1} predictive uncertainty error at the 95% level.

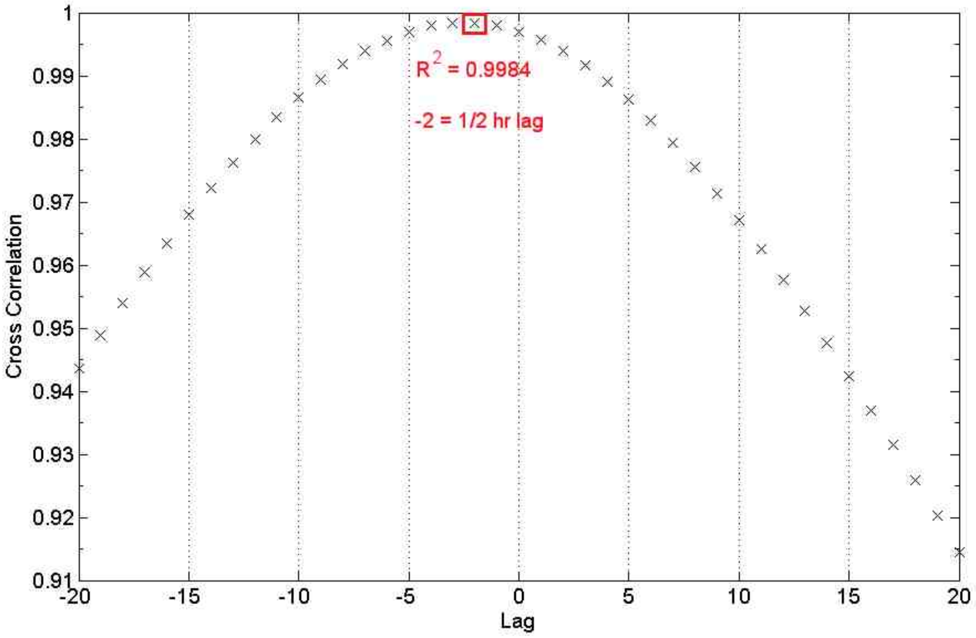
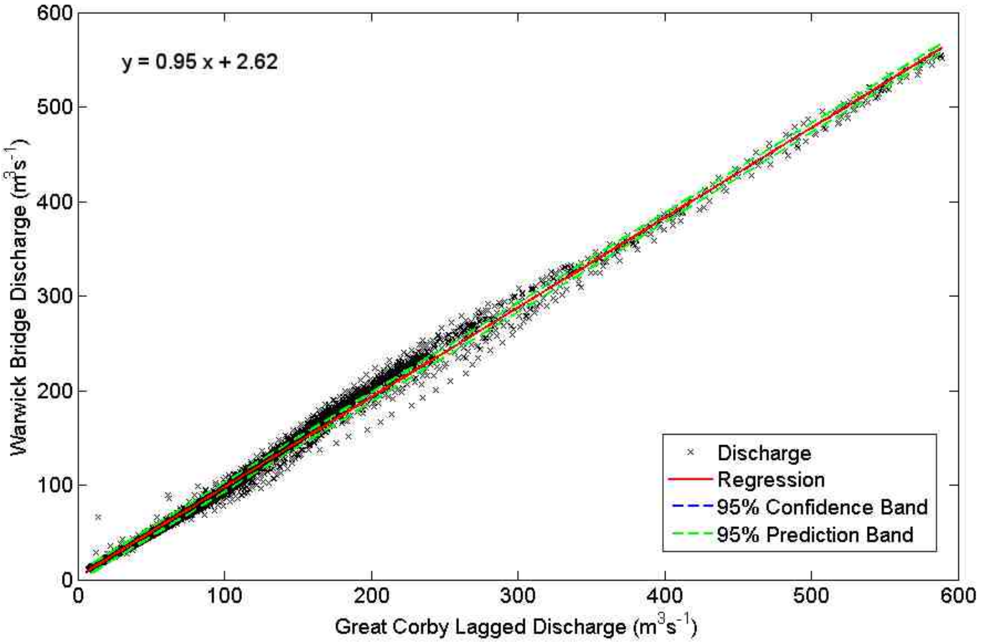


Figure 3.27 *Cross correlation plot between Great Corby and Warwick Bridge gauging stations. Lag refers to the data point number, which have a time step of 15 minutes. Therefore when lag = -2 = -2 * 15 = - 30 minutes.*



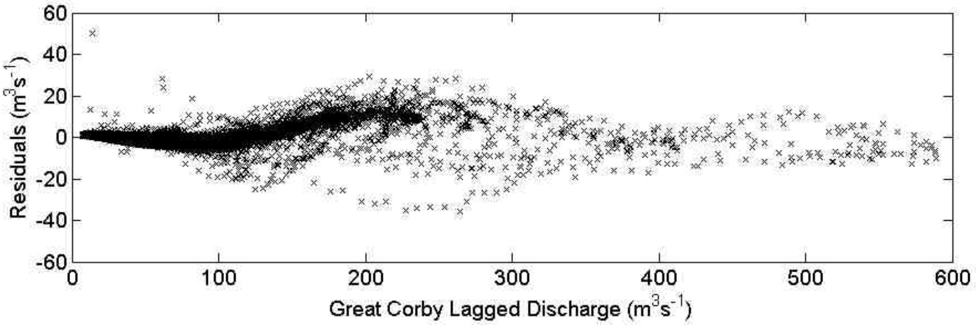


Figure 3.28 *Scatter plot showing relation between delayed Great Corby and Warwick Bridge discharges, with residuals shown in (b)*

		R2	RMSE	Sum Square Residuals
1	$Q_{WB} = 0.95\ Q_{GC}^{t-2} + 2.62$	0.99	±2.5	319009.9
2	$\mathbf{Q_{WB} = 0.95\ Q_{GC}^{t-2} - 0.33\ D + 2.69}$	**0.99**	**±2.5**	**317944.1**

Table 3.7 *Regression equations relating Great Corby to Warwick Bridge (chosen equation in bold). t = data point representing time at Warwick Bridge.*

3.3.2. Historical Timescale Record Construction

It has been shown in the literature that looking for trends in flood frequency over short timescales, such as 30 years, has several limitations, with the trend being highly sensitive to when the record starts and ends (Kundzewicz and Robson, 2004; Dixon, 2006). Robson *et al.* (1998) found that trends from short term records may differ considerably from the analysis of longer time series. The use of a longer term flood record can be used to put recent flood behaviour into a longer timescale context.

Therefore, a longer timescale flood record has been constructed for the River Eden at Carlisle, using multiple sources of information. The types of sources used are outlined below:-

a) *British Chronology of Hydrological Events (Black and Law 2004)*

This is a hydrological database founded in 1998 and allows users to search its contents for different rivers and over different timescales. It lists 128 records (as of July 13th 2009) for hydrological events in the Eden, of which 108 are floods. For each record there are four main components: (1) information on hydrological event (often with quote); (2) source reference; (3) date information (at least year); and (4) geographical location. Records For copyright reasons records should extend to 1931, although for the Eden a record exists for the 1968 flood. Below are a few examples of quotations from the database for the Eden.

1870 July 9 (p73) "Kirkby Stephen, the whole of the rain registered on this day (1.50) fell between 11.30 a.m. and 1 p.m.; the river Eden rose 3 ft. in twenty minutes, and subsided very rapidly, after doing much damage."

1904 November Observer, T.H.Hodgson, at Carlisle (Newby Grange) noted p[97] : "... There was no autumn flood till the end of November..."

1916 January 1 (p[46]) "The heavy fall at Alston (2.62 in.) marks a local downpour in the north-west of England which produced a "new year's flood" in the neighbourhood of Carlisle."

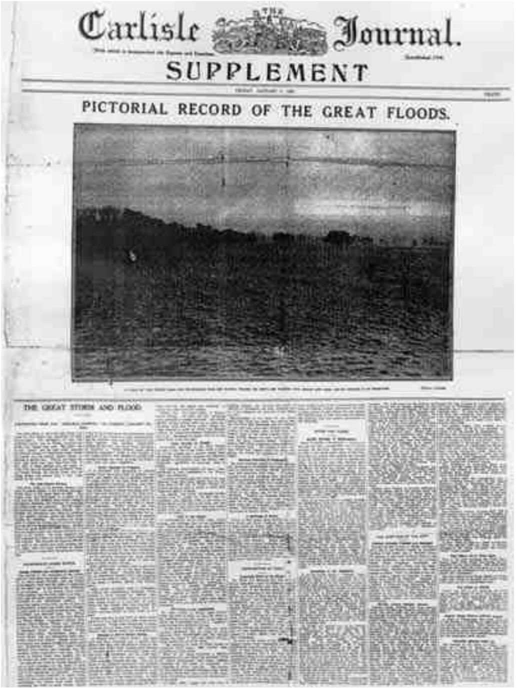
b) *Newspaper Records (www.carlislehistory.co.uk/carlislehistoryf)*

This website records several floods sourced from newspaper reports. The specific sources are the Carlisle Patriot, Carlisle Journal, Cumberland News, Evening News and Star, and the Carlisle Directory. Some of the records give specific details, such as a quotation, while others just list the event and source. Figure 3.29 shows the newspaper from 1925 reporting the flood in Carlisle. Other examples include:-

07.02.1809 Carlisle Parquet pg. 3. - Eden, Caldew and Petteril flooded; worst in memory.

22.01.1875 Carlisle Patriot - Storm; great proportion of Rickerby Park under water.

1968 Cumberland News pg. 166 – Images of Carlisle, flood Warwick Road.



Carlisle Journal.

SUPPLEMENT

PICTORIAL RECORD OF THE GREAT FLOODS.

Figure 3.29. *Newspaper reporting 2nd January 1925 flood*

Figure 3.30. *Epigraphic markings on Eden Bridge in Carlisle*

c) <u>*Epigraphic marks on Eden Bridge (Figure 3.29)*</u>

Flood levels recorded on Eden Bridge in Carlisle by indentations with associated years indicate the peak flood water stage. Figure 3.30 shows markings for the 1822, 1856, 1868, 1925, 1952 and 1968 floods. The flood level of the January 2005 flood event was one metre higher than the highest previous flood mark. Such marks need to be assessed for their originality, by checking the age of the structure on which they are preserved (Brazdil et al 2006). Eden Bridge was built in 1815 and consists of five long arches. Therefore all the epigraphic markings are thought to be legitimate. However, a limitation of using the flood levels is that the bridge width was doubled in 1932. This will have changed the conveyance water downstream. Water levels are controlled by both discharge and conveyance, meaning that epigraphic markings are generally good at indicating a flood, but are less good at indicating the magnitude of the event.

d) Smith and Tobin (1979)

Smith and Tobin (1979) ranked all the major known floods since 1800 according to the approximate extent of flooding. In total there were 49 known floods from 1800 to 1968 in Carlisle. Table 3.8 shows the return periods of these floods. This was an important source of information as it allowed the threshold for floods to be standardised between the different sources and timescales of the floods. Any discrepancies between the sources, in terms of the exact year or proposed magnitude relate to the different sources of information and the differences between annual and hydrological years. The British Chronology of Hydrological Events only recorded floods up until 1931, while gauged data starts in 1959. Table 3.10 was used to fill the gap between 1931 and 1959. However, Table 3.8 overlaps with both the other main sources of information allowing for a threshold to be estimated. The Peak over Threshold events, which exceed a threshold of 460 m^{3}s^{-}1 at Warwick Bridge were compared to the flood events in Table 3.8.

Major floods (known) between 1800 and 1970, ranked according to the approximate extent of flooding in Carlisle

Rank	Years	No. Of Floods	Recurrence Interval
1	1856	1	171 years
2	1822, 1925, 1968	3	42.75 years
3	1809, 1852, 1874, 1924, 1931	6	17.1 years
4	1809, 1815, 1868, 1899, 1924	5	11.4 years
5	1851, 1891, 1891, 1891, 1892, 1903, 1914, 1916, 1918, 1921, 1926, 1929, 1933, 1947	14	5.9 years
6	1891, 1891, 1896, 1898, 1903, 1914, 1926, 1928, 1928, 1929, 1930, 1931, 1932, 1933, 1941, 1954, 1954, 1954, 1954, 1964	20	3.49 years

Recurrence Interval = Tr = (n + 1) / m (assuming a representative record)
n = years of record, m = number of records up to a given magnitude
Total number of floods = 49, Years of record = 170.

Table 3.8. *Magnitude and Frequency of floods in Carlisle (1800-1970) (Smith and Tobin, 1979)*

e) *<u>Gauged records at Warwick Bridge and Sheepmount post 1959</u>*

Warwick Bridge gauging station began operating in 1959 and closed in 1997, while Sheepmount gauging station opened in 1976 and is still operating. The number of floods recorded in the documentary evidence was compared to the POT series for these two gauging stations to determine the threshold for the longer timescale flood record. At Warwick Bridge the threshold was calculated to be 460 m^3s^{-1} and at Sheepmount the threshold is 500 m^3s^{-1}.

3.4. Approaches to assess Flood Frequency and Magnitude

Flow Duration Curves (FDC's) (Section 3.4.1) were used to assess the whole range of flows occurring at the chosen stations for the period 1976-2007. The number of flood events which exceeded the Q1 value was used to assess flood frequency (Section 3.4.2), while the Annual Maximum (Amax) (Section 3.4.3) was used to assess flood magnitude. The Q1 value defines the discharge at which 1% of flows exceed this threshold during the chosen period. These indices were applied to the discharge data from the chosen gauging stations for the period 1976-2007.

3.4.1. Flow Duration Curves

A flow duration curve is a cumulative frequency diagram which summarises the hydrological frequency characteristics of stream discharge. It shows the probability of a specific flow discharge being equalled or exceeded for a particular river for a particular historic time period. For gauged catchments, they are simple to calculate, as once the resolution of data has been decided (15 minutes, hourly, daily), the discharges are ranked in descending order. The probability (P) that each flow will occur is calculated using the following equation (Fetter, 1994)

$$\mathrm{P} = 100 \times \frac{R}{N+1}$$

Where R is the flows ranked position and N is the number of observations

There are many options which have been used to display these data and several indices which have been devised to highlight specific aspects of the river flow regime. Figure 3.31a has both x and y on a linear scale meaning that the area beneath the curve is directly proportional to the total discharge. However, the flow extremes (floods and hydrological droughts) are less clear. In Figure 3.31b discharge (y) is plotted on a logarithmic scale which makes the extremes clearer. Third, Figure 3.31c shows normalised probability scales used to provide detail on the flow extremes.

The shape, and specifically the slope, of the curve are highly dependent upon the time resolution chosen, with the annual timescale being the most simplistic, with many of the flow dynamics averaged out, while the sub-daily timescale captures the most detail, with flood events being captured. Furthermore any length of data record can be used, but longer records reduce sampling error, although shorter records allow more stations to be used and compared (Coopstake and Young, 2008). Young (2002) found that between six and ten years of data are needed to minimise sampling errors for the Q5 flow duration value. However the chronology of flows is masked by a flow duration curve, so that it is impossible to determine what seasonal flows are like and whether flood events are few but continuous or if there are multiple minor events (Gregory and Walling, 1973).

The shape of the flow duration curve is influenced by rainfall pattern, catchment area and catchment physiographic characteristics (Vogel and Fennessey, 1994). If the high flow part of the curve is steep, then this indicates that floods are caused by heavy rainfall in a small flashy catchment, while if the gradient is flatter then floods may be caused by snowmelt or flow regulation by reservoirs may attenuate the peak flows (Shao *et al*., 2009).

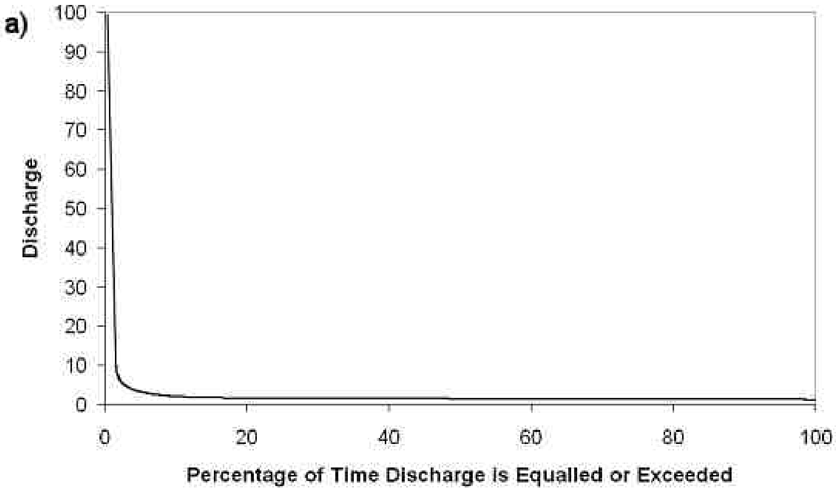


Figure 3.31a *Flow Duration Curve – untransformed axes*

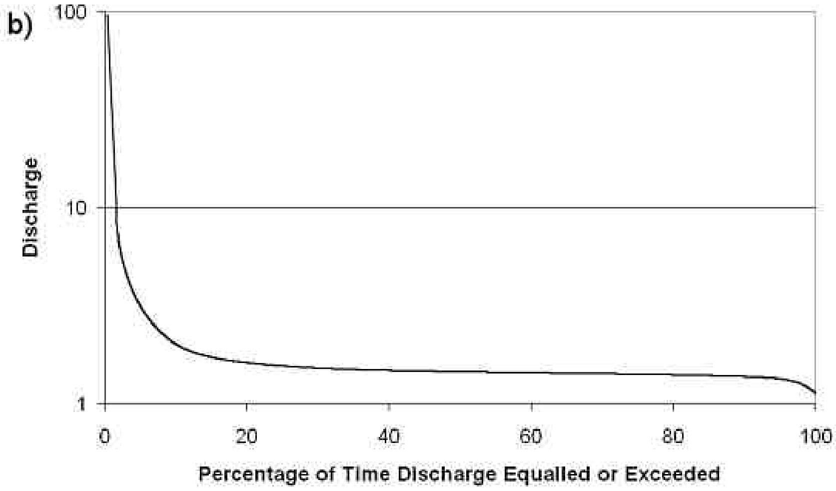


Figure 3.31b *Flow Duration Curve – Discharge transformed by logarith*m

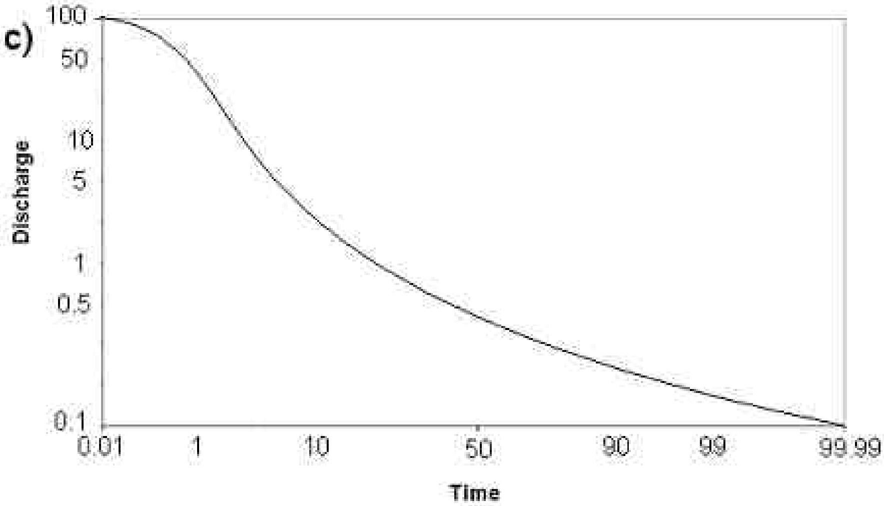


Figure 3.31c *Flow Duration Curve – Normalised Probability scaled axes.*

3.4.2. Exceedence of the Q1 value

The number of flood events per year that exceeded the Q1 value (defined over a 30 year period) was found. Often records are irregular with multiple peaks in certain years and none in others, which allows flood frequency to be analysed as well as flood magnitude (Robson, 2002). Furthermore, the events need to be independent of each other, which is achieved by the requirement of the time interval between floods being three times the time of the rising limb (Bayliss and Jones, 1993), averaged for five flood events (shown in Table 3.9). A summary of the criteria is given in Table 3.10. Using this threshold meant that the dataset had a greater number of events, which are likely to have been caused by multiple mechanisms. MacDonald *et al.* (2010) recommended having a lower threshold, and used a series which 4.5 floods/ year on average. The FSR (1975) had an average of 8 floods per year.

Flood Event	Sheep mount	Warwick Bridge	Temple Sowerby	Kirkby Stephen	Udford	Harraby Green	Cumm ersdale	Green holme
22nd Sept 85	29.5	28.25	28.25	4.75	25.75	12.75	28.0	15.25
23rd Mar 89	38.0	22.25	13.5	6.5	14.25	12.5	8.75	11.5
10th Feb 97	29.0	10.75	10.5	9.25	13.25	15.75	9.0	10.5
8th Jan 05	36.75	28.25	26.5	7.5	29.25	35.0	15.0	27.25
25th Oct 05	21.75	18.25	13.25	8.0	12.5	25.0	9.75	13.5
Average	31.0	21.55	18.4	7.2	19.0	20.2	14.1	15.6
3 * Average (Hours)	93.0	64.65	55.2	21.6	57.0	60.6	42.3	46.8
3 * Average (Days)	3.88	2.69	2.3	0.90	2.38	2.53	1.76	1.95
Time Interval	4 days	3 days	3 days	1 day	3 days	3 days	2 days	2 days

Table 3.9 *Time of the Rising limb for eight gauging stations*

	Q1	**Time Interval**
Sheepmount	347.02	4 days
Warwick Bridge	228.00	3 days
Temple Sowerby	130.40	3 days
Kirkby Stephen	28.39	1 day
Udford	99.92	3 days
Greenholme	69.01	2 days
Harraby Green	17.37	3 days
Cummersdale	50.93	2 days

Table 3.10 *Criteria used for each gauging station to define independent floods.*

3.4.3. Annual maximum

Annual maxiumum series record the largest instantaneous flood peak per hydrological year (Svensson *et al.*, 2005). The major advantage of this approach is that data are easy to extract, but insignificant flows can be included in the record, if a year was particularly flood poor.

3.5. Chapter Summary

Data are important in any modelling investigation and this chapter summarised the types of data used and highlighted the limitations of the data. This chapter focussed on the discharge data and concluded that for the chosen gauging stations the quality of the gauged flows at high flows is good enough for the analysis to be worthwhile. A suitable gauging station was found in each of the major sub-catchments, which will allow spatial patterns of flood trends of magnitude and frequency to be assessed. Furthermore, a flood record was constructed for two different timescales. Firstly, the instrumented period for each of gauging station can be assessed using indices such as exceedence of the Q1 threshold and Annual maximum. This can be done for Warwick Bridge from 1959, but most stations did not start until 1976. Statistical techniques, such as time series cross correlation were employed to form continuous time series for all the chosen gauging stations from 1976 to 2007. Secondly, a flood record for the historical period was constructed using documentary evidence. From these the flood record was extended back to 1770. The next chapter (Chapter 4) focuses on using these two time series to identify trends in both flood frequency and flood magnitude. Chapter 5 then goes on to downscale this downstream risk of flooding to the contributing tributaries using the data evaluated in this chapter through both a statistical and a numerical modelling approach.

Chapter 4

High Flow History in the Eden catchment

4.1. Chapter Scope

This thesis aims to identify the most important upstream contributing sub-catchments in causing downstream flooding. However, firstly the extent of the flood risk problem has to be assessed. It is important to assess temporal trends in high river flows before trying to determine the causes of these changes and how the risks can be managed. This chapter seeks to address objective 1, which is to “assess the problem of flood risk in the case study catchment (River Eden) including how the frequency and magnitude of flooding has changed over different spatial and temporal scales, and the potential drivers of these changes”. To do this it will use the flood records, using the spatial disaggregation of the catchment into sub-catchments outlined in Chapter 3.

This chapter starts by assessing the continuous range of river flows through flow duration curves (Section 4.2) What follows is firstly a qualitative review of the flooding history in the Eden catchment (Section 4.3), which focuses on the extreme January 2005 event. This is developed by a quantitative assessment of flooding trends in terms of flood frequency and magnitude, over various spatial (Section 4.4) and temporal scales (Section 4.5). Once the trends in river flows have been identified, possible causes of these changes are investigated. As discussed in Chapter 2, there are two main hypotheses to explain changes in river flows; (1) Climate Change, and (2) Land Use Changes. These are commented on in Section 4.6, with the first of these being assessed through the use of Lamb Weather Types. The effect of land use changes on flood risk, which is the focus of this thesis, is also discussed and the different approaches used in these type of studies, outlined in Chapter 2, are evaluated in terms of their appropriateness to this case study from what has been found from identifying the trends and causes in this chapter.

4.2. Flow Duration Curves

Flow duration curves were calculated for the gauging stations outlined in Section 3.2. Data for Kirkby Stephen only extended back to 1981. Before then, the record had multiple long gaps of several months, which could not be filled using the interpolation method outlined in Section 3.2.2. Therefore to ensure comparability between results, flow duration curves were calculated for all eight gauging stations for the period 1981-2007. Young (2002) found that between six and ten years of data are needed to minimise sampling errors for the Q5 flow duration value. Therefore, using this 27 year record should provide reliable estimates of the flow exceedance statistics, which are given in Table 4.1. For example, Q_1 means that 1% of the flows exceed the threshold.

The main River Eden unsurprisingly shows that the gauging stations further upstream exhibit lower flows for each of the flow statistics, due to the smaller upstream contributing area. The gradients of the flow duration curves for the gauging stations on the River Eden, show that the very highest flows ($Q_{0.1}$ to Q_1 statistic) have a steep gradient, suggesting that the Eden is quite a flashy catchment (Table 4.2). This is also confirmed by the average flood for all sites lasting for less than a day from source to output. However, the $Q_{0.1}$ and Q_1 statistics are the most likely to be unreliable as they are highly dependent upon a single event, although the 27 year record should be adequate to calculate these reliably. As the catchment size decreases, the gradient of the high flow part of the curve becomes steeper, suggesting that smaller sub-catchments have a flashier regime. The $Q_{0.1}$:Q_1 ratio becomes larger for smaller sub-catchments (Sheepmount = 1.85, Warwick Bridge = 1.96, Temple Sowerby = 2.03, Kirkby Stephen = 2.45) (Figure 4.1). Ratios from the gauging stations on the tributaries are also plotted for comparison to the main River Eden. The smaller sub-catchments have a low $Q_{0.1}$:Q_1 ratio, while larger tributaries have a higher ratio. The exception to this is the River Petteril, which has an area of 160 km^2 and a relatively high $Q_{0.1}$:Q_1 ratio.

	Min	Max	$Q_{99.9}$	Q_{99}	Q_{95}	Q_{90}	Q_{75}	Q_{50}	Q_{25}	Q_{10}	Q_{5}	Q_{1}	$Q_{0.1}$
Eden - Sheepmount	5.23	1516.40	5.94	7.49	9.71	11.51	16.94	31.49	64.52	118.22	168.62	347.02	642.28
Eden - Warwick Bridge	2.82	813.93	3.22	4.64	7.17	9.22	13.40	22.40	42.60	78.20	113.00	228.00	446.17
Eden - Temple Sowerby	0.94	390.60	1.11	1.41	1.84	2.20	3.48	6.91	15.68	33.86	54.82	130.40	265.35
Eden - Kirkby Stephen	0.07	177.50	0.08	0.11	0.17	0.22	0.43	0.99	2.49	5.96	10.31	28.39	69.60
Eamont - Udford	0.42	295.00	0.52	1.33	2.13	3.00	4.98	9.60	19.72	34.91	49.17	99.92	176.61
Irthing - Greenholme	0.73	277.67	0.76	0.87	1.10	1.26	1.86	3.62	8.19	16.78	26.65	69.01	135.40
Petteril - Harraby Green	0.13	82.57	0.18	0.21	0.26	0.30	0.47	1.09	2.49	5.30	7.98	17.37	34.90
Caldew - Cummersdale	0.62	288.50	0.74	0.87	1.18	1.49	2.38	4.35	8.83	16.40	23.87	50.93	115.21

***Table 4.1**.* *Flow duration statistics for different gauging stations in the Eden catchment (discharges in m^3s^{-1})*

	Min-$Q_{99.9}$	$Q_{99.9}$-Q_{99}	Q_{99}-Q_{95}	Q_{95}-Q_{90}	Q_{90}-Q_{75}	Q_{75}-Q_{50}	Q_{50}-Q_{25}	Q_{25}-Q_{10}	Q_{10}-Q_{5}	Q_{5}-Q_{1}	Q_{1}-$Q_{0.1}$	$Q_{0.1}$-Max
Eden - Sheepmount	7.1	1.7	0.6	0.4	0.4	0.6	1.3	3.6	10.1	44.6	328.1	8741.2
Eden - Warwick Bridge	4.0	1.6	0.6	0.4	0.3	0.4	0.8	2.4	7.0	28.8	242.4	3677.6
Eden - Temple Sowerby	1.7	0.3	0.1	0.1	0.1	0.1	0.4	1.2	4.2	18.9	149.9	1252.5
Eden - Kirkby Stephen	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.9	4.5	45.8	1079.0
Eamont - Udford	1.0	0.9	0.2	0.2	0.1	0.2	0.4	1.0	2.9	12.7	85.2	1183.9
Irthing - Greenholme	0.3	0.1	0.1	0.0	0.0	0.1	0.2	0.6	2.0	10.6	73.8	1422.7
Petteril - Harraby Green	0.5	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.5	2.3	19.5	476.7
Caldew - Cummersdale	1.2	0.1	0.1	0.1	0.1	0.1	0.2	0.5	1.5	6.8	71.4	1732.9

Table 4.2 *Gradients of FDC between different exceedance levels (m^3s^{-1})*

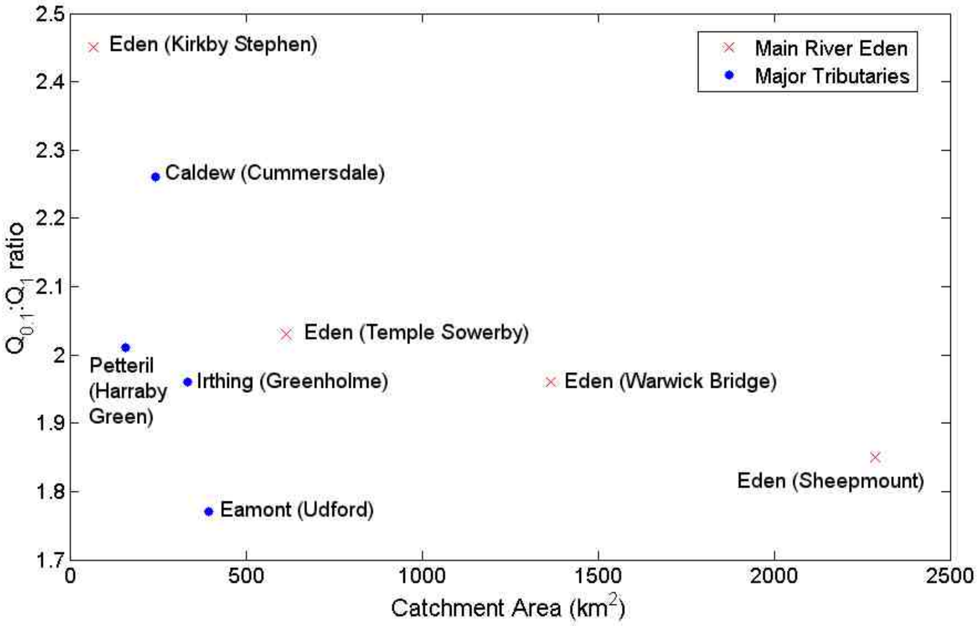


***Figure 4.1**. Scatter plot of the $Q_{0.1}$:Q_1 ratio against catchment area, categorised by rivers.*

The eight gauging stations used in the analysis can be separated into four groups of 2 stations, based upon their flow regime: (1) Sheepmount and Warwick Bridge; (2) Temple Sowerby and Udford; (3) Greenholme and Cummersdale; and (4) Kirkby Stephen and Harraby Green (Figure 4.2). The Lower Eden at Sheepmount and Warwick Bridge have significantly higher high flows than any other station and their low flows are not as severe. The gradients of these two curves are very similar, especially from Q_{99} to Q_{50} (Table 4.2), while the rest of the curve is flatter for Warwick Bridge, suggesting that high flows are more common at Sheepmount than Warwick Bridge. The second group comprises the Eden at Temple Sowerby and the Eamont at Udford. These are the next two largest sub-catchments by area (619 km^2 and 408 km^2 respectively), and as they of a similar size, they have similar high and low flows. However, there are subtle differences between the flow regimes of these two rivers. The high flows in the Upper Eden are larger than the Eamont, as would be expected given the larger upslope contributing area, but between the Q_{10} and Q_{95} statistics the Eamont flows are higher. This suggests that the slope of the Eamont curve is flatter (Table 4.2), which may be caused by attenuating effects of Lake Ullswater and Haweswater reservoir. The Greenholme (Irthing) and Cummersdale (Caldew) gauging stations have similar flow regimes, with a maximum flow of 277 m^{3}s^{-1} and 288 m^{3}s^{-1} respectively. Again these two gauging stations exhibit interesting changes throughout the range of flows. Higher flows occur less often for the Caldew than for the Irthing, as the gradient between $Q_{0.1}$ and Q_{10} is higher for the Irthing (5.8 m^3s^{-1}) than for the Caldew (3.9 m^3s^{-1}). The final pair of sub-catchments is the Upper Eden at Kirkby Stephen and the Petteril at Harraby Green. These two sub-catchments are the smallest in the Eden catchment in terms of area. Therefore, it is as expected that these two gauging stations record the lowest flows. The Upper Eden exhibits significantly higher flows even though the upstream contributing area is significantly smaller (Kirkby Stephen = 69 km^2, Harraby Green = 162 km^2). However, the gradient of the Upper Eden flow duration curve is steeper than the River Petteril's (Table 4.2) and at Q_{25} the two curves cross (Table 4.1). This means that the Upper Eden also has lower flows than the River Petteril.

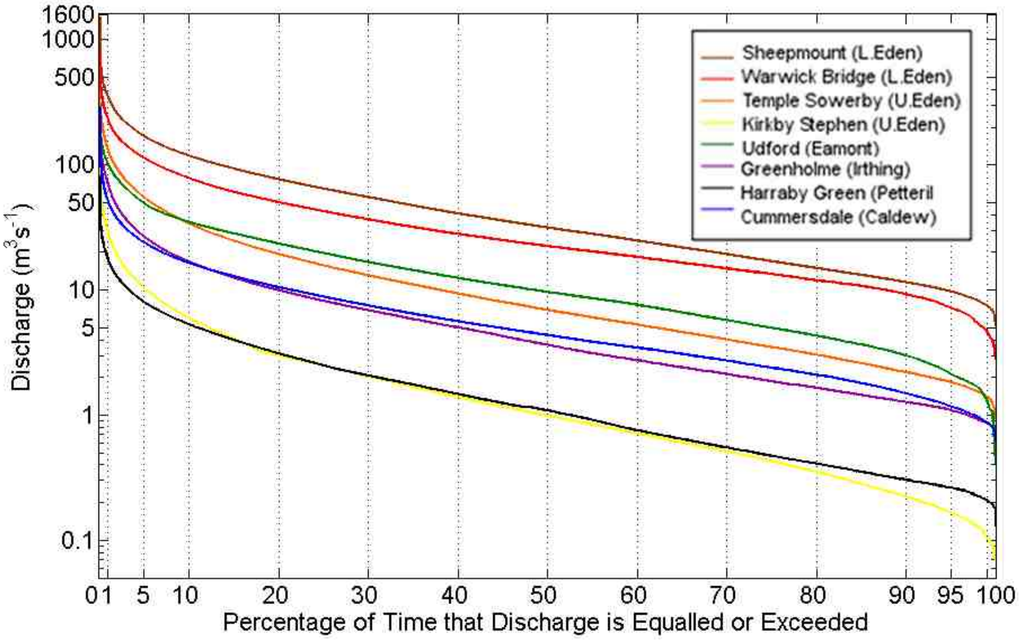


***Figure 4.2**. Flow Duration Curves for different gauging stations in the Eden catchment from 1981 to 2007*

Figure 4.3 shows a comparison of two time periods for the flow duration curves of four stations where the gauging record extends back to 1976; Sheepmount (Eden at Carlisle), Temple Sowerby (Upper Eden), Greenholme (Irthing) and Harraby Green (Petteril). The flow duration curves for the periods 1981-2007 are extremely similar to the whole period (1976-2007) flow duration curves. This suggests that the trends shown in Figure 4.2 are representative of the whole time period.

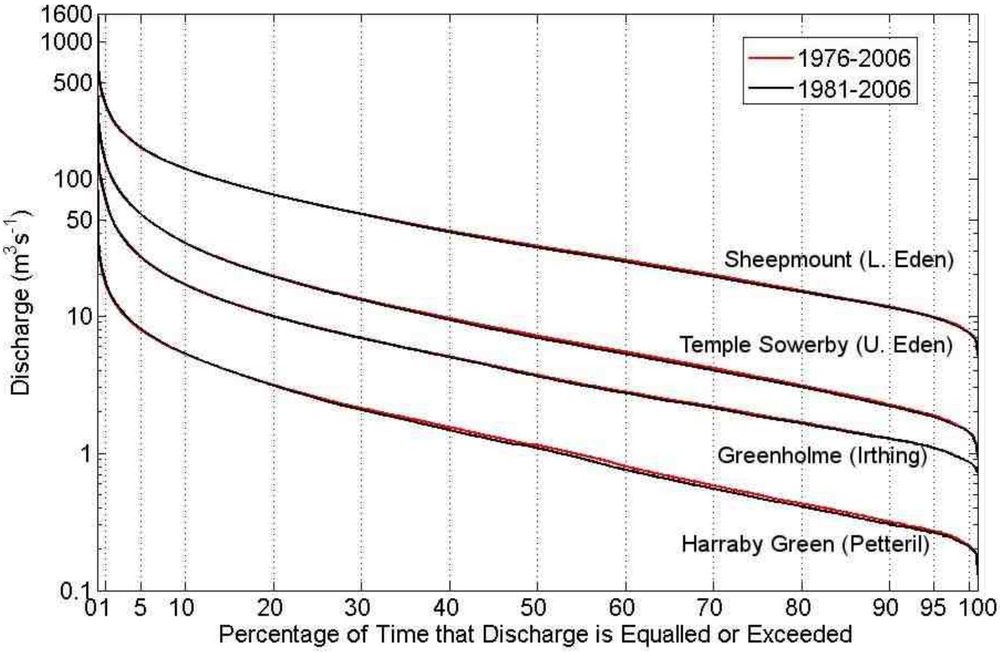


Figure 4.3 *Flow Duration Curves for gauging stations for both 1981-2007 and 1976-2007 periods.*

4.3. Review of flooding history of the Eden catchment

This section starts with a qualitative account of past flooding in the Eden catchment (Section 4.3.1), before providing a more in-depth analysis of past flood magnitude and frequency at different spatial and temporal scales in Section 4.4 and Section 4.5.

4.3.1. Historical Flood Events

There have been several flood events in the Eden catchment, with settlements throughout the catchment being affected, especially Carlisle and Appleby. Approximately 70 locations, which are shown in Figure 4.4, have been flooded in the last 200 years to 1979 according to a search of local archives and newspapers by Smith and Tobin (1979). Appleby has experienced 23 floods since 1822, of which six had a return period of more than 31.2 years (Smith and Tobin, 1979) (1822, 1856, 1899, 1928, 1968 and 2005). Carlisle has experienced five major floods (1822, 1856, 1925, 1968 and 2005). Figure 4.5 shows the epigraphic markings on Eden Bridge (Carlisle). The January 2005 flood was 1 m higher than the previous highest level of 1822. Rickergate (a part of Carlisle) flooded for the first time since 1822, as flood defences were overtopped. Figure 4.6 shows photographic evidence of flooding in the city of Carlisle over the last 100 years.

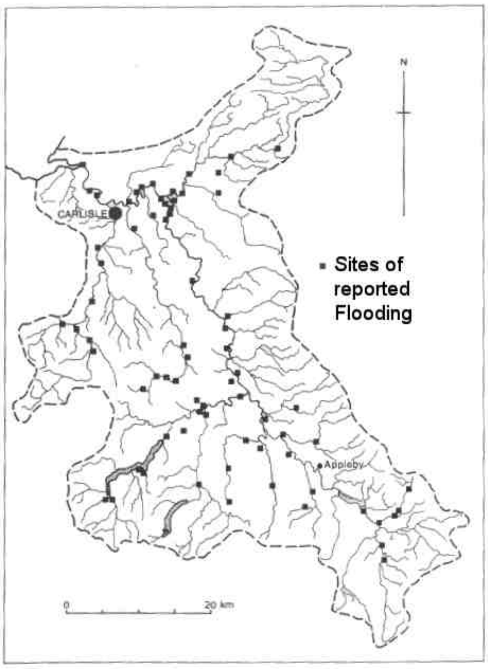


Figure 4.4 *Sites of reported flooding on during the last 200 years (Smith and Tobin, 1979)*

Figure 4.5 *Epigraphic markings Eden bridge in Carlisle.*

Flooding in the Eden catchment is mainly a winter occurrence, with 92% of floods in Carlisle and 89% of floods in Appleby occurring in winter, defined as between October and March (Smith and Tobin, 1979). The floods of 1925, 1947 and 1968 were caused by snowmelt. The 1968 flood occurred on the 23rd March and the catchment received 5% of the average annual precipitation on this and the previous day, as well as rapid snowmelt. The cost of this flood was £500,000 (about £5 million in today’s money) in Carlisle and £250,000 (about £2.5 million in today’s money) in Appleby. 11% of Carlisle was inundated during this flood and 6000 people were affected. The next section provides details on the causes and effects of the worst recorded flood on the Eden, January 2005.

Figure 4.6 *Photographs of flooding in Carlisle over the past 100 years.*

4.3.2. The January 2005 Flood

The January 2005 flood event was the most extreme the catchment has ever experienced in the historical and measured record. The flood level in Carlisle was 1 m higher than the previous worst flood on record. The storm event which caused this flooding extended from the 6th to the 9th January and affected Northern England, Southern Scandinavia, Germany and the Baltic Region (Figure 4.7) (Carpenter, 2005).

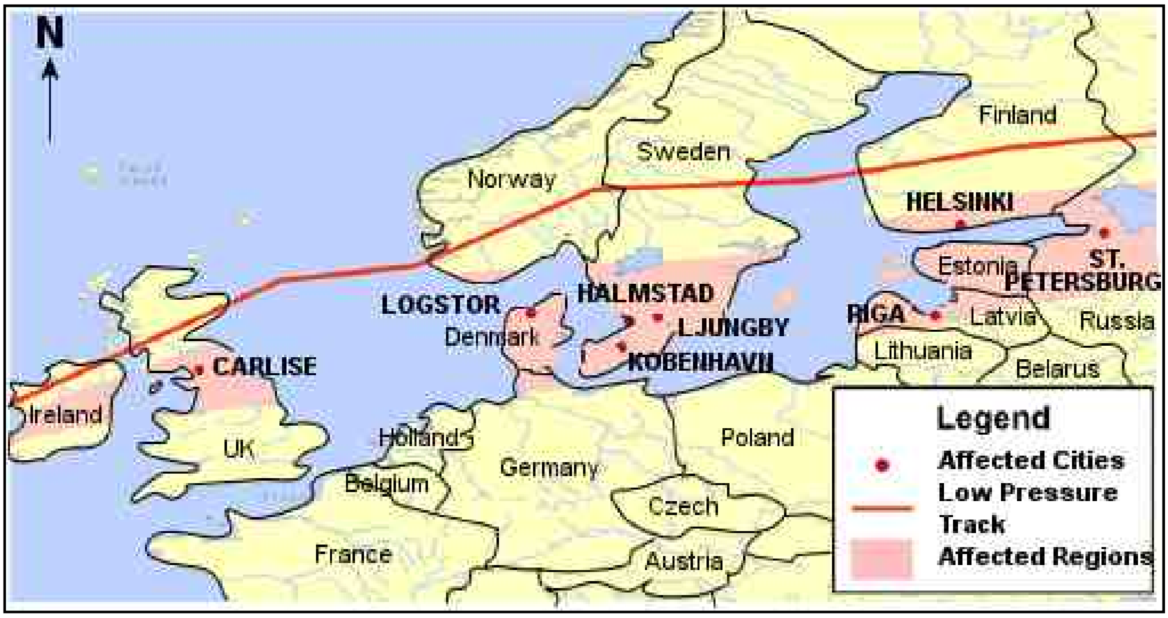


Figure 4.7 *Map showing storm track and areas affected by flooding (adapted from Carpenter 2005)*

In Northern England, the Eden and Tyne (Archer *et al.*, 2007a; 2007b) catchments were severely affected. The meteorological cause of the storm was an eastward extension of the Azores high and deep low pressure over Iceland causing a warm front of mild and moist tropical maritime air to move from the SW across the United Kingdom. A cold front separated this warm airmass from a colder polar airmass, which was quasi-stationary over Northern England. The introduction of this cold air led to rapid development of an area of intense low pressure. The associated frontal system was occluded and wrapped itself around the depression, causing rainfall to return south, accompanied by heavy winds of up to 60 knots (Environment Agency, 2006). This may have been caused by the formation of a sting jet (Browning and Field, 2004), a mesoscale air flow originating in the cloud head of a deepening cyclone and gaining speed as it descends to the tip of the cloud head. Furthermore, orographic enhancement of rainfall occurred due to the seeder-feeder mechanism (Bader and Roach, 1977; Roberts et al., 2009), whereby rain becomes more intense as it falls through lower level clouds formed as moist air flows over mountainous terrain. Figure 4.8 shows a schematic of this process

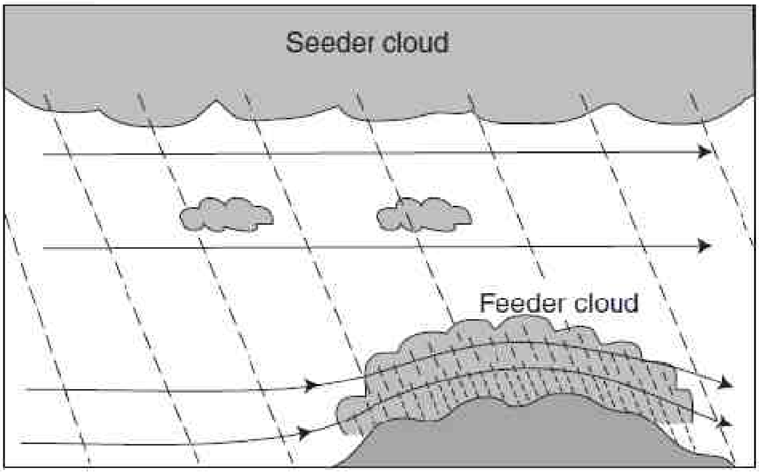


Figure 4.8 *A schematic of the seeder-feeder mechanism adapted (Roberts et al. 2009) from the Forecasters Reference book (Meteorological Office, 1997)*

The rarity of the event is linked to its duration, rather than the intensity of the rainfall. Overall, this storm has been estimated as having a return period of 50-100 years (0.02-0.01 annual probability). The most significant rainfall was orographical, in the South of the catchment in the Lake District. Wet Sleddale in the Eamont sub-catchment recorded 207mm rainfall over the three days of the event, which has a return period of c.173 years (0.58%). The peak intensity registered was 24mm/hr (6mm in 15 minutes), which only has a return period of 1 in 5 years (20%) (Environment Agency, 2006). However, the most intense rainfalls in this region probably occur during summer convective storms, and therefore this rainfall total may be significant for a winter frontal rainfall event.

This rainfall resulted in an extreme hydrological response, with all river systems experiencing high flows (Table 4.3). Figure 4.9 shows that for the Eden (R = 0.98), Eamont (R = 0.75) and Irthing sub-catchments (the rivers with more than one gauging station), as the upslope contributing area increases, the return period of the flood increases. This demonstrates the spatially extensive high magnitude rainfall experienced in this event, rather than localised high intensity precipitation.

Gauging Station	Peak Discharge	Estimated Return Period
Kirkby Stephen (Upper Eden)	129	25
Great Musgrave (Upper Eden)	277	25
Appleby (Upper Eden)	No data	50-100
Temple Sowerby (Upper Eden)	391	25
Great Corby (Lower Eden)	950	100
Sheepmount (Lower Eden)	1520	175
Pooley Bridge (Eamont)	108	50
Dacre Bridge (Eamont)	49	20
Burnbanks (Eamont)	28	10
Eamont Bridge (Eamont)	198	35
Udford (Eamont)	295	50
Coalburn (Irthing)	3	10
Greenholme (Irthing)	278	75
Harraby Green (Petteril)	107	100
Cummersdale (Caldew)	253	75

Table 4.3 *List of gauging stations peak flows and associated estimated return periods (Environment Agency, 2006*

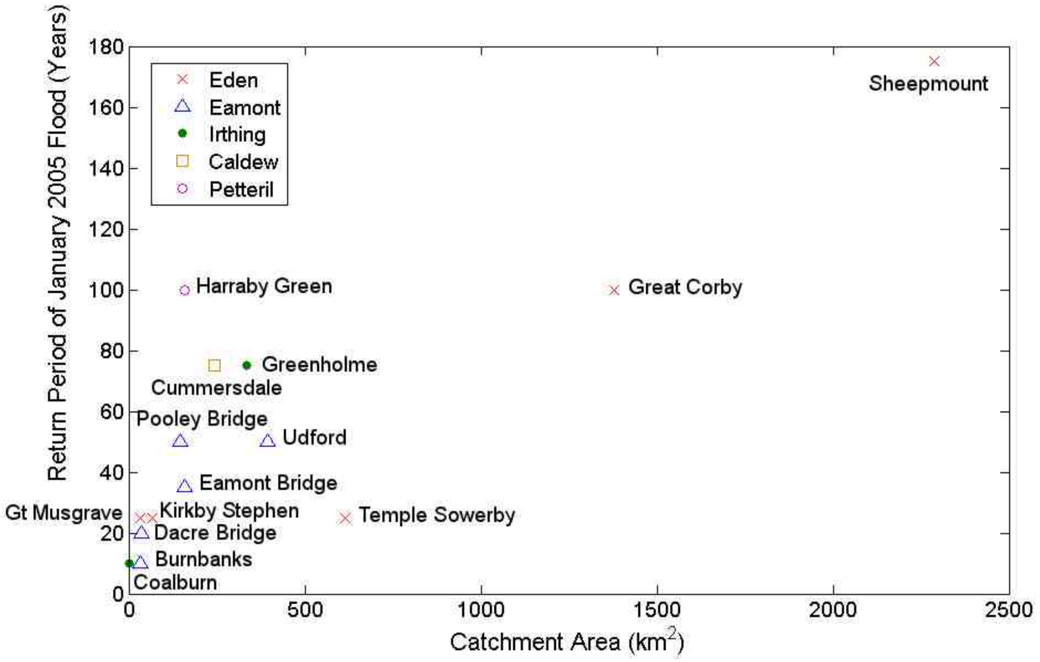


Figure 4.9 *Scatter plot of the return of the January 2005 flood at different gauging stations against catchment area.*

There was also widespread flooding throughout the catchment. The River Eden in Carlisle (Sheepmount) peaked at 1520m^{3}s^{-1} and the city was severely inundated (Figure 4.10). The settlements of Appleby, Penrith and Eamont Bridge were also affected by flooding. The lakes and reservoirs in the Eamont sub-catchment did not attenuate flood peaks significantly. Lake Ullswater recorded its maximum level

(2.54m) in a record extending back to 1961. Haweswater reservoir was 2m below the dam spill before the storm and began spilling at 8pm on the 7th January. Its peak level was the 3rd highest on record (since 1997) (Spencer *et al.*, 2007). Wet Sleddale (which received the highest precipitation) was spilling before the event and during the event the level rose from 16.92m to 19.22m.

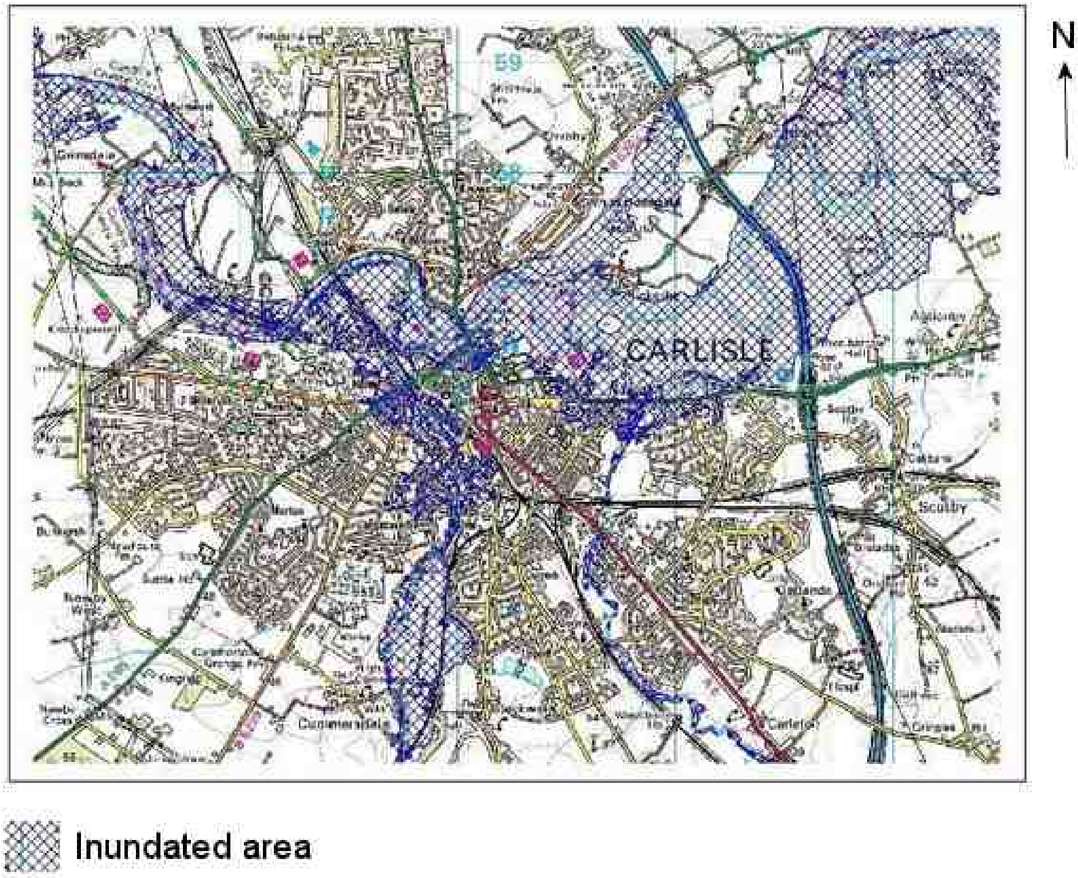


Figure 4.10 *Flood extent in Carlisle for the January 2005 flood event. (Environment Agency, Eden CFMP)*

The January 2005 flood had devastating effects on the residents of Carlisle and other settlements throughout the catchment. Figure 4.11 shows photographs of different parts of the city during the flood event. Flooding in Carlisle was caused by multiple factors. First, the flood defences were overtopped by fluvial flooding, an example of this is at Warwick Bridge where the defences overtopped at 8:30am on the 8th January and where water levels peaked at 0.7m above local defence height. Secondly there was surcharge from the sewage and road drains at the beginning of the storm. Third, there was backing up of the tributaries of the Eden and bridge blockages caused out of bank flows.

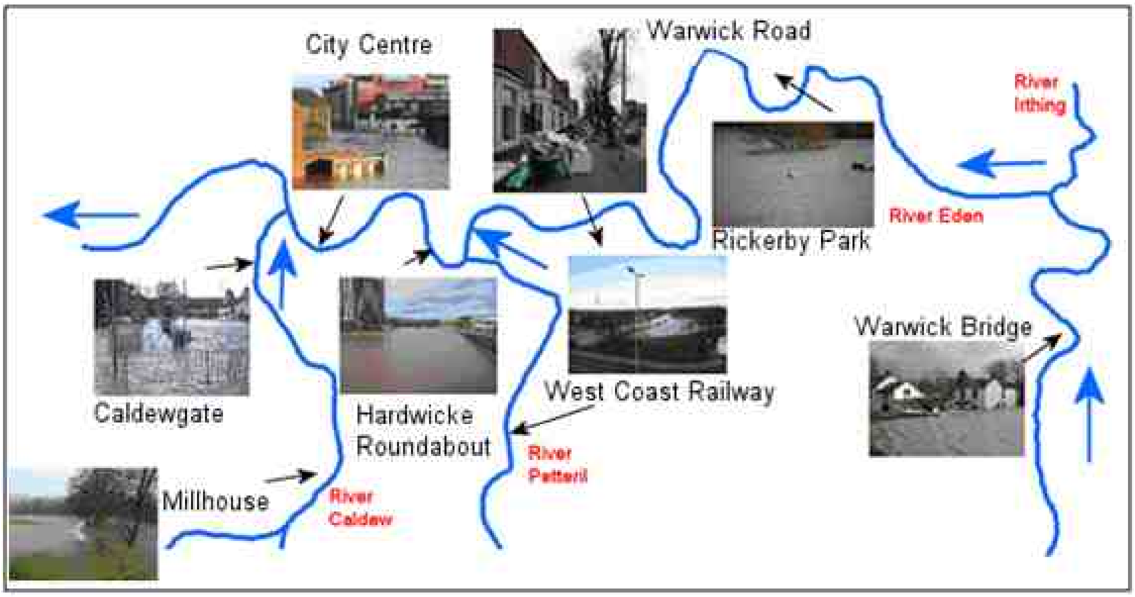


Figure 4.11 *Photographs of the Carlisle January 2005 flood throughout the city.*

However, flooding was not limited to Carlisle and Figure 4.12 shows the flood in other areas. Figure 4.13 indicates the number of properties affected by the flood in different parts of Carlisle and throughout the catchment. In total 2016 properties were flooded throughout the catchment, of which 1865 were in the city of Carlisle. A mixture of residential, industrial and commercial properties were flooded and key infrastructure, including the emergency services, transport, schools and public services was disrupted (Environment Agency, 2006). Four percent (79 properties) of the properties that were flooded in Carlisle were not covered by insurance. The total economic cost of the flood was between £350million and £400million. However, there were also more intangible impacts on people’s lives. Flooding often causes the loss of both valuable and sentimental possessions, many of which cannot be replaced. A support group set up after the flood called Communities Reunited showed that the social impacts of the flood are significant, with many people suffering from stress and depression, ranging from tiredness and nervousness to anxiety and panic attacks. Over a year after the flood approximately 320 homes were still uninhabitable and during a personal visit to Warwick Road in July 2007 (2½ years after the flood) it was found that some homes were still empty and repairs were ongoing.

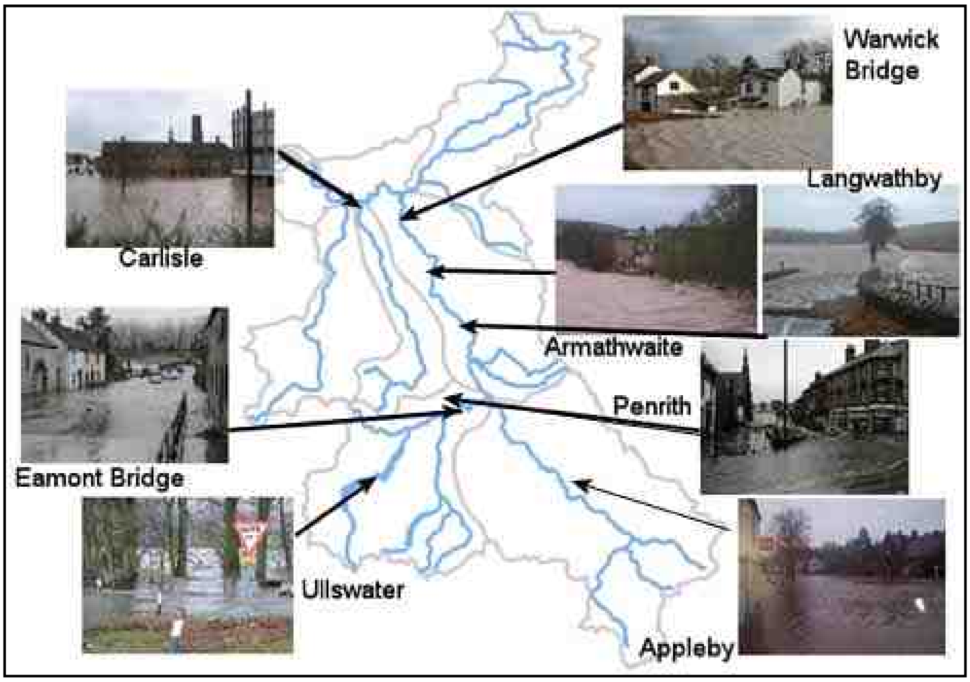


Figure 4.12. *Photographs of the January 2005 floods throughout the Eden catchment.*

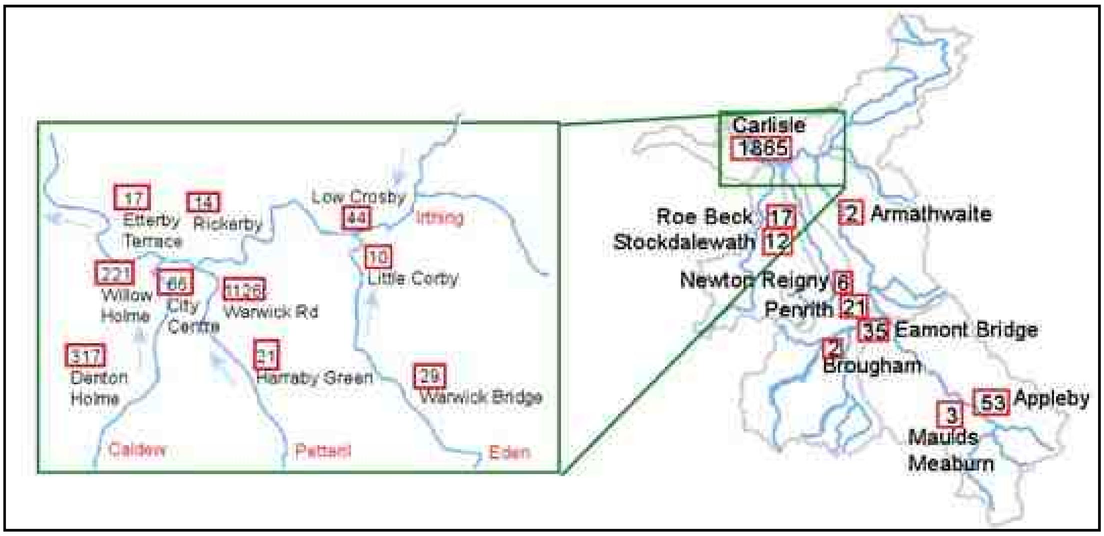


Figure 4.13. *Number of properties affected by January 2005 floods in Eden catchment.*

Businesses were also affected by the flood event, with approximately 300 businesses flooded in Carlisle. Of these, Communities Reunited estimates that half of these have ceased trading or have moved premises. The emergency services were also badly affected by the flood, with the Cumberland Infirmary cancelling non-emergency operations. Overall, this flood led to three deaths and approximately 120 injuries or illnesses. Carlisle police station was flooded to a depth of 2.5m and 18 months later the police service was still in temporary accommodation. Appleby police station had flood waters 1.5m deep, causing damage of up to £100,000 and was not fully operational for five months (Environment Agency, 2006). The fire station in Carlisle was flooded to a depth of 2.5m in Warwick Road. The road network was severely disrupted, with the M6 closed due to high winds and the A66 at Temple Sowerby closed for 2 hours on the 8th January due to flooding of the River Eden. The A66 was also closed at Eden Bridge and the A69 was closed due to flooding at Warwick Bridge for two days. The A595 was closed until the 10th January. The train network was also affected with the West Coast Mainline being closed until the 17th January due to landslides. Utilities services in Carlisle were also disrupted, with the electricity substation at Willow Holme flooded, cutting power supplies to 60,000 properties (Environment Agency, 2006).

4.4. Trends in flooding throughout the Eden catchment

This section looks at all the floods that have occurred in the Eden catchment during the instrumented period. It is important to consider all floods, and not just the extreme events, as their may only be trends in certain magnitude floods, as they may be influenced more by potential changes in climate or land use. Flood magnitude and frequency has been assessed for each of the gauging stations outlined in Section 3.2.1. For the stations (Cummersdale/Holm Hill and Warwick Bridge/Great Corby) which have been closed and replaced by another, the rating equations developed in Section 3.3.1 have been used to form one complete record. Flood magnitude has been assessed through the annual maximum flood discharge. Flood frequency has been investigated through the number of flood events per hydrological year exceeding the Q1 value of 347.0 m^3s^{-1}. A hydrological year begins on the 1st October and ends on the 30th September the following year. Furthermore, the magnitudes of all these events were assessed. Details of these approaches were given in Section 3.4.

4.4.1. Flood Frequency

Figure 4.14 shows the number of flood events which exceed the Q1 value per year since gauging records began in each sub-catchment. On average there are 4.2 high flows per year for the River Eden in the city of Carlisle (Sheepmount). The late 1960s and 1970s were relatively flood poor, with fewer than the average number of floods per year every hydrological year except 1967 to 1968 and 1974 to 1975 (Figure 4.14a), which were the years with the most floods in the whole of the record. Floods occurred in every year except 1995 to 1996, a year of hydrological drought.

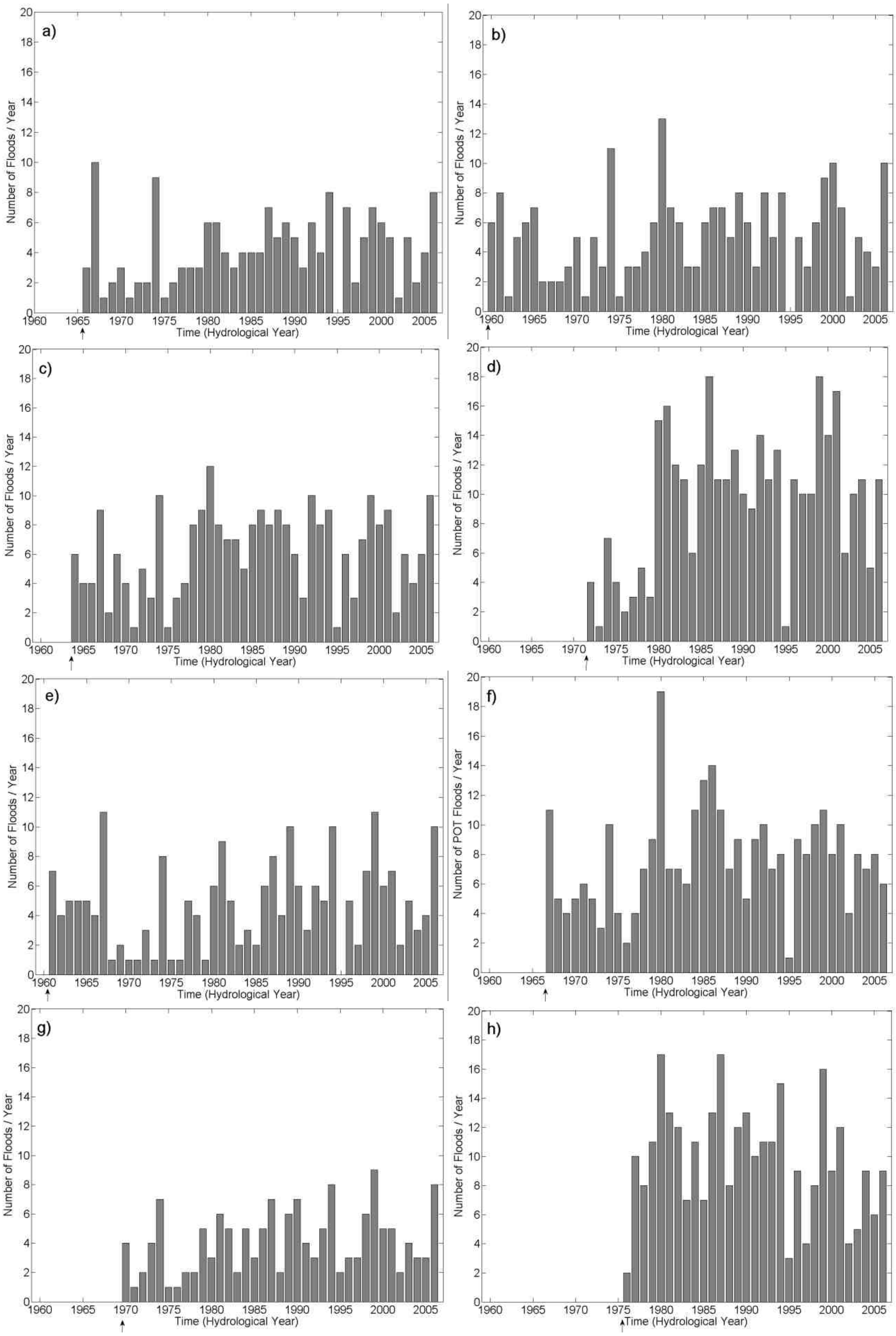


Figure 4.14. *Number of floods per year that >Q1 for a) Lower Eden in Carlisle (Sheepmount) , b) Lower Eden (Warwick Bridge), c) Upper Eden (Temple Sowerby), d) Upper Eden (Kirkby Stephen), e) Eamont (Udford), f) Irthing (Greenholme), g) Petteril (Harraby Green), and h) Caldew (Cummersdale). Arrow shows start of record.*

It is also important to assess the flood hazard in the individual sub-catchments of the Eden. Figures 4.14b, c and d show the number of floods per year for gauging stations on the main Eden. From these it is clear that more floods exceeding the Q_1 flow occur on the Upper River Eden than on the Lower River Eden at Carlisle. This is particularly clear for the station at Kirkby Stephen, which only represents 69.4 km^2, where 9.6 high flows occur each year on average. The flood poor nature of the 1970s compared to the later decades is more evident for the Upper River Eden, particularly Kirkby Stephen (Figure 4.14d) than the Lower River Eden. Table 4.4 shows that the number of flood events at Kirkby Stephen on the Upper River Eden is a positive function of time ($r = 0.39$, $p < 0.05$). This is due to the flood poor nature of the beginning of the record and the higher number of floods at the end of the record. No other flood frequency records on the main River Eden show statistically significant trends over time.

Gauging Station	**Correlation of Number of events over time**
Eden (Carlisle) - Sheepmount	0.211 (0.187)
Lower Eden - Warwick Bridge	0.179 (0.229)
Upper Eden - Temple Sowerby	0.219 (0.159)
Upper Eden - Kirkby Stephen	0.388 (0.021)
Eamont - Udford	0.206 (0.170)
Irthing - Greenholme	0.147 (0.365)
Petteril - Harraby Green	0.305 (0.066)
Caldew - Cummersdale	- 0.202 (0.275)

Table 4.4 *Correlation coefficients for the POT series over the gauged period for various stations in the Eden catchment (statistical significance shown in brackets).*

The flood frequency records for the main tributaries of the Eden indicate that the River Eamont and River Petteril seem to have relatively few floods per year, with an average of 4.7 and 4.1 respectively. Possible reasons for this might be the regulation of the River Eamont, with lake Ullswater and Haweswater reservoir, and the relatively small area and low altitude of the River Petteril sub-catchment. The River Caldew sub-catchment has an average of 9.7 events every year. However the trend over time is negative for this station (Table 4.4), meaning that recent years have experienced fewer events than the late 1970s and early 1980s, but this trend is not statistically significant. The flood frequency record for the River Irthing at Greenholme has an average of 7.7 floods per hydrological year, with the maximum being 18 events in 1980-1981. Overall, none of the gauging stations show strong trends through time, although this analysis does show that some stations, notably at Kirkby Stephen, Cummersdale and Greenholme, have more events per year on average than the other sub-catchments.

4.4.2. Flood Magnitude

Flood magnitude is firstly assessed by the Annual maximum (Amax) flood event for each hydrological year (Figure 4.15). Overall, there are no apparent trends in the Amax series for any of the rivers in the Eden catchment. A second, more robust approach used to assess flood magnitude is the magnitude of the flood events that exceed the Q1 threshold (Figure 4.16). However, there are also no statistically significant trends in any of these records. A key observation on extreme floods is that the January 2005 flood is distinctly different to anything that has happened previously at three gauging stations: Sheepmount; Warwick Bridge and Harraby Green, while at the other stations it was not different to previous flood magnitudes.

Figure 4.17 shows both the flood frequency series and Amax (magnitude) series plotted on the same graph. It is hypothesied that flood rich years will have both a high frequency of floods and high magnitude floods, while flood poorer years will have fewer floods and lower magnitude floods. An initial visual inspection of Figure 4.17 backs up this hypothesis, for example for the Eden at Carlisle (Sheepmount), 1967 to 1968, 1974 to 1975 and 1994 to 1995 had lots of floods and had a high annual maximum flood. Further evidence supporting this hypothesis is found in the correlation coefficients shown in Table 4.5. For Sheepmount the R^2 value is 0.47, which is statistically significant at the 99% level. However, there are years which are exceptions, such as the hydrological year 2004/2005, which had the extreme 1516 m^3s^{-1} flood, but few others.

Other stations show similar patterns. Udford shows the strongest correlation (0.54), with 1967-1968 and 1974-1975 being good examples of flood rich and severe years. All the sub-catchments have statistically significant trends between number of floods and Amax magnitude at the 95% level. The weakest relationship is at Warwick Bridge, where the largest floods occurred in years with few other floods (1967-1968, 1980-1981 and 2004-2005).

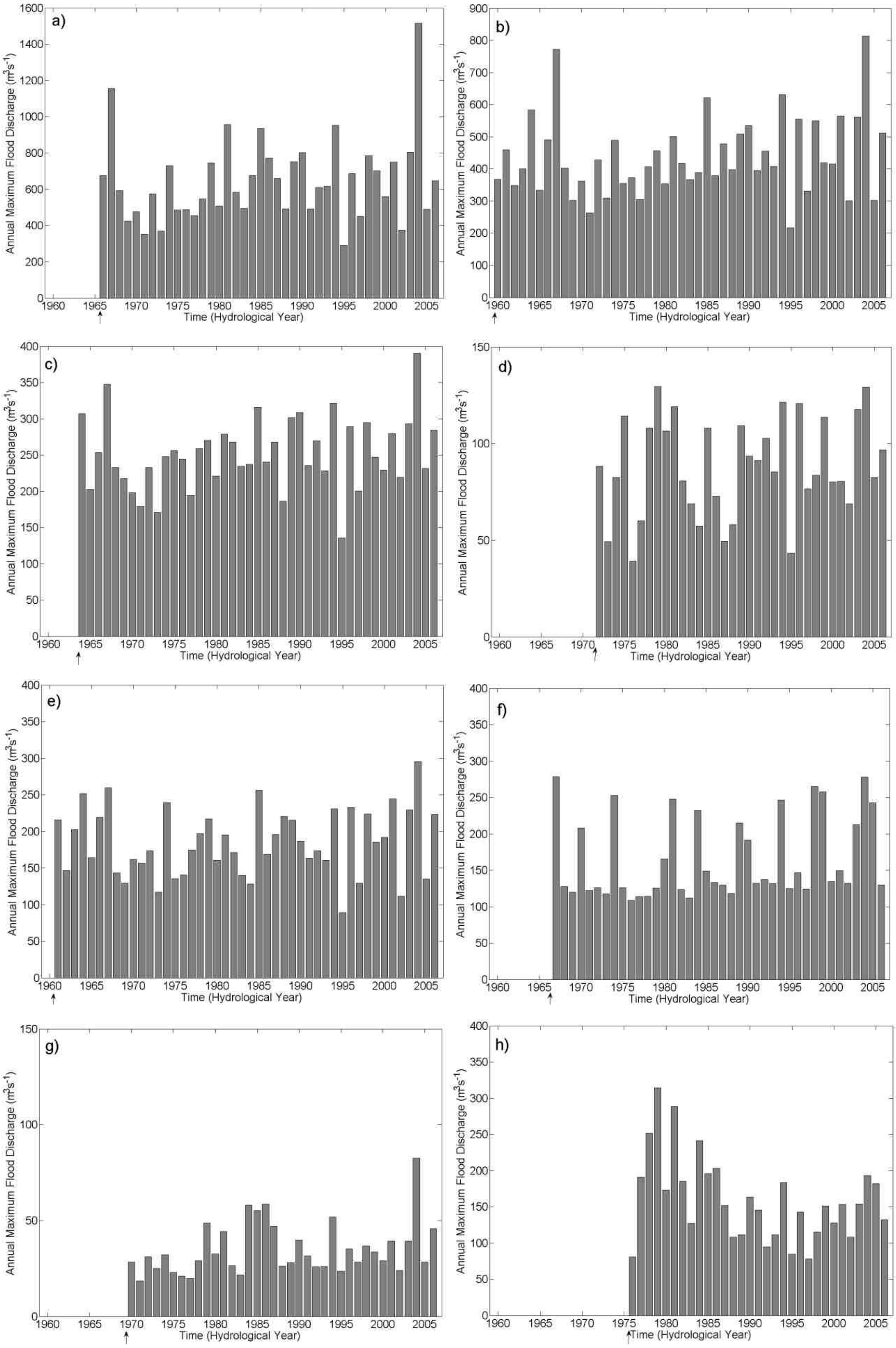


***Figure 4.15**. Amax floods for a) Lower Eden in Carlisle (Sheepmount) , b) Lower Eden (Warwick Bridge), c) Upper Eden (Temple Sowerby), d) Upper Eden (Kirkby Stephen), e) Eamont (Udford), f) Irthing (Greenholme), g) Petteril (Harraby Green), and h) Caldew (Cummersdale). Arrow shows start of record.*

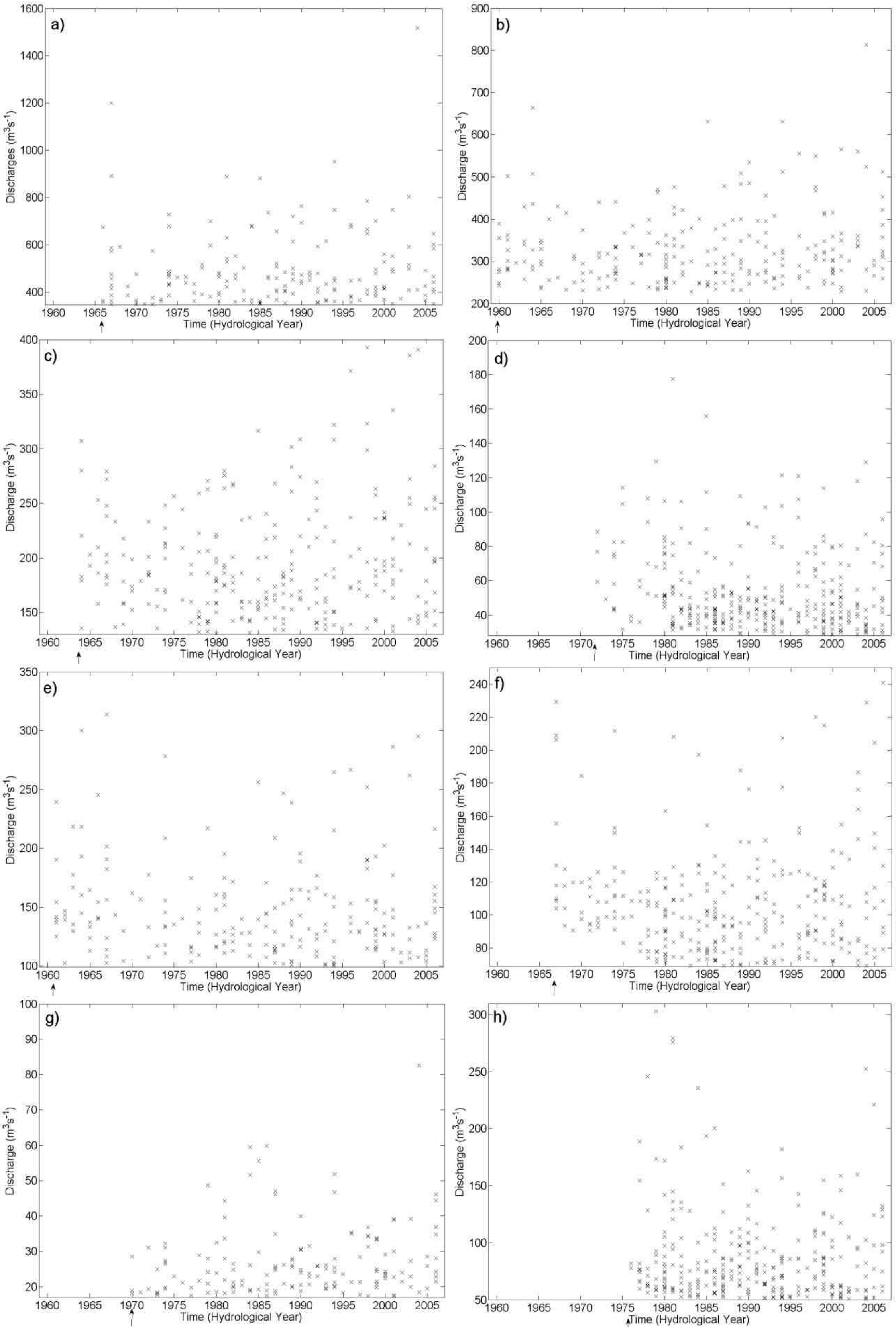


Figure 4.16. *Magnitude of the >Q1 flood events for a) Lower Eden in Carlisle (Sheepmount) , b) Lower Eden (Warwick Bridge), c) Upper Eden (Temple Sowerby), d) Upper Eden (Kirkby Stephen), e) Eamont (Udford), f) Irthing (Greenholme), g) Petteril (Harraby Green), and h) Caldew (Cummersdale). Arrow shows start of record.*

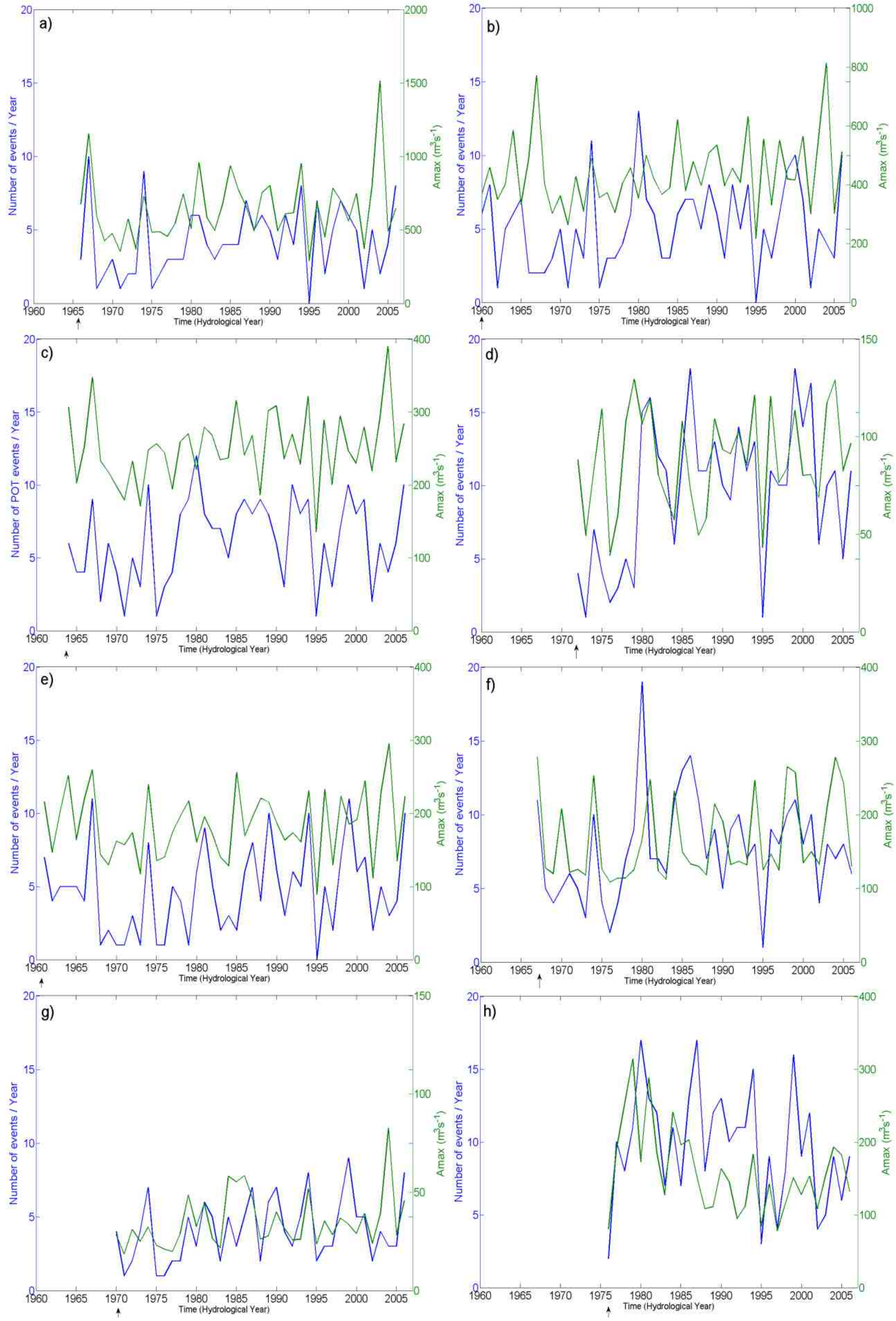


Figure 4.17. *Number of >Q1 flood events per hydrological year and the Amax series over time for each gauging station. a) Lower Eden in Carlisle (Sheepmount) , b) Lower Eden (Warwick Bridge), c) Upper Eden (Temple Sowerby), d) Upper Eden (Kirkby Stephen), e) Eamont (Udford), f) Irthing (Greenholme), g) Petteril (Harraby Green), and h) Caldew (Cummersdale). Arrows shows start of record.*

Gauging Station	Frequency-Magnitude Correlation
Sheepmount	0.47 (0.002)
Warwick Bridge	0.29 (0.05)
Temple Sowerby	0.39 (0.009)
Kirkby Stephen	0.37 (0.03)
Udford	0.54 (0.0001)
Greenholme	0.33 (0.04)
Harraby Green	0.40 (0.01)
Cummersdale	0.39 (0.03)

Table 4.5 *Correlation coefficients for each gauging station between Amax and Number of POT events per hydrological year. (significance p values in brackets)*

In summary, the trends in the number of floods occurring in the Eden catchment do not seem to change significantly over time, but some sub-catchments do experience more floods than others. The sub-catchments which experience the most floods are the Upper Eden at Kirkby Stephen, the Irthing at Greenholme and the Caldew at Cummersdale. There are also no strong trends over time in the Amax series for each of the gauging stations. Furthermore, there are no trends in the magnitudes of the POT events. However, the sub-catchments seem to be correlated highly with each other both in terms of flood frequency and flood magnitude per hydrological year.

4.5. Trends in flooding over different temporal scales at Carlisle

It is important to put the annual timescale patterns into the context of sub-annual and historical timescales. Firstly, seasonal patterns in flooding at Carlisle in the Eden catchment will be assessed. Secondly, a longer flood record will be assessed using documentary evidence outlined in Chapter 3.

4.5.1. Seasonal Patterns

Flooding in Britain is mainly a winter phenomenon, with Robson *et al.,* (1998) concluding that only one in every five floods occurs in summer, where Robson *et al.,* (1998) defined summer as May to October. Black and Werritty (1997) found that for northern Britain 78% of floods occurred between October and March. For the Eden, Smith and Tobin (1979) found that 92% of floods since 1800 in Carlisle have occurred between October and March, of which over half occurred in either December or January. Furthermore the highest magnitude floods were found to occur in winter. Possible explanations for this were the higher precipitation totals in winter, along with potential snowmelt floods, such as the 1925, 1947 and 1968 floods.

The 138 events which exceeded the threshold value of 347.0 m^3s^{-1} at Sheepmount since 1976 were analysed for any seasonal patterns and for comparison to the longer term study of Smith and Tobin (1979) outlined above. This threshold includes in-bank high floods as well as out of bank floods. Formal season definitions will be used here, with winter including the months of December, January and February, while summer is June through till August. Figure 4.18 shows the percentage of floods occurring in each month of the year. Most floods since 1976 have occurred in December (21.0%), closely followed by February (20.3%) and January (18.8%). This leads to a total of c.60% of floods occurring in winter (December-February). No floods have occurred in either April or June, while few have occurred in the other summer months. Only 2.2% of floods have been in summer (June-August), while 11.6% have occurred in spring (March-May) and 26% in autumn (September-November). In comparison to Smith and Tobin (1979) and Black and Werritty (1997), 94.2% of floods have occurred between October and March. Using the winter (November to April) / summer (May to October) classification of Robson *et al.*, (1998), 15.2% of floods have occurred in summer. These statistics indicate the Eden is typical of other British rivers, with the majority of floods occurring in winter, with a possible greater proportion of floods occurring between the months of December and February. This might be because of the Eden's geographical location in north west England, while other cited statistics were national or regional averages.

Smith and Tobin (1979) also stated that the highest magnitude floods occurred in winter. This is corroborated by using the POT series post 1976, where the floods were divided into three categories; large >600 m^3s^{-1}, medium 400-600 m^3s^{-1}, and small 347-400 m^3s^{-1}. Of the 138 floods, only 26 were considered to be large events, while 76 were medium-sized and 35 had a relatively small magnitude. Figure 4.19 shows that the highest magnitude floods are exclusive to the months between September and March, with significantly more large magnitude events occurring in January and February than the other months in winter and autumn. However, there is no significant difference between the percentages of floods in each month for different magnitude events.

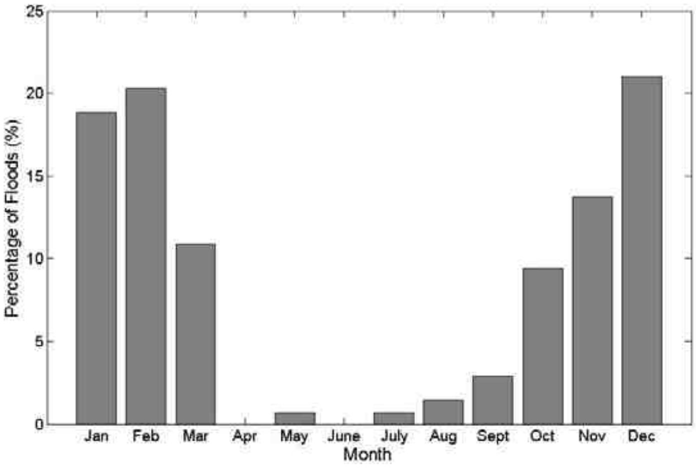


Figure 4.18 *Monthly distribution of floods at Carlisle since 1978.*

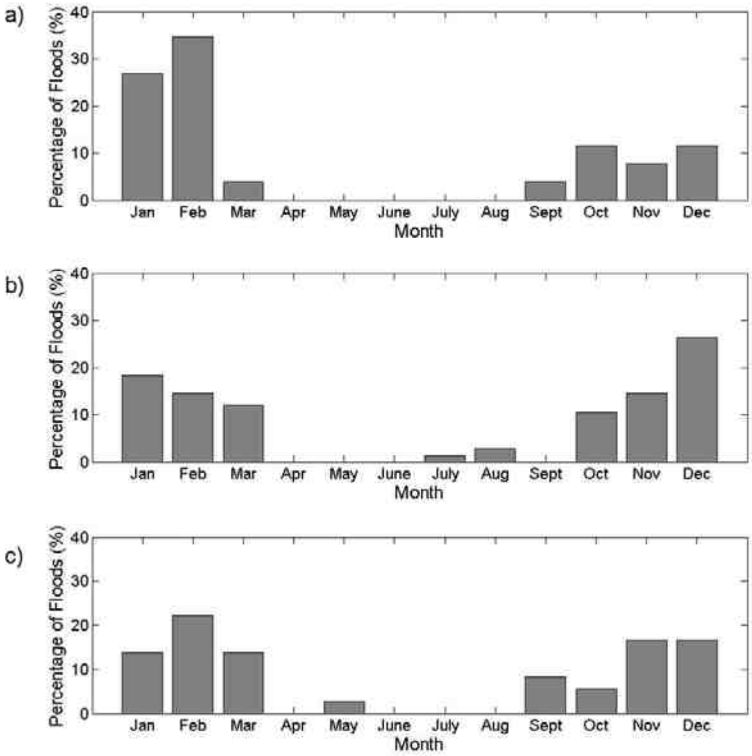


Figure 4.19 *Monthly distribution of floods at Carlisle since 1978 for a) large floods, b) medium floods, and c) small floods*

4.5.2. Historical Timescales (1770-2007)

Figure 4.20 shows the number of floods during each hydrological year since 1770. The definition of a flood for the historical period differs to the gauged record, as only out-of bank events are recorded in documentary evidence. The years with the most floods are 1877 and 1891, with five floods recorded in these years. The period before

1850 has very few floods, which is likely to be due to the lack of evidence for them occurring, rather than a lack of existence. However, it is assumed that the largest events have been recorded.

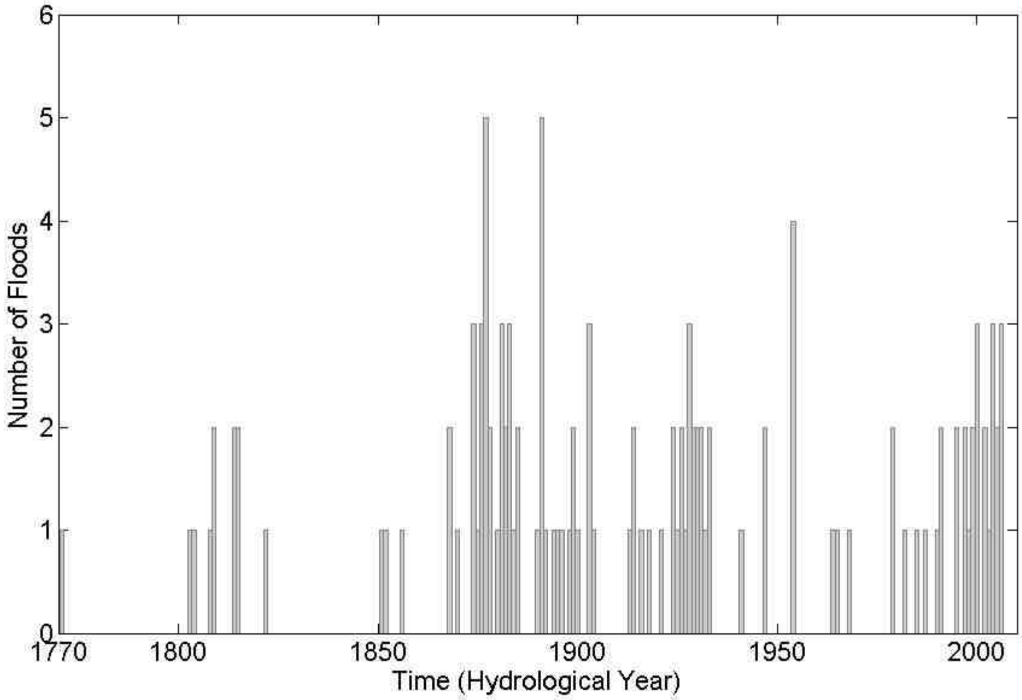


Figure 4.20 *Plot showing the number of floods per year since 1770.*

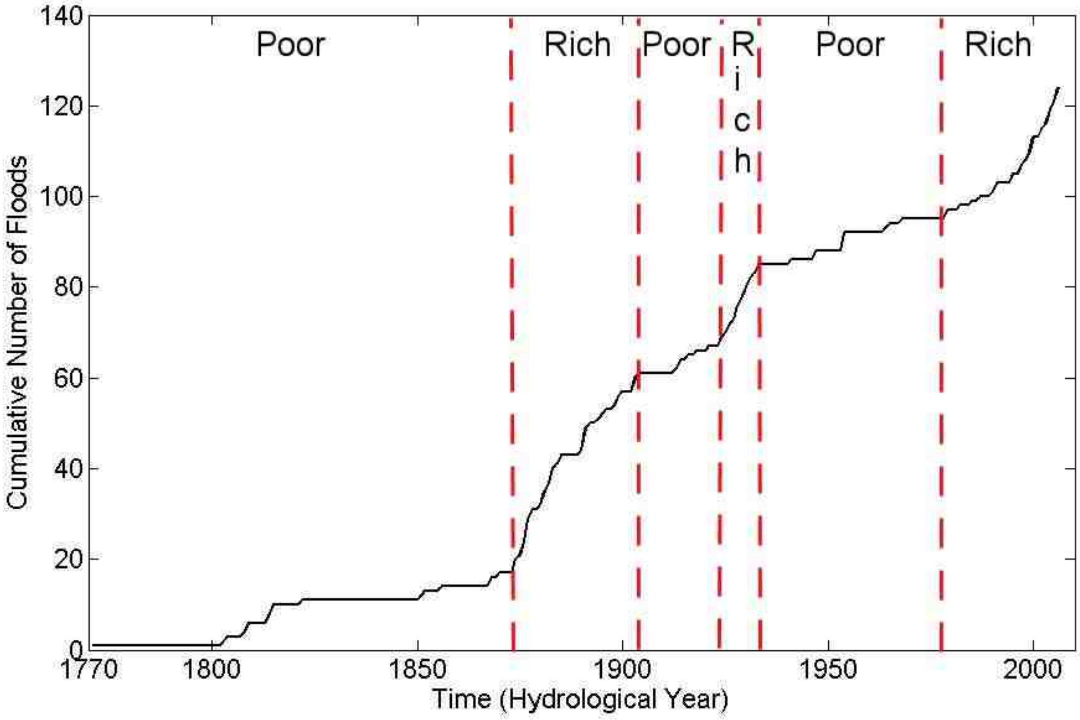


Figure 4.21 *Plot showing cumulative number of floods over time since 1770, with flood rich and flood poor period defined.*

It is clear that there have been periods that have been relatively more flood rich than others. The most recent two decades have experienced a clustering of flood events, but it is evident from this long term record that there have been other periods of flood clustering throughout the last 240 years. There is nothing unique or significant in terms of the 1990s and 2000s, which appear to be no different to other flood rich periods such as the 1920s and late 19th century.

Figure 4.21 shows the same data on a cumulative plot. The periods where the gradient of the line is steep indicate flood rich periods. Times when the line is flatter are flood poor. There have been three flood rich periods over the past 240 years: (1) 1873-1904; (2) 1923-1933; and (3) 1994-present, separated by periods which were relatively flood poor. Several other studies have identified flood rich and poor periods in historical flood records (Grew and Werritty, 1995; Werritty *et al.*, 2002; Macdonald, 2006; Macdonald *et al.*, 2006b; McEwen, 2006). These examples, along with the River Eden, indicate that there are flood clusters throughout the historical period. However, a conclusion from Macdonald (2006) was that these flood rich periods are not nationally synchronous, which indicates that regional climatic variability and catchment specific characteristics are important in controlling flooding frequency. This aspect of potential flood causing factors, focussing on the Eden catchment is expanded upon in Section 4.6.

The Environment Agency report (2006) assessed the 2005 flood within a longer timescale context (1770-present). Recent floods (post 1967) have been recorded at the Sheepmount gauging station in Carlisle. Floods before 1967 have been either recorded or estimated at Eden Bridge and then converted to an equivalent stage at Sheepmount, using rating relationships. Not all the floods from the long term flood record constructed above are included in this assessment of flood magnitude, but the largest floods are. Table 4.6 shows the 11 largest floods to have been recorded in the Eden catchment. The two largest floods have occurred in approximately the last 40 years (1968 and 2005). The January 2005 flood was the highest magnitude flood within the last 240 years. The peak stage was one metre higher than the previous largest flood to occur in Carlisle and is the only flood to exceed the bankfull height of 7 m at Sheepmount. The other 26 floods on Figure 4.22 are separated by only 0.84 m, which converts to a c.265 m^3s^{-1} difference in discharge, assuming the rating curve has stayed constant over the whole period. There is no pattern in the distribution of the flood magnitudes over time, indicating that there has been no trend in increasing flood magnitude at Carlisle over the 240 year timescale.

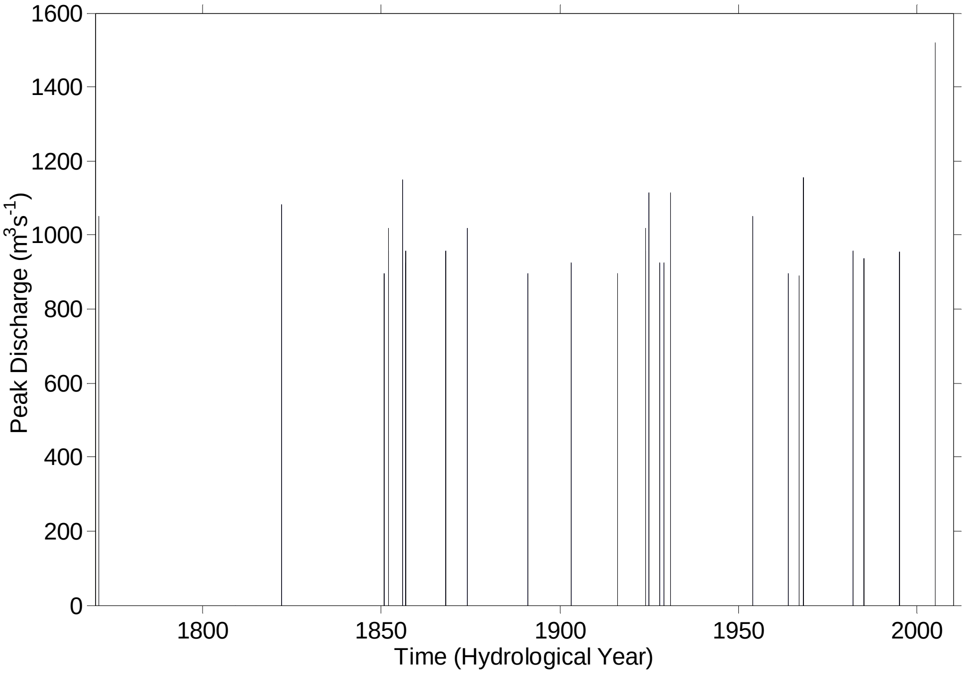


Figure 4.22. *Flood magnitude over time (discharge) (Environment Agency, 2006)*

Rank	Year	Stage (m)	Discharge (cumecs)
1	2005	7.23	1518.89
2	1968	6.2	1155.68
3	1856	6.18	1149.03
4=	1925	6.08	1116.04
4=	1931	6.08	1116.04
6=	1822	5.98	1083.44
6=	1771	5.88	1051.25
6=	1954	5.88	1051.25
9=	1852	5.78	1019.45
9=	1874	5.78	1019.45
9=	1924	5.78	1019.45

Table 4.6 *Largest 11 Floods over the past 200 years ranked by magnitude*

4.6. Possible causes of high river flow trends

Section 4.4 indicated that during the relatively short timescale of gauged data from the Eden catchment there are no significant trends in either flood frequency or magnitude, except for the occurrence of more floods in the last decade than what occurred in the 1970s. However the construction of a longer timescale flood record for Carlisle allowed the short term flood series to be put into a historical context. Section 4.5.2 and Figure 4.21 showed that there have been periods throughout the last 240 years that have been more flood rich, separated by periods which were relatively flood poor.

There are two main possible hypotheses as to why floods may cluster through time; (1) climate change / variability, and notably the frequency, magnitude and duration of extreme wet periods, are leading to a greater magnitude and/or frequency of hydrological extremes (Arnell, 2003); and (2) catchment-specific land use changes / management and how these change the relationship between extreme climate events and hydrological extremes (O'Connell *et al.,* 2007). The first of these will be assessed through looking at Lamb weather types. The land use hypothesis is far less likely to explain the clustering of floods in flood rich and poor periods. Furthermore, it is harder to test as changes are difficult to detect, and the influence of land use changes is far more uncertain. Therefore, the second hypothesis is not tested, but comments are made on the appropriateness of the two options for testing the impact of land use on flooding following what has been concluded from the trend analysis in this chapter, quasi-catchment experiments and numerical modelling.

4.6.1. Lamb Weather types

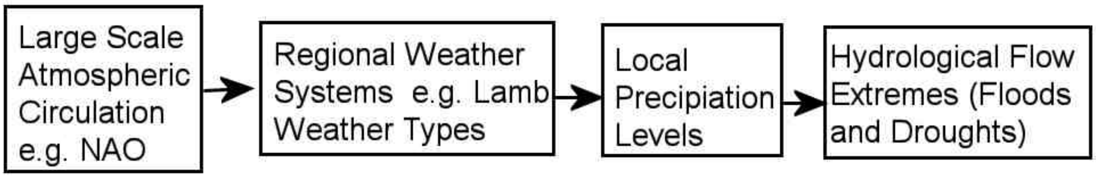
Weather System type describes the prevailing atmospheric pressure characteristics and hence indicates the presence and tracks of storms over the catchment and therefore where and when precipitation occurs. Hence, weather type encapsulates two variables: (1) propensity to rainfall; and (2) its space-time distribution, the latter being particularly important in large river catchments. This aspect was investigated through exploring the Lamb (1972) classified weather types which caused the floods in this period.

The UK's weather is determined by the position, origin and storm tracks of airmasses. Atmospheric circulation systems can be classified into categories (El Kadi and Smithson, 1992). In Europe the Grosswetterlagen system developed by Baur (1944) has 30 classes under three main headings of zonal (westerly), mixed and meridional (easterly). These have been used in many studies including Hess and Brezowsky (1977), Yarnal (1994) and Petrow *et al.,* (2007) to investigate the links between large scale atmospheric processes and regional weather and hydrology. In the UK Lamb (1950; 1972) developed a weather type classification, which extends from 1861 to 1971. This is based on a division by both synoptic pressure and direction of flow. This resulted in seven classes (Westerly, North-Westerly, North-Easterly, Easterly, Southerly and Anti-cyclonic and Cyclonic) which were representative of weather systems over the whole of the UK. This subjective classification which relied on an expert basing a decision on a synoptic chart was developed further by Jenkinson and Collinson (1977) to make the classification more objective. It has now been applied from 1881 to the present day. It is based upon the daily mean sea level pressure, which is used to indicate wind flow direction, shear vorticity and flow strength (Jones *et al.,* 1993). The Objective Jenkinson classification has 27 classes, sub-divided by direction (N, NE, E. SE, S, SW, W, NW), non-direction (Cyclonic, Anticyclonic), combined complex hybrid types (CN, CNE, CE. CSE, CS, CSW, CW, CNW, AN, ANE, AE. ASE, AS, ASW, AW, ANW) and unclassifiable (U). Jones *et al.*, (1993) found a strong correlation between the Lamb classification and the Objective Jenkinson classification.

There are several advantages to using a weather type classification to investigate multivariate climatological factors: (1) the classes are simple and easy to use; (2) the length of the record allows for long term trends to be investigated; and (3) they are based on physical linkages between the climate (large scale processes) and weather patterns (local scale).

However there are several limitations in the use of these classifications (O’Hare and Sweeney, 1993). First, there is an issue regarding the balance between number of classes and ease of use. The seven Lamb weather types were thought to be too simplistic, so Jenkinson and Collinson (1977) added another 20 classes. This allowed the UK weather to be better represented but made the system more complex and harder to use. Second, some days experience multiple weather types, making them difficult to classify. The Objective Jenkinson system has an unclassified category, but this provides no information on the specific weather types experienced. Third, the UK also experiences different weather types in different regions. Questions have been raised over how representative of UK weather types these classifications are of the UK as a whole. Fourth, the Lamb weather type classification is subjective, although the changes made by Jenkinson and Collinson (1977) have made it more objective. However Yarnal and White (1987) suggest that there are still problems in the use of objective classifications. Fifth, there are problems associated with the assigning a daily weather type, when climatological variables do not operate on daily timescales. Sixth, the relationship between weather type and rainfall totals is not always reliable and it has changed over the timescale of the record. Seventh, the classifications indicate direction of origin but not the specific region, which may differ considerable in their characteristics, including tropical, maritime, continental air masses. Also air masses from the same origin have different characteristics at different times of the year. Eighth, weather type classifications indicate large scale synoptic atmospheric processes and lack detail on meso-scale frontal and orographic systems, which cause a lot of the UK precipitation. Finally, the weather system classification scheme is inherently autocorrelated, as when one weather type becomes more frequent, others have to decrease in their occurrence.

Lawler *et al.*, (2003) introduced the concept of the “chain of causality”, which links large scale atmospheric circulations to regional weather systems and rainfall patterns and finally to hydrological effects.



Many studies have looked at different parts of this chain, but few have investigated the full sequence of processes at different spatial and temporal scales. What follows is a review of the existing literature on the individual processes, starting at the largest spatial and temporal scales and downscaling to more local and specific examples.

First, the link between weather types and larger scale atmospheric processes and circulations will be addressed. For the UK, one of the most significant large scale atmospheric circulation indices is thought to be the North Atlantic Oscillation Index

(Kingston *et al.*, 2006). This is a measure of the pressure gradient between the Icelandic Low and the Azores High (Hurrell and Van Loon, 1997). It is often used as a measure of westerly weather systems over the UK and it has been found that Lamb weather types correlate well with the NAO, especially Anti-Cyclonic and Westerly weather types (Jones *et al.*, 1997). There have been four main phases of the NAO from the pre-20th century to the present day: (1) pre-20th century when the NAO was near zero; (2) 1900-1930 when the NAO had a strong positive phase; (3) 1930-1960s when the NAO had a low positive index; and (4) 1960s to present when the NAO had a strong positive index (Wilby *et al.*, 1997). These changes will be compared to the changes in weather types and flood frequency in this study. Hurrell (1995) found links between shifts in the NAO and changes in UK temperatures and precipitation totals. Fowler and Kilsby (2002a) found a positive correlation between the NAO and the precipitation quantities in the west of the UK and a negative correlation in the east. However, the relationship does not seem to be that simple, with Wedgbrow (2002) finding a lag between the changing NAO index and the change in UK weather. This was hypothesised to be caused by either climatological memory effects, such as seasonal patterns, or hydrological memory effects, for example groundwater levels or antecedent moisture levels. Along with the weather type classifications, this index also has limitations for its use, as it represents complex multivariate interrelationships very simply (Kingston *et al.*, 2006).

The link between weather type classifications and precipitation quantity has also been intensely studied. Lane (2003) highlighted the timing of precipitation over different parts of the catchment is also influenced by the direction of the weather system, leading to varying sub-catchment hydrological responses. Stone (1983a; 1983b) found an association between high precipitation levels and Cyclonic, Cyclonic-Westerly and Westerly weather types for England. Sweeney and O’Hare (1992) found that the greatest daily rainfall totals are for the Cyclonic South-Westerly (4.9mm), Cyclonic-South (4.7mm) and South-Westerly (4.6mm) weather systems (Figure 5.23).

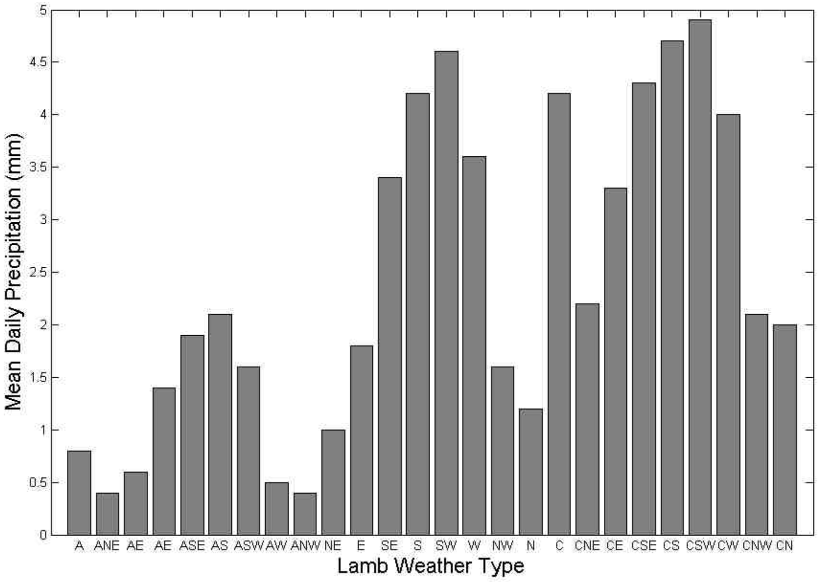


Figure 4.23 *Mean daily precipitation for different Lamb weather types (Sweeney and O'Hare, 1992)*

Malby *et al.*, (2007) used the original Lamb weather type classification and for two sites in the Eden catchment found that easterly and north-easterly weather systems contributed only a small percentage of the precipitation over the last 30 years. The south-westerly and westerly weather systems contributed the most to the decadal precipitation totals. Also, it is clear from Figure 4.24 that the percentage of winter rainfall delivered by these weather systems has increased over the last 30 years. Table 3 from Malby *et al.*, (2007) has been plotted as Figure 4.25. This shows that the precipitation associated with each westerly weather system has increased between the 1970s and the 1990s for five rainfall gauging stations in the Eden catchment. The quantity of rainfall supplied by south-westerly weather systems was highest in the 1980s.

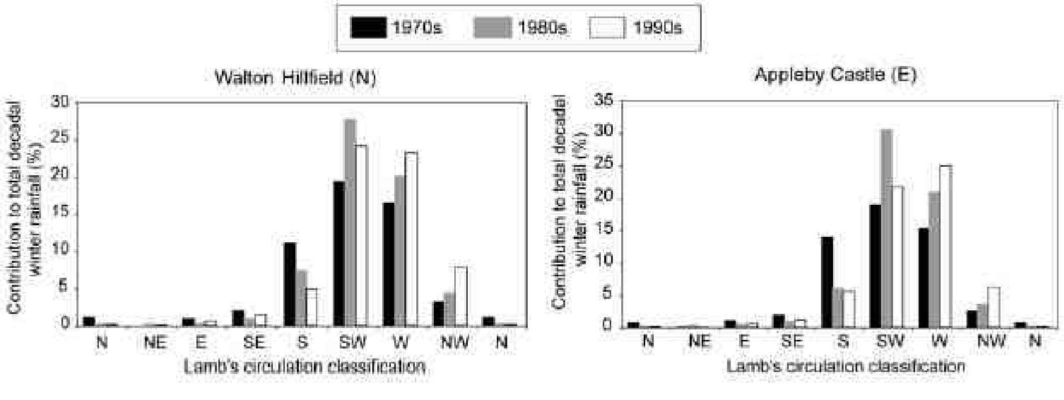


Figure 4.24 *Contribution of rain bearing circulation types to decadal winter rainfall for two raingauges in Eden catchment. (Malby et al., 2007)*

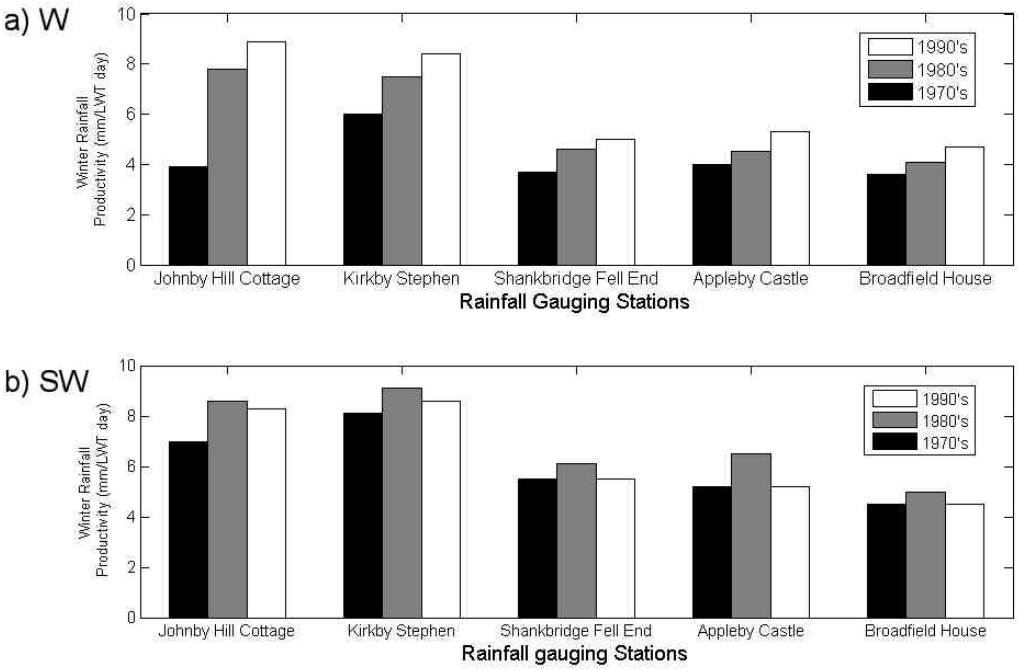


Figure 4.25 *Winter precipitation productivity of Lamb defined weather advection types (adapted from Malby et al., 2007)*

The link between weather systems and hydrological flows, particularly extremes (floods and droughts) has been investigated by a few studies. Knox (1993) was one of the first studies to look at the links between weather types and flood frequency in America. Higgs (1987) investigated the link between weather types and floods for the River Severn at Bewdley, using the 101 year record. Zonal (Westerly) weather systems were found to be associated with the highest magnitude floods. Rumsby and Macklin (1994) studied the flooding frequency and magnitude of the River Tyne, considering weather types as a controlling factor. Major floods were found to be linked to meridional circulation (easterly weather types), while more moderate floods occurred in periods when zonal weather systems dominated (westerlies). A possible explanation for this was through the high amplitude waves associated with meridional circulations, which are linked to situations when high pressure cause blocking of depressions, leading to long duration, high intensity precipitation. A further study by Rumsby and Macklin (1996) compared the western Severn catchment, with the eastern Tyne catchment. The west of England is more susceptible to zonal precipitation (westerlies), while the north-east of England is in the rainshadow of the Pennines, so receives more precipitation from meridional (easterly) weather systems which absorb moisture over the North Sea.

Grew (1996) used daily weather system classifications, unlike the previous studies which used monthly or annual categories, for 130 POT series in Scotland. Cyclonic, Westerly and South-Westerly weather systems were found to trigger flood events in Scotland. A similar approach was taken by Longfield and Macklin (1999) for the River Ouse in Yorkshire. Westerly, Cyclonic, Cyclonic Westerly and South-Westerly weather systems were found to have caused 79.7% of the floods in the flood record since 1875. One of the main conclusions from Grew (1996) was that there is no simple relationship between weather systems and increased flooding, as it depends upon the location of the catchment.

Weather type classifications have also been used to explain drought occurrence (Stahl and Demuth, 1999; Fowler and Kilsby, 2002b). A prolonged period of anti-cyclonic atmospheric circulation contributes to low river flows (Wilby et al., 1994). This is because anti-cyclones are high pressure systems which have low moisture contents and also block the path of depressions which bring precipitation. Fowler and Kilsby (2002b) found that eastern England droughts often occur during E and CE weather types, while on the west of England, W and CW lead to droughts developing. The 1995/1996 Yorkshire drought coincided with a 28.4% and 17.7& increase in easterly and anti-cyclonic weather systems respectively. Furthermore, there was a 15.3% decrease in the occurrence of westerly weather types. Fowler and Kilsby (2002b) also highlighted the importance of the sequencing and persistence of particular weather types in the formation of droughts.

4.6.2. Weather types for instrumented period floods

Using the Objective Jenkinson Weather Types, downloaded from www.cru.uea.ac.uk/cru/data/lwt, it was found that 13 of the 25 types have caused floods in the last 30 years in the Eden catchment, of which 5 (Cyclonic =31.8%, Westerly =18.1%, South Westerly =16.7%, Cyclonic South Westerly =10.9, Cyclonic Westerly =12.3%) accounted for 89.9% of the floods. This is similar to the results of Longfield and Macklin (1999) found for the Yorkshire Ouse Catchment, where four circulation types (W, C, CW and SW) accounted for 79.7% of all events. These particular weather types highlight the importance of both cyclonic weather types and weather systems from a westerly and south-westerly direction to floods occurring in Carlisle. Cyclonic weather systems are likely to cover a greater spatial area and lead to a more coherent catchment response. Sweeney and O'Hare (1992) estimated that the average daily rainfall total on a day with a cyclonic weather system was 4.2 mm, the joint fifth highest weather type for rainfall quantity. Rumsby and Macklin (1996) and Malby *et al.,* (2007) highlighted the importance of westerly weather systems for catchments on the west of the UK. The importance of westerly and south westerly weather types might be due to the weather system passing across the Atlantic Ocean, increasing in moisture content, then depositing precipitation on the West of Britain, including the Eden catchment. Sweeney and O'Hare (1992) estimated that cyclonic south westerly systems had the highest propensity and quantity of precipitation; 4.9mm per day on average. Cyclonic westerlies also produced more than 4mm of rainfall per day on average. Figure 4.26 shows that the other Lamb weather types are insignificant in causing floods, with only 14 floods being caused by the other 20 weather types.

Figure 4.27 shows that the number of weather types causing floods has decreased from the late 1970s/early 1980s where 13 types caused floods, while in the 1988-1997 and 1998-2007 decades only 6 and 8 weather types caused floods respectively. The five weather types, identified as flood generating weather types in the Eden account for a greater proportion of the floods since the late 1980s, with 79.5% of floods occurring on days with these weather types in the first decade (1978-1987) and 98.0% and 91.1% in the 1988-1997 and 1998-2007 periods respectively. There has been an increase in the number of floods occurring during cyclonic synoptic events, from 51.3% and 52.1% in the first two decades respectively to 68.8% in the last decade. The proportion of floods occurring due to weather systems from a westerly / south-westerly direction increased in the 1987-1997 period from 48.7% in the first period and 51.1% in the last period to 73.0%.

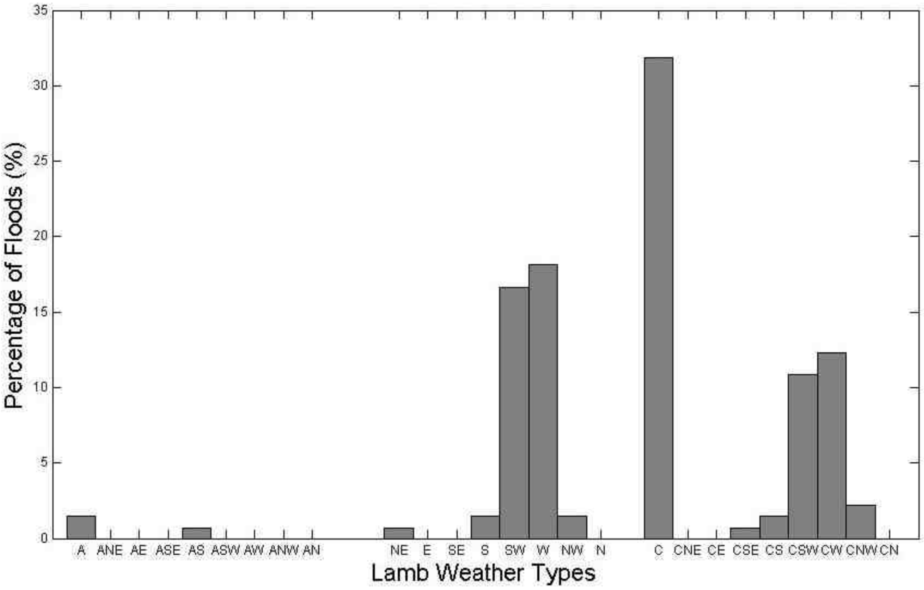


Figure 4.26 *Percentage of floods since 1978 which have occurred on days of particular Lamb weather types.*

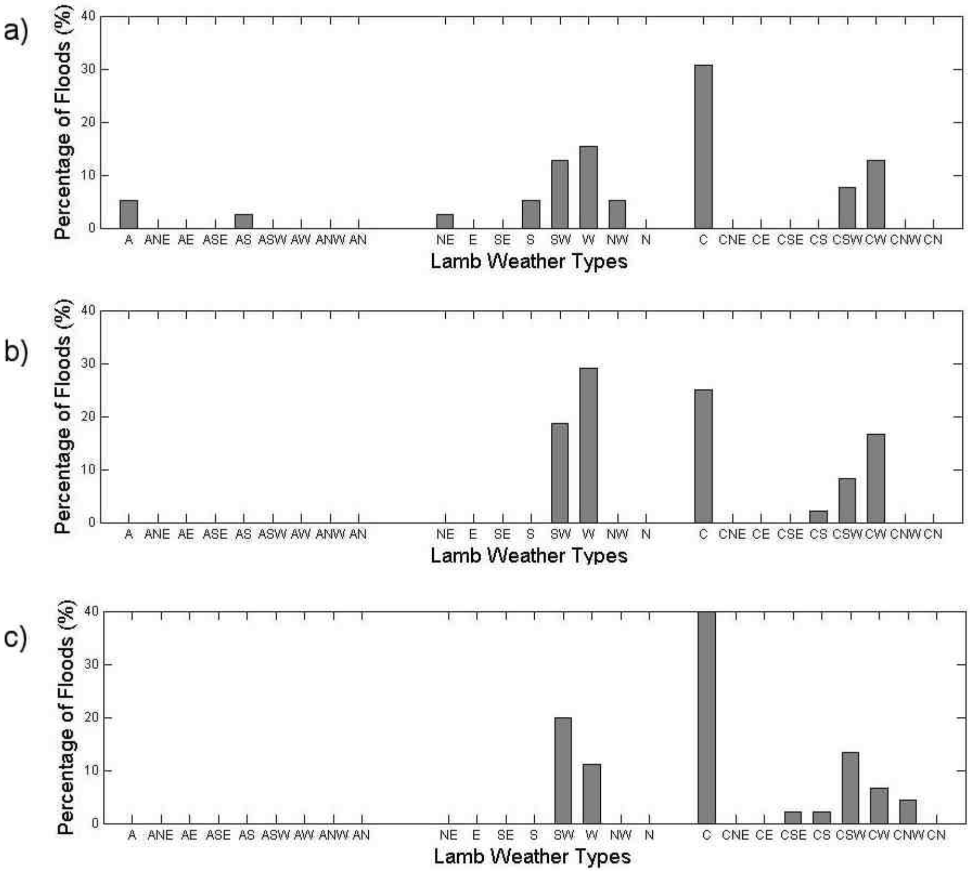


Figure 4.27 *Percentage of floods since 1978 which have occurred on days of particular Lamb weather types. a) 1978-1987; b) 1988-1997; c) 1998-2007*

Figure 4.28 shows that for small, medium and large floods, weather systems from a westerly or south-westerly direction and cyclonic were always important. The five flood generating weather types were most important for moderate (93.5%) and small (88.9%) floods, while they only explained 80.7% of larger floods. This might be because larger floods are caused over multiple days and therefore the weather type chosen to represent the day of the flood might not have been the causing weather system. Cyclonic weather types were most important for moderate flood events, accounting for 64.5% of medium floods since 1976. Anti-cyclonic systems have only caused a few small floods over the past 30 years. Longfield and Macklin (1999) also assessed the influence of Lamb weather types on flood magnitude. For the Ouse, it was found that westerly and cyclonic weather systems dominated all magnitude floods, with westerly systems being more dominant for moderate floods, while cyclonic systems were most important for the highest magnitude floods. The weather type on the day of the January 2005 flood event was Cyclonic Westerly.

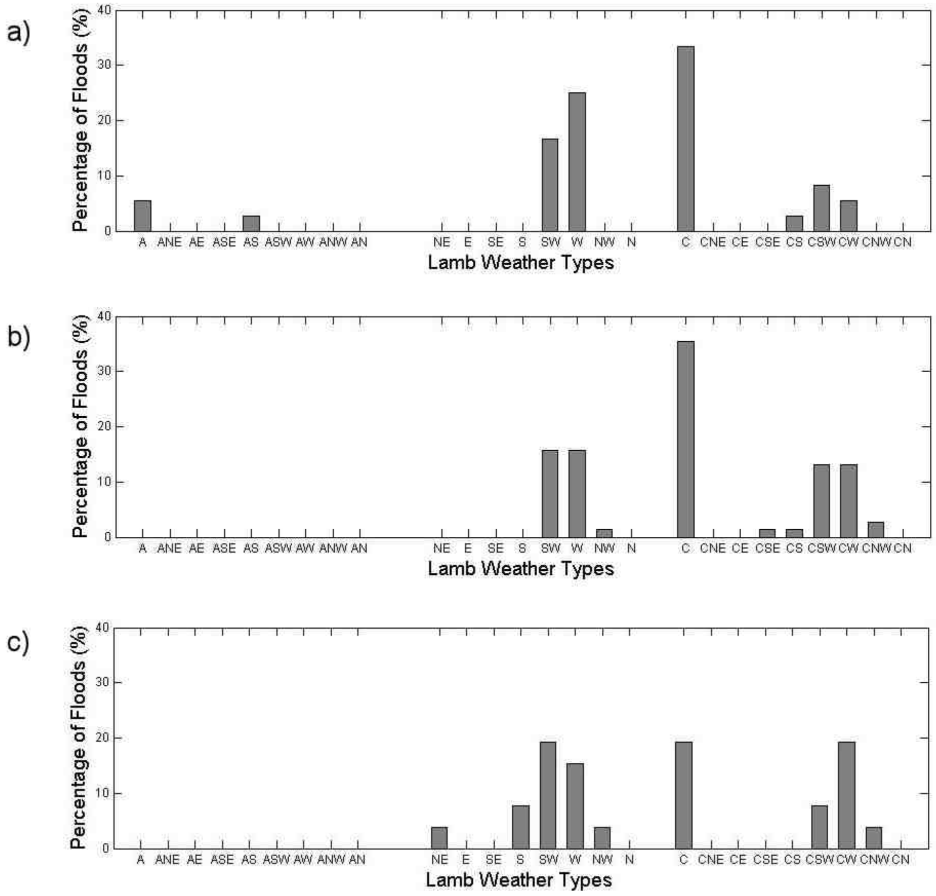


Figure 4.28 *Percentage of floods since 1978 which have occurred on days of particular Lamb weather types. a) Small floods (300 m^3s^{-1}); b) Medium floods (400-600 m^3s^{-1}); c) Large floods (>600 m^3s^{-1})*

As the Eden is quite a large catchment (2400 km^2), the number of days of precipitation that result in a flood downstream may be more than just the day of the flood. Grew (1996) stated that the number of days of precipitation is dependent upon the specific catchment characteristics, including area and gradient. Longfield and Macklin (1999) devised a method using daily rainfall records to assess the number of days responsible for flood generation. The previous four days were included and each day given a weighting dependent upon the amount of rainfall. The Lamb weather type on the day with the most rainfall was taken as the dominant synoptic system that caused each flood. However, this approach removes important information about the antecedent conditions in the catchment and the sequencing of weather types. In this thesis, the weather types on the previous two days as well the day of the flood are assessed. First, each day will be looked at separately; and second, the sequence of days will be investigated.

Figure 4.29 indicates that the most common weather types on the two preceding days are the same as the most common on the day of the flood itself. However, while cyclonic weather systems are the most common on the day of the flood, weather systems from a south-westerly (36% on previous day, 22% on two days before flood) and westerly (25% on previous day, 22% on two days before flood) direction are the most common on the two preceding days. Cyclonic weather systems are less common on the days previous to a flood occurring (11% on previous day, 10% on two days before flood). Furthermore, cyclonic weather systems from a westerly and south-westerly direction are also less common on the days prior to a flood.

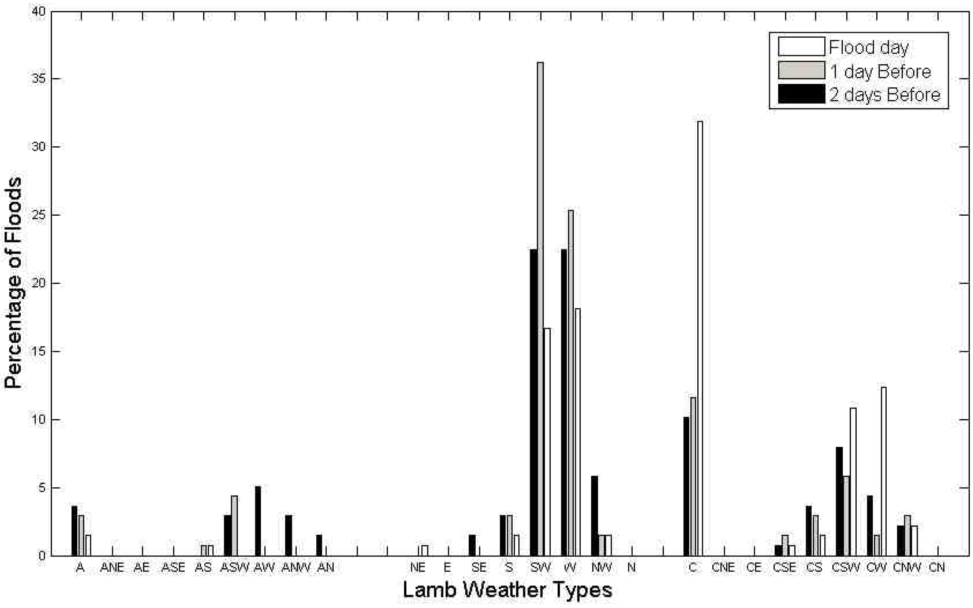


***Figure 4.29**. Percentage of floods which have occurred on days and preceding days of particular Lamb weather types*

The sequencing of the weather types is also important in causing downstream flooding, as they control the antecedent conditions of the catchment. This is assessed in terms of whether or not the previous two days and the day of the flood were classified as a flood generating weather type (C, W, SW, CW, and CSW). Table 4.7 shows that over half of the floods since 1978 have had flood generating weather types on both the day of the flood and the previous two days, while a further 23.2% of floods occurred on days with both the day of the flood and the day before classified as a flood generating weather type. Only 8 floods occurred on days classified as a flood generating weather type, but neither of the previous two days were. Three of floods since 1978 occurred on days when none of the days investigated were classified as any of the flood generating weather types.

Sequence	% of floods
1 1 1	51.4
1 1 0	23.2
1 0 0	5.8
1 0 1	9.4
0 1 1	3.6
0 1 0	1.4
0 0 1	2.9
0 0 0	2.2

***Table 4.7**. Percentage of floods of each sequence of flood generating weather types*
1 = flood generating weather type (C, W, SW, CW, CSW)
0 = day with another weather type

However, even though Figure 4.26 shows that the most floods occur on days which are classified as the UK experiencing a cyclonic weather type, this takes no account for the proportion of the year associated with each weather type. Therefore Figure 4.30 shows the percentage of the (a) whole 1880-2007, and (b) 1978-2007 periods classified as each weather type. Similar patterns are shown between the whole period and the gauged period studied above. Anti-cyclonic and cyclonic weather systems dominate, accounting for 20.7% and 13.8% respectively for the whole period and 21.1% and 13.0% respectively of the last 30 years. Weather systems from a south-westerly and westerly direction also are important individually, as well as for anti-cyclones and cyclones.

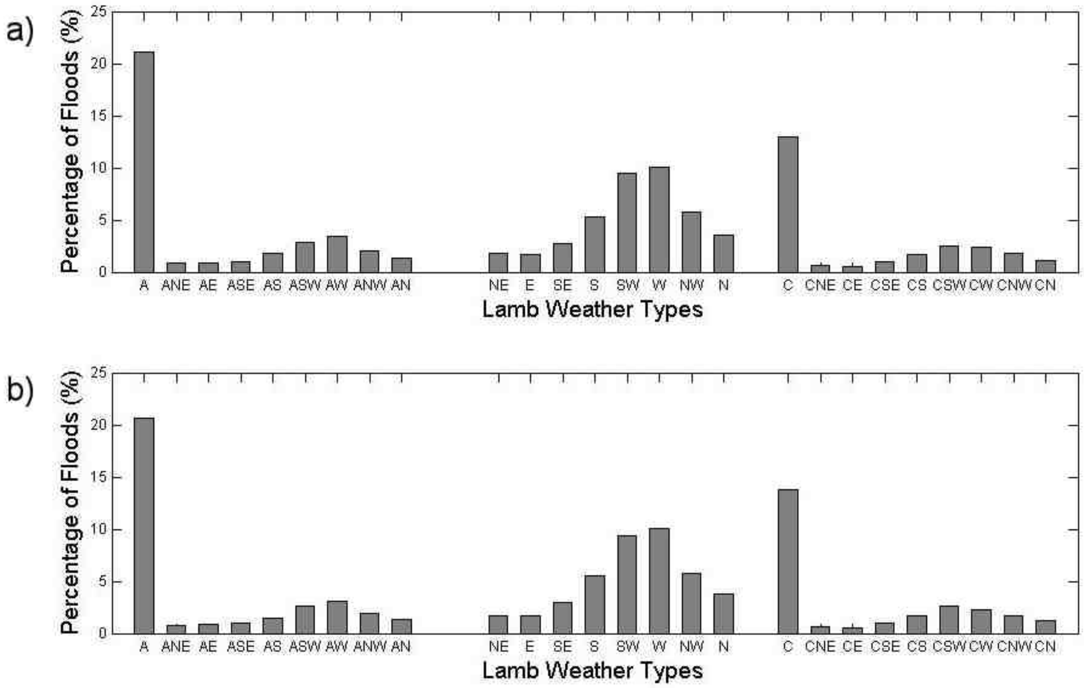


Figure 4.30 *Percentage of the year classified as each Lamb weather type. a) 1978 2007, b) 1880-2007*

The likelihood of a particular weather system causing a flood can be determined by dividing the number of floods occurring on days of a particular weather type by the total number of days of the same weather type over the same period. Figure 4.31 shows that the most likely weather type to cause a flood in Carlisle is the Cyclonic Westerly, with a 1.6% chance of a flood occurring on a day with this weather system over the UK. This is because it is the least common of the flood generating weather types over the 30 year period in terms of occurrence, but has still caused 17 floods. Cyclonic synoptic events have a 0.7% chance of leading to a flood occurring, as although most floods occur on cyclonic days, these weather systems occur most often, meaning that a greater proportion of cyclonic days do not lead to flooding. When cyclones are combined with a south-westerly or westerly direction then flooding in the Eden catchment is most likely.

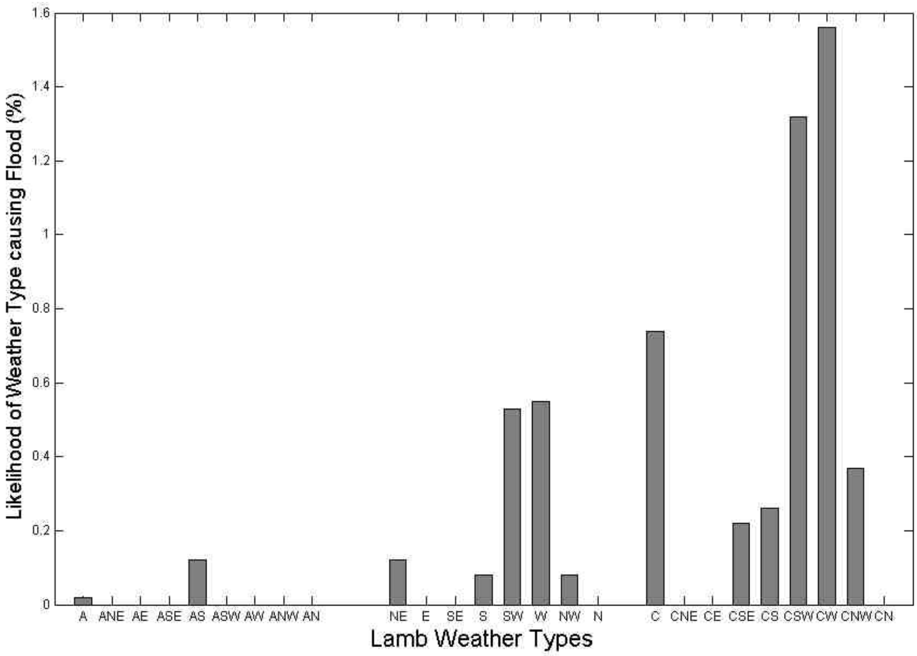


Figure 4.31 *Probability that a day with a particular Lamb weather type will also have a flood occurring.*

The correlations between the proportion of the year of certain weather types and the frequency and magnitude of floods are shown in Table 4.8. The five flood generating weather types identified are significantly correlated with the number of floods occurring in each hydrological year, whereby as the proportion of the year of these five weather types increases, the number of floods increases. However, as Figure 4.32 shows this relationship has considerable scatter. The correlations between the individual flood generating weather types do not have significant relationships with either series since 1966. This indicates that there must be other factors other than the weather system influencing floods, although from the above analysis there does seem to be some link between Lamb weather types and flood frequency, but less so with flood magnitude.

	Number of floods exceeding Q1	**Amax**
CW %	0.14	0.21
CSW %	0.23	0.19
C %	0.05	-0.10
W %	0.15	0.12
SW %	0.13	0.16
All	0.31 (0.0521)	0.18

Table 4.8 *Correlation coefficients of proportion of the year as each weather type and the >Q1 and Amax series from 1978-2007. Shaded cells indicate statistically significant results at the 95% level)*

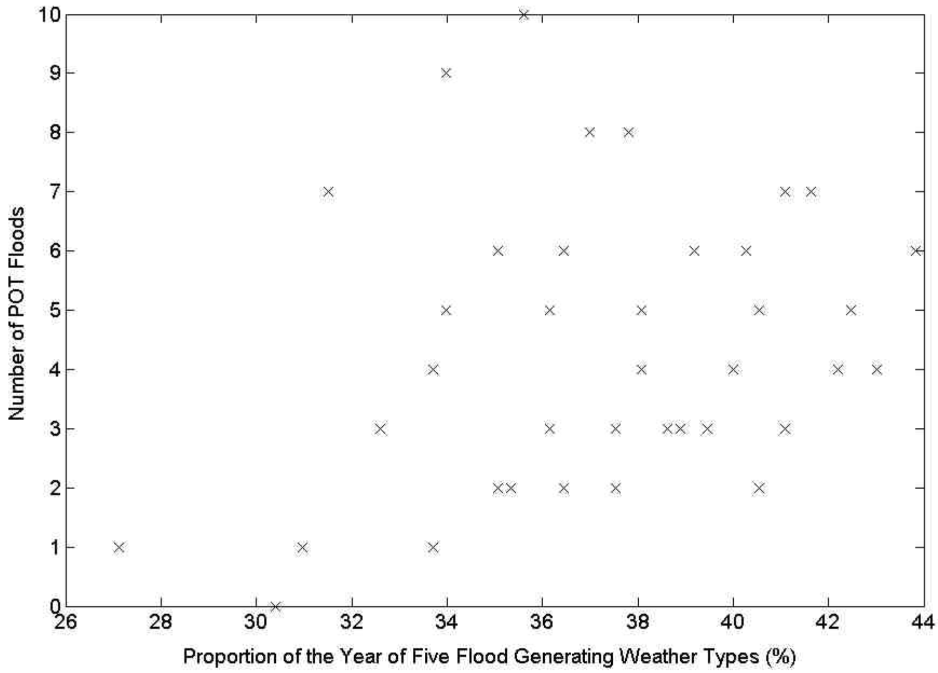


Figure 4.32 *Plot of Number of POT flood events against the proportion of the year classified as the five flood generating weather types.*

4.6.3. Weather types for the Historical Period

The relationship between weather systems and flood frequency will now be investigated over a longer timescale, using the historical flood record constructed in Section 4.5.2. This assumes that the weather types that cause flooding have not changed over time. A few previous studies have looked into how weather type frequency has changed over approximately the last 100 years (Lamb, 1972; Jones and Kelly, 1982; Briffa, 1990; Sweeney and O'Hare, 1992). Many of these investigations reported a decrease in the number of westerly days since the 1950s, while cyclonic and anti-cyclonic weather systems have become more common since the 1980s.

The methodology used to do this consisted of the following steps. First, the Lamb Weather Type dataset was sourced, which starts in 1880 and continues to the present day, then the percentage of each hydrological year for the five flood generating weather types were calculated, both individually and combined. The average of the 1880-2007 period was calculated, then the average was subtracted from each hydrological year. This meant that positive values represented years which had a greater than the average proportion of the year of these five weather types, while negative values had less than the average. The cumulative was then calculated for the deviations from the average. The cumulative deviation is plotted through time in Figure 4.33. The positive gradient sections of the graph show periods where the proportion of the year of the five flood generating weather types were greater than the average, while the negative gradient sections indicate periods where less than the average proportion of the year were the identified flood generating weather types.

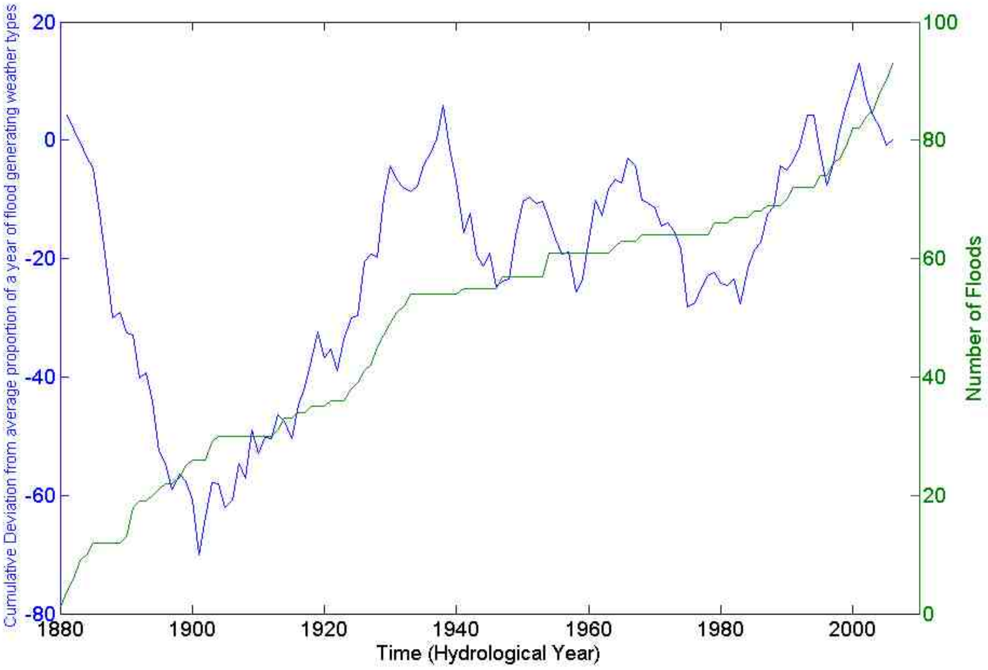


Figure 4.33 *Plot showing how the proportion of the year classified as the five flood generating weather types and flood frequency have changed over time.*

There are two main periods where the proportion of the hydrological year with the identified flood generating weather types is greater than the average; 1902-1938; and 1983-Present day. These two periods match the Wilby et al (1997) classification of the NAO being strongly positive. Jones et al (1997) found a strong correlation between the NAO index and westerly weather systems, which is one of the flood generating weather types. Also in the period between these two periods there were a few short fluctuations, with the period from 1958 to 1966 also having a greater than the average proportion of the year of the flood generating weather types. Between 1880 and 1902, the proportion of the year of these five weather systems was significantly less than the average for a sustained period, with only minor fluctuations.

Also plotted on Figure 4.33 is the historical flood record. The periods which were classified as being flood rich in Section 4.5.2 occur during the periods where the proportion of the year of the five flood generating weather types is greater than the average. The period from 1880-1904 was classified as being flood poor and the proportion of the year classified as one of the five flood generating weather types was significantly below average. The 1923-1933 flood rich period is within the first period when the flood generating weather systems increase, although there is a lag between the proportion of the year of the flood generating weather types increasing and the flood frequency increasing. This might be caused by the Lamb weather type classification missing some climatic signals, such as precipitation intensity or quantity, as it is only a broad categorical system. This happens again for the most recent flood rich period which was defined as starting in 1994, while the flood generating weather types have increased since 1983. This lag time has also been observed between the shift to a strong positive NAO and an increase in flooding (Wedgebrow, 2002). A hydrological memory effect was hypothesised to explain this lag, potentially groundwater stores or antecedent conditions.

The correlations between the proportion of the year classified as the flood generating weather types and flood frequency over the longer historical period are shown in Table 4.9. Only the westerly weather type correlation is statistically significant. This indicates that some weather systems are more important than others within the five classified as flood producing weather types. This will be investigated further by looking at how the proportion of the year of the individual five weather types change over the last 130 years.

	POT
CW %	0.032
CSW %	0.146
C %	0.064
W %	-0.205 (0.0212)
SW %	0.130
All	0.049

Table 4.9 *Correlation coefficients of proportion of the year as each weather type and the POT from 1880-2007.*

Figure 4.34 shows the how the individual weather types proportion of the year change over time. Firstly, the Cyclonic-Westerly (a) weather system does not vary significantly from the average, with only a range of 4.9% (0.6% to 5.5%). Also periods with more Cyclonic-Westerly weather systems do not correlate well with the periods of increased flood activity in the Eden. The Cyclonic South-Westerly (b) weather type varies by 4.7% (0.6% to 5.2%) and seems to match the flood rich and flood poor periods visually quite well. Pre-1918, the proportion of the year classified as a Cyclonic South-Westerly weather type decreased, while flooding had a low frequency. Between 1919 and 1955, the proportion of the year categorised a Cyclonic South-Westerly increased, which occurred simultaneously with the 1923-1933 flood rich period. Since the mid-1950s to the present day, the proportion of Cyclonic South-Westerly per year has stayed quite constant, although there has been a slight increase since the mid-1980s. The Cyclonic (c) weather system has varied by 17.8% (5.5% to 23.3%) in terms of the proportion of the year classified as this weather type over the last 130 years. During the pre-1923 flood poor period, this weather type was decreasing in terms of the proportion of the year classified as it. It then increased during the 1923-1933 flood rich period. It has also increased since the mid-1970s, although specific years have had less than the average proportion of the year classified as cyclonic. The Westerly (d) weather system has varied by 9.6% (5.2% to 14.8%) throughout the whole period. This weather system does not seem to match the flood rich periods well, with a decline in the proportion of the year of the westerly weather type since the mid-1990s, which coincides with the start of the flood rich period. Finally, the South-Westerly (e) weather system has varied by 11.5% (3.6% to 15.1%). This weather type has the highest level of agreement with the flood frequency, with the proportion of the year classified as south-westerly increasing from 1900-mid 1930s, falling significantly from 1960 to 1980 and then increasing again in the current flood rich period.

Overall, this section has shown that floods occur on days with certain weather types. Five weather types, C, CSW, CW, SW and W, have been identified as flood generating weather types. These are similar to what previous UK studies have found. Longfield and Macklin (1999) identified W, C, CW, and SW as causing 79.7% of floods in the Ouse record. The addition of CSW increases this only to 82.6%, suggesting this weather type is more important in the Eden than the Ouse. This confirms previous studies which have found East-West gradients in the weather types that cause flooding. Rumsby and Macklin (1996) found this for the Tyne (East) and Severn (West), with easterlies and westerlies being important respectively. Although

Grew (1996) has noted that there are no simple general patterns, and flood generating weather types seem to be catchment specific. The importance of Westerlies in the Eden catchment is supported by Malby *et al.* (2007) who found SW and W weather types are associated with the highest precipitation totals in the Eden catchment.

Over the historical period, the flood generating weather types have been shown to relate to the flood richer periods throughout the last 130 years, although the links between C and SW are the strongest. These periods are also strongly correlated with a strong positive NAO index (Wilby *et al.*, 1997). However, the increase in the proportion of the flood generating weather types seems to occur before the increase in flooding. This indicates that the measure of Lamb weather types is missing some aspect of the controls on flood risk in the Eden, which may be climatic or could be complicated by land use and management changes. This lag also seems to exist between the switch in the NAO index and the increase in flooding (Wedgebrow, 2002) and may be due to some kind of hydrological memory effect such as antecedent conditions.

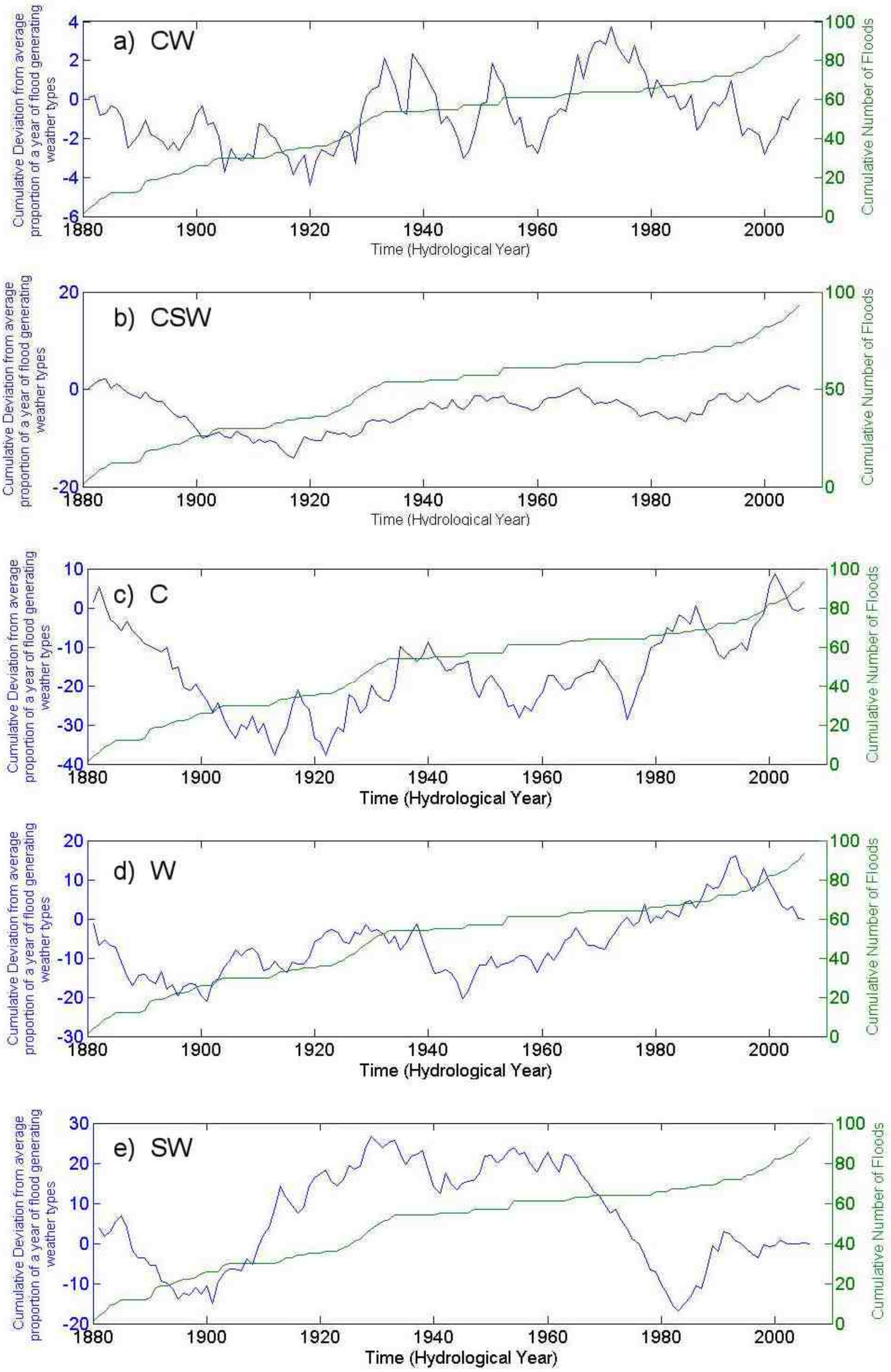


Figure 4.34 *Plot showing how individual flood generating weather types have changed over time a) CW; b) CSW; c) C; d) W; and e) SW.*

4.6.4. Land Use Change hypothesis

The difficulty of finding a land use signal in gauged data has been discussed by O'Connell *et al.* (2004). The main reasons for this is the lack of suitable data, as the quality often is questionable and record lengths are too short to detect statistically significant and meaningful trends (Robson, 2002). Even if a statistically significant trend is detected, then it cannot necessarily be attributed to land use change. O'Connell *et al.* (2004) noted that changes in data records could be caused by one of three factors; (1) measurement problems (e.g. rating relationship change); (2) catchment changes (e.g. land use, channel changes); and (3) climatic variations. Some empirical studies, notably Lane (2003) have found a correlation between land use variables and flood characteristics. Sansom (1999) showed a qualitative link between stocking densities and flooding, while Lane (2003) used regression analysis to identify "some form of correlation" for the River Ouse, Yorkshire. However, natural rainfall variations mean that changes in flood frequency and magnitude could not be conclusively attributed to upstream land use change. Another reason why it is difficult to prove a link between land use change and flood risk is that there is a lack of land use data. Lane (2003) concluded that we have insufficient techniques to disentangle the land use signal from natural climatic variability at the catchment scale.

The focus of this thesis is identifying the impact of land use change on flood characteristics. This chapter has identified trends in flooding in the Eden catchment over both the gauged and historical periods. Furthermore, a correlation with Lamb weather types has been identified. This means that if there is a land use signal in the data then it will likely be inseparable from the climate signal. Also there is no quantitative land use data available for the Eden catchment.

As reviewed in Chapter 2, there is an alternative approach to using empirical quasi-experiments to investigate the influence of land use on flooding; numerical modelling. It is therefore this approach that will be used within this thesis to try and establish a link between land use and flooding at the catchment scale. The reason why numerical modelling is suitable is that climatic variations can be removed by using the same period of time as model inputs and just changing the land use parameters.

4.7. Chapter Summary

This chapter has given a review of the flooding problem in the Eden catchment and in the city of Carlisle in particular. First, the whole range of flows was assessed through the development of a flow duration curve for each sub-catchment. This indicated that the Caldew sub-catchment is quite flashy, while the Eamont is has a slower response to precipitation. Section 4.3.1 gave a qualitative review of flood risk in the Eden catchment, focussing particularly on the extreme January 2005 flood event. Details on the physical causes, along with the human impacts were given. Following on from this, the gauged data that were evaluated in Chapter 3 were used to assess flood characteristics of the different sub-catchments. Flood frequency was assessed through the number of floods which exceeded the Q1 value, while flood magnitude was investigated using the annual maximum flood (Amax) value for each hydrological year and the magnitude of the peak over threshold events. The results from this analysis indicated that there are no statistically significant trends in flood frequency or magnitude. Flood risk on different timescales were then investigated, with flooding in the Eden being a mostly winter phenomenon. To put the recent changes in flood risk in the context of longer timescales, a multiple source search of the archives resulted in approximately 90 floods since 1770 in Carlisle. From this it was clear that some decades were more flood rich than others. Three flood rich periods were defined as; (1) 1873-1901; (2) 1923-1933; and (3) 1994-present. There is not a significant change in the magnitude of these floods, except that the January 2005 flood was one metre higher than any other flood in the historical record. However, stage is not only influenced by flow, but factors such as sediment aggradation and the channel cross section. There are two main factors which influence flooding; (1) climate change / variability; and (2) land use change. These were assessed for the Eden catchment over the last 130 years. Climate was assessed through using Lamb weather types, which are thought to be a good indicator of multiple climatic factors. Five weather types were identified as flood generating weather types; Cyclonic; Westerly; South-Westerly; Cyclonic Westerly and Cyclonic South-Westerly. Although the most floods are caused on days which are classified as Cyclonic, a greater proportion of the year is of this weather type, meaning that once the frequency of each weather type was taken into account, then Cyclonic-Westerly became the most likely weather system to cause a flood in Carlisle. This weather type is also associated with the highest mean daily rainfall total (Sweeney and

O'Hare, 1992), which may provide an explanation of why this weather type is associated with flooding. The change in the proportion of the year of each weather type was then assessed over the whole record of Lamb weather types, since 1880. This showed that the proportion of the year classified as any of the five so-called flood generating weather types fluctuated over the 130 year record. Periods which had a greater proportion of the year classified as one of the flood generating weather types correlated with the flood rich periods. However, there is a lag between the increase in these particular weather types and the increase in flood frequency. Changes in Cyclonic and South-Westerly matched the changes in flood risk best. However, these weather types are just part of the "chain of causality" (Lawler *et al.,* 2003) which leads from large scale atmospheric processes to local scale flooding. Overall, the problem of flood risk in the Eden has changed over the historical period, which has been associated with changes in weather types. However, it is incredibly difficult to separate the effects of these changes, as they are not mutually exclusive in the signal in the data available. Therefore, a numerical modelling approach will be used to isolate the land use signal and attempt to identify a link with flooding.

Chapter 5

Spatial Downscaling of catchment scale flood risk: Methodology

5.1. Chapter Scope

The previous chapter showed that the trends in flood risk over time cannot be fully explained by changes in weather patterns. Chapter 2 showed how land use and downstream flood risk are theoretically related. Time series of flooding variables are hard to test for either climate or land use change impacts, as they are not mutually exclusive (DEFRA, 2008). Thus, this thesis uses a numerical modelling approach to test the hypothesis that land use change impacts downstream flood risk.

This chapter outlines two methods used to fulfil objective 2, which is "*to determine which parts (sub-catchments) of the catchment are the most important in explaining downstream flooding in terms of both the magnitude and timing of the flows*".

The first approach used to downscale the catchment scale problem of flooding to the contributing sub-catchments is a statistical methodology (Section 5.2). Chapter 3 summarised how the raw data were prepared ready for this analysis. The gauging stations used to represent the flow from each sub-catchment for each flood are shown in Figure 3.16. This approach uses simple uni-variate descriptive statistics (Section 5.2.2; Section 5.2.3), bi-variate correlation (Section 5.2.4), and multi-variate transformation and regression (Section 5.2.5; Section 5.2.6).

The second approach is based on numerical modelling (Section 5.3), specifically hydraulic models which are reviewed in Section 5.3.1. A summary of the modelling strategy used to downscale catchment scale flood hazard to the individual contributing upstream tributaries is given in Section 5.3.3. Section 5.3.4 will outline of the specific model for the Eden catchment and give details of model development (Section 5.3.5), assessment (Section 5.3.6) and calibration (Section 5.3.7). The results of the downscaling approach are reported in Chapter 6.

5.2. Statistical Downscaling Methodology

Sub-catchment flooding trends were assessed through investigating variable distributions (Section 5.2.2) and basic descriptive statistics (Section 5.2.3). Sub-catchment interactions were then investigated through looking at correlations between the different sub-catchment variables (Section 5.2.4). The relative importance of each sub-catchment was then examined through combining the multivariate technique of principal components analysis (Section 5.2.5) with stepwise regression (Section 5.2.6). Finally, the uncertainties associated with these predictions were then estimated using the technique of bootstrapping (Section 5.2.7). These statistical techniques will be expanded upon in the sections below.

5.2.1. Importance of tributary peak flow magnitude and timing on downstream flood risk

There have been a few past studies which have aimed to identify the most important areas of catchments in causing downstream flooding. However, the lack of nested hydrometric gauging stations makes identifying flood producing sub-catchments difficult (Roughnai *et al.,* 2007). Therefore past studies have focussed on using models to spatially prioritise areas to reduce flood risk at the catchment. However, the common use of lumped rainfall-runoff models has prevented their use for this purpose. Therefore, spatially distributed hydrological models are needed, whereby sub-catchments can be discretised and their influence on catchment flooding assessed. Ghaemi and Morid (1996) used both meteorological variables and catchment characteristics to rank sub-catchments. Islam and Sado (2000) used similar catchment properties, e.g. elevation, land cover, to construct flood hazard maps. Juracek (2000) ranked sub-catchments using their potential runoff contributions estimated through using the topographic index. Saghafian and Khosroshahi (2005) developed a Unit Flood Response (UFR) method using the HEC-HMS rainfall runoff model and Muskingham channel routing to identify sub-catchment contributions. The approach consisted of removing each unit sequentially and assessing its impact on downstream flood magnitudes. Roughnai *et al.* (2007) developed a similar approach whereby sub-catchment contributions were either removed or modified to represent flood risk control measures and floodplain storage.

These studies have concluded that both peak flow magnitude and timing are important factors to consider when assessing how sub-catchments respond to rainfall and interact to cause downstream flooding. Therefore both these factors are accounted for in both methods. Table 5.1 shows an example of the time and magnitude of the peak flows for the January 2005 flood (7th/8th Jan). Relative timing is calculated by subtracting the time of the peak flow in the sub-catchment from the time of peak flow downstream in the Lower Eden at Sheepmount. Table 5.2 shows the relative timing of the peak flow of each tributary with respect to Carlisle. For the Eamont, the relative timing is calculated by subtracting the timing of the Eamont peak flow (5:45) from the time of the flood peak at Sheepmount (14:30) to give the lag time of 8 hours 45 minutes, which is represented in the dataset by a value in decimal hours of 8.75.

The dataset used in further analysis therefore consists of eight discharge magnitude variables, one of which is in Carlisle which is the dependent variable, leaving seven sub-catchment magnitude variables and seven Carlisle relative sub-catchment timing variables (Table 5.1 and Table 5.2). This dataset is in Appendix A, which also shows which of the data observations were estimated through the approach of data augmentation outlined in Section 3.3.

Station	**Date**	**Time**	**Discharge (m^2s^{-1})**
Upper Eden - Kikrby Stephen	07/01/2008	21:45	129.0
Upper Eden - Temple Sowerby	08/01/2008	04:00	390.6
Eamont - Udford	08/01/2008	05:45	295.0
Lower Eden - Warwick Bridge	08/01/2008	10:45	854.3
Irthing - Greenholme	08/01/2008	06:45	277.7
Petteril - Harraby Green	08/01/2008	07:30	82.6
Caldew - Cummersdale	08/01/2008	03:15	193.3
Lower Eden - Sheepmount	08/01/2008	14:30	1516.4

Table 5.1 *Example of data extraction for January 2005 flood*

	Relative Timing (Hrs)
Carlisle - Upper Eden (Kirkby Stephen)	16:45
Carlisle - Upper Eden (Temple Sowerby)	10:30
Carlisle - Eamont	08:45
Carlisle - Lower Eden (Warwick Bridge)	03:45
Carlisle - Irthing	07:45
Carlisle - Petteril	07:00
Carlisle - Caldew	11:15

Table 5.2 *Example of relative timing calculation for January 2005 flood*

5.2.2. Assessing variable distributions

The sub-catchment peak flow magnitude and relative timing variables were assessed by looking at their distributions through simple probability exceedance curves. These are calculated in the same way as flow duration curves. The Shapiro-Francia W' and Shapiro-Wilk W tests were used to determine whether the variable distributions differed significantly from a normal distribution. However for more precise comparisons of variables then a quantitative measure of the distribution is needed through using summary statistics.

5.2.3. Descriptive Statistics

Descriptive statistics for the sub-catchment peak flow magnitude and relative timing variables were calculated. These were measures of central tendency; the mean and median, and measures of dispersion; the standard deviation, range, maximum and minimum. These were then used to assess sub-catchment trends and behaviour. Specifically, a comparison between the extreme January 2005 flood and the long term average was carried out.

5.2.4. Correlation

A graphical way to represent the link between two variables is the scatter plot, which allows the pattern and strength to be visualised. However, this relationship can be measured by a numerical value, which examines the strength of the linear association between two sets of data. The Pearson's Product Moment Coefficient was used for this purpose. This examines the covariance of each variable for the same observation. The sign of the covariance is important, where positive correlation is when both variables have the same sign covariance for the same observation. The correlation coefficient is dimensionless, as the covariances are divided by the standard deviations of the variables. The data requirements for this statistical test are that the relationship between the two variables should be linear; the data should be pair-wise uncorrelated and independent and should have a normal distribution. However, correlation does not imply a causal relationship. The correlation coefficients were used to try and identify links between sub-catchments and their interactions.

5.2.5. Principal Components Analysis

Principal components analysis has been used in many academic fields for several decades. Its usage in hydrology spans several themes, from water quantity and quality to water and sediment tracing, and also other related disciplines such as ecology and meteorology. One of the main reasons for PCA to be used in hydrology is to reduce the number of variables in large datasets. For example, Olden and Poff (2003) used 171 indices to describe hydrological regimes and then applied PCA to identify patterns of inter-correlation and recommendations of optimum sub-sets of indices which covered broad aspects of hydrological regimes, such as flooding, droughts, seasonal and daily patterns. It was essential that these sub-sets described the main sources of variation, but minimised the redundancy in the dataset. Failure to reduce the amount of repeated pattern in the data would lead to problems of multicollinearity in regressions (Zar, 1999) and erroneous selection of variables (Olden and Jackson, 2000). Olden and Poff (2003) found that statistically two to four specifically chosen indices could account for the dominant aspects of hydrological regimes, although for more focussed ecological research questions, a minimum of nine indices were recommended. Another reason that PCA is used is to identify the most important factors influencing a certain process or factor. There are several examples of this type of usage from multiple areas of hydrology. Firstly, in water quality research, sources of precipitation pollution (Hooper and Peters, 1989), biogeochemical processes (Haag and Westrich, 2002) and catchment scale factors resulting in water quality issues (Petersen *et al*., 2001) have all been identified using PCA approaches. A study by Haag and Westrich (2002) found that biological processes explained 79% of the oxygen saturation level of the water, indicating that the dynamics of phytoplankton and the process of eutrophication were the dominant control. Another example of PCA being used to identify the most important factors is a flood loss study by Thieken *et al*., (2005). They investigated both the physical and human factors that influence the cost of floods. It was found that the physical controls of water level, flood duration and contamination were the most important factors, as when these increased so did flood losses. However, the effect of house value, age and the socioeconomic measures of the household did not have a significant influence on flood losses. Furthermore, it was found that flow velocity did not seem to be a critical control on flood losses.

A third reason for PCA to be used in hydrological research is regionalisation. This allows hydrologically similar areas to be identified. An example of this is from meteorology, where Baeriswyl and Rebetez (1997) divided Switzerland into seven regions with coherent rainfall characteristics. This was done by grouping stations of similar precipitation regimes. This usage of PCA can be extended from just simple clustering of similar observations to using them to trace water and sediment sources in catchments. Burns *et al*., (2001) characterised runoff from different areas of a catchment using isotopes and found that 50-85% of the peak streamflow was generated from an area of a third of the catchment, through combining PCA with a mixing model. Groundwater sources were found to be important during the start of the rising limb and throughout the falling limb. The same principle can be applied to sediment source tracing, through a technique known as sediment fingerprinting (Collins *et al*., 1997; Collins and Walling, 2002; Collins and Walling, 2004). Source sediments are ascribed a source type e.g. land use or geology, and then sediment properties are used to differentiate between them. PCA is a useful technique to determine the optimum set of properties to characterise different sediment sources. An unmixing model (Walling *et al*., 1999) or a mixing model (Slattery *et al*., 2000) is then used to assign relative contributions of suspended sediments to each source type.

Finally, PCA has been used in aquatic ecology research to reduce large datasets and to identify important factors (Wiegleb, 1980). Dugdale *et al*. (2006) used PCA to determine the factors which influence fish population dynamics in the River Eden. These included factors at three spatial scales; the local scale e.g. bed sediment size, barriers; the riparian scale e.g. tree cover, bank erosion; and the catchment scale e.g. land cover, connectivity. It was shown that different factors are important for different fish species and that processes from different spatial scales are important in determining fish populations.

The general premise of principal components analysis is to simplify multi-variate datasets where variables are intercorrelated. Principal components analysis is a data transformation technique, which maintains the same amount of variability within the same number of variables, but the new transformed components are independent of each other. The first principal component accounts for the most variability, while the subsequent components account for as much of the unexplained variance as possible while being uncorrelated and orthogonal with the other components. This means that all components are significant, but normally it is only the first few which account for most of the original variability. A limitation of this approach is the number of components problem (Howard and Gordon, 1963; Frane and Hill, 1976), where there are no rules for the number of components taken to be significant. If too few are included then there is an underestimation of the variability accounted for and a loss of useful information, while if too many are used then spurious variables are included often with redundancy (Franklin *et al*., 1995). There are several approaches used to decide which components are discarded from further analysis, these include; (1) components with eigenvalues less than one are eliminated (Pocock and Wishart, 1969); (2) a certain proportion of the variability is maintained (e.g. 80/90%) (Morrison, 1967); and (3) components whose individual contribution to account for original variance is less than a set criteria (e.g. 5/10%).

It is also important to consider which of the original variables are put into the principal components analysis, as this determines the result of the analysis. This is especially the case when several variables which all measure the same characteristic are included, which results in the first component explaining a high proportion of the variability. In this situation it is best to discard redundant variables which repeat similar information (Daultrey, 1970).

It is possible to interpret the components in terms of the original variables, through the loadings. Furthermore, the individual observations can be related to the components, producing scores which have a mean of zero for each component. It is important to note that principal components analysis does not need the original variables to be normally distributed, but the use of Pearsons Correlation does require this. Therefore the interpretations of what the new components represent in terms of the original variables needs to be undertaken with caution (Daultrey, 1970).

As the controls on downstream flooding are complex and the variables intercorrelated, a basic multiple regression would not be able to identify the most important predictors due to the problem of multicollinearity. Therefore, principal components analysis is applied to the dataset of sub-catchments peak flow magnitudes and relative timings with respect to Carlisle. The criterion of Pocock and Wishart (1969) is applied whereby components with eigenvalues less than one are eliminated. This reduces the dimensionality of the dataset, while still accounting for the complex sub-catchment interactions.

5.2.6. Stepwise Regression

Basic regression is the formation of a statistical relationship between a dependent/response variable and a series of independent/explanatory variables. In this case, the principal components (independent/explanatory variables) are used to predict downstream flood magnitude in Carlisle (dependent/response). However, to achieve the optimum equation, which explains the greatest proportion of downstream flood magnitude at a certain significance level, a specific type of multiple regression is used, called stepwise regression. This is a sequential approach to equation development.

There are three types of stepwise regression; forward, backward and optimising. Forward stepwise regression starts with just the constant, and then searches for the predictor variable which best explains the outcome variable (highest individual correlation). Then the second predictor variable that explains the highest proportion of the unexplained outcome (highest semi-partial correlation) is added. This is then either retained if it significantly improves the predictability of the equation or rejected if it is not significant at the level stated. This procedure continues until the last added variable does not improve the performance of the regression. The backward stepwise regression approach starts by including all the predictors in the equation, and proceeds to remove the variable which contributes least to the predictability of the equation. Optimising stepwise regression allows variables to be added or removed at each stage of the process. However, by considering only one variable at a time a bias can be introduced into the regression, whereby two variables combined may be useful in explaining the dependent variable, but may offer no predictive power singly.

It is commonly believed that the backward stepwise regression method is the best approach to use, as it reduces the possibility of suppressor effects, which occur when the predictor has a significant effect but only when another variable is held constant. Often both approaches are used in combination, and then the performances of the equations are compared (Rogerson, 2006).

The final stage of the statistical spatial downscaling approach is to use stepwise regression to form a relationship between the significant principal components and the flood peak magnitude downstream in the city of Carlisle. A significance level of 95% is used to determine whether an additional component should be included in the regression model. The equation is then interpreted in terms of the original variables which are accounted for by each of the components in the regression. This is done by determining what proportion of each component is explained by each of the original variables, through using the loadings (correlations between original variables and components), and accounting for how much each component contributes to the regression relationship (regression coefficients).

5.2.7. Uncertainty Estimates

When making important decisions about future research directions and especially policy and management, it is essential that model predictions are stated with some indication of the uncertainty associated with them. Here, the technique of bootstrapping is used to analyse the distribution of a sample statistic. Bootstrapping is the process of creating multiple samples of the same size from the whole population of data. The bootstrap samples are generated by sampling with replacement from the original sample. Bootstrap samples have the same number of observations as the original dataset. Sampling with replacement means that each observation is equally likely to be chosen each time a value is selected for inclusion in the bootstrap sample. The statistical analysis is then carried out on all the bootstrap samples. The variability across the bootstrap samples is then used to establish confidence intervals for the original dataset. The proportion of downstream flood magnitude that can be predicted from the magnitude and timing of the sub-catchments is then assessed by bootstrapping the use of the principal components in the stepwise regression. This can then be used to determine the uncertainties associated with the relative importance of each sub-catchment in explaining downstream flooding.

Another type of uncertainty introduced into the analysis is the conversion of the measured river stage to discharge by the rating equation. After the January 2005 flood, several of the gauging stations used in this analysis underwent a review of the rating curves. The rating equations at Great Corby (Lower Eden), Cummersdale (Caldew), Harraby Green (Petteril), Udford (Eamont), Temple Sowerby (Upper Eden) and Greenholme (Irthing) have been changed and extended to higher flows. Table 5.3 lists the previous and updated rating equations and the curves are shown in Figure 5.1. The main reason why it was thought that the original rating curves were underestimating flows was because at high flows water bypassed the channel on the floodplain. To account for this a combined 1D-2D iSIS-Tuflow hydraulic model was constructed by consultancy companies (Halcrow, 2006a; 2006b; Morriss, 2006;) on behalf of the Environment Agency. Several of the gauging stations have seen the peak flow for the January 2005 flood increase due to the extension of the rating curves to high flows. The peak flow at Temple Sowerby for the January 2005 flood changed from $390m^3s^{-1}$ to $925m^3s^{-1}$ (Table 5.4), while Great Corby has increased to $1373m^3s^{-1}$. The peak flow from the Irthing has decreased from $277m^3s^{-1}$ to $228m^3s^{-1}$. The gauging stations at Sheepmount (Lower Eden) and Kirkby Stephen (Upper Eden) did not change. The statistical analyses outlined in this chapter were carried out for both the original rating curve and the updated discharge values, to indicate how sensitive the results were to the discharge values used.

A simple mass balance of the sub-catchments (Great Corby, Greenholme, Harraby Green and Cummerdale) which contributes to the flows in Carlisle at Sheepmount, suggest that the updated ratings significantly overpredict the discharge at Sheepmount. Using the original rating relationships the mass balance of the contributing tributaries is 1408.4 m^3s^{-1}, while the updated discharges sum to 1962.5 m^3s^{-1}. This suggests that the accuracy of the updated rating curves may be worse than the original ones, especially for Great Corby and Temple Sowerby which have changed significantly, while the gauges upstream (Kirkby Stephen) and downstream (Sheepmount) have not changed at all.

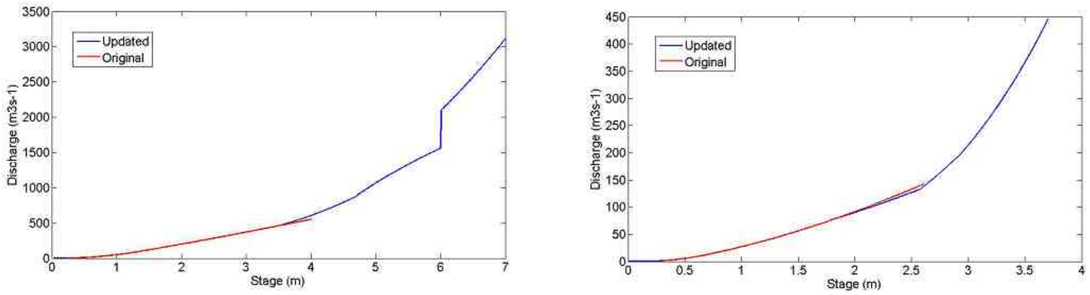
Gauging Station	Previous Rating	Updated Rating
Great Corby (Lower Eden)	$(0.0m < h < 0.51m)$ $Q = 26.0918 * (h - 0.029)^{1.31221}$ $(0.51m < h < 1.141m)$ $Q = 68.1778 * (h - 0.158)^{1.83327}$ $(1.141m < h < 5.0m)$ $Q = 138.716 * (h - 0.621)^{1.13458}$	$(0.0m < h < 0.50m)$ $Q = 26.0918 * (h - 0.029)^{1.31221}$ $(0.50m < h < 1.141m)$ $Q = 68.1778 * (h - 0.158)^{1.83327}$ $(1.141m < h < 3.50m)$ $Q = 138.716 * (h - 0.621)^{1.13458}$ $(3.50m < h < 4.70m)$ $Q = 0.01156 * (h + 5.0127)^{4.9441}$ $(4.7m < h < 6m)$ $Q = 1027.08 * (h - 3.93159)^{0.5771}$ $(h > 6m)$ $Q = 22.188861 * (h\ 0.75078)^{2.554803}$
Cummersdale (Caldew)	$(0.303m < h < 0.397m)$ $Q = 36.652 * (h + 0.127)^{3.963}$ $(0.397m < h < 0.760m)$ $Q = 37.797 * (h - 0.108)^{2.089}$ $(0.760m < h < 2.261m)$ $Q = 38.1084 * (h - 0.21)^{1.507}$	$(0.0m < h < 0.4m)$ $Q = 36.652 * (h + 0.127)^{3.963}$ $(0.4m < h < 0.76m)$ $Q = 37.797 * (h - 0.108)^{2.089}$ $(0.760m < h < 1.79m)$ $Q = 38.1084 * (h - 0.21)^{1.507}$ $(1.79m < h < 2.58m)$ $Q = 31.073 * (h)^{1.5349}$ $(2.58m < h < 2.90m)$ $Q = 7.1256 * (h)^{3.0918}$ $(2.90m < h < 3.70m)$ $Q = 4.5237 * (h)^{3.5086}$
Harraby Green (Petteril)	$(0.0m < h < 0.73m)$ $Q = 24.7294 * (h - 0.03)^{1.5946}$ $(0.73m < h < 1.436m)$ $Q = 31.207 * (h - 0.102)^{1.7247}$	$(0.0m < h < 0.73m)$ $Q = 24.7294 * (h - 0.03)^{1.5946}$ $(0.73m < h < 1.479m)$ $Q = 31.207 * (h - 0.102)^{1.7247}$ $(1.479m < h < 1.6545m)$ $Q = 1.21005 * (h + 1.04944)^{4.09839}$ $(1.6545m < h < 2.0m)$ $Q = 0.0032448 * (h + 0.0224)^{7.67606}$
Udford (Eamont)	$(0.0m < h < 0.868m)$ $Q = 54.653 * (h + 0.025)^{1.5729}$ $(0.868m < h < 2.50m)$ $Q = 129.217 * (h - 0.522)^{0.9789}$	$(0.161m < h < 0.832m)$ $Q = 47.6898 * (h + 0.0762)^{2.0724}$ $(0.832m < h <2.850)$ $Q = 31.8873 * (h + 0.2634)^{2.2282}$
Temple Sowerby (Upper Eden)	$(0.183m < h < 0.65m)$ $Q = 30.619 * (h + 0.065)^{2.0}$ $(0.65m < h < 1.83m)$ $Q = 44.304 * (h - 0.145)^{1.52}$	$(0.0m < h < 3.40m)$ $Q = 31.3691 * (h + 0.0249)^{1.7953}$ $(3.40m < h < 4.50m)$ $Q = 0.79697 * (h)^{4.81501}$

Greenholme (Irthing)	$(0.193m < h < 0.374m)$ $Q = 64.9226 * (h + 0.079)^{3.419}$ $(0.374m < h < 1.289m)$ $Q = 44.1178 * (h - 0.097)^{1.8026}$ $(1.289m < h < 2.786m)$ $Q = 106.906 * (h - 1.01)^{0.4463}$ $(2.786m < h < 3.340m)$ $Q = 5.323 * (h)^{3.1769}$	$(0.0m < h < 0.374m)$ $Q = 64.9226 * (h + 0.079)^{3.419}$ $(0.374m < h < 1.289m)$ $Q = 44.1178 * (h - 0.097)^{1.8026}$ $(1.289m < h < 2.60m)$ $Q = 106.906 * (h - 1.01)^{0.4463}$ $(2.60m < h < 3.23m)$ $Q = 5.786 * (h + 1.171)^{2.358}$ $(3.23m < h < 3.55m)$ $Q = 14.519 * (h - 0.299)^{2.388}$ $(3.55m < h < 3.90m)$ $Q = 0.001132 * (h)^{9.710548}$
Sheepmount (Lower Eden)	$(0.549m < h < 0.990m)$ $Q = 42.285 * (h - 0.139)^{2.06783}$ $(0.990m < h < 5.516m)$ $Q = 56.6122 * (h - 0.298)^{1.69866}$	
Kirkby Stephen (Upper Eden)	$(0.039m < h < 0.492m)$ $Q = 9.68857 * (h + 0.004)^{1.58121}$ $(0.492m < h < 2.496m)$ $Q = 38.0633 * (h - 0.307)^{1.46883}$	

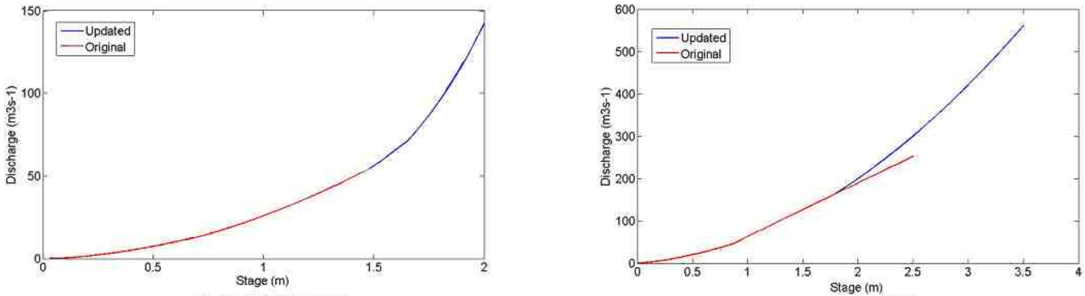
Table 5.3 *Rating equations for the Gauging stations used in analysis*

	Stage	**Original Q**	**Updated Q**
Great Corby	5.585	854.86	1372.88
Cummersdale	3.147	193.34	252.59
Harraby Green	1.86	82.57	108.27
Udford	2.846	295.03	381.63
Temple Sowerby	4.33	390.32	924.99
Greenholme	3.472	277.67	228.80
Sheepmount	7.226	1516.41	1516.41
Kirkby Stephen	2.604	129.12	129.12

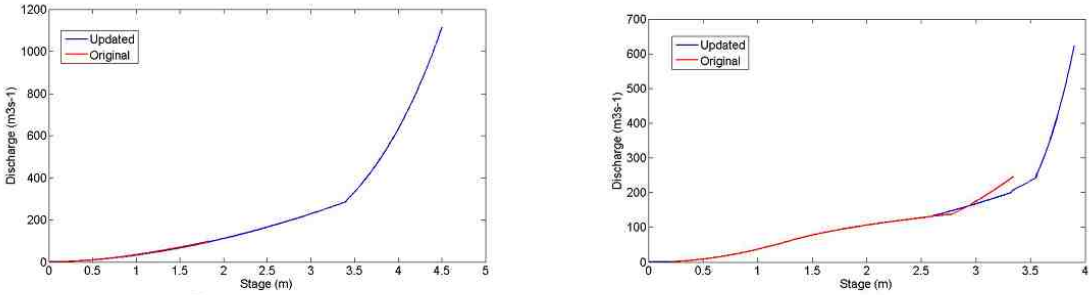
Table 5.4 *Comparison of January 2005 flood peak discharges by original and updated rating equations.*



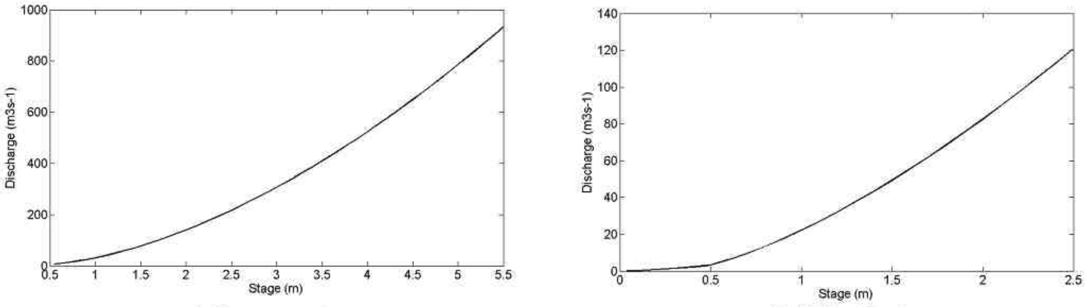
a) Great Corby b) Cummersdale



c) Harraby Green d) Udford



e) Temple Sowerby f) Greenholme



g) Sheepmount h) Kirkby Stephen

Figure 5.1 *Rating Curves for the gauging stations used in the analysis*

5.3. Numerical Modelling Methodology for Downscaling

This section outlines the numerical modelling methodology used to downscale catchment scale flooding to the upstream contributing tributaries using a hydraulic modelling approach. This numerical modelling approach uses a hydraulic model, iSIS-Flow. The next section will outline hydraulic models in general, before giving details of the iSIS-Flow model.

5.3.1. Review of Hydraulic models

Hydraulic models are representations of water flow within the river channel, which route water along the modelled reach. The following sections will review how channel flow hydraulics are represented in models of different complexity. It will then go on to outline the hydraulic model chosen in this thesis to aid the downscaling of catchment scale flooding and to test land use scenarios, both in general terms and in terms of the specific Eden model.

There are three main groups of flood routing model; (1) hydrological / storage methods; (2) convection-diffusion equation based methods; and (3) methods using the St. Venant equations (FSR, 1975). The simplest flood routing methods are based on basic hydrological or storage principles and take no account of flow resistance. The fundamental concept that underlies these methods is the continuity equation, which relates the rate of change of storage (dS/dt) to the difference between the input (Q_I) and the output (Q_O).

$$\frac{\delta S}{\delta t} = Q_I - Q_O$$

The most common method which uses this principle is the Muskingham method (McCarthy, 1938), which has the following relationship:

$$S = K[\varepsilon Q_I + (1 - \varepsilon) Q_O]$$

Where S = Storage

K = Storage parameter

$= \frac{\Delta x}{c}$ where c = flood wave celerity, Δx = distance increment

ε = relative importance of the inflow and outflow

$= 0.5\left[1 - \frac{Q}{B\, S_O\, c\, \nabla x}\right]$ where B = Bottom width or average width,

S_O = bed slope,

This was later developed into the Muskingham-Cunge method (Cunge, 1969; Price, 1978), which converts the method based on hydrological theory to one based on hydraulic principles. This was done by deriving equations for the parameters K and ε, which are shown in the equation above. This flood routing method can reproduce slow rising flood hydrographs for reaches with flat slopes, but struggles to simulate rapidly rising hydrographs due to the omission of the acceleration term from the momentum equation.

Another simplified flow routing model is the kinematic wave (Lighthill and Whitham, 1955), which is based upon the convection-diffusion equation of Hayami (1951). It has been suggested that this model should only be used if the slope exceeds 0.002 and for non-tidal rivers (Haestad *et al.,* 2003).

$$Q_c = \propto_c A_c^{m_c}$$

Where A_c = Cross sectional area, Q_c = discharge, α_c and m_c = kinematic wave parameters.

The final set of flood routing models use a numerical method to solve the St. Venant equations. The basic principles of these hydraulic modelling approaches are detailed by Lane (1998) and Bates and Anderson (2001). All hydraulic models are based on the Navier-Stokes momentum equation, and the Continuity equation. The three-dimensional Navier-Stokes equation for an incompressible fluid with a constant density can be expressed in Cartesian vector notation as:

$$\rho \frac{Du}{Dt} = -\nabla p + \mu \nabla^2 \mathrm{u} + \mathrm{F}$$

Where ρ is the fluid density (ML^{-3}) p is the pressure (MLT^{-2})
u is the velocity (LT^{-1}) μ is the viscosity (MLT^{-2})
t is the time (T) F is gravity, coriolis force and friction

The general form of the continuity equation is:

$$\nabla \cdot u = 0 \qquad where\ u = (\, u\ v\ w)$$

3D Hydraulic models represent detailed hydraulic flow processes such as secondary circulation. However, due to this they are highly computationally demanding and therefore can only be constructed on a small scale, with only in-bank processes being represented for short reaches (Horritt, 2000). Some of the 3D effects can be represented in 2D approaches as energy loss processes (Sellin and Willets, 1996). Lane and Richards (1998) incorporated an analytical correction for the effects of secondary circulation into a 2D hydraulic model. This was found to simulate some of the observed streamwise transfer of momentum, but these effects were minor.

These St. Venant equations can be simplified for models using fewer dimensions. Two dimensional models assume that the flow velocity is averaged over the water depth. This results in the formation of the depth averaged shallow water equations (Henderson, 1966), which assume hydrostatic pressure distributions and take the form of:

Momentum equations

$$\frac{\delta u_d}{\delta t} + \vec{u}_d \cdot \overrightarrow{grad}(u_d) + g\frac{\delta h}{\delta x} - div\left(v_t \cdot \overrightarrow{grad}(u_d)\right) = S_x - g\frac{\delta Z_f}{\delta x}$$

$$\frac{\delta v_d}{\delta t} + \vec{u}_d \cdot \overrightarrow{grad}(v_d) + g\frac{\delta h}{\delta y} - div\left(v_t \cdot \overrightarrow{grad}(v_d)\right) = S_y - g\frac{\delta Z_f}{\delta y}$$

Continuity equation

$$\frac{\delta h}{\delta t} + \vec{u}_d \cdot \overrightarrow{grad}(h) + hdiv(\vec{u}_d) = 0$$

Where

u_d and v_d are the depth averaged velocity components in the x and y directions (LT^{-1})

Z_f is the bed elevation (L)

V_t is the kinematic turbulent viscosity (L^2T^{-1})

S_x and S_y are the set of friction, coriolis force and wind stress terms

G is the gravitation acceleration (LT^{-2})

Full 2D hydrodynamic models are based on the shallow water equations and are becoming more popular in flooding studies. The use of these models was initially restricted by the lack of topographic data (Horritt and Bates, 2001), but now high resolution LiDAR (Light detection and ranging) data allow the floodplain to be represented at a 1-2m resolution, with an elevation accuracy as good as ±0.1 m. However, the use of LiDAR requires time consuming pre-processing (Cobby et al., 2003). Also the computational constraints of the conventional finite element or finite volume approaches cannot solve at the scales achieved by this topographic data (McMillan and Brasington, 2007). These 2D models achieve a high level of physical process representation, but still require some combining of parameters (e.g. friction depth-averaged). The work of Wilson *et al.,* (2007) and Trigg *et al.,* (2009) on the Amazon, indicate that 2D models can be constructed for extremely long reaches (285 km reach of Amazon). The model used for their study was LISFLOOD-FP which can be integrated within a Geographical Information System (GIS) framework (De Roo *et al.,* 2000).

Finally, these St. Venant equations can be simplified even further to the one dimensional form (Fread, 1984; Ervine and MacLeod, 1999), where flow momentum is conserved between two cross sections. These 1D equations are expressed as:

Momentum equation

$$\frac{\delta Q}{\delta t} + \frac{\delta (Q^2/A)}{\delta x} + gA\left(\frac{\delta h}{\delta x} + S_f\right) = 0$$

Continuity equation

$$\frac{\delta Q}{\delta x} + \frac{\delta A}{\delta t} = 0$$

Where Q is the flow discharge (L^3T^{-1})

A is the flow cross section area (L^2)

S_f is the friction slope

h is the water depth

One dimensional hydraulic models are the most commonly used (Chow, 1959; Bhallamudi and Chaudhry, 1991; Niekerk *et al.,* 1992) as they are computational less demanding but still reproduce natural features of flood events (e.g. propagation and diffusion of the flood wave) (Moussa and Bocquillon, 1996). However, they cannot represent spatially complex topography and are limited to the bed slope and channel cross sections, which are accurate, but time consuming, to survey. This approach to representing the channel means that features between cross-sections are not included. This means that representing floodplain storage is problematic. They also assume that lateral and vertical variations of flow characteristics are negligible and therefore are suitable for modelling in-bank flows (Knight and Shiono, 1996), but inappropriate for overbank flows on the topographically complex floodplains. This is because the roughness parameter represents multiple forms including; friction, form resistance, turbulence, floodplain topography and vegetation. The parameterisation of roughness is a fundamental aspect of hydraulic modelling. This is because the roughness of the channel and floodplain differ and therefore affect the conveyance of water in different ways (Hunter *et al.,* 2005). The most common parameter used to represent roughness is Manning's n, which combines the effect of numerous factors which cause flow resistance, including vegetation (Mason *et al,* 2003), channel planform, obstructions, stage-discharge relationship and sediment interactions. One of the main problems with using Manning's n is that it is constant over time, whilst in reality roughness effects are spatially and temporally variable (Holz and Nilsche, 1982). 1D models can be used to represent the floodplain, but do so with simplistic storage and routing approaches (Rashid and Chaudhry, 1995), with either an extension of channel cross sections or a parallel channel. However, these approaches require some *a priori* knowledge of flow paths (Bradbrook, 2006). Furthermore, important channel features, such as meanders are only accounted for in the lumped friction parameter.

Examples of 1D hydraulic models include HEC-RAS (Haestad et al., 2003), MIKE 11 (DHI, 2000) and iSIS-Flow. These are all industry developed hydraulic models, with user interfaces that simulate steady and unsteady flows for single and dendritic channels, as well as whole channel networks (Thomas and Nisbet, 2007). They can also represent channel structures, such as bridges, culverts and weirs. More details will be given on iSIS in Section 5.3.2.

A slightly more complex model structure represents the channel in 1D and has floodplain storage units attached (Aureli *et al.,* 2005; Huang *et al.,* 2007) to allow flow exchange (i.e. flooding and emptying of cell storage), where the volume and area of flood inundation is some function of elevation (Kuznier *et al.,* 2002; Faganello and

Attewill, 2005). However, there is the problem of circular reasoning, whereby the user defines the size and shape of floodplain storage units, meaning that results are dependent upon these decisions. Lindenschmidt *et al.* (2006) and Baptist *et al.* (2006) used this approach to model channel-floodplain interactions, while Huang *et al.* (2007) modelled dyke breaches. Aureli *et al*. (2005) compared the performance of a full 2D hydrodynamic model with this type of floodplain storage cell model and found fairly good agreement between the two types of models. Water stage was initially poorly reproduced, as the storage cells were not capable of reproducing rapidly varying flows. However, there was good agreement of the maximum stage. Tayefi *et al*. (2007) also compared one and two dimensional approaches, this time for rural upland floodplains. It was concluded that the 1D extended cross section and floodplain cell storage approaches were conceptually problematic, as storage areas were not affected by dynamic flux transfer processes, although these could be parameterised to give a good fit.

A similar type of model is a coupled 1D-2D hydraulic model (Dhondia and Stelling, 2002). Syme (2001) noted that the great advantage of these models is their computational efficiency, which is due to the parsimonious and reduced complexity nature of the model structure. An example of a coupled 1D-2D model is iSIS-Tuflow, where iSIS represents the channel in 1D, while Tuflow is a full 2D floodplain model.

Wicks *et al.* (2004) compared the suitability of both 1D and 2D hydraulic models for the use of floodplain representation and found that the computation time needed for 2D models was 1000× higher than what was required for a 1D model. 2D raster models were also found to be scale dependent upon the spatial discretisation, with resolutions of 5-100m often used. However, Hunter *et al.* (2005) solved this problem through developing an adaptive time step model which produced results that were independent of the grid size and time step. Bates *et al.* (1996; 1998) also notes that there is a lack of appropriate data for validation and calibration of hydraulic models. Data are not usually available on variables such as flow velocity and inundation extent (Hunter *et al.,* 2008). Also the data on variables that are available e.g. stage and discharge, may only be available at few points in the system due to the sparse density of gauging stations, with Bates *et al.* (1998) finding that the gap between stations to be approximately 15 km in the UK. Therefore, the use of 2D models may not always be appropriate, as the data required to validate them is often not available in 2D, e.g. cross section averaged discharge (Bates and Anderson, 2001). Validation can be either external or internal, depending on where the outputs are sourced from. In external validation, the source of the data is the outlet of the system, while internal validation data originate from the interior of the model (Bates *et al.,* 1998). However, Wicks *et al.* (2004) concluded that 2D models were the most appropriate type of model to use if flows over the floodplain are important, as floodplain representation is better in 2D models.

A further way in which the way space has been represented in hydraulic models is through sub-grid scale parameterisation. This has been used to represent high resolution features such as buildings in urban areas (Yu and Lane, 2006a; 2006b; McMillan and Brasington, 2007; Fewtrell *et al.,* 2008; Neal *et al.,* 2009) and vegetation (Mason *et al.,* 2003). This takes advantage of the large increase in the availability of high resolution topography with the development of LiDAR. Bates and De Roo, (2000) believe that topographic resolution is more important than the process representation for modelling flood inundation extent. Fewtrell *et al.* (2008) found that the resolution of the topography needs to be similar to the length of the shortest building axis or building separation to accurately simulate urban floodplain inundation.

The way in which time is represented in hydraulic models is also of great importance. There are two types of simulations for hydraulic models models: (1) steady flows; and (2) unsteady flows. Steady flows are when the flow velocity does not change over time. For unsteady flows, the velocity of the flow varies through time.

The model timestep is also important as the run time of a model is directly proportional to the number and length of the timesteps. The chosen time timestep for the model needs to be a compromise between accuracy and run time. If the timestep is too large then the model will be numerically unstable, but if it is too short then the model will take a long time to run. A computational advance in terms of temporal representation was the development of an adaptive timestep (Press *et al.,* 1992), which allowed the timestep to vary in length depending upon the rate of change of the flow. Some hydraulic models can simulate in real time and are used to predict flood levels and to generate warnings (Romanowicz and Beven, 1998; Beven, 2001).

It has been decided that the 1D hydraulic model iSIS-Flow will be used throughout this thesis. There are several reasons for this. Firstly, 1D models have been shown to represent the process of flood wave propagation accurately, and this is the process of importance within this thesis. Horritt and Bates (2002) showed that the performance of 1D and 2D hydraulic models were comparable for certain river reaches. Secondly, the data available for model validation only consists of gauged stage and discharge records, and not spatially distributed flood inundation extents. This type of data is more compatible with 1D hydraulic models (Horritt and Bates, 2002). Finally, the Environment Agency had existing iSIS-Flow models available for the Eden catchment which could act as a starting point for model development.

5.3.2. iSIS-Flow

iSIS is a 1D hydrodynamic model which was developed by Halcrow and HR Wallingford between 1975 and 2007. It has a wide range of components and applications including the sub-models of iSIS-PDM (Probability Distributed Moisture) and iSIS-Hydrology, where hydrological models can be used to create inputs to the core hydraulic model, iSIS-Flow. The Flood Estimation Handbook methodology is also integrated into iSIS-Flow. Further add-ins includes iSIS-Sediment for sediment transport and channel change through erosion and deposition, and iSIS-Quality for water quality and water temperature. iSIS flow creates the flow hydraulics used in all these models, and can simulate both steady and unsteady flows. An adaptive timestep can be used to optimise model run time and to enhance model stability to produce more accurate and robust results (Evans *et al.,* 2007). It can also model simple flood routing, when fewer data are available, through equations such as Muskingham-Cunge. Channel structures, such as bridges, sluices and weirs can also be represented in multiple ways by standard equations. It is based in a Microsoft Windows framework and can be integrated with GIS. This provides one of its many interactive visualising capabilities, aided by georeferencing of the river network. Data inputs and model results can also be viewed for individual cross sections, the long profile and as time-series.

The data needs of iSIS-Flow are similar to most 1D hydraulic models and are; (1) channel topographic data; (2) initial and boundary conditions; (3) floodplain topographic data; (4) channel roughness information; and (5) validation and calibration data. Channel cross sections are needed especially at the upstream and downstream end of channel structures like bridges, at changes in channel slope or width (>20%), at locations where flow data is available and at confluences. The spacing of channel cross sections is also a critical factor and was investigated by Burnham and Davies (1990) to assess the errors introduced by lowering cross section resolution and survey inaccuracies. Samuels (1995) related cross section spacing to channel slope and recommended the values in Table 5.5.

Channel Slope (m/km)	Section Spacing (m)
3.3 – 1.0	75
1.0 – 0.3	200
0.3 – 0.1	500
< 0 .1	1000

Table 5.5 *Cross Section Spacing Recommendations in 1D Hydraulic models*

Initial conditions for hydraulic models consist of flow inputs from the start of the reach and any tributary inputs. A steady flow simulation requires the flow at the start of the period of investigation. The output of this steady simulation may then provide the initial conditions to an unsteady simulation. The boundary conditions include the whole input hydrographs for any tributaries and also a rating curve which relates stage to discharge at the end of the modelled reach.

iSIS-Flow allows the floodplain to be represented in several approaches. The simplest approach is just an extension of the channel cross sections, with different roughness parameter values used for the channel and the floodplain. A limitation of this approach in iSIS is that an implicit assumption of the model is that the water level is equal throughout the whole cross section, meaning that separated channel areas are filled even if they are not connected to the flow. An extension of this approach is when regions of storage are given conveyance values of zero. Another way in which the floodplain can be represented is if there are spill units at the top of the channel banks connecting the channel to the floodplain, which can either be represented by a parallel channel or storage / reservoir units (Lin, 2006). This approach is a more accurate representation, but is more computationally demanding. Information is also needed on the roughness of both the channel and the floodplain throughout the modelled reach. These values are often derived from comparing photographs of the river of interest with photographs and descriptions of published values (Chow, 1959; US Army Corps of Engineers, 1995;

Hicks and Mason, 1998). Finally data are needed to validate and to calibrate the model. Usually discharge or stage data are used.

The iSIS model works by solving the 1D continuity and St. Venant momentum equations outlined in Section 5.3.1 (pg. 168), for every node and all timesteps. iSIS uses a matrix solver to calculate the properties of the flow over the whole river in one go. To do this, several iterations are often needed to converge on a stable answer, whereby a linear approximation is made using the previous state to predict the next answer. This iterative process continues either until the previous iteration answer is less than 0.01 different to the current iteration, or the number of iterations reaches the maximum number, which is six by default. If this process does not produce a stable answer, then non-convergence is reported, which is a sign of model instability. This is assessed by the Courant number (C) which is calculated by the following equation:

$$C = \frac{V \cdot \Delta t}{\Delta x}$$

Where V = velocity

Δt = change in time

Δx = cross section spacing

This implies that a small time difference is needed for cross sections which are close together. While the answer to the Courant equation is greater than one, the timestep is kept the same, if it falls below one then the timestep is reduced.

For steady flow in iSIS, the St. Venant and Continuity equations are simplified, as changes through time (δ/δt) can be ignored. The “direct method” uses ordinary differential equations to solve the numerical model, while the “pseudo-timestepping method” uses the full equations but with a constant discharge (Q). The “direct method” is preferred as it is the quickest. Additional cross sections can be used to improve model stability. The flow resistance is calculated using the Manning equation, which takes the following form:

$$S_f = \left[\frac{nQ}{AR^{\frac{2}{3}}}\right]^2$$

Where S_f = Friction slope

n = Manning's roughness parameter

Q = Discharge

A = Cross section area

R = Hydraulic Radius

This indicates that as the parameter n is doubled then the friction slope is quadroupled, with the corresponding changes in head loss (h), calculated by the Bernoulli loss equation:

$$h = \frac{KV^2}{2g}$$

where K = Energy loss (Bernoulli)

V = Velocity at upstream and downstream nodes

g = acceleration due to gravity

Head loss in this case is the change in water stage due to a change in the channel characteristics e.g. width/ roughness. This equation is particularly applicable to calculating the head loss caused by channel structures like bridges (Atabay, 2007). The following section will outline details of the downscaling approach and the specific iSIS model constructed for the River Eden.

5.3.3. Downscaling Methodology

A catchment scale hydraulic model, which incorporates the major tributaries of the Upper Eden, Eamont, Irthing, Petteril and Caldew (Figure 3.16) (the same as the statistical approach) will be developed from an existing model sourced from the Environment Agency. The inputs to each tributary will be the hydrograph from a flood event. The modelling experiment will consist of changing these inputs in terms of both the magnitude of the flows and the timing of the flows. For the magnitude of the flow, the individual sub-catchment's hydrograph will be reduced by the values shown in Table 5.6.

Magnitude Scenarios (%)	Timing Later Scenarios (Hours)	Timing Earlier Scenarios (Hours)
0.1	+0.25	-0.25
0.5	+0.5	-0.5
1	+1	-1
2	+2	-2
5	+3	-3
10	+4	-4
15	+6	-6
20	+8	-8
25		

Table 5.6 *Hydrograph shift scenarios in terms of magnitude and timing*

This means that there are a total of 45 simulations (nine magnitudes for five tributaries). For timing, the hydrographs of individual sub-catchments will be shifted both forwards and backwards, meaning that the peak flows occur earlier and later. The time shifts are shown in Table 5.6 and total 80 simulations, 40 for delays and 40 for tributaries peaking earlier. There are eight scenarios for the five sub-catchments. The effect on the peak flow will be assessed by calculating the percentage change. Scenarios involving more than one of the major tributaries will also be tested, as well as experiments including both timing and magnitude shifts simultaneously. This is because it may be easier to change the flows from more than one sub-catchment by a smaller amount and still achieve the same effect as shifting one sub-catchment by a large amount. Furthermore, it is very unlikely that land use change scenarios will affect either the magnitude or the timing of the flows (Thomas and Nisbet, 2007). Land management scenarios, especially floodplain storage will most likely cause flows to be attenuated, meaning that high flows are both reduced in terms of magnitude and delayed in terms of timing. However, the process of attenuation does not function by just delaying and reducing the peak flow, it changes the shape of the hydrograph. Therefore, two methods of simulating the effect of attenuation of peak flows are proposed. First, the hydrograph can be stretched in the terms of time and squashed in terms of flow magnitude simultaneously, through:

$$Magnitude = Original \times Change\ factor$$

$$Time = Original \div Change\ factor$$

The second approach to simulating attenuation, was to start to store water after a certain time, by subtracting a certain percentage of the flow and then add this stored water back into the river at a rate proportional to the total amount of water. Both these scenarios maintain conservation of mass, but the period over which the water volume occurs is changed.

The modelling downscaling approach differs from the statistical approach as it uses a whole flood event hydrograph rather than just the peak flow. However, the benchmarking approach of using two separate methods for the same purpose will allow comparison of the results from the two downscaling approaches to determine which the optimum sub-catchments to focus flood management resources are.

5.3.4. Eden iSIS-Flow model

The Eden iSIS model is thought to be the first operational real time hydrodynamic model in the UK, and was developed by Atkins in 1999. The original model takes inflows from the Eamont and the Upper Eden and routes them down to Great Corby using the muskingham-cunge method (Cunge, 1969; Price, 1978). From Great Corby the model is a 1D hydraulic model, with inputs from the major tributaries of the Irthing, Petteril and Caldew (Chen, 2007). The model consisted of 950 nodes, such as channel cross sections, reservoir units, spill units and structures. The model can forecast 12 hours ahead, but is more reliable for 6 hours ahead with peak levels being predicted to ±0.1m at 6 hours, although prediction of the timing of the peak flow can be in error by up to 3 hours. This model had performed well for floods before the January 2005 event. In January 2005, the peak was underestimated by 1 metre or 450 m^3s^{-1} (Spencer et al., 2007). The model was then improved by the Environment Agency by improving the rating relationships for the flow inputs and using new topographic data. The rating equation changes were reported in Section 3.4.7 and were found by Spencer et al., (2007) to improve the accuracy of the model by 0.5m. However, the improved model, of 1100 nodes still had an error of 0.3m in its prediction of the peak stage for the January 2005 event. This model is the starting point for the hydraulic model development.

This section will outline the needs that the model must fulfil and how the model was developed to achieve these. It is essential that the model includes inputs from the five major sub-catchments, so that each can be tested in terms of its impact on flows through Carlisle. This is a problem in the original Environment Agency model, as the inputs from the major tributaries were not easily identifiable. For example the Environment Agency model was calibrated by adding water into the Eamont hydrograph to account for minor tributary inputs between the Eamont and Upper Eden confluence, such as Raven Beck and Croglin Water. Another objective for the model is that it should have good stability during the simulation, especially at the flood peak. This will be assessed using the model output for model convergence, which should be below the threshold of 0.001, and iterations per timestep, which should be lower than the 15. Model performance also needs to be assessed. This will be achieved through using the simulated stage record compared to the observed stage record. Stage is used instead of discharge, as it reduces the number of sources of error, as the uncertainty introduced by the rating curve is eliminated. As the focus is on the city of Carlisle and the impacts of the five major tributaries, the main station used for validation will be Sheepmount, which is located after the confluences of the major tributaries. Furthermore, the errors associated with this station were found to be minimal in Chapter 3. However, other stations will also be used, namely Great Corby and Linstock. Great Corby is located in the Lower Eden, but before the confluence with the Irthing, while Linstock occurs after the confluence with the Irthing, but before the confluence with the Petteril. It is important to use multiple stations to assess model performace, as it will ensure all reaches of the system as suitably represented and tributary interaction is accurate. The most important feature of the hydrograph will be the timing and magnitude of the peak stage, as this contributes to the severity of flood risk and was also included in the statistical downscaling methodology, so allows comparison. Therefore, the model will be calibrated for the January 2005 flood event, using the 14 indices outlined in Table 2.1, but more weight will be given to the error on the timing and magnitude of the peak flow.

5.3.5. Model Development

It was decided to build the model from scratch using the cross sectional data from the Environment Agency model. This was because the tributary inputs were unidentifiable and the model would not run properly. Model development was undertaken in a stepwise fashion so that after each iteration model performance could be assessed. First, the main stem of the River Eden was added to the iSIS-Flow interface using cross section units, from Great Corby downstream. Then, the Irthing, Petteril and Caldew inputs were added sequentially. These were represented by gauging stations at Greenholme, Harraby Green and Cummersdale respectively. The model was set up for the January 2005 flood event in the Eden catchment. These flow inputs were represented in the model as a QT (Discharge-Time) boundary. At the downstream end of the model (Solway Firth), the boundary condition consisted of a QH (Discharge-Head) boundary, which is specified as a discharge-stage rating curve. The effects of minor tributaries were then accounted for by adding in more QT boundary units for each one, which were generated using the ReFH method (Kjeldsen, 2005; 2007). The spreadsheet version of the model required input of catchment descriptors and details of the design rainfall event to be modelled. This followed the depth-duration model of Faulkner (1999). For this, the return period and duration of the event had to be specified. The spreadsheet macro then used these parameters and values to calculate the storm hydrograph generated for the rainfall event. Floodplain storage was then added, firstly on the right bank of the Eden only, then storage on the left bank and tributaries. This would increase and delay the peak stage through attenuation.

The next step was to separate the contribution from the upper catchment, the Eamont and Upper Eden, with Udford being used to represent the inflows from the Eamont and Temple Sowerby for the Upper Eden. However, there were no cross sections between the Eamont-Upper Eden confluence and Great Corby. This reach of the river had to be represented by flood routing units using the Muskingham-Cunge algorithm. This was done by iSIS through a Muskingham cross section unit which uses the upstream cross section to derive the wavespeed and attenuation parameters. A schematic of the final model structure is given by Figure 5.2.

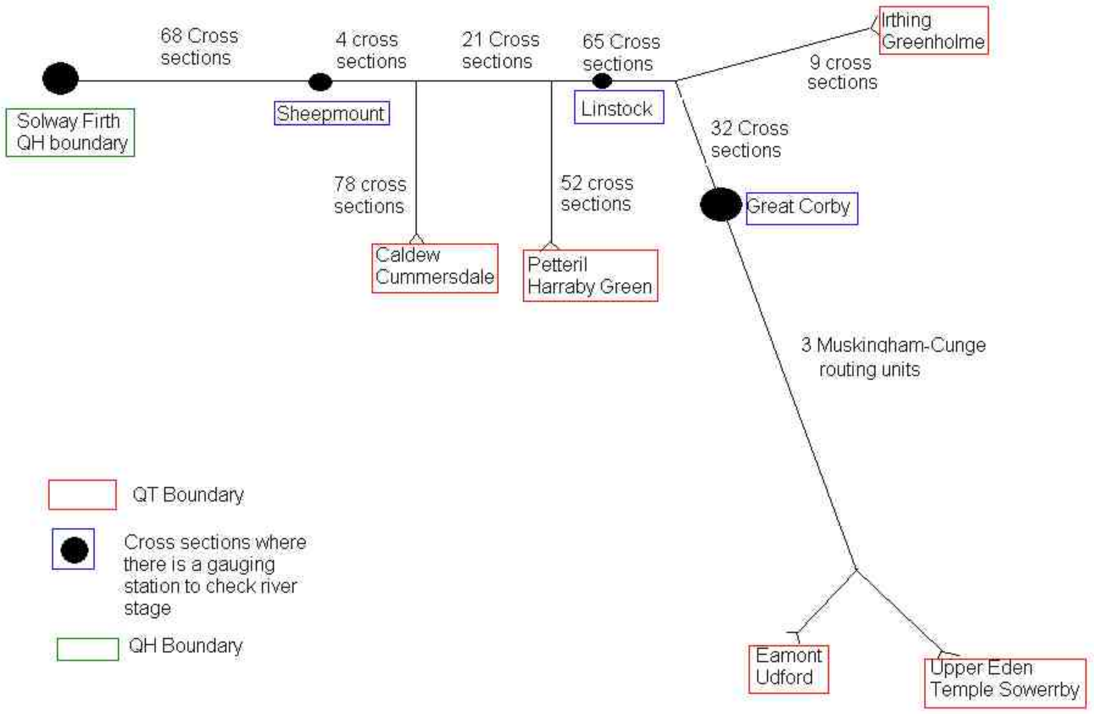


Figure 5.2 *Schematic of Full Eden model structure*

5.3.6. Model assessment

This section outlines the performance of the model at various stages in the model development and discusses what the results mean in terms of which sub-catchment contributes most to the January 2005 flood. Simulations start at midday on the 7th January.

Figure 5.3 shows the model output at the Sheepmount gauging station compared to the measured data in terms of stage for several steps in the model building process. With just the main Eden and the inflow from Great Corby included, the peak of the flood event was underestimated by 1.77 m (12.5%) (Table 5.7). Each major tributary was added sequentially, starting with the Irthing (Greenholme), then the Petteril (Harraby Green) and finally the Caldew (Cummersdale). The effect of adding the Irthing on model performance was not significant, with the volume of the event only increasing by 1.18% and the peak increasing by only 0.34%. However, the effects of the Petteril and the Caldew were greater, with the simulation of the peak stage improved by 4.07% by adding the Petteril and another 3.11% by including the input hydrograph from the Caldew. This suggests that the Petteril and Caldew were more important than the Irthing in contributing to the January 2005 flood in Carlisle. The volume of water under the hydrograph for the simulation including all the main tributaries is nearly the same as the actual hydrograph (obs = 755.5, sim = 754.8). However, the shapes of the measured and predicted hydrographs are different and they are particularly different in terms of timing (-18.85% error on peak time). The simulation with just right bank storage predicted the magnitude more accurately than the model with full storage, but the timing of the peak was still -9.84%, while with all storage it was only an hour late (3.28%). A reason why the maximum peak stage is never reached is likely to be the lack of tidal effects being represented in the model, as the January 2005 flood was influenced in Carlisle by water being backed up due to tidal influences.

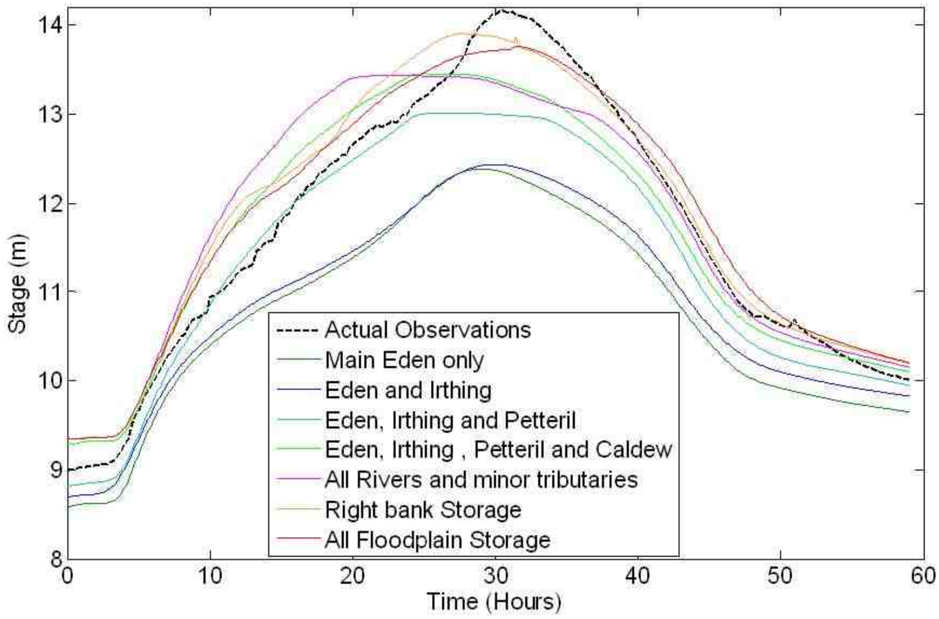


Figure 5.3 *Hydrograph for January 2005 flood at Sheepmount compared to model simulations*

The performance of the model at various stages of development is shown in Table 5.7 and assessed in detail here. The performance of the model with full storage had a Nash-Sutcliffe model efficiency value of 0.96. However the Nash-Sutcliffe index of the model without any storage was 0.93. These values are very similar, even through the shape of the hydrograph for the simulation without storage is dissimilar to the observed hydrograph. This relates to the weakness of the Nash-Sutcliffe index noted by Garrick et al. (1978), where model efficiency does not improve much with much better fitting models. The RMSE value for the model with full storage is ±0.28m, which is well within the performance of other comparable hydraulic models in the literature. For example Neal et al., (2009), using LISFLOOD-FP for the Eden catchment had a maximum RMSE value of ±0.32 m, although this study used flood inundation extents to assess model performance.

	Eden Only	Eden + Irth	Eden + Irth + Pet	Eden + Irth + Pet + Cal	All Rivers and Tribs	Right bank Storage	All Storage
Sum of Squared Residuals	265.16	213.28	54.69	39.75	62.69	26.18	19.14
Sum of Absolute Residuals	227.24	196.26	83.23	4.78	-29.05	-44.25	-40.88
Nash-Sutcliffe Model Efficiency	0.51	0.60	0.90	0.93	0.88	0.95	0.96
Normalised Objective Function	0.09	0.08	0.04	0.04	0.04	0.03	0.02
RMSE	1.06	0.95	0.48	0.41	0.52	0.33	0.28
Reduced Error Estimate	0.70	0.63	0.32	0.27	0.34	0.22	0.19
Proportional Error of Estimate	1.28	1.13	0.57	0.50	0.65	0.44	0.38
Standard Error of Estimate	1.06	0.95	0.48	0.41	0.52	0.33	0.29
% Error in Peak Stage	-12.49	-12.15	-8.08	-4.97	-5.07	-1.79	-2.82
% Error in Peak Time	-4.92	-2.46	-16.39	-18.85	-22.13	-9.84	3.28
% in Stage Mean	-8.19	-7.07	-3.00	-0.17	1.05	1.59	1.47
Area for Observed	626.17	626.17	626.17	626.17	626.17	626.17	626.17
Area for Simulated	567.12	575.97	604.96	625.47	634.25	638.30	637.51
% Error in Volume	-7.82	-6.64	-2.81	-0.09	1.07	1.60	1.50
Variance	1.12	0.90	0.23	0.17	0.26	0.11	0.08
Mean Deviation	0.96	0.83	0.35	0.02	-0.12	-0.19	-0.17

Table 5.7 *Goodness of fit statistics for steps in model development*

The next step in the model development was to represent the Eamont and Upper Eden as two separate inputs. Figure 5.4 shows the simulated hydrographs as compared to the observed hydrograph at Sheepmount gauging station in Carlisle, when these two tributaries are represented separately. It is clear that the shape of the hydrographs, using the Manning's n values shown in Figure 5.4, is dissimilar from the observed hydrograph, with the peak stage being extended over a long period rather than having a well defined peak. As the only change to the model was the representation of the river network upstream of Great Corby, it was thought sensible to check the stage at Great Corby (Figure 5.5). Figure 5.5 shows that the predicted peak at Great Corby was about 10 hours late, meaning that the flows from the upper catchment were occurring after the peak stages from the lower sub-catchments, rather than combining with them, meaning that the period of high stages was extended but lower in magnitude (Figure 5.4).

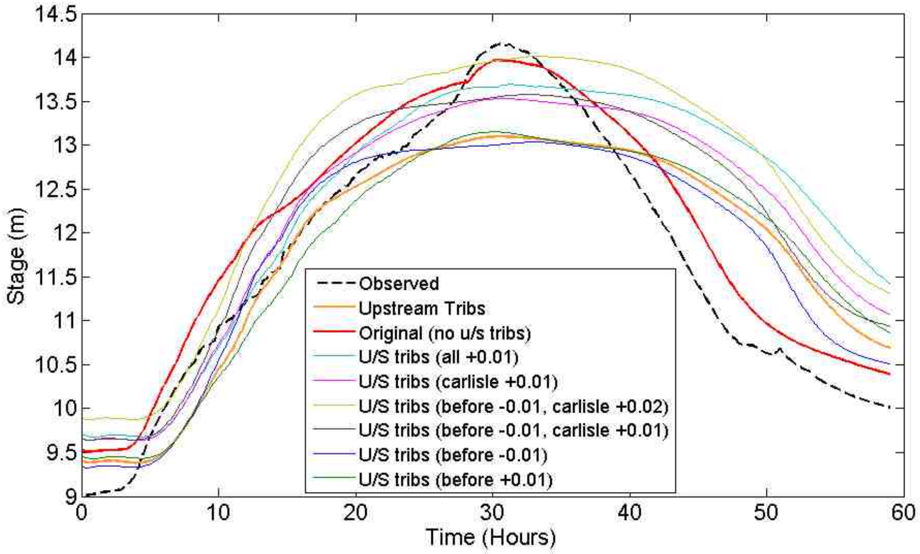


Figure 5.4 *Sensitivity analysis of Sheepmount hydrograph to Manning's n. Simulations represent changing Manning's n in different reaches of Eden. e.g. U/S tribs (before -0.01, Carlisle +0.01 = Manning's n decreased by 0.01 before Carlisle and increased by 0.01 in Carlisle itself.*

To overcome the problem of the main River Eden peaking too late at Great Corby, the model simulation was started earlier, so that the model could stabilise before the main flood event started. Therefore, the model simulation now started at 00:00 on the 7th January 2005 and ran till 23:45 on the 9th January 2005, so the model run was now 71.75 hours in duration. Figure 5.6 shows the effect of starting the simulation earlier, and there is now greater coincidence of the simulated flood peak with the observed flood peak at Great Corby, so that the error is only 2.88% (0.75 hours). This is because the event starts earlier for the upstream tributaries, so the simulation needs to be started earlier.

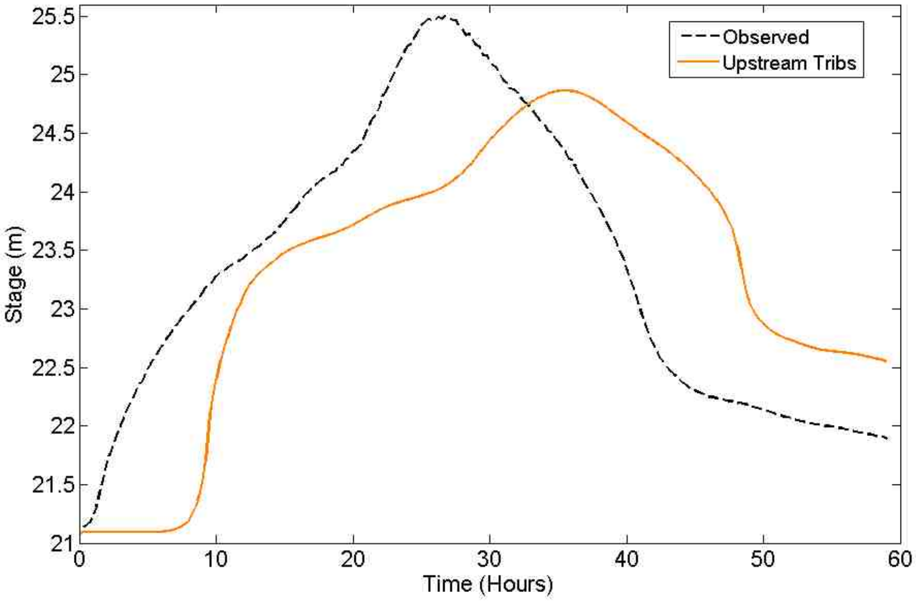


Figure 5.5 *Simulated and Observed Hydrograph at Great Corby*

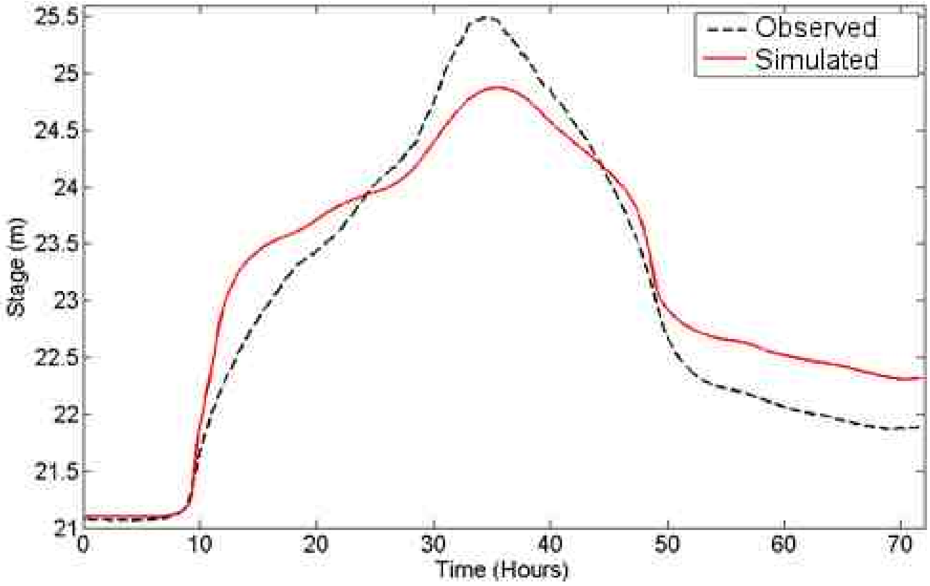


Figure 5.6 *Simulated and Observed Hydrograph at Great Corby for longer time period*

5.3.7. Model Calibration

The calibration of the model was undertaken using the Manning's n parameter, as the model is highly sensitive to changes in its value. Lane (2005) highlights the crucial value of roughness in 1D hydraulic models in compensating for inadequacies in process representation. Manning's n is the roughness parameter and it controls the resistance to downstream flow. Therefore, increasing Manning's n reduces conveyance, with local stage increasing as a result. Manning's n values vary at each cross section in the model, with different values for the channel and floodplain. Changes in Manning's n could be done: (1) globally; (2) before Sheepmount; (3) after Sheepmount; (4) at Sheepmount (between CaldewConJD and Etterby Scauer 2) (Figure 5.7).

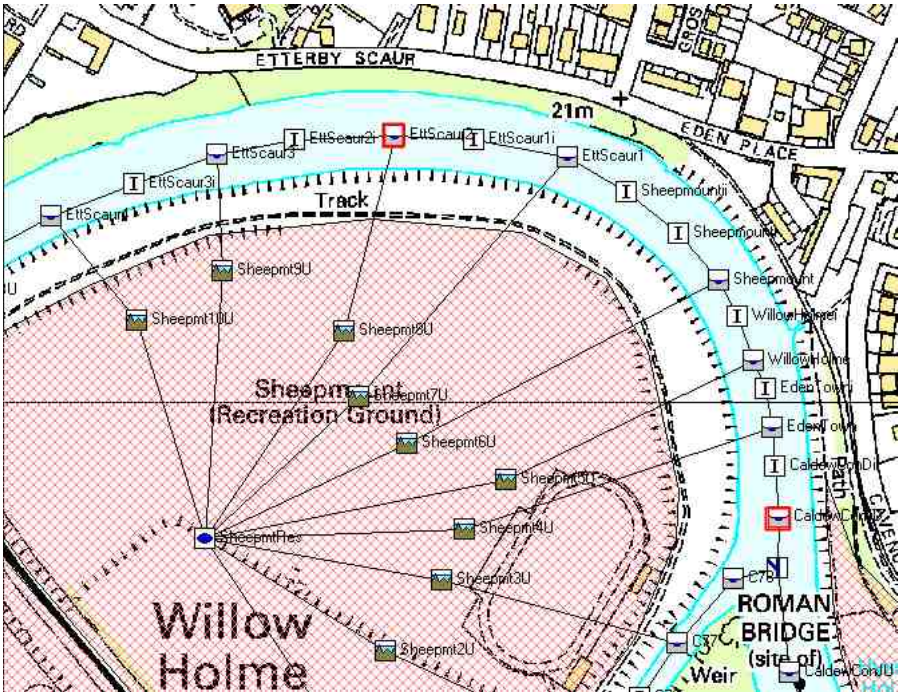


Figure 5.7 Schematic of the Eden iSIS model showing reservoir units representing floodplain storage

To increase peak stage at Sheepmount several changes to Manning's n were considered: (1) if roughness was increased at Sheepmount itself; (2) if roughness upstream of Sheepmount was decreased, so that water would reach Sheepmount faster; and (3) if roughness was increased downstream of Sheepmount, conveyance would be reduced after Sheepmount. These scenarios were tested in isolation and in combination by changing Manning's n by a range of 0.01 to 0.02. This range of changes was decided upon, as it was shown that small shifts in Manning's n had significant impacts on the stage hydrograph. Hydrographs were primarily compared for the Sheepmount station, but Great Corby and Linstock were also used.

Figure 5.8 shows the visual comparison of observed stage and simulated stage for Sheepmount. When Manning's n was increased by 0.01 in Carlisle (0.05 for channel, 0.075 for floodplain), the peak stage was more closely matched, with an error of -5.27% and -1.19% in terms of magnitude and timing respectively. However, when the roughness in Carlisle was increased by 0.02, the peak stage was over-predicted by 1.73%. Changes to Manning's n coefficient before and after were combined with these two changes in Carlisle itself and the results are shown in Figure 5.8. The hydrograph produced by increasing roughness before and in Carlisle by 0.01 produced a similar result to just increasing roughness in Carlisle itself. Although these scenarios had a lower Nash-Sutcliffe coefficient and a higher RMSE than the original Manning's n simulations, the peak of the event was better predicted in terms of both magnitude and timing for these simulations. For the simulation with roughness increased by 0.01 before and in Carlisle, the prediction of the peak stage was -1.5% in terms of magnitude and 3.3% in terms of timing.

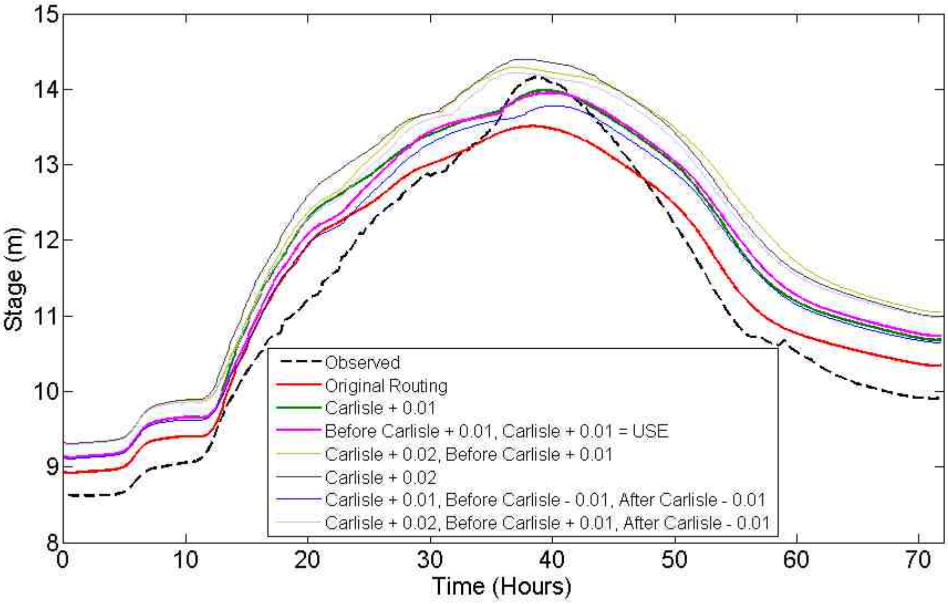


Figure 5.8 *Sensitivity analysis of Sheepmount hydrograph to Manning's n over longer time period*

	Original	Carlisle +0.01	Before +0.01, Carlisle +0.01	Carlisle +0.02, Before +0.01	Carlisle +0.02	Carlisle +0.01, Before -0.01, After -0.01	Carlisle +0.02, Before +0.01, After -0.01
Sum of Squared Residuals	43.92	129.34	128.18	282.69	282.15	96.11	222.37
Sum of Absolute Residuals	-61.63	-170.86	-168.80	-266.34	-271.53	-136.80	-236.78
Nash-Sutcliffe Model Efficiency	0.95	0.84	0.85	0.66	0.66	0.88	0.73
Normalised Objective Function	0.03	0.06	0.06	0.09	0.09	0.05	0.08
RMSE	0.39	0.67	0.67	0.99	0.99	0.58	0.88
Reduced Error Estimate	0.23	0.40	0.39	0.58	0.58	0.34	0.52
Proportional Error of Estimate	0.60	1.07	1.06	1.56	1.55	0.93	1.40
Standard Error of Estimate	0.39	0.67	0.67	0.99	0.99	0.58	0.88
% Error in Peak Stage	-4.56	-5.27	-1.45	0.96	1.73	-2.61	0.45
% Error in Peak Time	-0.65	-1.19	3.25	-5.19	-3.25	3.90	-4.55
% in Stage Mean	1.90	1.07	5.20	8.21	8.37	4.22	7.30
Area for Observed	808.65	808.65	808.65	808.65	808.65	808.65	808.65
Area for Simulated	823.96	851.20	850.68	875.00	876.31	842.69	867.62
% Error in Volume	1.89	5.26	5.20	8.21	8.37	4.21	7.29
Variance	0.15	0.45	0.45	0.98	0.98	0.33	0.77
Mean Deviation	-0.21	-0.59	-0.59	-0.92	-0.94	-0.48	-0.82

Table 5.8 *Full Eden model calibration for Sheepmount gauging station*

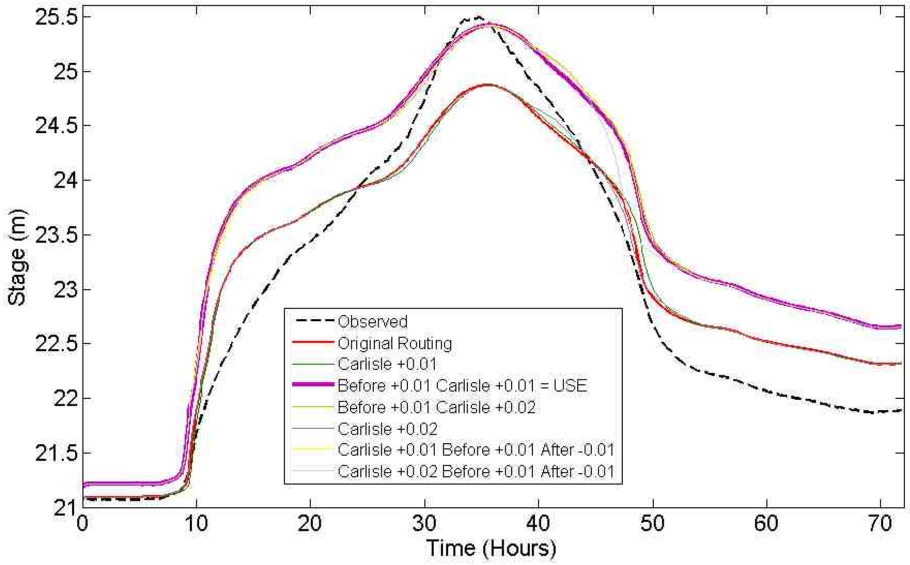


Figure 5.9 *Sensitivity analysis of Great Corby hydrograph to Manning's n over longer time period*

To assist the decision over which model is best to use, either the +0.01 in Carlisle only or the +0.01 upstream of Sheepmount and in Carlisle, it is important to assess the performance of the model at gauging stations upstream of Carlisle. This is because the model is going to be applied to simulating the downstream effects of upstream changes, so catchment interactions have to represented correctly. Figure 5.9 shows the stage hydrographs for Great Corby. There are two groups of simulations on Figure 5.9, the higher curves are simulations where the roughness before Great Corby has been increased by 0.01. This makes the flow resistance greater and means that the stage rises in this part of the channel. The lower simulations on Figure 5.9 are ones where the roughness before Great Corby has been left the same, so that the water travels down this reach of the Eden faster and therefore has a lower peak stage. There is very little difference between the two groups of simulations in terms of timing. This is because the river channel between the QT boundary and Great Corby consists of Muskingham-Cunge routing units.

The predicted stage hydrographs from Great Corby indicate that the best model to use is the model with Manning's n increased by 0.01 both upstream of Carlisle and in Carlisle. This is because the model with Manning's n increased by 0.01 in Carlisle only does not represent the stage at Great Corby very well.

The goodness of fits statistics for this calibrated model (roughness increased by 0.01 upstream of Carlisle and at Sheepmount) are shown in Table 5.9 for the gauging stations at Sheepmount, Great Corby and Linstock. However, the assessment using the Linstock gauging station is limited to only the 44.5 hours of the simulated event, as battery power was lost at the Linstock station between 08/01/2005 21:45 and 10/01/2005 15:00. However, as Figure 5.10 shows the peak of the flood has occurred at 37.75 hours, so it is just the falling limb which is missed. The simulated hydrograph also shows the peak has passed and it is just the falling limb that cannot be assessed in terms of accuracy.

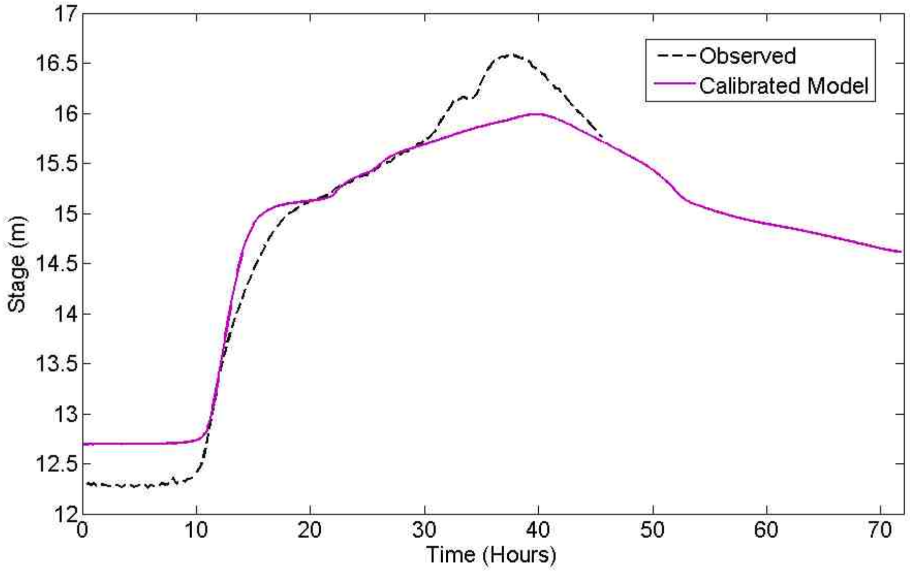


Figure 5.10 *Sensitivity analysis of Linstock hydrograph to Manning's n over longer time period*

The RMSE of the chosen calibration at Sheepmount is ±0.67 m, while the Nash-Sutcliffe coefficient is 0.85. The performance of the model at Great Corby is also good, with a RMSE of ±0.67 m and a Nash-Sutcliffe of 0.75. The prediction of the peak stage is even better, with an error of -0.31% in terms of magnitude and 2.88% in terms of timing at Great Corby. At Linstock, the RMSE error is ±0.32 m and the Nash-Sutcliffe coefficient is 0.96, while the prediction of the peak stage has an error of -3.56% and 5.3% in terms of magnitude and timing respectively. These are all within cited recommended limits of model performance (Roughani et al. 2007; Wu and Johnston, 2008). However, any error in water level gives larger errors in predicted damages that will occur from flooding.

	Sheepmount	Great Corby	Linstock
Sum of Squared Residuals	128.18	130.99	19.03
Sum of Absolute Residuals	-168.80	-166.31	-3.70
Nash-Sutcliffe Model Efficiency	0.85	0.75	0.96
Normalised Objective Function	0.06	0.03	0.02
RMSE	0.67	0.67	0.32
Reduced Error Estimate	0.39	0.50	0.21
Proportional Error of Estimate	1.06	0.51	0.31
Standard Error of Estimate	0.67	0.68	0.32
% Error in Peak Stage	-1.45	-0.31	-3.56
% Error in Peak Time	3.25	2.88	5.30
% in Stage Mean	5.20	2.51	0.14
Area for Observed	808.65	1651.09	670.14
Area for Simulated	850.68	1692.56	671.02
% Error in Volume	5.20	2.51	0.13
Variance	0.45	0.45	0.10
Mean Deviation	-0.59	-0.58	-0.02

Table 5.9 *Goodness of fits statistics for calibrated Full Eden model at Sheepmount, Great Corby and Linstock.*

The performance of the calibrated model needs to be good throughout the whole network, so that the tributary interactions are accurately represented. This is necessary as the hydrographs from these sub-catchments are going to be altered in the model application of spatial downscaling downstream flooding to the contributing sub-catchments. These goodness of fit statistics indicate that the calibrated Eden iSIS model performs well at the downstream point of Sheepmount, with a 0.208 m and 1 hour error on the magnitude and timing of the peak stage respectively. This converts to a 76 m^3s^{-1} (1519 m^3s^{-1} to 1443 m^3s^{-1}) error in peak discharge (5.0%). At Great Corby the model also performs relatively well, with an error of 0.079 m and 0.83 hours on the magnitude and timing of the peak stage. This corresponds to a 15 m^3s^{-1} error in terms of peak discharge (854 m^3s^{-1} to 839 m^3s^{-1}) (1.8%). However, at Linstock the model performs less well, with an error of 0.59 m and 1.83 hours. There is no rating curve at Linstock to assess the effect on flow. The accuracy of the Linstock gauged record is questionable, as it stopped working soon after the peak stage. Overall, the model is fit for its purpose, and when interpreting the results, the poorer performance of the model at the Linstock station will be considered.

5.4. Chapter Summary

This chapter has outlined two methodologies to downscale catchment scale flood hazard to the contributing tributaries. The first used gauged data, and the multivariate approach of principal components analysis and stepwise regression to predict downstream flood magnitude from the relative timings and magnitudes of the peak flows from the five major sub-catchments. The second consisted of a numerical hydraulic (iSIS) modelling approach, where the sensitivity of downstream flooding could be explored in terms of the magnitudes and the timing of high flows from the sub-catchments. Firstly the theory behind general hydraulic models was explained, before giving details on the industry developed iSIS model. Model development for the whole Eden river network was then detailed, including model assessment. Once the model performance had been evaluated and optimised through calibration, the model could be applied to the problem of determining the dominant sub-catchments in causing downstream flooding in Carlisle. The experimental design was then outlined, whereby the input hydrographs were shifted both in terms of magnitude and timing, and the effect on downstream peak stages assessed.

The benefits of using either one of these downscaling approaches are threefold. First, as stated previously, the optimum sub-catchment in terms of magnitude and timing which affects downstream flood risk can be determined. This links to the second benefit, which is that once the dominant sub-catchment has been identified, it can be focussed upon in future analysis and therefore make the use of time and resources more efficient. Traditional hydrological modelling can be used on a smaller sub-catchment scale which also has advantages to whole catchment models, such as model run-time reduction. The third and most important advantage of using either of the downscaling approaches is that targets can be found for how much flows from each sub-catchment have to be changed to have the desired effect on flooding downstream. Specifically an objective for downstream flood reduction can be set, and then downscaled to the contributing sub-catchments, where targets for hydrograph change in terms of flood peak magnitude and timing can be determined which will deliver the required downstream effect. Chapter 6 reports the results of the two spatial downscaling approaches outlined in this chapter to determine which sub-catchment to focus on for the rest of the thesis.

Chapter 6

Identifying where to focus land management change for optimum flood risk reduction

6.1. Chapter Scope

The previous chapter outlined two methodologies for the spatial downscaling of catchment scale flooding to the upstream contributing sub-catchments. The results of both the data-based statistical and the hydraulic model-based spatial downscaling approaches are reported in this chapter. Both these approaches assume that the magnitude and relative timing with respect to Carlisle of the peak flows are the factors which influence downstream flood magnitude. The first section (6.2) of this chapter reviews why these two factors might be important in determining catchment scale flooding, before assessing sub-catchment behaviour in the Eden and how the sub-catchments interact to cause downstream flooding. This is done by: (1) analysing the distributions of these variables for the major sub-catchments for the gauging stations outlined in Chapter 3; (2) assessing the sensitivity of downstream flood magnitude to sub-catchment peak flow magnitude and timing through simple variable correlation; and (3) comparing the January 2005 flood with the long term average flood event, yielding insights into why this flood was so extreme. Section 6.3 presents the results of the statistical downscaling approach, whereby principal components analysis is used to simplify sub-catchment interactions before stepwise regression is used to predict downstream flood magnitude. The uncertainties of this prediction are considered using both bootstrapping and alternative rating relationships to derive new estimates of sub-catchment peak magnitudes. Section 6.4 details the results of the hydraulic modelling downscaling methodology. Section 6.5 compares the results from the two spatial downscaling approaches, before the results are used to determine which sub-catchment to focus further analysis on in Section 6.6. The reasons for the chosen sub-catchment are then justified both in terms of the results outlined previously in this chapter, data needs for land use change modelling and practical knowledge of the sub-catchment.

6.2. Flood characteristics at the catchment and sub-catchment scales

Downstream flood risk is obviously caused by the quantity of water flowing from the sub-catchments, but another factor that has been considered less in past studies is the timing of the flows from each sub-catchment. There are four main exceptions; First, in the "Wise Use of Floodplains" project on the River Cherwell, Acreman *et al*. (2003), calculated time delay of tributaries peak flows. They found that both floodplain storage and channel restoration had the potential to attenuate the hydrograph, although only a negligible effect was seen on peak flow, with more of an impact on the timing of the peak flow. Second, the Ripon Land Management Project (JBA, 2007) acknowledged that the timing of the flood peaks and how the flows combined in the main river would influence the magnitude of the flood downstream, but found that land management changes altered timing of flows only slightly. This research used a combination of a PDM model and a hydraulic model for the River Skell and Laver. It was found that certain land management measures could significantly change localised flows in headwater catchments, but the effect at the catchment scale was highly dependent upon the precise scenario and location it is implemented. For example grip blocking was seen to cause 8% decrease on flood magnitude and changed the time of the peak flow by 1.5 hours, which may alter tributary synchronisation. Third, a hydraulic modelling study for the River Parrett (Thomas and Nisbet, 2007) found that floodplain woodland may have a potential role in downstream flood alleviation. The reach scale effects of planting riparian woodland were simulated and it was found that flood storage increased by 15-71% and that flood peaks could be delayed by 30 to 140 minutes, as water velocity was reduced by about 50%. Furthermore local stage was increased by 50-270mm causing significant backwater effects up to 400 m upstream. This land management approach changes the floodplain roughness and slows peak flows. Therefore the modelling strategy was to change the floodplain Manning's n parameter. A significant finding from this research was that a small area relative to the catchment size could achieve significant changes in the propagation of flood flows. However, although Thomas and Nisbet (2007) stated that this change could desynchronise sub-catchment contributions, the effect of this land management change on the catchment scale at the downstream outlet was not assessed. The fourth study was by Lane (2003) on the River Ouse in Yorkshire, which analysed the thirty largest floods between the early 1990s and 2001. The most important tributaries in terms of both the magnitude and timing of the peak flow were identified through the multivariate technique of principal components analysis. Flow magnitudes accounted for 77.9% of the downstream flood peak variability, whilst relative timing also emerged as a crucial control on downstream flows, explaining 11.2%. The sequencing of sub-catchment response was therefore highlighted as being significant.

The main hypotheses proposed to impact flooding, climate change and land management change, imply the need to consider the timing of sub-catchments peak flows and therefore how sub-catchments interact to result in downstream flooding. Climate change could result in a systematic shift in the dominant direction of rain-bearing cyclones and therefore the spatial-temporal pattern of precipitation and land management change could alter the runoff rate and lead to a faster or slower hydrological response.

The next section assesses the distributions of the peak flow magnitudes and relative timing with respect to the downstream gauging station of Sheepmount in Carlisle of each of the five major sub-catchments. All the analysis within this chapter uses data evaluated in Chapter 3 and the data given in Appendix A.

6.2.1. Sub-catchments interactions during flood events - Magnitudes

The descriptive statistics of the magnitudes of the peak flows of all the major tributaries are given in Table 6.1. These statistics are derived for the POT events at Sheepmount gauging station. Figure 6.1 shows that the downstream gauging stations on the main River Eden have the broadest range of peak flows (Warwick Bridge = 673.5 m^3s^{-1}, Sheepmount = 1164.9 m^3s^{-1}). The flows from the five major sub-catchments are similar in terms of their magnitude, with the Upper Eden (Temple Sowerby) having the largest mean peak flow reflecting its greater catchment area. The mean flow of the Eamont (137.1 m^3s^{-1}), Irthing (106.0 m^3s^{-1}) and Caldew (103.6 m^3s^-1) are similar, while the Petteril has a considerably lower average peak flow (25.7 m^3s^{-1}). Peak flows from the Upper Eden, Eamont, Irthing and Caldew are also similar in terms of peak flow variability, with a standard deviation of approximately 50 m^3s^{-1}. The maximum peak flow for each sub-catchment is from the January 2005 flood event, which will be analysed in more detail in Section 6.2.3. The minimum flows from each sub-catchment which have resulted in a POT flood downstream indicate that small floods in Carlisle are caused by high flows from only some of the sub-catchments.

	Eden - Kirkby	Eden - Temple	Eamont	Eden - Warwick	Irthing	Petteril	Caldew	Eden - Sheepmount
Mean	61.7	209.3	137.1	347.3	106.0	25.7	103.6	497.3
Median	53.8	197.6	130.7	326.6	103.3	24.0	90.7	452.5
Std Dev	27.8	54.3	47.7	102.4	49.6	11.9	48.2	155.9
Max	155.8	390.6	295.0	813.9	277.7	82.6	302.9	1516.4
Min	7.2	58.7	33.7	140.4	20.4	2.5	24.9	351.5
Range	148.6	331.9	261.3	673.5	257.3	80.1	278.0	1164.9

Table 6.1 *Descriptive statistics for sub-catchments peak flow magnitudes for the 138 POT events (all values in* m^3s^{-1}*)*

	Eden - Kirkby	Eden - Temple	Eamont	Eden - Warwick	Irthing	Petteril	Caldew	Eden - Sheepmount
Mean	0.89	0.34	0.35	0.25	0.32	0.16	0.42	0.22
Median	0.78	0.32	0.33	0.24	0.31	0.15	0.37	0.20
Std Dev	0.40	0.09	0.12	0.07	0.15	0.07	0.20	0.07
Max	2.24	0.63	0.74	0.60	0.83	0.52	1.24	0.66
Min	0.10	0.10	0.09	0.10	0.06	0.02	0.10	0.15
Range	2.14	0.54	0.66	0.49	0.77	0.50	1.14	0.51

Table 6.2 *Descriptive statistics for sub-catchments peak flow magnitudes standardised by catchment area (all values in* m^3s^{-1}*).*

The magnitude and variability of the peak flows in each of the sub-catchments are standardised by catchment area in Table 6.2. This shows that the average peak flows are greatest in the Upper Eden (Kirkby Stephen), being more than double the average of any other sub-catchment. This suggests that flows in this sub-catchment are large considering the small contributing area, likely to be caused by rapid runoff in this upland area. However, the peak flows at Kirkby Stephen are also the most variable, with the highest standard deviation and range. This might be caused by variable rainfall rates over this upland catchment varying significantly between events.

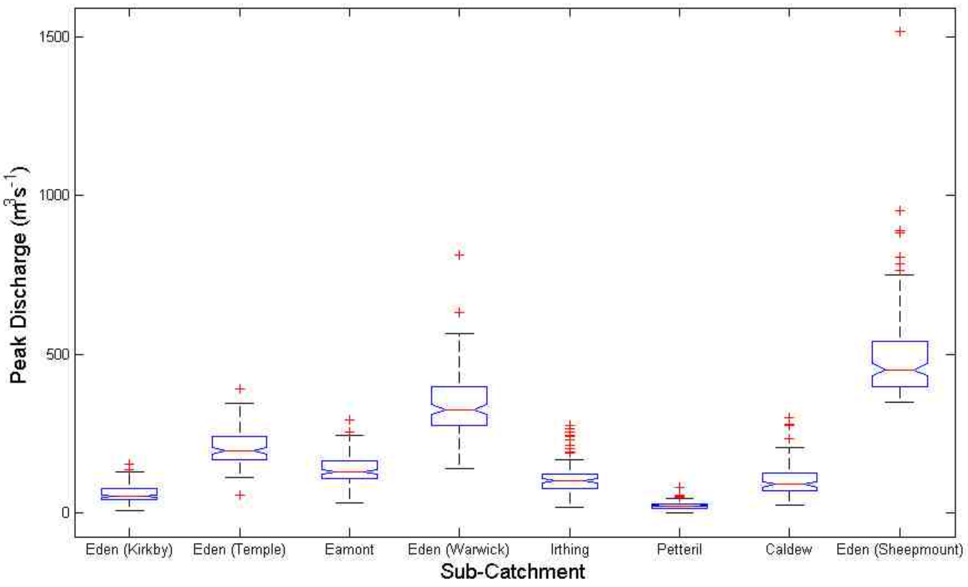


Figure 6.1 *Box plots of sub-catchments peak flow magnitudes with Red lines indicating the median, blue lines the upper/lower quartiles, whiskers represent the most extreme values within a range of 1.5x interquartile range and the red + are outliers*

Figure 6.2 shows the probability distribution function (PDF's) for each of the sub-catchments. These show the same data as the box plots. This shows that the flows in the Petteril are the smallest, even though the contributing area of this catchment is greater than the Upper Eden (Kirkby Stephen). The similarity of the Irthing and Caldew sub-catchment flows is also evident from the whole range of peak flows as well as just the descriptive statistics of the peak flows.

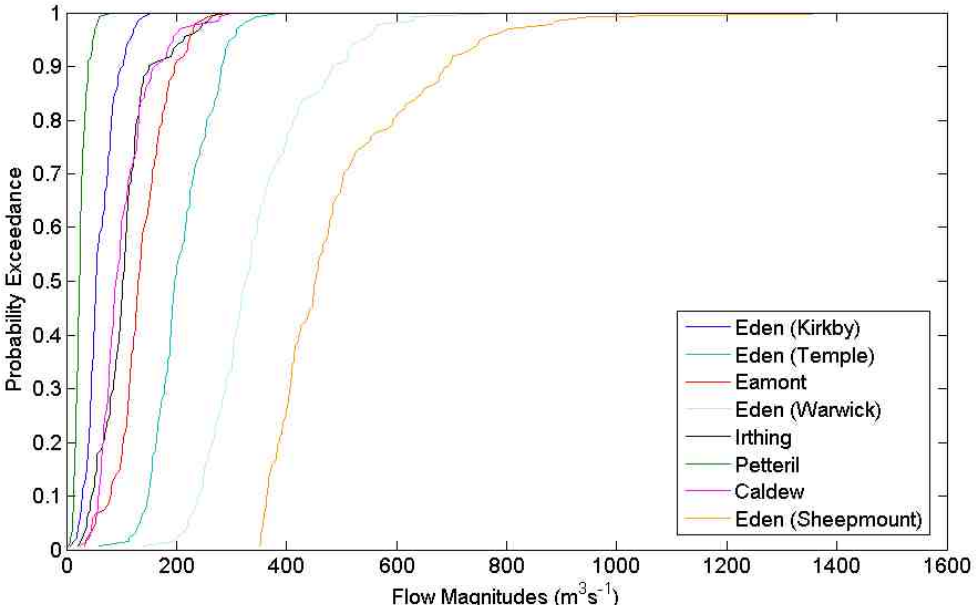


Figure 6.2 *Probability Distribution Functions of sub-catchment peak flow magnitudes*

An important characteristic of sub-catchment contributions is whether or not they have changed over time. Figure 6.3 shows how the peak flow magnitudes in the sub-catchments that caused downstream POT floods have changed over time. Most sub-catchment peak flows show statistically insignificant positive correlation over the period of the shortest gauged records (Table 6.3). However, two tributaries have significant trends over the past 30 years. First, the Eamont peak flow magnitudes increase over time (Figure 6.3c), with a correlation coefficient of 0.18, which is significant at the 95% level. This may suggest that the Eamont is becoming more important in causing downstream flooding in terms of the quantity of water flowing from it over time. This may be due to the presence and management of Haweswater and Wet Sleddale reservoirs, with water supply pressures meaning reservoir levels are maintained at a high level. Second, the Caldew (Figure 6.3g) exhibits a negative correlation (-0.23) between peak flow discharge and time. Therefore, the Caldew may becoming less important in causing downstream flooding, as it is contributing less water over time.

	Correlation	**Significance**
Eden (Kirkby)	-0.087	0.31
Eden (Temple)	0.023	0.79
Eamont	0.18	**0.035**
Eden (Warwick)	0.076	0.38
Irthing	0.12	0.18
Petteril	0.10	0.24
Caldew	-0.23	**0.0075**
Eden (Sheepmount)	0.07	0.42

Table 6.3 *Correlation of sub-catchments peak flow magnitudes against time (significant correlations at 95% limit highlighed in bold)*

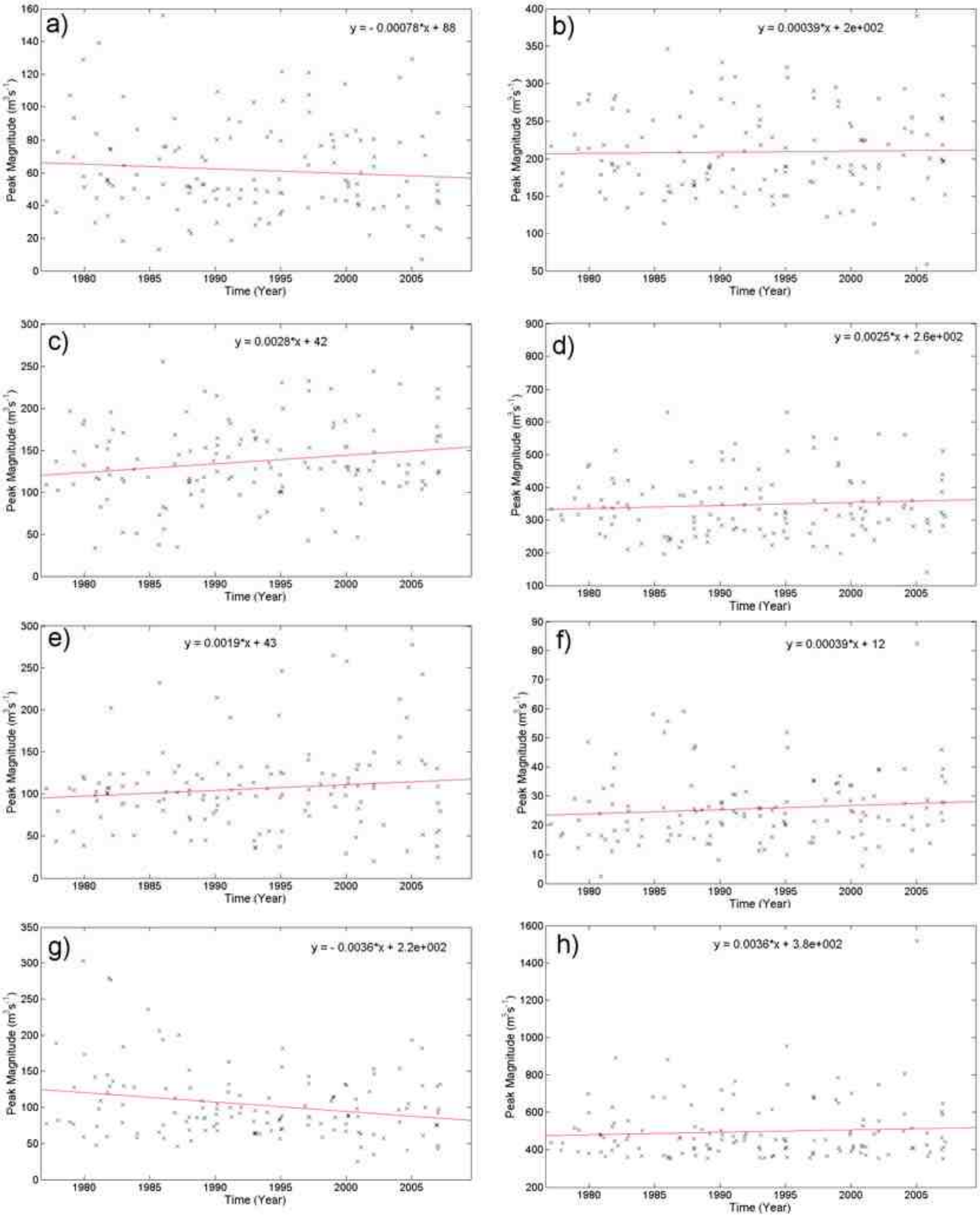


Figure 6.3 *Trends in peak flow magnitudes for POT events in sub-catchments a) Upper Eden (Kirkby Stephen), b) Upper Eden (Temple Sowerby), c) Eamont (Udford), d) Lower Eden (Warwick Bridge), e) Irthing (Greenholme), f) Petteril (Harraby Green), g) Caldew (Cummersdale), and h). Lower Eden in Carlisle (Sheepmount). The time period over which these trends are assessed is limited by the length of the shortest record.*

The peak flow magnitude at Carlisle correlates strongly with the contributing sub-catchments peak flow magnitudes (Table 6.4). The highest correlation (0.87) is between the flow at Carlisle and the Lower Eden at Warwick Bridge. This suggests that the flow from the main Eden is very important in determining peak flows in Carlisle, as

Warwick Bridge is upstream of the inputs of the Irthing, Petteril and Caldew. The likely reason for this is the very large contributing area of the main Eden at Warwick Bridge (60%). The Petteril also is consistently highly correlated (0.80) with Carlisle throughout the whole study period. All the correlations between the sub-catchments peak flow magnitudes and the flood magnitude in Carlisle are statistically significant. Along with the Petteril, the Upper Eden (Temple Sowerby) (0.74) and the Eamont (0.71) are strongly correlated with the magnitude of the flood at Carlisle. The Caldew's (0.56) and the Upper Eden's (Kirkby Stephen) (0.58) peak magnitudes are less correlated with downstream flood magnitude. The small contributing area of the Upper Eden at Kirkby Stephen (3%) and all the other sub-catchments that join the main Eden downstream of this gauging station, mean that flow at Kirkby Stephen is not strongly correlated with downstream peak flows. The Caldew is the least correlated with Carlisle which may be caused by its north-westerly location meaning it is affected by different weather systems to the majority of the catchment. Lane (2003) found similar findings for the correlations between tributaries and the flows in the city of York for the Ouse catchment.

	Eden (Kirkby)	Eden (Temple)	Eamont	Eden (Warwick)	Irthing	Petteril	Caldew
Eden (Temple)	0.67						
Eamont	0.51	0.73					
Eden (Warwick)	0.63	0.91	0.87				
Irthing	0.44	0.36	0.24 (0.006)	0.40			
Petteril	0.38	0.50	0.51	0.63	0.50		
Caldew	0.32 (0.0002)	0.34 (0.0001)	0.34	0.40	0.40	0.67	
Eden (Sheepmount)	0.58	0.74	0.71	0.87	0.67	0.80	0.56

Table 6.4 *Correlations between the sub-catchments peak flow magnitudes*

There are also some interesting relationships between sub-catchments (Table 6.4). The Irthing correlates quite poorly with all the other sub-catchments, which may be due to its different climate and land use. The Irthing is the only significant right bank tributary of the Eden and as such extends into the north escarpment of the Pennines and hence may respond to different weather systems than the Lake District and Howgill Fells sub-catchments. Westerly weather systems often result in a high magnitude flow from the western catchments; Eamont, Caldew, while all the precipitation has been deposited by the time the weather system reaches the further east Irthing sub-catchment, so it responds less. Another reason why the Irthing responds differently to the other sub-catchments is that the Irthing land use is significantly different to the other areas, with a lot more forestry, which may reduce runoff from this catchment. The Caldew also correlates poorly with the other sub-catchments, except the Petteril (0.67). A possible reason for the closest relationship for the Caldew being with the Petteril is that they are both towards the north-west of the Eden catchment and respond similarly to weather systems. The Eamont correlates well with the flows on the Upper Eden, due to their southerly location and similar topography and land use.

6.2.2. Sub-catchments interactions during flood events - Relative Timing

As discussed in Section 6.2, the relative timing of the peak flows from the sub-catchments with respect to Carlisle may be important as it determines the synchroneity of the flood peaks. Table 6.5 shows the descriptive statistics of the relative timings for the POT events. These timings are expressed as a lag time, where a postive lag time indicates that the peak flow at Carlisle occurs after the peak flow in the sub-catchment. The largest time lag between a sub-catchment peak flow and the peak flow at Carlisle is for the Upper Eden at Kirkby Stephen (11.87 hours). This is expected as it is the furthest distance from Carlisle and has a small contributing area. However, the second longest time lag is for the Caldew (9.62 hours), which is the nearest tributary to Carlisle. A possible reason why the Caldew responds earlier than the other sub-catchments is that it is on the west of the catchment, so may receive rainfall earlier than the other areas, as it has been shown that a high proportion of floods in Carlisle are caused by westerly weather systems (Chapter 4). The Caldew has the shortest distance to travel to Carlisle, so its flood wave may pass through Carlisle before other flood peaks arrive. However, this depends on the time sequencing of the flows from the Caldew with respect to the Eden. Figure 6.4 illustrates two cases; (a) when the Caldew peaks significantly before the Eden so doesn’t contribute to the flood peak in Carlisle, and (b) when the peaks of the Caldew and Eden are much closer, meaning that the Caldew does contribute to the peak flow in Carlisle, meaning it is higher in magnitude.

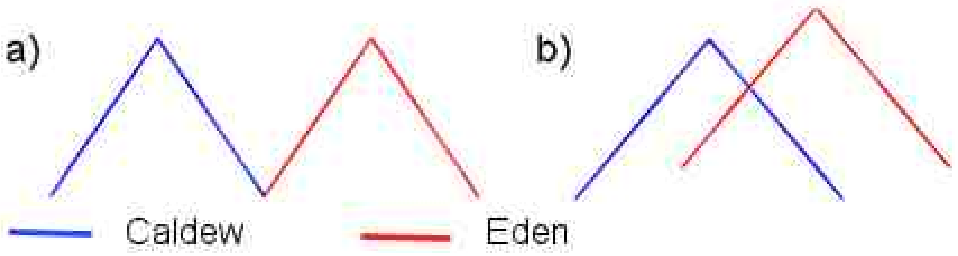


Figure 6.4 *Effect of tributary (Caldew) synchroneity with respect to the main Eden on downstream peak flow magnitudes.*

The average sequence of the tributaries peak flows in order of first to last is as follows: Eden (Kirkby Stephen); Caldew; Eamont; Eden (Temple Sowerby); Irthing; Eden (Warwick Bridge) and the Petteril. On average, there is between a 1.5 and 2 hour separation in the peak flows of the Eamont and the Upper Eden (Temple Sowerby). The variability of the relative timing of the sub-catchments peak flows ranges from 2.94 hours (Eden at Warwick Bridge) to 6.36 hours (Eden at Kirkby Stephen). Figure 6.5 shows the boxplot of the relative timing variables, from which it is clear that the distributions of the Upper Eden (Temple Sowerby) and Eamont are very similar, although as shown by the PDF (Figure 6.6), the Eamont lag times are slighly longer.

	Eden (Kirkby)	Eden (Temple)	Eamont	Eden (Warwick)	Irthing	Petteril	Caldew
Mean	11.87	6.52	8.17	2.33	6.08	1.85	9.62
Median	11.13	6.50	8.25	2.25	5.50	1.75	8.75
Std Dev	6.36	3.64	3.84	2.94	3.99	4.04	5.38
Maximum	34.50	23.25	24.75	19.25	29.50	16.75	32.25
Minimum	-8.25	-6.75	-5.25	-7.00	-6.00	-12.00	1.00
Range	42.75	30.00	30.00	26.25	35.50	28.75	31.25

Table 6.5 *Descriptive statistics for sub-catchments peak flow relative timing with respect to Carlisle (Hours).*

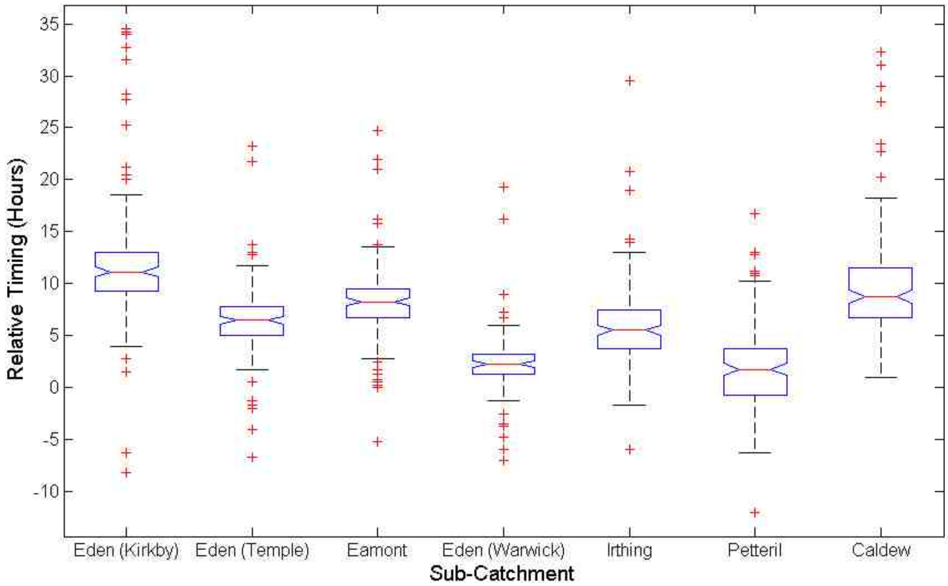


Figure 6.5 *Box plots of sub-catchments peak flow relative timing with respect to Carlisle with Red lines indicating the median, blue lines the upper/lower quartiles, whiskers represent the most extreme values within a range of 1.5x interquartile range and the red + are outliers*

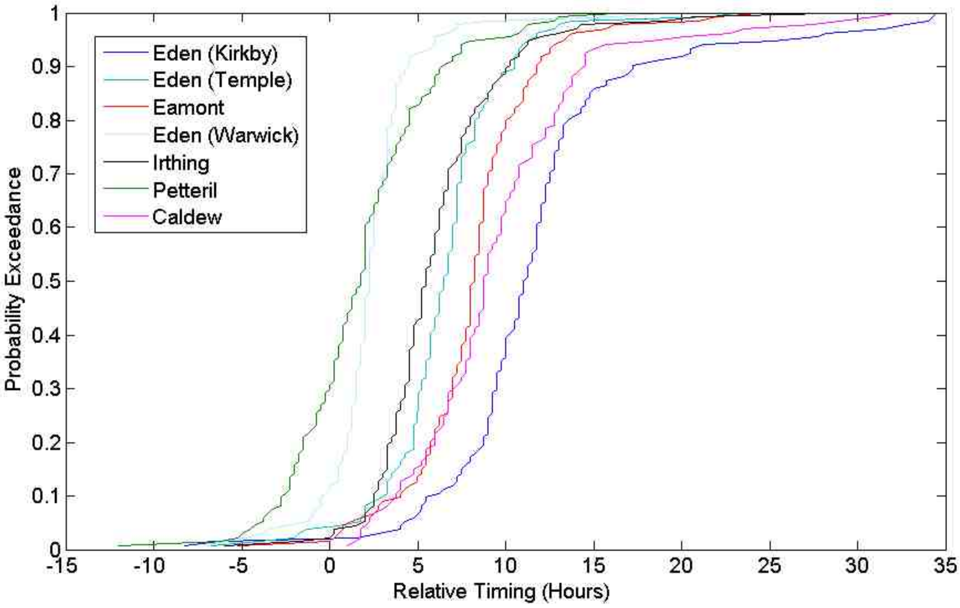


Figure 6.6 *Probability Distribution Function of sub-catchment peak flow relative timing with respect to Carlisle.*

The relative timing of the peak flows is affected by both the speed of the flood wave and the distance between the sub-catchment and Carlisle. The speed of flood wave propagation, wave celerity (C) is calculated by the following equation:

$C = \frac{\partial x}{\partial t}$ where x = distance in the direction of flow; and t = time

Sub-catchment	Distance (km)	Mean Wave Celerity km h^{-1}
Eden (Kirkby Stephen)	100.2	8.44
Eden (Temple Sowerby)	61.9	9.49
Eamont	59.8	7.32
Eden (Warwick Bridge)	17.2	7.38
Irthing	17.3	2.85
Petteril	6.4	3.46
Caldew	5.7	0.59

Table 6.6 *Celerity of flood wave at different gauging stations*

Table 6.6 shows the mean wave speed propagation rates downstream (celerity). From this it is clear that the upper sub-catchments (Eden and Eamont) have significantly higher flood wave celerity than the lower sub-catchments (Irthing, Petteril and Caldew). The rate of flood wave conveyance between Kirkby Stephen and Temple Sowerby increases, due to the steep nature of the upland catchment, leading to little flow attenuation. However, flood wave attenuation occurs between Temple Sowerby and Warwick Bridge. This may be caused by the input of the Eamont, which has a slower flood wave celerity, or floodplain storage which is known to occur in the Middle Eden around settlements of Armathwaite and Langwathby.

	Correlation	Significance
Carlisle-Eden (Kirkby)	-0.1883	0.0293
Carlisle-Eden (Temple)	0.0355	0.6842
Carlisle-Eamont	0.1658	0.0555
Carlisle-Eden (Warwick)	0.1101	0.2052
Carlisle-Irthing	-0.033	0.7053
Carlisle-Petteril	0.1772	0.0405
Carlisle-Caldew	0.0258	0.767

Table 6.7 *Correlation of sub-catchments peak flow relative timing over time*

Figure 6.7 shows how the relative timing of peak flows from the different sub-catchments have changed over time. Few of the sub-catchments display a statistically significant trend over the last 30 years (Table 6.7). The Upper Eden at Kirkby Stephen (Figure 6.7a) has a correlation of -0.19, indicating that the lag time between the peak flow at Kirkby Stephen and at Carlisle is shortening. Positive relationships between relative timing over time are present for the Petteril (Figure 6.7f) (0.18) and the Eamont (Figure 6.7c) (0.17), meaning that the lag time between the peak flow in each tributary and Carlisle is increasing over time.

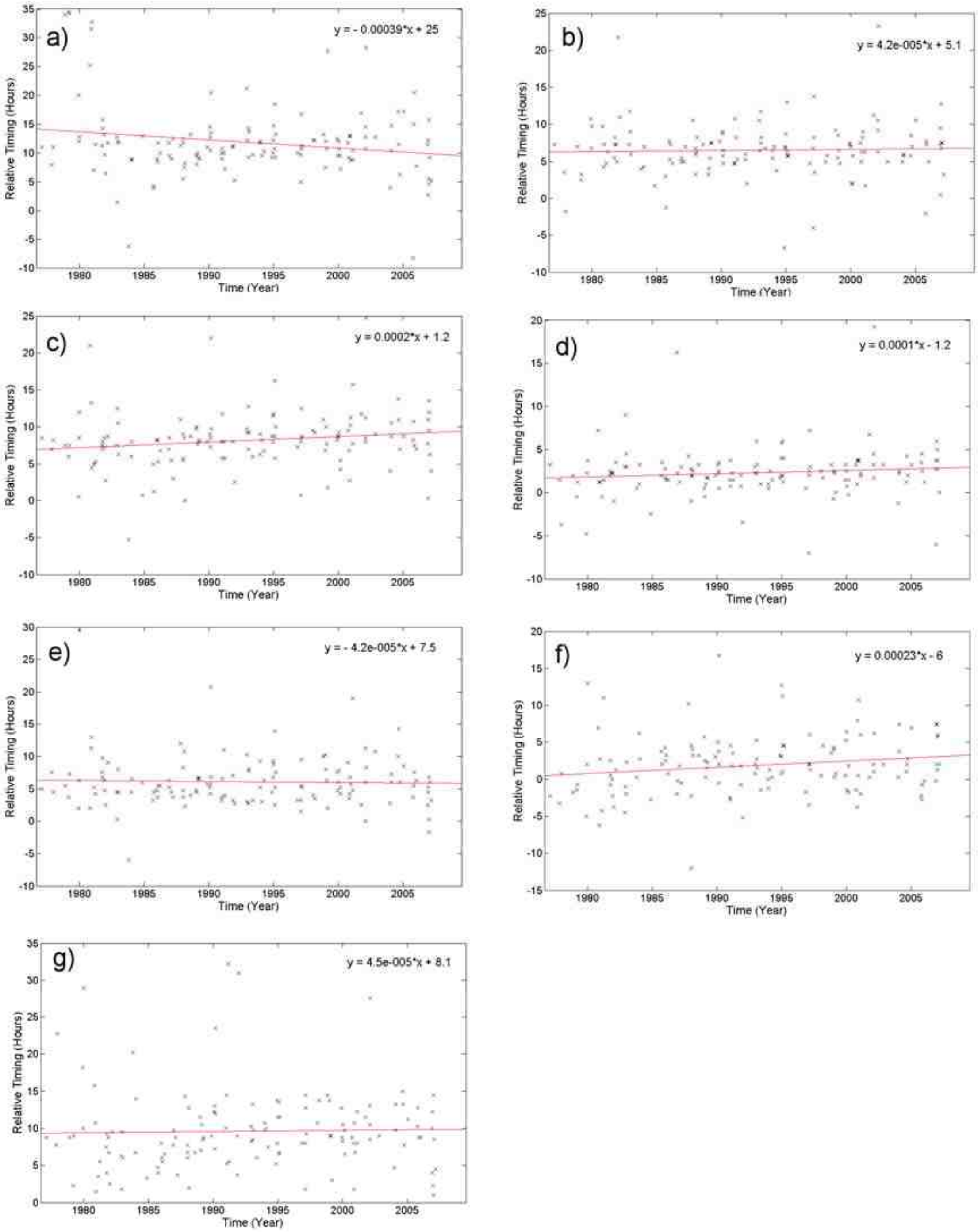


Figure 6.7 *Trends in peak flow relative timing for POT events in sub-catchments a) Upper Eden (Kirkby Stephen), b) Upper Eden (Temple Sowerby), c) Eamont (Udford), d) Lower Eden (Warwick Bridge), e) Irthing (Greenholme), f) Petteril (Harraby Green), and g) Caldew (Cummersdale).*

The relative timing correlations (Table 6.8) are more complex indicating the inter-dependency between sub-catchments response (Lane 2003). High correlations indicate that the two sub-catchments respond in a coherent manner with respect to

Carlisle in terms of the timing of their response. The highest correlations are between the Eden at Warwick Bridge and the upstream sub-catchments of the Upper Eden (Temple Sowerby) (0.56) and the Eamont (0.60). This suggests that the Upper Eden and Eamont tributaries are responding in a similar and consistent way to precipitation in terms of their timing of response. Further evidence for this coherent response is a correlation of 0.42 between the Upper Eden (Temple Sowerby) and Eamont with respect to Carlisle. Lane (2003) found a similar link between the Ure and Swale for the Ouse catchment in Yorkshire. He suggested that these two tributaries could be viewed as a combined system due to their similar response.

	Eden (Kirkby)	Eden (Temple)	Eamont	Eden (Warwick)	Irthing	Petteril
Eden (Temple)	0.27 (0.002)					
Eamont	0.35	0.42				
Eden (Warwick)	0.20 (0.02)	0.56	0.60			
Irthing	0.31 (0.0003)	0.15 (0.09)	0.46	0.15 (0.09)		
Petteril	0.05 (0.57)	0.23 (0.007)	0.42	0.27 (0.002)	0.36	
Caldew	0.13 (0.15)	0.22 (0.01)	0.42	0.17 (0.04)	0.42	0.23 (0.006)

Table 6.8 *Correlations between the sub-catchments peak flow relative timings relative to Carlisle (significance level shown in brackets, if not shown then significant at >99.9% level).*

6.2.3. Sub-Catchment interactions during extreme floods

As has been outlined in Chapter 4 the January 2005 flood was the most extreme flood in Carlisle on record. Possible causes of why this flood had such a high peak magnitude may be revealed by comparing this flood with the long term of average of all POT floods between 1977 and 2007, in terms of the flood peak magnitude (Figure 6.8) and relative timing (Figure 6.9) of the major tributaries.

The peak discharge through the city of Carlisle as measured by the Sheepmount gauging station was 1516 m^3s^{-1}, 304% of the long term average of the POT events between 1977 and 2007 (497 m^3s^{-1}). Possible causes for this extreme flood in terms of the contributing sub-catchment peak magnitudes are (1) a specific sub-catchment had an extreme response to rainfall and caused a large flood downstream; or (2) all the sub-catchments responded with greater than average peak flows; or (3) timing effects influencing sub-catchment interactions. The Petteril deviated the most from the long term average, with the 2005 peak magnitude on the Petteril being 335% of the long term average. However, this was still the lowest actual contribution (82.6 m^3s^{-1}) from any of the major sub-catchments. The Irthing contribution was 282% of the long term average, while the contribution from the Caldew (187%), Eamont (215%) and Upper Eden (Kirkby Stephen = 209%, Temple Sowerby = 187%) were all about double the long term average peak flow. This highlights the importance of scale in causing extreme floods in Carlisle, whereby all sub-catchments were contributing large flows, due to the synoptically coherent rainfall event. Out of the first two hypotheses, it is the second hypothesis that all the sub-catchments responded with greater than average peak flows that caused the extreme nature of the January 2005 flood.

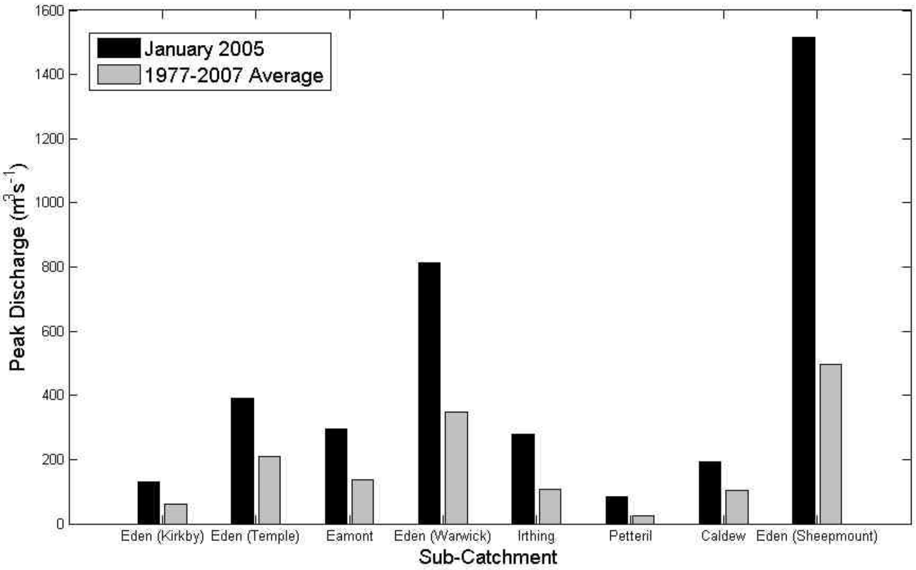


Figure 6.8 *Comparison of the January 2005 flood with the long term average in terms of peak magnitudes from each sub-catchment.*

The third hypothesis of the relative timing of the major tributaries with respect to the downstream gauging station of Sheepmount in Carlisle might alter the interaction of the flows from each sub-catchment (i.e. synchronicity), may also influence peak flow magnitude downstream. The timing of the Eamont was not significantly different to the long term average (107%). However, the timing of the Upper Eden was earlier than in the long term average flood by 4-5 hours. This meant that the sequencing of the Eamont and Upper Eden was switched around, so that the Upper Eden peaked first. Thus the Eamont peak flow combined with the Upper Eden peak flow, rather than flowing downstream before the Upper Eden peak flow. This highlights the potential of slowing the flow of the Eamont in reducing flood magnitude downstream.

The Petteril also seemed to peak significantly earlier (7 hours) than during other smaller floods with respect to the Eden. The Petteril also peaks earlier with respect to the all other sub-catchments. The most significant of these is that the sequencing of the Petteril and the Eden at Warwick Bridge was the opposite of the long term average. The Petteril peaked about 3.75 hours before the main Eden, so the high flow in Carlisle was maintained for a longer period, but the discharge was not as high as if the normal situation occurred, whereby the Petteril peaks after the Eden and the flows combine in Carlisle. The rest of the sub-catchments all peaked earlier than during the long term average flood, but the sequencing stayed the same.

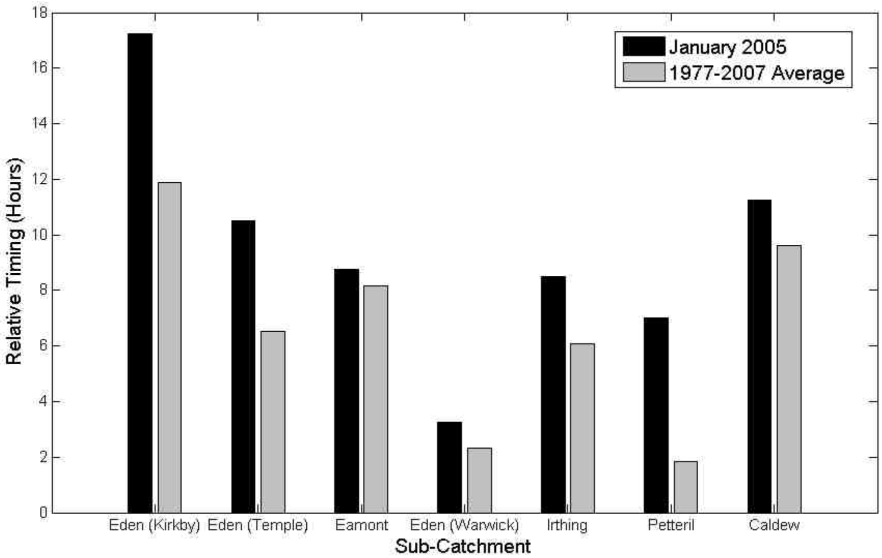


Figure 6.9 *Comparison of the January 2005 flood with the long term average in terms of the peak flow relative timing from each sub-catchment with respect to Carlisle.*

In conclusion, the likely reason why the January 2005 flood event was so extreme was because all the sub-catchments responded with significant peak flows, all more than double their long term average. Furthermore, the relative timings of the Upper Eden and Eamont tributaries were closer together, meaning that the Lower Eden peak was higher in magnitude and lower in duration. Furthermore, the Eden flows combined with the peak flows from the lower sub-catchments. Therefore, hypothesis 1 can be rejected and hypotheses 2 and 3 were the likely causes.

6.3. Spatial Downscaling of Catchment Scale Flood Risk - Statistical data-based approach

The following two sections reports the results of the spatial downscaling approaches outlined in Chapter 5. Section 6.3 outlines the statistical methodology results, while Section 6.4 outlines the hydraulic modelling results.

6.3.1. Test for variable normality

Many statistical tests require the input data to be normally distributed. Therefore, the normality of the magnitude and timing variables was assessed through the Shapiro-Francia W' and Shapiro-Wilk W tests. The results indicate that many of the original variables do not have a normal distribution (Table 6.9). Possible reasons why this is the case is that the dataset was formed by using the POT series for Sheepmount. However, Lane (2003) stated that the non-normal nature of the original variables does not violate the use of principal components analysis, on which the statistical downscaling methodology is based, although the interpretations of the results must be carried out with caution.

	Significance based on Shapiro-Francia W' test for Normality				Significance based on Shapiro-Wilk W test for Normality			
	W'	**V'**	**z**	**prob>z**	**W**	**V**	**z**	**prob>z**
Peak Magnitude Variables								
Eden-Kirkby	0.95	5.22	3.31	0.0005	0.95	4.78	3.53	0.0002
Eden-Temple	0.98	2.79	2.09	0.019	0.98	2.31	1.89	0.029
Eamont	0.98	2.18	1.60	0.055	0.98	1.97	1.53	0.064
Eden-Warwick	0.92	9.77	4.50	*	0.92	8.41	4.80	#
Irthing	0.90	11.1	4.74	*	0.90	10.2	5.24	#
Petteril	0.90	11.1	4.73	*	0.91	9.62	5.10	#
Caldew	0.87	14.8	5.26	*	0.87	13.3	5.83	#
Eden-Carlisle	0.74	28.9	6.47	*	0.76	25.7	7.32	#
Relative Timing Variables								
Carlisle-Eden (Kirkby)	0.82	20.2	5.83	*	0.83	17.9	6.50	#
Carlisle-Eden (Temple)	0.88	13.4	5.09	*	0.89	11.2	5.44	#
Carlisle-Eamont	0.90	11.6	4.81	*	0.91	9.68	5.12	#
Carlisle-Eden (Warwick)	0.78	25.0	6.21	*	0.80	21.6	6.92	#
Carlisle-Irthing	0.83	19.3	5.75	*	0.84	16.4	6.31	#
Carlisle-Petteril	0.96	4.72	3.12	0.0009	0.96	3.70	2.95	0.002
Carlisle-Caldew	0.86	16.4	5.45	*	0.86	14.7	6.06	#

Table 6.9 *Results of normality tests for the sub-catchment peak flow magnitude and relative timing variables, with * indicating not significant at the 0.00001 level, and # not significant at the 0.000001 level*

6.3.2. Principal Components Analysis

The principal components analysis transformation was undertaken using the data on peak flow magnitude and relative timing from the Upper Eden (Temple Sowerby), Eamont (Udford), Irthing (Greenholme), Petteril (Harraby Green) and the Caldew (Cummersdale). The data from Kirkby Stephen and Warwick Bridge were excluded from this part of the analysis, as the signal from Kirkby Stephen is included within the Temple Sowerby data, and the Warwick Bridge data repeat the signal from Temple Sowerby and Udford.

Figure 6.10 shows the scree plot of the eigenvalue associated with each principal component. A scree plot shows the fraction of the total variance in the original data accounted for by each transformed principal component. Using Pocock and Wishart (1969) which stated that the components with an eigenvalue of less than 1 should be eliminated, the first three components were considered significant and included in further analysis. These three components account for 65.6% of the variability within the original variables.

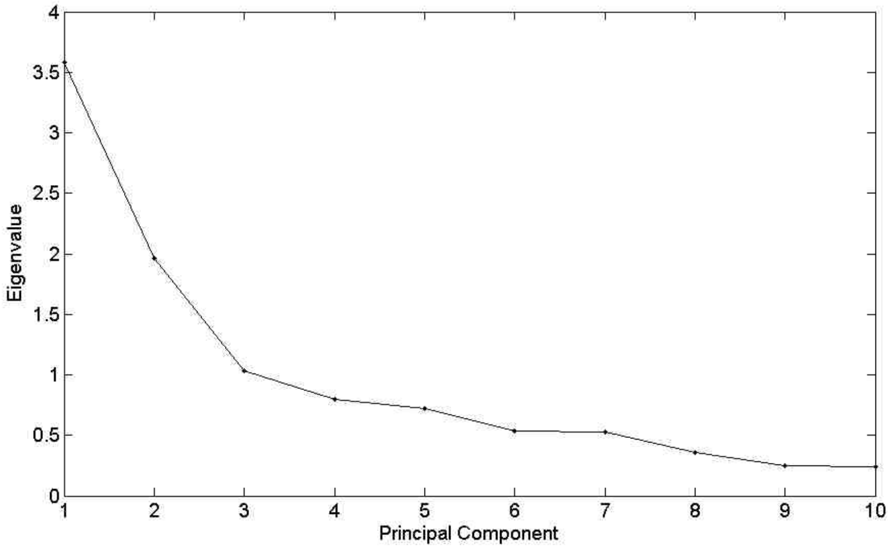


Figure 6.10 *Scree plot for principal components analysis*

The loadings were then calculated, which are the correlations between the transformed principal components and the original variables (Table 6.10). All the original variables are positively correlated with principal component 1 (PC1), indicating that as the principal component value increases so do the original variables i.e. magnitude increases; lag time increases (peak earlier). The magnitude variables are negatively correlated with principal component 2 (PC2), meaning that as the sub-catchment peak flow decreases, the principal component value increases. The timing variables are positively correlated with PC2, indicating that as the relative timing increases i.e. peaking earlier, the principal component value also increases. PC3 represents a range of variables with both positive and negative correlations with the principal component.

The proportion of each principal component accounting for each of the individual variables was then calculated by multiplying the squared loadings by the total eigenvalue for each component (Table 6.11). This shows that PC1 represents all the magnitude and timing variables from all five sub-catchments, but predominantly the flow magnitude variables, especially the magnitude of the Upper Eden (19.37%), Eamont (16.58%) and Petteril (11.99%). PC2 represents the relative timing of the Eamont (21.07%) and Petteril (13.17%) with respect to Carlisle and the magnitudes of the peak flow of the Petteril (17.12%) and Caldew (22.80%). PC3 represents the timing of the Upper Eden (45.17%) and Irthing (13.45%) and the magnitude of the Irthing (25.98%).

	PC1	**PC2**	**PC3**
Relative Timing			
Carlisle-Eden (Temple Sowerby)	7.98	2.05	-45.17
Carlisle-Eamont	6.86	21.07	-0.03
Carlisle-Irthing	9.33	9.30	13.45
Carlisle-Petteril	4.86	13.17	1.51
Carlisle-Caldew	9.20	5.23	5.20
Flow Magnitudes			
Eden (Temple Sowerby)	19.37	-0.25	-0.30
Eamont	16.58	-0.85	-8.32
Irthing	6.99	-8.16	25.98
Petteril	11.99	-17.12	0.00
Caldew	6.85	-22.8	-0.05

Table 6.11 *Proportions of each components represented by each of the original variables (sign indicates direction in which contribution acts).*

	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**	**PC9**	**PC10**
Carlisle-Eden (Temple)	0.53	0.20 (0.02)	-0.68	0.13 (0.13)	0.28 (0.001)	-0.11 (0.22)	-0.02 (0.82)	0.31 (0.0003)	-0.09 (0.33)	-0.03 (0.76)
Carlisle-Eamont	0.50	0.64	-0.02 (0.84)	0.11 (0.20)	0.36	-0.22 (0.009)	0.00 (0.98)	-0.38	0.09 (0.30)	-0.02 (0.86)
Carlisle-Irthing	0.58	0.43	0.37	-0.18 (0.04)	-0.18 (0.04)	-0.27 (0.001)	0.41	0.16 (0.07)	-0.14 (0.11)	0.03 (0.72)
Carlisle-Petteril	0.42	0.51	0.12 (0.15)	0.61	-0.23 (0.008)	0.34 (0.0001)	0.03 (0.72)	0.07 (0.43)	0.07 (0.43)	0.07 (0.39)
Carlisle-Caldew	0.57	0.32 (0.0002)	0.23 (0.007)	-0.45	0.30 (0.0004)	0.45	-0.13 (0.13)	0.06 (0.50)	-0.06 (0.49)	-0.03 (0.75)
Eden (Temple)	0.83	-0.07 (0.42)	-0.06 (0.53)	-0.15 (0.08)	-0.34 (0.0001)	-0.08 (0.37)	-0.13 (0.15)	0.05 (0.60)	0.26 (0.003)	-0.27 (0.002)
Eamont	0.77	-0.13 (0.14)	-0.29 (0.0006)	-0.20 (0.02)	-0.33 (0.0001)	-0.02 (0.86)	-0.18 (0.04)	-0.15 (0.08)	-0.07 0.41)	0.30 (0.0003)
Irthing	0.50	-0.40	0.52	0.23 (0.008)	0.22 (0.01)	-0.24 (0.004)	-0.36	0.15 (0.08)	0.00 (0.97)	0.08 (0.34)
Petteril	0.66	-0.58	0.00 (0.97)	0.23 (0.008)	-0.01 (0.89)	0.11 (0.21)	0.10 (0.24)	-0.20 (0.02)	-0.29 (0.0008)	-0.20 (0.02)
Caldew	0.50	-0.67	-0.02 (0.79)	0.00 (0.99)	0.26 (0.002)	0.11 (0.19)	0.39	0.01 (0.91)	0.23 (0.006)	0.13 (0.13)

Table 6.10 *Correlations between original variables (peak flow timing and magnitude from sub-catchments) with the transformed principal components.(relative timing variables shown in red, magnitude variables in black)*

6.3.3. Predicting downstream flood risk

Then, stepwise regression was used to predict the magnitude of the flow in Carlisle from the three significant principal components. The first two components were found to contribute to a significant level (95%) of explanation of downstream flood magnitude. 83.3% of the downstream flood magnitude could be explained together by PC1 (66.85%) and PC2 (16.45%). Lane (2003) found that a similar proportion (89.1%) of downstream flow magnitude could be predicted from the same sub-catchment variables for the Ouse catchment. This indicates that for both studies the magnitude and relative timing of tributaries peak flows are the main factors in determining downstream flood magnitude. The regression equation for this study was:

Carlisle peak flow magnitude = 67.4 PC1 - 45.2 PC2 + 497.3

	Coefficient	**Std. Error**	**t**	**P > t**	**95% Conf idence Intervals**	
PC1	67.4	2.94	22.9	0.00	61.6	73.2
PC2	-45.2	3.98	-11.4	0.00	-53.1	-37.3
Constant	497.3	5.55	89.6	0.00	486.3	508.3

Table 6.12 *Regression statistics for prediction of downstream flood magnitude from principal components.*

The proportion of each principal component accounted for by each of the original variables was calculated, using the loadings in Table 6.10, and then applied to the above equation. The relative importance of the tributary peak flow magnitudes (49.4%) is higher than the relative timing (34.0%) of the peak flows from the different sub-catchments. However, the effect of the timing is not that simple, as it has both a positive (25.6%) and negative (8.4%) correlation with downstream flood magnitude. This indicates that the overall effect of timing is positive; meaning that increasing the relative timing between the tributary peak flow and the peak flow downstream increases the magnitude of the resulting flood. Lane (2003) also found that magnitude was more important than the timing of the flows, but stated that timing was a crucial control on downstream flooding. Roughani et al., (2007) also highlighted the importance of timing on the effect of different tributaries on peak flow downstream, using the term “time of concentration” to reflect the concept of lag times. One of the main conclusions of that study was that the most effective sub-catchments in reducing downstream flood risk are ones that have a time of concentration to the catchment outlet of 50% of the overall catchment time to concentration.

Figure 6.11 shows the individual contributions of each sub-catchment in terms of magnitude and timing to downstream flood magnitude. The sub-catchment which explains the highest proportion of flood magnitude in Carlisle is the Eamont (19.3%), of which 11.2% is the magnitude and 8.1% is the timing of the peak flow. However, of this timing contribution 4.6% is positive and 3.5% is negative. This means that the resulting effect is positive (1.1%), meaning that as the Eamont peaks earlier the downstream flood increases in magnitude. The Upper Eden is the second most important sub-catchment in explaining downstream flood magnitude (18.7%). Again, the magnitude of the flow is more important (13.0%) than the timing (5.7%), but for the Upper Eden 5.0% of the timing effect is positive. Thus, overall, the Upper Eden is more important than the Eamont in determining downstream flood magnitude both in terms of magnitude and timing.

The Petteril and Caldew sub-catchments are slightly less important than the upstream sub-catchments, explaining 16.3% and 15.3% respectively. The Irthing tributary is the least important in causing downstream flooding (13.8%). In terms of the magnitude of these three tributaries, the Petteril is the most important (10.8%), the Caldew explains 8.3%, and the Irthing is least important accounting for 6.0% of downstream flood magnitude. In terms of timing the most important of the downstream tributaries are the Irthing (7.8%) and Caldew (7.0%), which explain similar amounts. However, the positive effect (downstream flood magnitude increases as relative timing increases i.e. tributary peaks earlier) of these tributaries indicates that the Caldew (5.3%) has a greater influence than the Irthing (4.7%). The Petteril is least important in terms of its timing with respect to Carlisle, with an overall contribution of 5.4% and a positive influence of only 1.0%. This highlights the issue of proximity of each sub-catchment to the catchment outlet. Saghafian and Khosroshahi (2005) found that the effect of the most proximal sub-catchments to the outlet were the lowest. This was because the flows from these tributaries reached the catchment outlet before the contributions from the other tributaries arrived. Roughani et al. (2007) also found that changes in tributaries close to the catchment outlet have the least impact on downstream flooding.

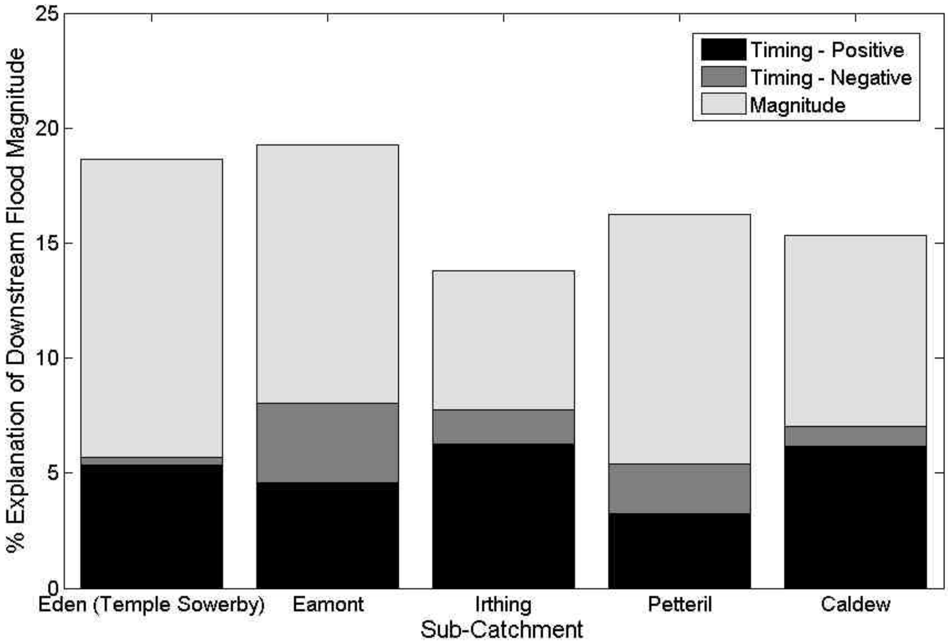


Figure 6.11 *Contribution of each sub-catchment in terms of peak flow magnitude and timing in explaining downstream flood risk.*

It has been hypothesied that the importance of each sub-catchment may be correlated with its area. However, Saghafian and Khosroshahi (2005) found that the ranking of sub-catchments by area and importance in effecting flooding may not be the same. This was thought to be caused by factors such as channel routing and the timing and synchronicity of flows. The relative importance of each sub-catchment can be standardised by investigating the contribution per kilometre square of catchment area. Table 6.13 shows that the Petteril sub-catchment becomes the most important tributary in terms of both the peak flow magnitude and relative timing. This is because the Petteril ranks third in terms of explaining downstream flood magnitude, but is the smallest sub-catchment. The importance of the Upper Eden decreases significantly, due to its area being nearly double that of any other sub-catchment. The importance of the Eamont has been assessed using two different catchment areas. Firstly, the whole catchment area (396.2 km^2) is used, and second the area downstream of Ullswater and Haweswater is used (218.2 km^2). The latter is thought to be more comparable to the other sub-catchments, as rainfall upstream of these lakes will not affect sub-catchment peak flow magnitude as water is stored in the lake. These features will affect peak flow relative timing due to the attenuating effect of these features. The Eamont either ranks second or third for magnitude and joint third or fourth in terms of peak flow relative timing. Furthermore, the importance of the Eamont becomes greater than the Upper Eden sub-catchment, both in terms of flow magnitude and relative timing.

Sub-Catchment	**Area (km^2)**	**Timing % / Km^2 Area**	**Magnitude % / Km^2 Area**
Upper Eden	616.4	0.009	0.021
Eamont	396.2 (218.2)	0.020 (0.023)	0.028 (0.051)
Irthing	334.6	0.023	0.023
Petteril	160.0	0.034	0.068
Caldew	244.0	0.029	0.034

Table 6.13 *Standardised contributions of each sub-catchment in explaining downstream flood risk per unit area.*

6.3.4. Sensitivty of Downstream flood risk to sub-catchment peak flow magnitude and timing

Systematic changes to the timing and magnitude of the January 2005 flood event were made and the principal components analysis repeated. The scoring coefficients for the January 2005 flood for PC1 and PC2 were outputted and applied in the regression equation derived in Section 6.3.3. This investigates the sensitivity of downstream flood magnitude to the peak flow magnitudes and timings of the contributing sub-catchments. The percentage change on downstream peak discharge and stage was calculated and are plotted in Figure 6.12 for magnitude changes and Figure 6.14 for timing changes.

The key observation from this analysis is that significant changes in sub-catchment flows only result in a small change in the downstream flood hazard. Figure 6.12 shows that the Petteril is the most effective sub-catchment per percentage change in magnitude in reducing flooding downstream. The effect on both peak discharge and stage are shown on the two y-axes. A 6% change in discharge corresponds to a 2.5% change in stage. This is because the peak flows from the Petteril have the smallest range (standard deviation = 11.9 m^3s^{-1}), so a 25% change in the peak flow (20 m^3s^{-1}) is 1.7 times the standard deviation. For the Upper Eden a 25% change is 98 m^3s^{-1}, 1.8 times the standard deviation.

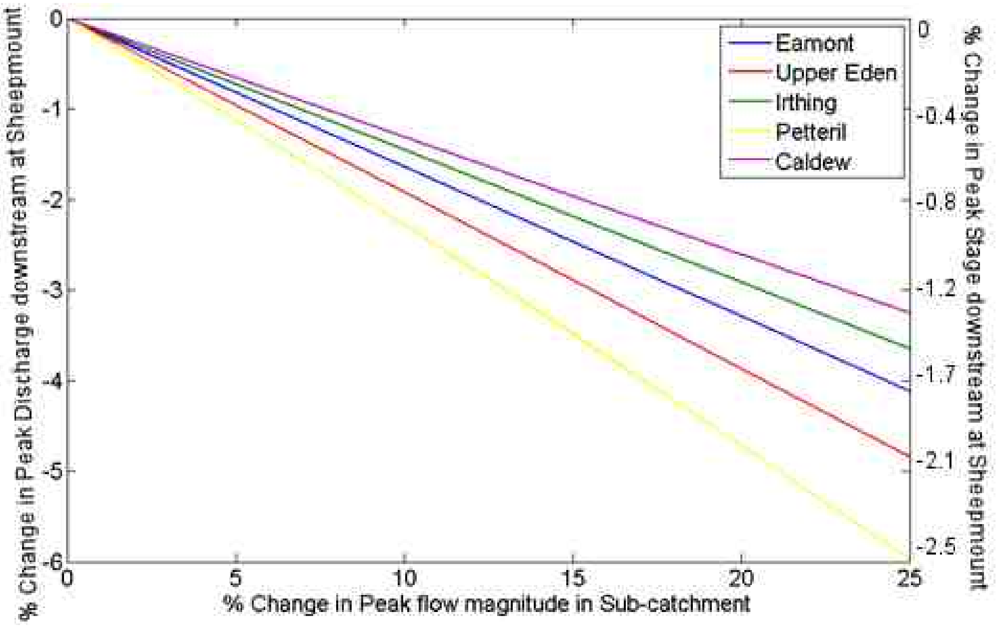


Figure 6.12 *Sensitivity of downstream flood risk to each of the sub-catchments peak flow magnitudes in terms of percentage changes.*

If the proportions of each principal component are studied (Table 6.11), it is found that the Petteril is important to both components, while the Upper Eden does not contribute to component 2. In the regression equation principal component 1 is more important than principal component 2, but the influence of the Petteril magnitude overall is more important than any other sub-catchment (Table 6.14). Figure 6.13 shows how reductions of the magnitude by various proportions of the standard deviation impact downstream flood magnitude. This makes the changes relative to each other, eliminating the effect of overall magnitude, and focussing on the specific sub-catchment distribution. These changes also show that the Petteril is the most important sub-catchment in terms of peak flow magnitude.

For the Eamont, a 25% change is 74 m^3s^{-1}, which is 1.5 times a standard deviation of 47.7 m^3s^-1. The Eamont is the third most effective tributary in terms of peak flow magnitude per percentage change. Table 6.14 shows that the Eamont is the fourth most important in terms of magnitude, in terms of the effect per unit discharge. A 25% change of the peak flow from the Irthing is 70 m^3s^{-1}, 1.4 times the standard deviation (49.6). Both the changes by different percentages and different proportions of the standard deviation show that the Irthing is one of the least important in terms of magnitude. The impact on downstream flooding of the Caldew peak magnitude per percentage change is the lowest. However, this is because 25% on the Caldew is only 1 standard deviation. Changes in the peak flow of the Caldew per unit discharge highlights that the Caldew is the second most important sub-catchment in term so magnitude.

	PC1 * 67.4	**PC2 * 45.2**	**Overall Contribution PC1 - PC2**	**% Contribution**
Relative Timing				
Carlisle-Eden (Temple)	537.9	92.7	445.2 (630.6)	5.6 (4.8) (0.8)
Carlisle-Eamont	462.4	952.4	-490.0 (1414.8)	12.6 (4.1) (8.5)
Carlisle-Irthing	628.8	420.4	208.4 (1049.2)	9.3 (5.6) (3.7)
Carlisle-Petteril	327.6	595.3	-267.7 (922.9)	8.2 (2.9) (5.3)
Carlisle-Caldew	620.1	236.4	383.7 (856.1)	7.6 (5.5) (2.1)
Flow Magnitudes				
Eden (Temple)	1308.5	-11.3	1319.8	11.7
Eamont	1117.5	-38.4	1155.9	10.3
Irthing	471.1	-368.8	839.9	7.5
Petteril	808.1	-773.8	1581.9	14.0
Caldew	461.7	-1030.6	1492.3	13.2

Table 6.14 *Contribution of each sub-catchments peak flow magnitude and relative timing to the sensitivity of downstream flood risk. Red numbers indicate positive correlation, while blue numbers represent negative associations.*

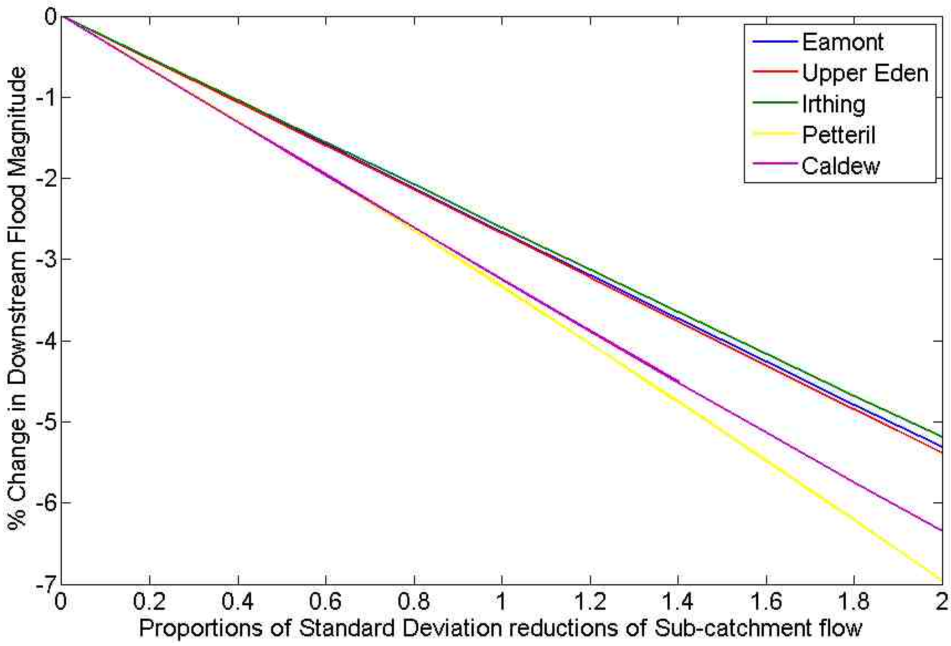


Figure 6.13 *Sensitivity of downstream flood risk to each of the sub-catchments peak flow magnitudes in terms of proportional standard deviation changes.*

The sensitivity of downstream flooding to changes in the timing of the peak flow of the different sub-catchments is more complex than magnitude effects (Figure 6.14). This is because the timing variables contribute in both a positive and negative relationship with downstream flood magnitude. The strongest timing effect is that of the Upper Eden. As the Upper Eden is delayed (peaks later) downstream peak stage is reduced, while the effect of the Upper Eden peaking earlier is that downstream flood magnitude is increased. However, the effect of timing is significantly lower than magnitude, with an 8 hour delay of the Upper Eden resulting in only a 1.5% reduction in peak flow downstream and an 0.6% reduction in peak stage. The Caldew and Irthing also have an overall positive correlation with downstream flooding, where delays (time lag decreases) in peak flow lead to decreases in downstream flood magnitude. However, the effect of the Eamont and Petteril is more complex, as the resultant effect is negative. This means that time delays lead to increases in downstream flooding. The effect of these tributaries peaking earlier is very small.

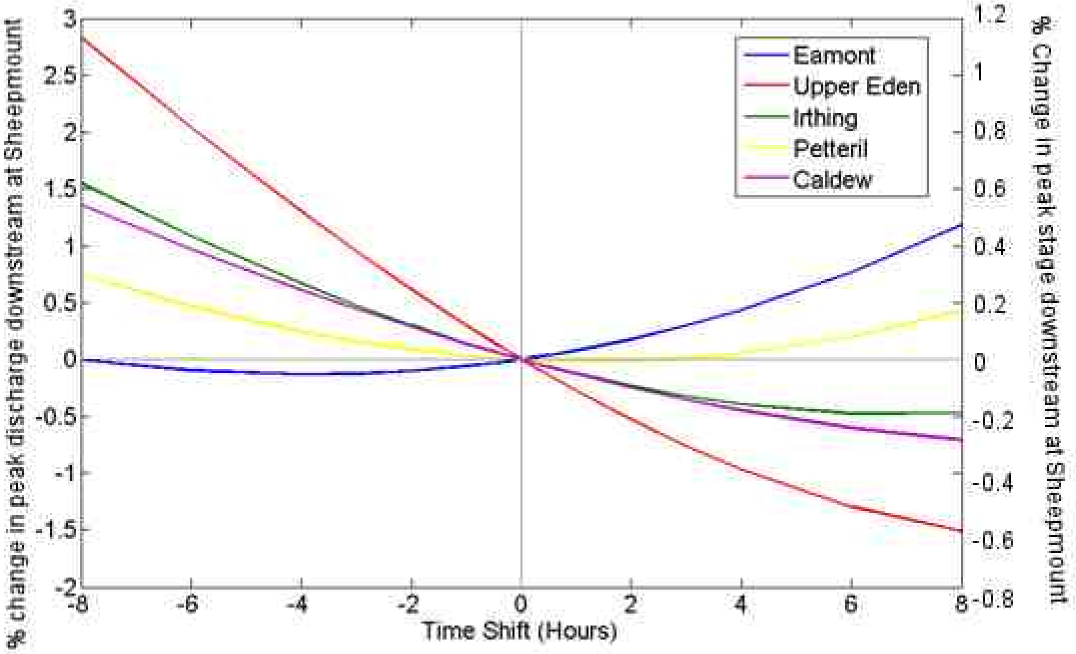
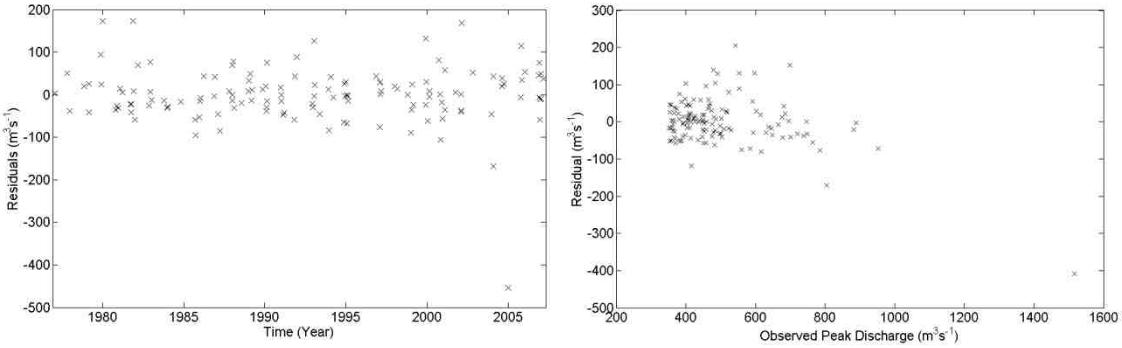


Table 6.14 *Sensitivity of downstream flood risk to each of the sub-catchments peak flow relative timings, with positive change representing time delays and negative changes indicating tributaries peaking earlier.*

6.3.5. Uncertainty of Predictions

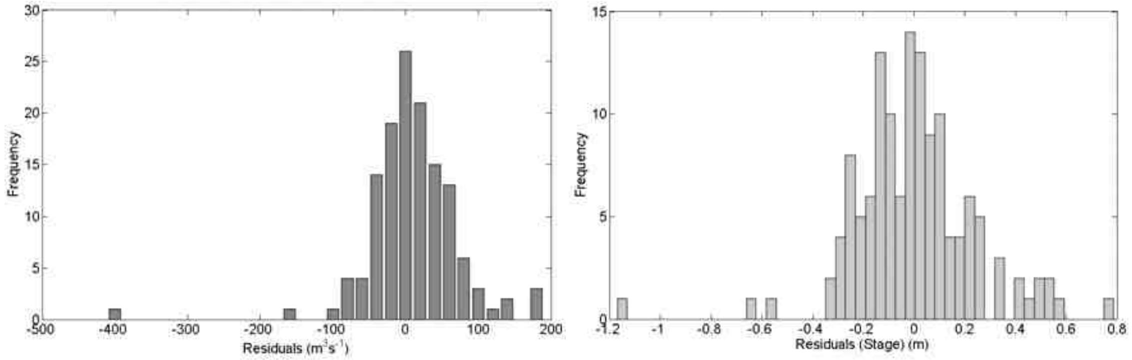
It is important to assess the uncertainties of the predictions of the statistical spatial downscaling approach. This is done by three analyses; firstly the residuals between observations and predictions were assessed; secondly bootstrapping was employed to robustly test how sensitive the predictions were to specific flood events included in the analysis; and thirdly the sensitivity of the predictions to the data input were assessed, whereby updated rating curves were used to generate alternative flow magnitudes.

The residuals (observed-predicted) are plotted for all 134 POT flood events since 1977 in Figure 6.15. There is no pattern in the residuals over time (Figure 6.15a) or for different magnitude flood events downstream (Figure 6.15b). Residuals range from -408.9 m^3s^{-1} to 205.7 m^3s^{-1}. This corresponds to a -1.17 m to 0.79 m error in peak stage. Larger flood events (>700 m^3s^{-1}) seem to be under-predicted by the statistical model, while smaller events have the smallest residuals, both over and under predicted. Figure 6.16 shows the distribution of the residuals, with only 6.7% of events having a residual of ±100 m^3s^{-1}.



a) Over time *b) Different magnitude floods*

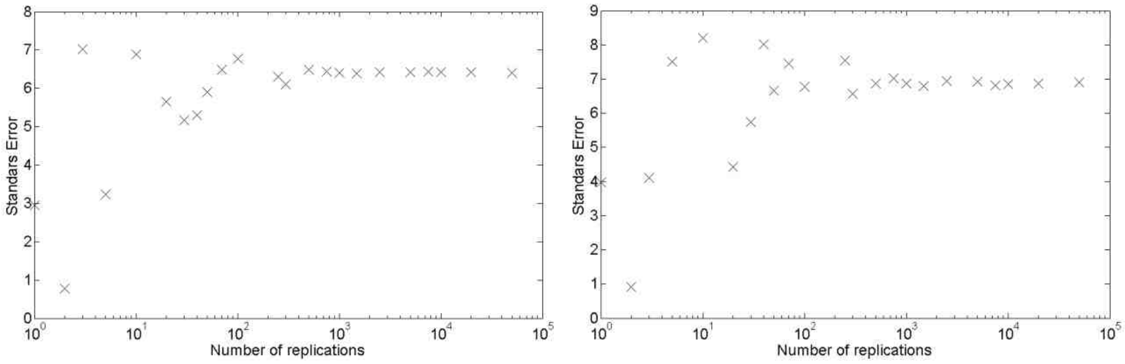
Figure 6.15 Residuals of regression



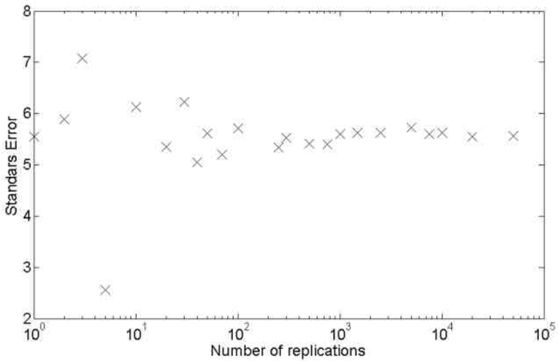
a) Discharge *b) Stage*

Figure 6.16 *Histogram of regression residuals*

The technique of bootstrapping was applied to the stepwise regression of the principal components to predict downstream flood magnitude. A sample size of 134 was used with the number of replications ranging from 1 to 50,000. Figure 6.17 shows the standard error associated with each of the components of the regression (PC1, PC2, and constant). The standard error associated with PC1 (Figure 6.17a) ranges from 0.78 to 7.02, but converges on a value of 6.4 as the number of replications increases. This stabilisation of the standard error occurs after 500 replications. The standard error for PC2 (Figure 6.17b) ranges from 0.91 to 8.2 and converges on 6.8 after 500 replications. The standard error associated with the constant (Figure 6.17c) ranges from 2.55 to 7.08 and converges on 5.6 after 1000 replications. This suggests that a minimum of 1000 replications is needed to test robustly the uncertainty of the regression coefficients.



a) PC1 *b) PC2*



c) Constant

Figure 6.17 *Standard error of different elements of the regression for the bootstrapping analysis.*

The regression coefficients and associated uncertainty statistics are shown in Table 6.15. The 95% confidence limit coefficients were used in the regression to calculate the 95% error bars on the prediction of downstream peak discharge. Figure 6.18 shows the 95% confidence limits around the prediction of the regression linking the principal components (original variables) to the magnitude of the peak flow downstream. This shows that several of the observed peak flows are outside of the 95% confidence limits of the regression, with 45 events being underestimated (observed above upper 95% confidence limit), and 41 events being overestimated (observed below lower 95% confidence limit). This means that 40% of the flood events were predicted by the regression within the 95% confidence limit.

	Coefficient	**Std. Error**	**t**	**P > t**	**95% Conf idence Intervals**	
PC1	67.4	6.35	10.62	0.00	55.0	79.9
PC2	-45.2	6.78	-6.67	0.00	-58.5	-31.9
Constant	497.3	5.60	88.80	0.00	486.3	508.3

Table 6.15 *Regression statistics for predicting downstream flood risk from principal components from the bootstrapping analysis with 100 replications.*

The residuals on these predictions are assessed in Figure 6.19. The range of residuals is from - 453.9 m^3s^{-1} to 173.4 m^3s^{-1} for the regression predictions. The average residual (either over or under estimated) is ± 21.2 m^3s^{-1}. The 95% confidence limit residuals range from - 458.9 m^3s^{-1} to 253.9 m^3s^{-1}.

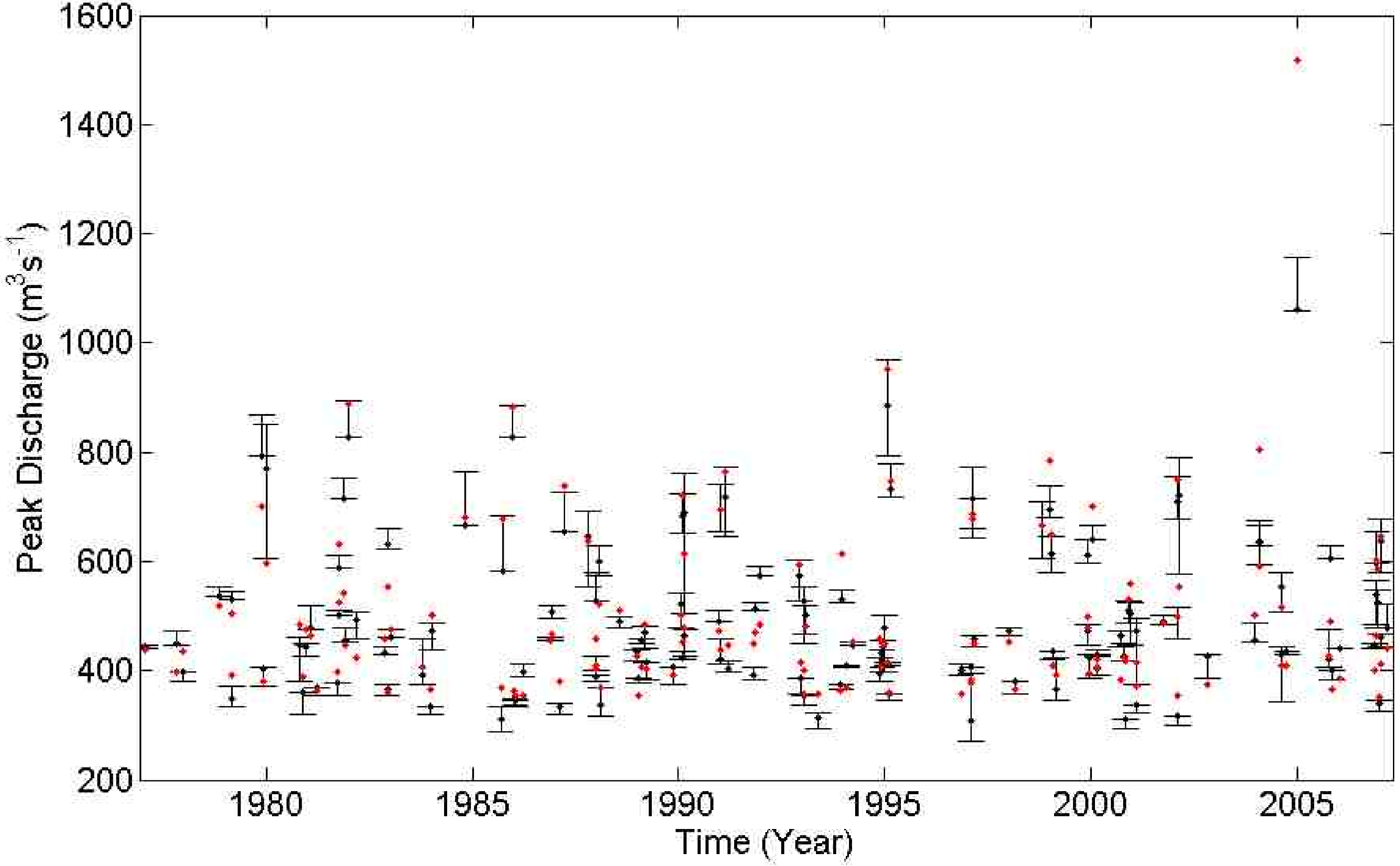


Figure 6.18 *Predictions of downstream flood magnitude using the regression equation. Black dots represent the value from the initial regression, while the error bars indicate the 95% confidence limits from the bootstrapping analysis with 1000 replications. The red dots show the actual observed value.*

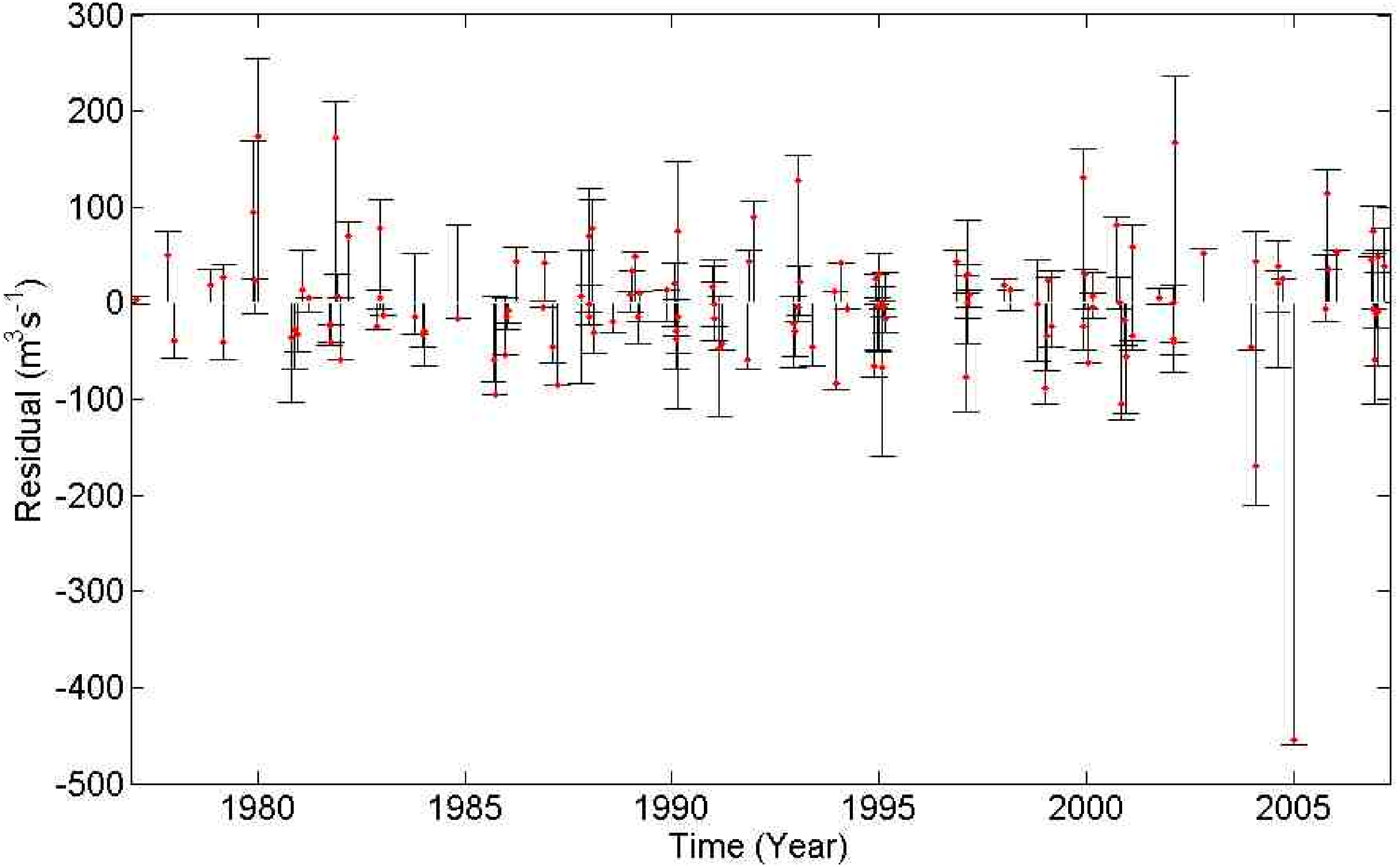


Figure 6.19 *Residuals of regression prediction, with the red dot representing the residual from the original regression, with the error bars showing the 95% confidence limits of the prediction.*

Another type of uncertainty is introduced by the input variables. Section 5.2.7 introduced revised rating curves used to convert stage to discharge at the gauging stations throughout the Eden catchment. Using these revised rating equations produces different peak flow magnitudes for the tributaries, while the peak flow relative timing stays the same. The whole principal components analysis was repeated using the revised discharge values. Again, the first three components are significant (eigenvalue > 1) accounting for 66.0% of the original variability. All three components are used in the stepwise regression to explain 89.9% of downstream flood magnitude. The contributions of each sub-catchment are shown in Figure 6.20. The Upper Eden and Eamont sub-catchments are again the most important in explaining downstream flood magnitude, accounting for 21.7% each. The Upper Eden is more important in terms of magnitude, while the Eamont is more important in terms of timing. The Petteril remains the third most important sub-catchment, a significant way between the upstream sub-catchments (Upper Eden and Eamont) and the Irthing and Caldew, which both account for about 14% of downstream flood magnitude. Overall, the general patterns from the principal components analysis using the original discharges and the revised discharges are similar, with slight variations in exact contributions.

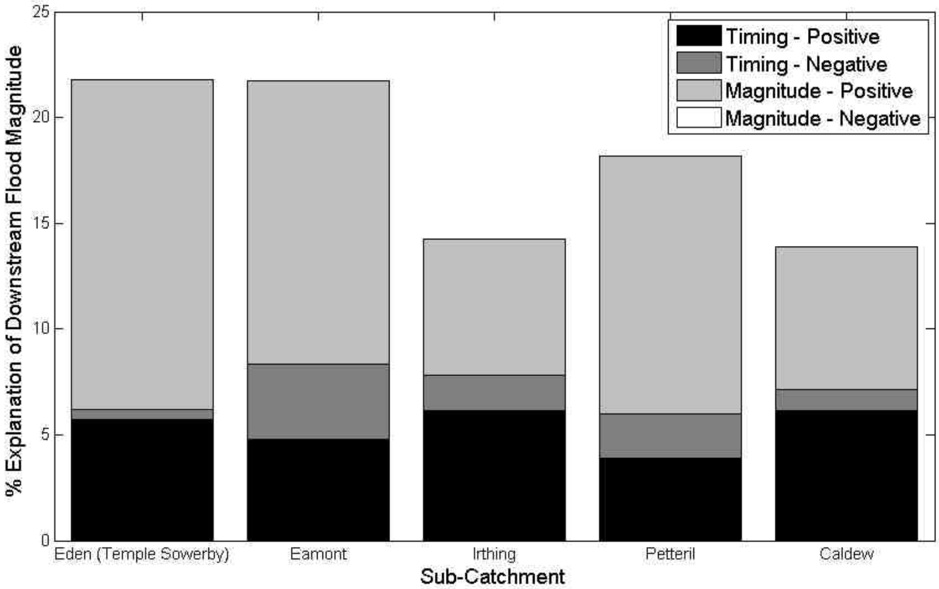


Figure 6.20 *Contribution of each sub-catchment in terms of peak flow magnitude and timing in explaining downstream flood risk for the principal components analysis using the revised sub-catchment rating equations for flood magnitude.*

6.3.6. Synthesis of statistical downscaling results

The multivariate techniques of principal components analysis and stepwise regression have been combined to predict downstream peak flow magnitude from the timing of, and the magnitude of, the peak discharge. The principal components analysis transformation found that three components accounted for 65.6% of the variability in the original variables. Next the stepwise regression found that 83.3% of the downstream flood magnitude could be predicted from the first two principal components, similar to what Lane (2003) found for the Ouse system (89.1%). Of this, 49.4% was explained by the magnitude of the peak flows in the sub-catchments, while 34.0% was explained by the timing of the peak flows from the tributaries. It was found that the Eamont was the most important sub-catchment, accounting for 19.3% of the downstream flood magnitude. The importance of the Eamont is increased when the results are standardised by catchment area. However, the importance of the Eamont in terms of the timing of the peak flow is relatively small due to the complex relationship between the original variables and the principal components. A sensitivity analysis was carried out to determine how sensitive downstream flood magnitude is to the sub-catchment peak flow magnitude and timing. It was found that the most sensitive sub-catchment was the Petteril in terms of magnitude and the Upper Eden in terms of timing. This is important because changes in sub-catchments could potentially result in changes in downstream flood hazard. Lane (2003) stated that a progressive change in how a sub-catchment responds to rainfall could lead to changes in peak water levels downstream. Both this thesis and Lane (2003) have shown that both the magnitude and the timing of the flows from the contributing sub-catchments matter in determining downstream flows. Lane (2003) hypothesied that these changes could be either caused by changing rainfall patterns (e.g. directions of rain bearing weather systems) or land use change (how catchment attenuates rainfall). The uncertainty of these predictions was then assessed using three approaches. Firstly, the residuals were assessed and were found to range from -408.9 m^3s^-1 to 205.7 m^3s^{-1}. However, importantly only 6.7% of the flood events had a residual of greater than 100 m^3s^{-1} and there was no pattern over time. The second approach was bootstrapping, whereby the 95% confidence limits of the predictions were determined. It was found that 40% of the flood events had predictions within the 95% confidence limits. Thirdly, revised rating curves were used to see how sensitive the predictions were to the input variables. It was found that overall the general conclusions were similar, with slight variations in specific contributions. The next section outlines the second spatial downscaling approach, which uses a hydraulic model.

6.4. Spatial Downscaling of Catchment Scale Flood Risk - Hydraulic modelling approach

An alternative spatial downscaling approach using the hydraulic model; iSIS-Flow was outlined in Section 5.3. The performance of the calibrated Eden iSIS model at three gauging stations is shown in Table 6.16. Overall, the performance of the model is good, with errors within the range found in the literature (Roughani *et al.,* 2007; Wu and Johnston, 2008). However, the model performs less well at Linstock gauging station. However, the reliability of the gauged record at this station is uncertain, as it failed during the event.

	Sheepmount	Linstock	Great Corby
Error on peak stage	0.208 m	0.59 m	0.079 m
Error on peak timing	1.0 hour	1.83 hours	0.83 hours

Table 6.16 *Performance of baseline iSIS model at different gauging stations in terms of the flood peak magnitude and timing.*

This section consists of 5 change scenarios; (a) magnitude reductions for individual sub-catchments; (b) timing shifts (delays and earlier) individual sub-catchments; (c) timing shifts from multiple sub-catchments simultaneously; (d) both timing and magnitude shifts from the same sub-catchment; and (e) hydrograph attenuation. All experiments are carried out for the January 2005 flood event.

6.4.1. Magnitude reductions for individual sub-catchments

Various percentage (0.5%, 1%, 2%, 5%, 10%, 15%, 20%, 25%) magnitude reductions were inputted for each sub-catchment separately and the effect at three stations (Sheepmount, Linstock and Great Corby) were assessed. There are several key observations on the effect of changing contributing tributaries flow magnitudes on peak stage downstream (Figure 6.21). First, the maximum reduction peak stage (0.331 m) in Carlisle was caused by a 25% reduction in the flows from the Upper Eden. The Upper Eden is always the most effective at reducing downstream stage, as it has the largest flow contribution of all the sub-catchments in actual discharge terms. The Irthing and Eamont offer similar amounts of flood magnitude reduction downstream (0.254 m and

0.219 m respectively). At lower percentage flow reductions the Eamont is more effective than the Irthing, but with greater than 10% flow reduction the Irthing becomes more beneficial. The Caldew has very little effect on peak stage in Carlisle until it is decreased by more than 10%. However, for greater than 15% flow decreases, the Caldew has no further positive effect on peak stage downstream in Carlisle. Reducing the flow contribution of the Petteril has very little effect on peak stage at Sheepmount, with a 25% reduction in the magnitude of the Petteril flows only resulting in a 0.052 m reduction in the peak stage downstream. This is because the flows of the Petteril are lowest in actual terms.

It is important to take account of the error associated with the model. The baseline simulation had a 0.208 m error on the peak stage at Sheepmount. To determine whether any of these change scenarios result in no out of bank flow, the error has to be subtracted from the bankfull level (solid black line). The threshold for the flow to be contained within the channel taking into account the error of the model is 13.712 m. The only magnitude change scenarios which result in a peak stage less than the bankfull are the Upper Eden 25% and 20% and the Irthing 25%.

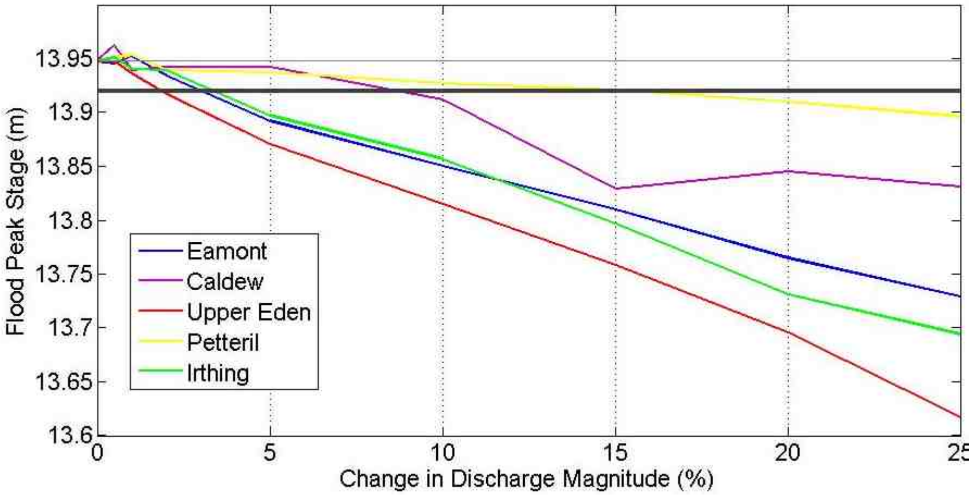
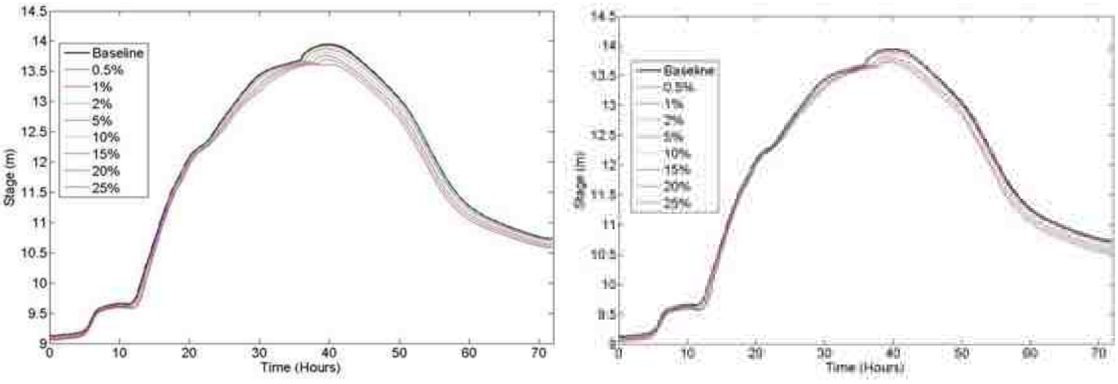


Figure 6.21 Sensitivity of peak stage at Sheepmount to percentage decreases in sub-catchment hydrograph contributions.(black line = bankfull height; grey line = baseline)

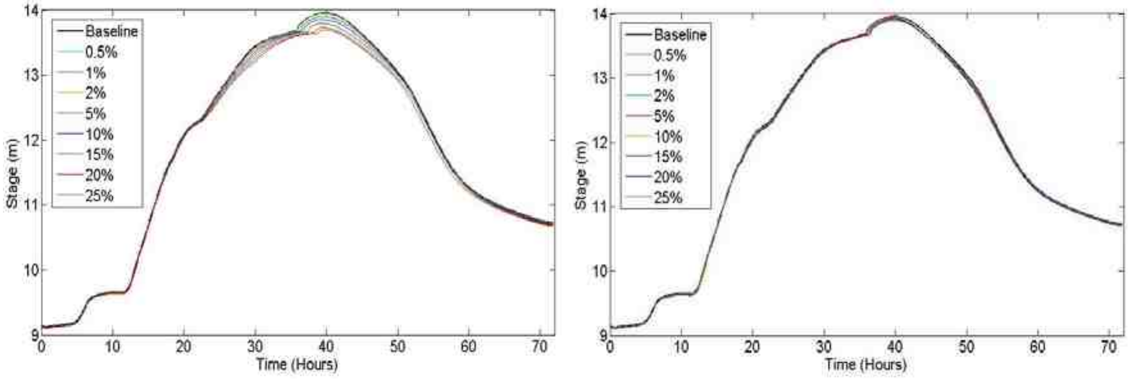
	0.5%	1%	2%	5%	10%	15%	20%	25%
Caldew	0.014	-0.009	-0.006	-0.006	-0.036	-0.119	-0.103	-0.117
Eamont	-0.003	0.004	-0.014	-0.056	-0.098	-0.138	-0.183	-0.219
Upper Eden	-0.001	-0.012	-0.031	-0.077	-0.133	-0.189	-0.252	-0.331
Irthing	0.003	-0.008	-0.009	-0.051	-0.091	-0.151	-0.217	-0.254
Petteril	0.003	0.006	-0.009	-0.011	-0.021	-0.027	-0.038	-0.052

Table 6.17 Impact of changes to sub-catchment hydrograph magnitudes on downstream peak stage (m).

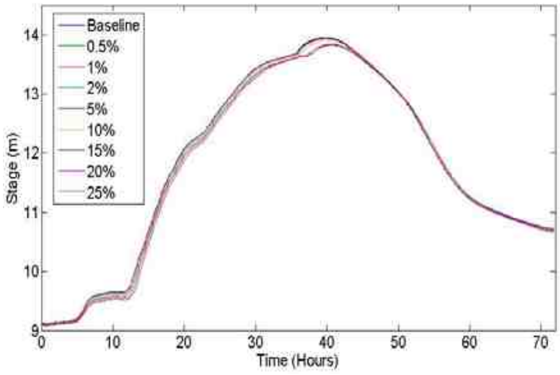
Figure 6.22 shows the impact of reducing the tributary hydrograph by each percentage on the flood hydrograph downstream at Sheepmount. The impact on the stage hydrograph downstream of reducing the Petteril flow is negligible (d). The Caldew (e) has a slight impact on the peak stage, but the rising and falling limbs are affected less. The impact of the Irthing (c) is significant during the highest stages between time 25 hours and 50 hours, but the rest of the hydrograph is not affected. The Eamont (b) reduces downstream stage from about 25 hours and significantly reduces the peak stage. In addition the falling limb stages are also reduced. Similar results occur for the Upper Eden (a), although the stage reduction is slightly greater.



a) Upper Eden *b) Eamont*



c) Irthing *d) Petteril*



e) Caldew

Figure 6.22 *Impact of changes in sub-catchment hydrograph magnitude on the downstream stage hydrograph at Sheepmount.*

The effect at Linstock is not as large as at Sheepmount (Figure 6.23). Linstock gauging station is located on the River Eden between the confluence of the River Irthing and the River Petteril. Therefore, the effect of the tributary inputs downstream of this gauging station (i.e. Petteril and Caldew) are minimal on the peak stage at Linstock, with the maximum reduction in peak stage being 0.031 m for a 15% reduction of the Caldew's flow input. The maximum effect of the Petteril is only a 0.014 m reduction of peak stage at Linstock. The tributaries upstream of the Linstock gauging station all have a greater effect. The Upper Eden has the largest impact on peak stage at Linstock, with a 25% reduction of the Upper Eden flows resulting in a 0.167 m reduction in peak stage. The effect of the Irthing and Eamont are similar, with a 25% reduction in flows leading to a 0.14 m reduction in peak stage downstream at Linstock.

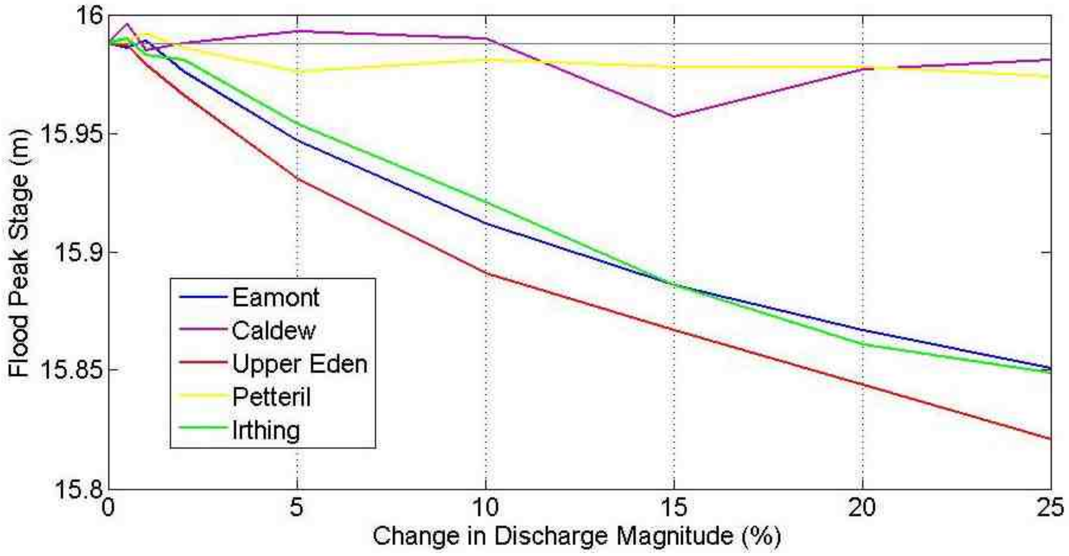


Figure 6.23 *Sensitivity of peak stage at Linstock to percentage decreases in sub-catchment hydrograph contributions.(grey line = baseline)*

At Great Corby, the gauging station downstream of the Upper Eden and Eamont, but upstream of the other tributaries, the peak stage is only affected significantly by the upstream sub-catchments. The effect of these tributaries on peak stage at Great Corby is linear, with the Upper Eden having a greater effect than the Eamont (Figure 6.24). This is because 1% of the flow from the Upper Eden is greater than for the Eamont, as it has a greater contributing area. The impact on downstream stage is 0.38 m and 0.28 m for a 25% reduction in the flows coming from the Upper Eden and Eamont respectively. Bankfull stage at Great Corby is 24.914 m. Accounting for model error on the peak stage, a threshold of 24.835 m will determine whether there is out of bank flows at Great Corby. All scenarios lead to peak stages higher than this threshold at Great

Corby, meaning that when taking account of model error, all peak flows will be out of bank at Great Corby.

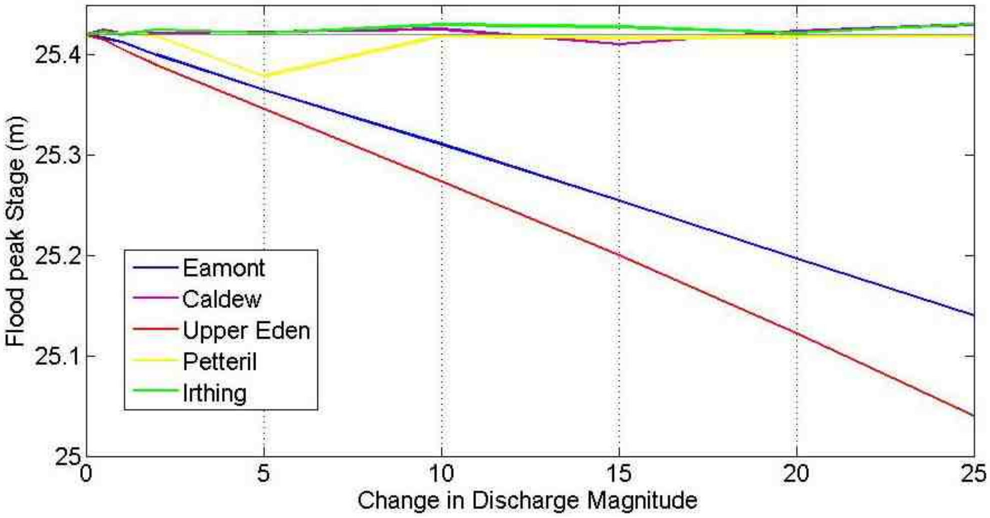


Figure 6.24 *Sensitivity of peak stage at Great Corby to percentage decreases in sub-catchment hydrograph contributions.*

6.4.2. Timing shifts (delays and earlier) of individual sub-catchments

Various timing shifts (15 minutes, 30 minutes, 1 hour, 2 hours, 3 hours, 4 hours, 6 hours, 8 hours) were inputted for each sub-catchment separately and the effect at three stations (Sheepmount, Linstock and Great Corby) were assessed. These consisted of the hydrograph being both shifted earlier and delayed by the timings outlined above and the results are shown in Figure 6.25 and Table 6.18a and Table 6.18b. The light grey horizontal line on Figure 6.25 is the baseline peak stage. The effect of changing the timing of the Petteril has a minimal effect on the peak stage. Delaying the upper sub-catchments (Upper Eden and Eamont) reduces peak stage, while when these tributaries peak earlier, peak stage increases. The longer these tributaries are delayed, the greater the reduction in peak stage downstream. Delaying these tributaries has a similar effect on peak flow in Carlisle up to a delay of 6 hours with a peak stage reduction of 0.24 m and 0.23 m respectively. However, a delay of 8 hours of the Upper Eden has a greater effect than the same shift on the Eamont, with a 0.32 m and 0.27 m reduction in peak stage respectively. The effect of these tributaries peaking earlier is for peak stage downstream to increase by 0.05 m for the Upper Eden and 0.08 m for the Eamont.

The effect of speeding up the response of the Caldew by 8 hours is the same as caused by delaying the Upper Eden by 8 hours: a peak stage reduction of 0.33 m.

Delaying the Caldew results in higher peak stages at Sheepmount, with an increase of 0.16 m with an 8 hour delay. Similar trends are shown for the Irthing, with a 0.26 m decrease in peak stage when the Irthing is speeded up by 8 hours. However, a more complex trend is evident when the Irthing is delayed. A delay of up to 4 hour leads to a slight increase in peak stage downstream, with the effect of a 1 hour delay having the greatest impact on stage. However, a delay of greater than 4 hours leads to a decrease in peak stage in Carlisle. An 8 hour delay of the Irthing results in a 0.09 m decrease in peak stage downstream.

As determined earlier, the threshold for overbank flow, accounting for model error, is 13.712 m. It is evident that significant changes in the timing of the tributaries are needed to lead to peak stages below this threshold. Firstly, a 6 hour (13.704 m) and 8 hour (13.625 m) delay of the Upper Eden results in a peak stage in Carlisle within bank. An 8 hour delay of the Eamont is required, resulting in a peak stage of 13.674 m. Other scenarios that lead to no out of bank flow are when the Caldew peaks 6 hours (13.699 m) or 8 hours (13.616 m) earlier or the Irthing peaks 8 hours earlier (13.692 m).

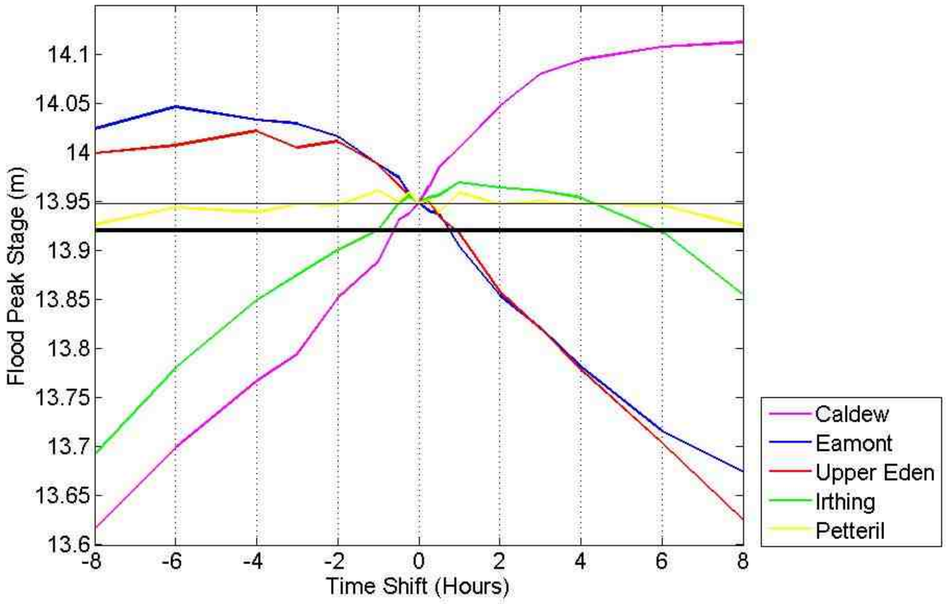


Figure 6.25 *Sensitivity of peak stage at Sheepmount to timing shifts of the contributing sub-catchments hydrograph - light grey line = original peak flow, dark grey line = bank full.*

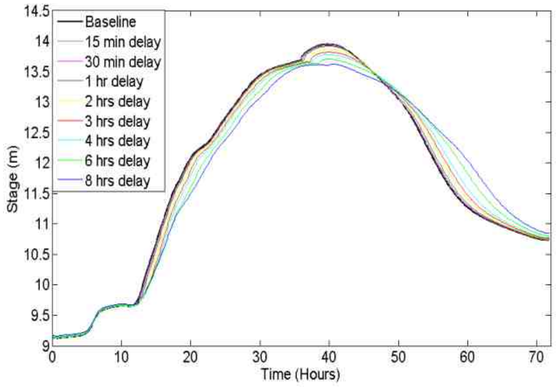
	0.25 hr	0.50 hr	1 hr	2 hrs	3 hrs	4 hrs	6 hrs	8 hrs
Caldew	0.017	0.036	0.057	0.099	0.132	0.146	0.159	0.164
Eamont	-0.008	-0.011	-0.044	-0.094	-0.127	-0.167	-0.232	-0.274
Upper Eden	0.002	-0.014	-0.031	-0.09	-0.128	-0.17	-0.244	-0.323
Irthing	0.006	0.008	0.021	0.016	0.013	0.006	-0.029	-0.093
Petteril	0.003	-0.01	0.011	-0.001	0.002	-0.001	-0.002	-0.023

Table 6.18a *Effect of delaying each sub-catchment on the peak stage at Sheepmount (Values given in metres)*

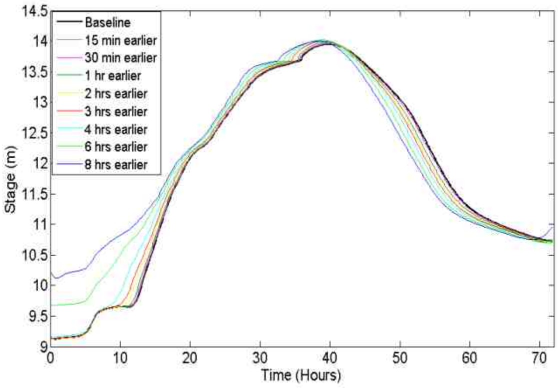
	0.25 hr	0.50 hr	1 hr	2 hrs	3 hrs	4 hrs	6 hrs	8 hrs
Caldew	-0.011	-0.017	-0.059	-0.097	-0.154	-0.181	-0.249	-0.332
Eamont	0.01	0.026	0.039	0.068	0.081	0.085	0.098	0.076
Upper Eden	0.008	0.018	0.039	0.063	0.057	0.074	0.059	0.051
Irthing	0.007	-0.001	-0.027	-0.048	-0.073	-0.099	-0.168	-0.256
Petteril	0.011	0.001	0.013	-0.002	-0.001	-0.009	-0.004	-0.022

Table 6.18b *Effect of speeding up each sub-catchment on the peak stage at Sheepmount. (Values given in metres)*

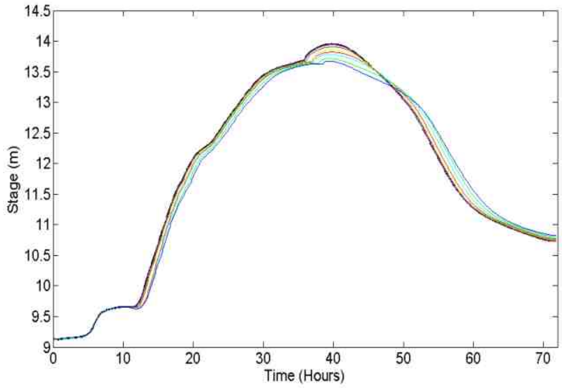
The effects of changing the timing of tributary peak flows on the stage hydrograph downstream at Sheepmount are shown in Figure 6.26. Figure 6.26a and Figure 6.26c show that the effect of delaying the upper sub-catchments (Upper Eden and Eamont) is to reduce the peak stage by having a less steep rising limb and eliminating the rapid rise in stage at 35 hours. Also the rate of recession is slower. This suggests that it may be the timing of the peak flows from the upper sub-catchments coinciding with peak flows from the lower sub-catchments that are causing the rise in stage at 35 hours. The effect of making these tributaries peak earlier does not have an effect on peak stage; it just shifts the hydrograph to earlier in time. The influence of the Irthing timing differs in that a delay shifts the hydrograph forwards in time with the hydrograph shape staying the same. Shifting it earlier makes the hydrograph smoother without the rapid rise at 35 hours. Changes to the timing of the Petteril make no difference to the shape, timing or magnitude of the hydrograph downstream in Carlisle. Delaying the Caldew makes the flood peak higher at Sheepmount. This is because the Caldew peaks early in the storm event, so delaying its peak flow makes it occur closer in time to the peaks from the other tributaries. Shifting the Caldew hydrograph earlier makes the peak flow at Sheepmount lower and eliminates the rise at 35 hours, making the hydrograph shape smoother.



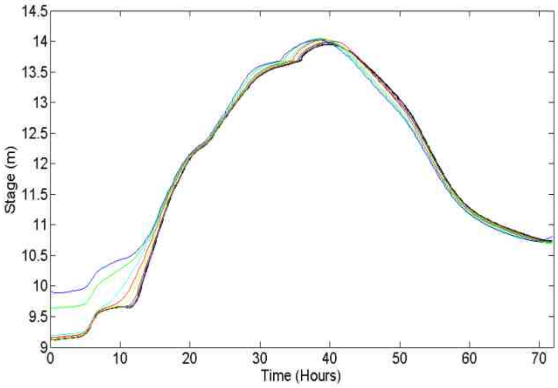
a) Upper Eden delay



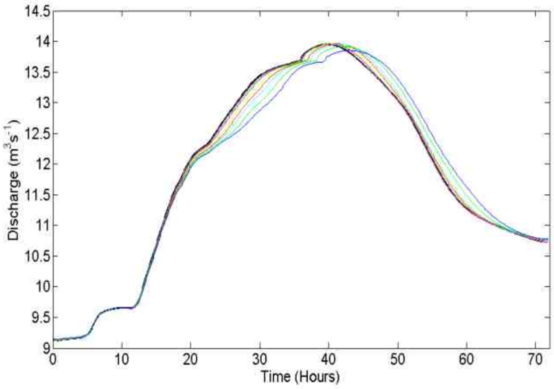
b) Upper Eden earlier



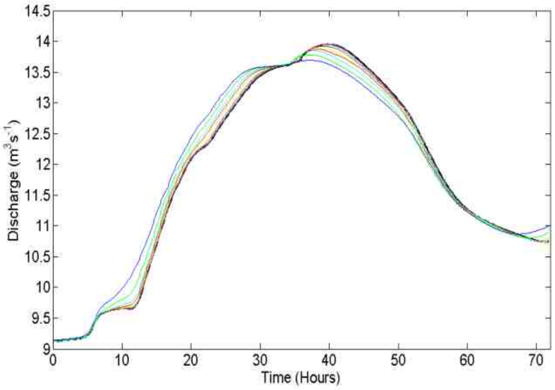
c) Eamont delay



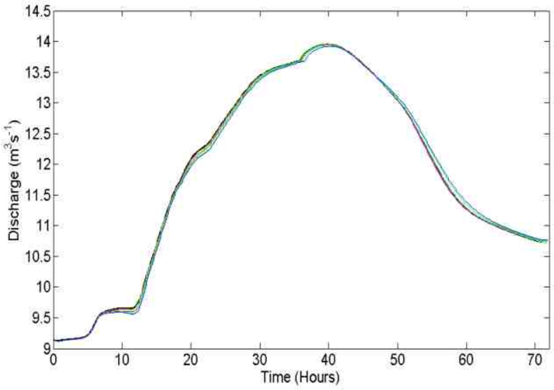
d) Eamont earlier



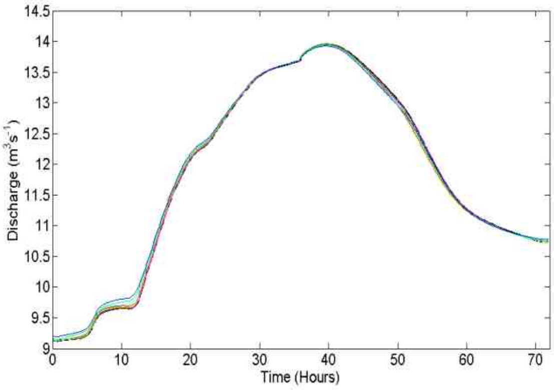
e) Irthing delay



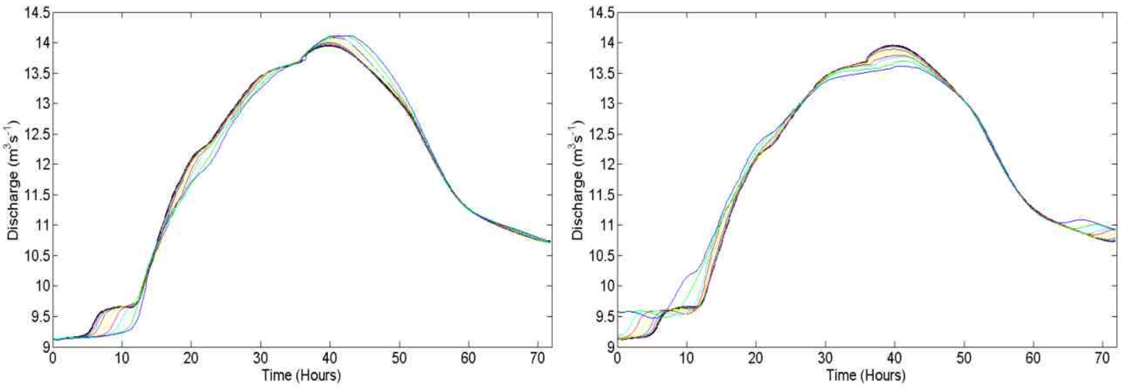
f) Irthing earlier



g) Petteril delay



h) Petteril earlier



i) Caldew delay *j) Caldew earlier*

Figure 6.26 *Impact of changes in sub-catchment hydrograph timing on the downstream stage hydrograph at Sheepmount.*

The effect of tributary peak flow timing on peak stage at Linstock is assessed in Figure 6.27. The effect of the Petteril and Caldew is minimal, as these tributaries are downstream of the Linstock gauging station. The small effect at Linstock is probably caused by backing up of the flow by the Petteril and Caldew tributaries. Delaying the peak flow of the Eamont and Upper Eden by 8 hours reduces the peak stage at Linstock by 0.167 m and 0.162 m respectively. This differs to the Sheepmount station where the timing of the Upper Eden has the greatest effect. The greatest amount of peak stage reduction at Linstock is caused by shifting the Irthing peak earlier by 8 hours, resulting in a 0.224 m decrease in peak stage at Linstock.

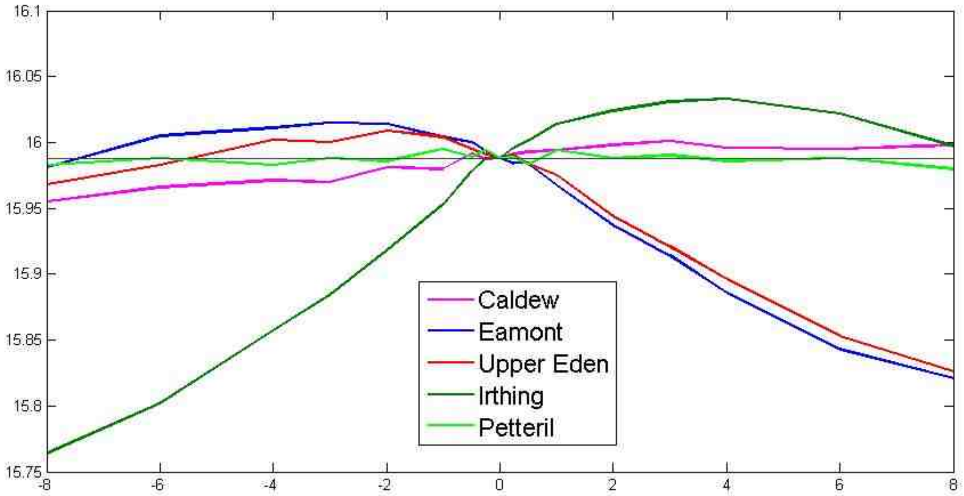


Figure 6.27 *Sensitivity of peak stage at Linstock to timing shifts of the contributing sub-catchments hydrograph.*

At Great Corby none of the downstream tributary timings have a significant effect on peak stage (Figure 6.28). The effect of the timing of the upstream tributaries is more interesting. Both a delay and shift earlier of the peak flow leads to peak stage reduction at Great Corby of a similar amount (0.21m - 0.26 m). Delaying the Eamont has a greater effect, while shifting the Upper Eden earlier has a larger flood stage reduction at Great Corby. A possible reason why both a delay and speeding up of these sub-catchments flow cause flood stage reduction at Great Corby is that the flood peaks from each sub-catchment will become less co-incident with each other. However, taking account of the model error on the peak stage, none of the timing scenarios lead to contained flows at the peak of the event.

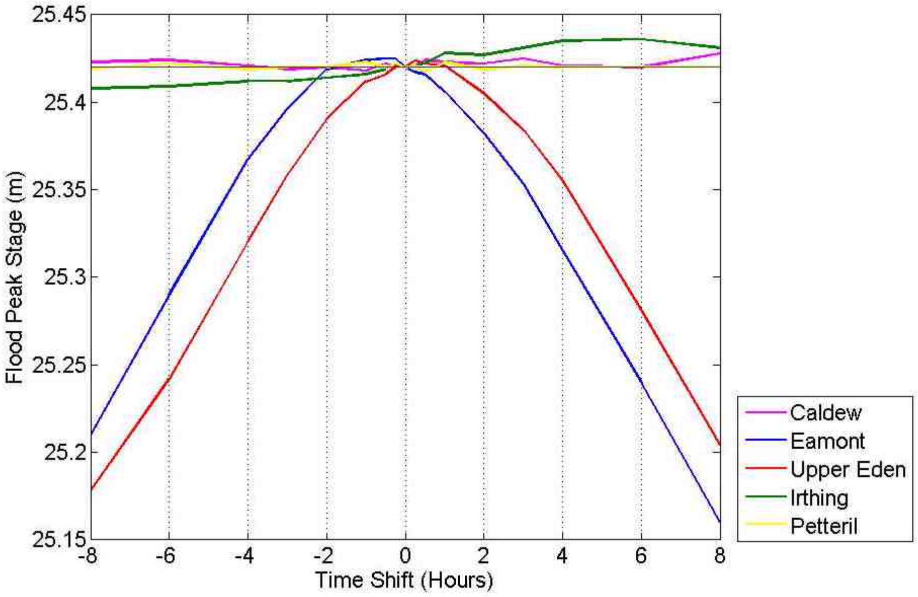


Figure 6.28 *Sensitivity of peak stage at Great Corby to timing shifts of the contributing sub-catchments hydrograph*

Changes to both the timing and magnitude of the flows from the Upper Eden and the Eamont have been shown to have the largest effect on downstream peak stage. Therefore, combined scenarios of both sub-catchments timing and magnitude changing together will be investigated. First, the timing of both sub-catchments will be changed simultaneously. Second, the timing and magnitude of each sub-catchment will be shifted.

6.4.3. Timing shifts from multiple sub-catchments (Eamont and Upper Eden)

Each sub-catchment hydrograph was shifted by 0 hours to 8 hours in all possible combinations. Results, in terms of the effect on peak stage downstream at Sheepmount are shown in Table 6.19. This shows that the maximum stage reduction is achieved by a time delay of both tributaries by 8 hours in combination (0.445 m). However, the same effect as delaying one of the tributaries by 8 hours can be achieved by delaying both tributaries by 4 hours each (0.32 m). Figure 6.29 shows the sensitivity of downstream peak stage reduction to timing of both tributaries. At low time delays (< 5 hours) both tributaries are both as effective as each other in terms of the effect of delaying their flow. However, beyond this the effect of each tributary differs with each becoming more important for different scenarios. In scenarios where the time delay of the Eden is high (> 6 hours), downstream flood stage is more sensitive to the Eamont if it is delayed by more than 3 hours. This means that beyond 6 hours delay of the Eden, the peak stage in Carlisle decreases more per unit time delay greater than 3 hours of the Eamont than the Eden. However, in scenarios where the time delay of the Eden is less than 6 hours, downstream flood stage is more sensitive to the Eden when the Eamont is delayed by more than 5 hours. This means that for a time delay of the Eden by less than 6 hours and a time delay of the Eamont by more than 5 hours, the peak stage in Carlisle decreases more per unit time delay of the Eden than the Eamont.

The combination of different timing delays from both the Eden and Eamont together sometimes provides additional benefits over when the stage reduction caused by each tributary in isolation are added together (Table 6.19). This synergy means that smaller changes in both sub-catchments may be equal to larger shifts from just one tributary. This is the case for the scenarios which include any time delay of one of the tributaries in addition to a lower time delay for the other (≤1 hour for the Eden and ≤0.50 hour for the Eamont). This is important given the expected ease of achieving smaller delays through land management change. When both tributaries are delayed by larger amounts the amount of peak stage reduction in Carlisle is less than the separate effects of delaying each tributary added together. The same effect downstream can be achieved by smaller time delays of both tributaries simultaneously or a longer time delay of just one of the rivers. For example, an hour delay of the Eden results in a 0.031

m reduction of the peak stage at Sheepmount, while a half hour delay of both tributaries together results in a 0.032 m decrease.

Eam **Eden**	**0**	**0.25**	**0.5**	**1**	**2**	**3**	**4**	**6**	**8**
0	0	-0.008	-0.011	-0.044	-0.094	-0.127	-0.167	-0.232	-0.274
0.25	0.002	**-0.006** (-0.006)	**-0.023** (-0.009)	**-0.056** (-0.042)	**-0.095** (-0.092)	**-0.135** (-0.125)	-0.174 (-0.165)	**-0.237** (-0.230)	**-0.288** (-0.272)
0.5	-0.014	**-0.033** (-0.022)	**-0.032** (-0.025)	**-0.061** (-0.058)	**-0.109** (-0.108)	**-0.144** (-0.141)	-0.179 (-0.181)	**-0.248** (-0.246)	**-0.296** (-0.288)
1	-0.031	**-0.049** (-0.039)	**-0.069** (-0.042)	**-0.082** (-0.075)	**-0.127** (-0.125)	**-0.16** (-0.158)	**-0.201** (-0.198)	**-0.266** (-0.263)	**-0.322** (-0.305)
2	-0.09	-0.092 (-0.098)	**-0.104** (-0.101)	-0.126 (-0.134)	-0.164 (-0.184)	-0.199 (-0.217)	-0.236 (-0.257)	-0.307 (-0.322)	-0.352 (-0.364)
3	-0.128	**-0.14** (-0.136)	**-0.149** (-0.139)	-0.166 (-0.172)	-0.198 (-0.222)	-0.234 (-0.255)	-0.276 (-0.295)	-0.352 (-0.360)	-0.371 (-0.402)
4	-0.17	**-0.176** (-0.178)	**-0.183** (-0.181)	-0.203 (-0.214)	-0.238 (-0.264)	-0.279 (-0.297)	-0.318 (-0.337)	-0.371 (-0.402)	-0.389 (-0.444)
6	-0.244	**-0.253** (-0.252)	**-0.261** (-0.255)	-0.277 (-0.288)	-0.312 (-0.338)	-0.356 (-0.371)	-0.375 (-0.411)	-0.402 (-0.476)	-0.419 (-0.518)
8	-0.323	**-0.333** (-0.331)	-0.337 (-0.337)	-0.344 (-0.367)	-0.363 (-0.417)	-0.38 (-0.450)	-0.396 (-0.490)	-0.424 (-0.555)	-0.445 (-0.597)

Table 6.19 *Effect of delaying multiple sub-catchments on the peak stage at Sheepmount.(numbers in brackets are summed separate effects of each tributary)*

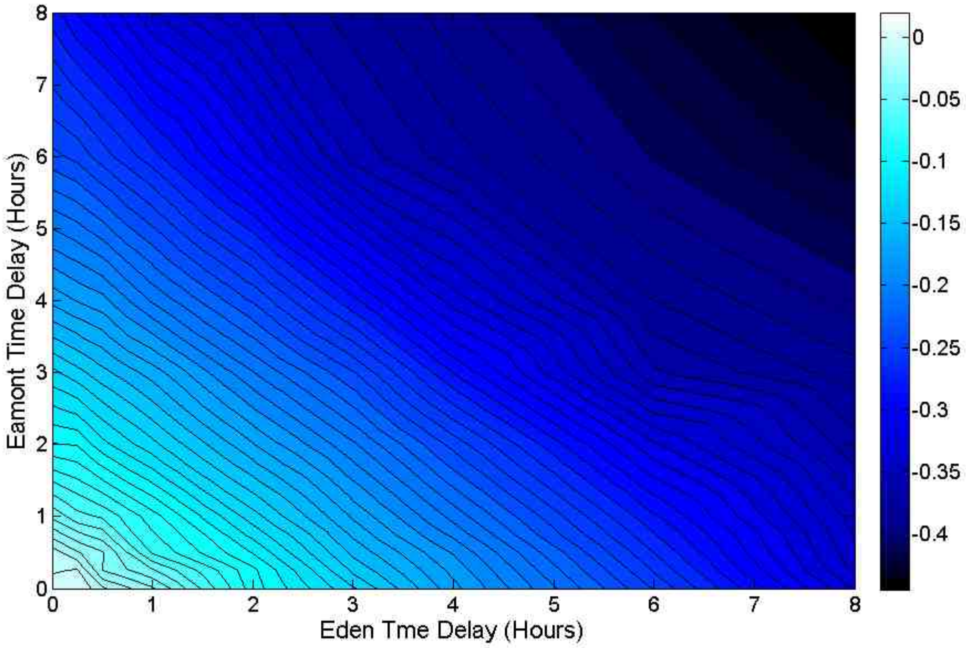


Figure 6.29 *Sensitivity of peak stage at Sheepmount to timing shifts from multiple sub-catchments*

6.4.4. Timing and magnitude Shifts

Scenarios of combined magnitude and timing shifts were made for the Upper Eden and Eamont. The effect of shifts in timing and magnitude for the Upper Eden are shown in Figure 6.30 and Table 6.20. The maximum peak stage reduction at Sheepmount is 0.42 m, caused by an 8 hour delay and a 25% decrease in magnitude. For scenarios of timing delays less than 5 hours and magnitude reductions of less than 10%, the effect on downstream peak stage is equally sensitive to timing and magnitude changes in the Upper Eden. The importance of timing delays increases after 5 hours, with peak stage reduction being more sensitive to changes to timing than magnitude above this threshold. This means that beyond 5 hours delay of the Eden, the peak stage in Carlisle decreases more per unit time delay than per percentage decrease of flow magnitude. The sensitivity of downstream flood stage to magnitude shift is high for shifts greater than 20% when the Upper Eden is shifted in time by less than 5 hours. This means that changes of flow magnitude beyond 20% have a greater effect on downstream peak stage than large changes in the timing of that flow.

The combinations of different timing and magnitude shifts sometimes produce added benefit to both the scenarios separately. The scenarios which fit this criterion are shown in red bold font in Table 6.20. This suggests that small time delays (≤ 1 hour) in addition to any magnitude reduction combined provides more than the expected amount of peak stage decrease downstream, if implemented separately. The greatest gain is for the smallest magnitude increase and smallest time delay (2% magnitude, 0.25 hours), with 0.015 m extra stage decrease in Carlisle. However, for the scenarios combining larger magnitude decreases and time delays, less than the expected stage decrease is found downstream, with a 25% decrease in magnitude causing 0.331 m, and an 8 hour delay causing 0.323 m separately, but in combination they only cause a 0.419 m decrease in downstream peak stage instead of 0.654 m.

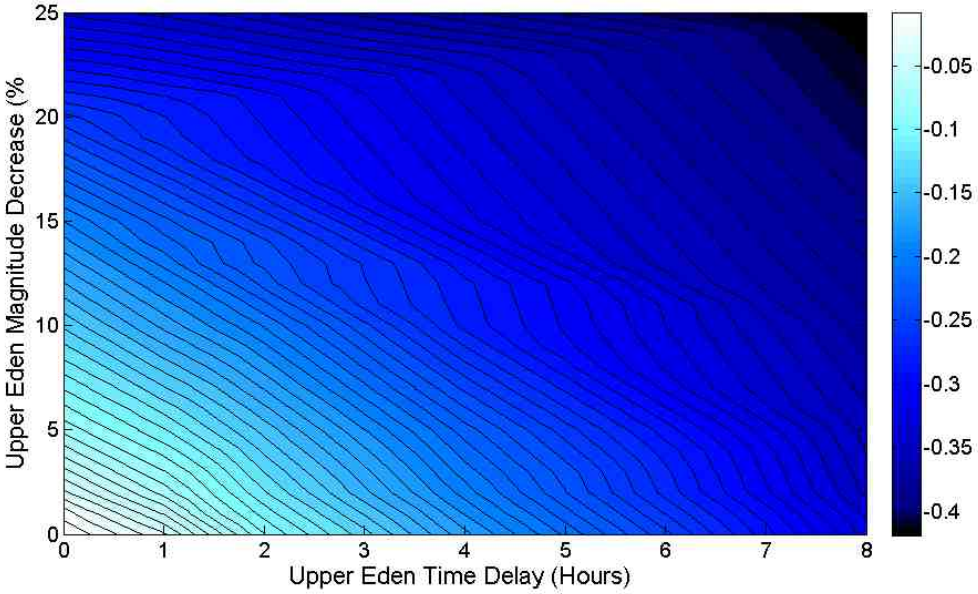


Figure 6.30 *Sensitivity of peak stage at Sheepmount to both timing delays and magnitude reductions of the Upper Eden*

Timing / Magnitude	**0 hrs**	**0.25 hr**	**0.50 hr**	**1 hrs**	**2 hrs**	**4 hrs**	**8 hrs**
0%	0	0.002	-0.014	-0.031	-0.09	-0.17	-0.323
2%	-0.031	**-0.044** (-0.029)	**-0.053** (-0.045)	**-0.069** (-0.062)	-0.114 (-0.121)	-0.193 (-0.201)	-0.339 (-0.354)
5%	-0.077	**-0.085** (-0.075)	**-0.092** (-0.091)	-0.106 (-0.108)	-0.143 (-0.167)	-0.218 (-0.247)	-0.349 (-0.400)
10%	-0.133	**-0.141** (-0.131)	**-0.148** (-0.147)	**-0.167** (-0.164)	-0.198 (-0.223)	-0.274 (-0.303)	-0.367 (-0.456)
25%	-0.331	**-0.332** (-0.329)	-0.335 (-0.345)	-0.34 (-0.362)	-0.352 (-0.421)	-0.377 (-0.501)	-0.419 (-0.654)

Table 6.20 *Effect of both timing delays and magnitude reductions of the Upper Eden on the peak stage at Sheepmount. (numbers in brackets are summed separate effects of each tributary)*

The effect of shifts in timing and magnitude for the Eamont are shown in Figure 6.31 and Table 6.21. The maximum peak stage reduction at Sheepmount is 0.38 m, caused by an 8 hour delay and a 25% decrease in magnitude. This indicates that the peak stage at Carlisle is more sensitive to changes in the flows (both magnitude and timing) of the Upper Eden than the Eamont. Figure 6.31 shows that downstream flood stage reduction is more sensitive to the timing than the magnitude for lower magnitude changes. This means that smaller changes in the timing of the hydrograph have a greater effect on downstream stage than changes in the magnitude of the flows from the Eamont. This is a particularly useful finding as it is expected that delivering time delays will be easier than changing the flow magnitude through land management changes. However, for higher magnitude changes (>20%), magnitude becomes more important than the timing of the peak in impacting downstream peak stage, especially for small time delays.

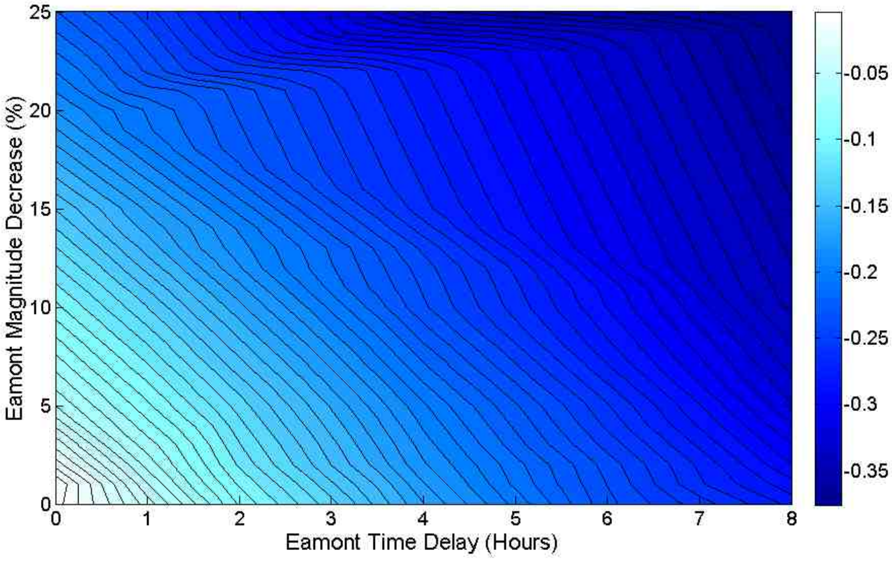


Figure 6.31 *Sensitivity of peak stage at Sheepmount to both timing delays and magnitude reductions of the Eamont*

Scenarios combining both magnitude decreases and time delays of the Eamont have an added benefit on downstream flood stage as compared with the expected reduction from each separate scenario added together. For a magnitude decrease of 2%, combined with any of the timing delays produce a peak stage downstream lower than what is expected by each individual change combined. However, for changes in magnitude greater than 2% only small time delays (≤0.50 hour) produce more than the expected amount of peak stage reduction downstream.

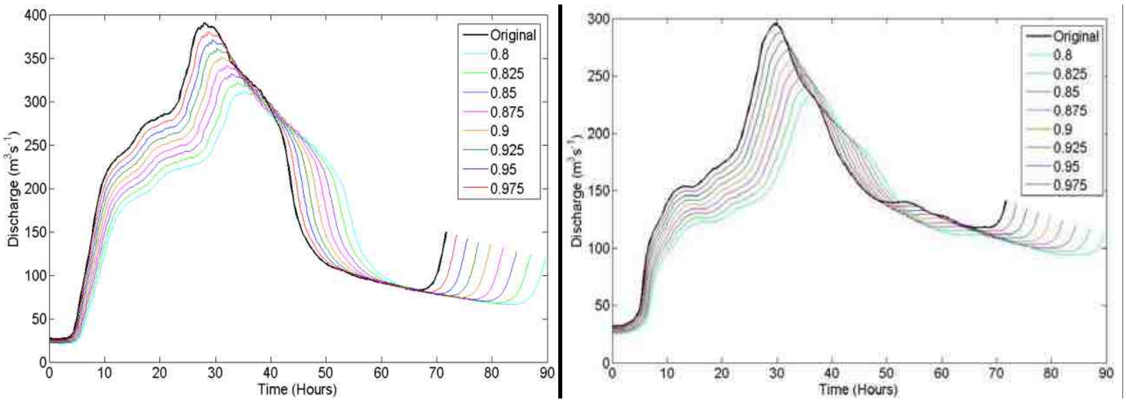
Timing Magnitude	**0 hrs**	**0.25 hr**	**0.50 hr**	**1 hr**	**2 hrs**	**4 hrs**	**8hrs**
0%	0	-0.008	-0.011	-0.044	-0.094	-0.167	-0.274
2%	-0.014	**-0.028** (-0.022)	**-0.042** (-0.025)	**-0.066** (-0.058)	**-0.109** (-0.108)	**-0.181** (-0.181)	**-0.294** (-0.288)
5%	-0.056	-0.061 (-0.064)	**-0.075** (-0.067)	-0.091 (-0.100)	-0.126 (-0.150)	-0.196 (-0.223)	-0.316 (-0.330)
10%	-0.098	**-0.107** (-0.106)	**-0.112** (-0.109)	-0.13 (-0.142)	-0.165 (-0.192)	-0.233 (-0.265)	-0.341 (-0.372)
25%	-0.219	-0.229 (-0.227)	**-0.235** (-0.230)	-0.246 (-0.263)	-0.28 (-0.313)	-0.345 (-0.386)	-0.376 (-0.493)

Table 6.21 *Effect of both timing delays and magnitude reductions of the Eamont on the peak stage at Sheepmount (metres). (numbers in brackets are summed separate effects of each tributary)*

6.4.5. Attenuation

In reality, the effects of land management changes or floodplain storage are not expected to be simple shifts of the hydrograph in either magnitude or time separately or in combination. It is far more likely that the shape of the hydrograph will change through the process of flood wave attenuation. This involves the flood peak being both extended in time and reduced in magnitude. As explained in Section 5.3 two approaches to representing attenuation in the January 2005 flood hydrograph have been developed: (1) stretching in time / reduction in magnitude by constant change factor; and (2) subtracting of water from certain times and adding it back through time at a rate proportional to total amount. These two approaches are applied to the Upper Eden and Eamont tributaries as changes in these have been found to have the greatest effects downstream.

Figure 6.32 shows how the observed January 2005 hydrograph from the Upper Eden (a) and Eamont (b) are changed when applying different change factors via approach 1. In both cases, the flood peak is delayed in time, extended in duration and lowered in magnitude. Mass is conserved but the duration of the event is extended from 72 hours to 90 hours for the smallest change factor (0.8).



a) Upper Eden b) Eamont

Figure 6.32 *Input hydrographs for a) Upper Eden, and b) Eamont for attenuation scenarios of varying degrees by approach 1.*

The impact of these scenarios on downstream peak stage is shown in Figure 6.33. This shows that the effect of attenuation of the Upper Eden has a greater effect on downstream peak stage than the same amount of attenuation of the Eamont, although the differences between the impact of each tributary are minor. As the amount of attenuation increases, the amount of peak stage reduction downstream increases.

Furthermore, as the amount of attenuation increases, the effect of the Upper Eden diverges from the effect of the Eamont. This suggests that the Upper Eden is more effective at reducing downstream peak stage. However, while the gradient of the Eamont line is reasonably constant, the Upper Eden becomes less effective for a change factor lower than 0.85 (Figure 6.33).

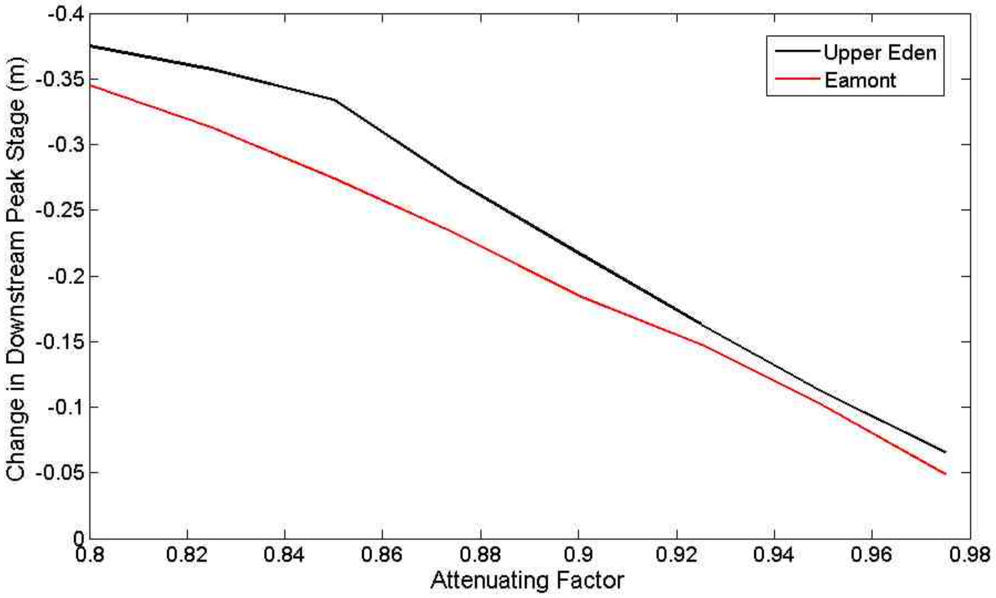
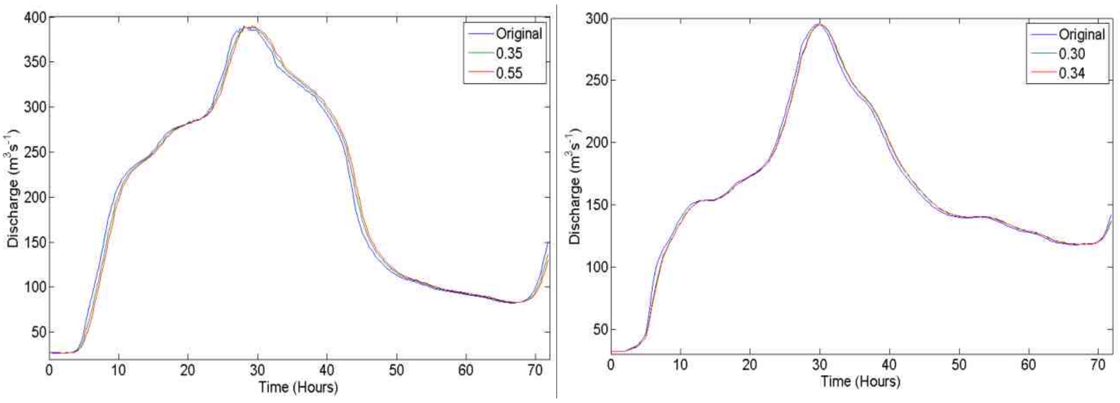


Figure 6.33 *Impact of varying degrees of attenuation of peak stage at Sheepmount.*

The other approach of representing attenuation was less successful. This was because only a very small range of attenuation factors allowed the peak to be both delayed and reduced in magnitude. This was because the overall flood hydrograph duration was kept constant at 72 hours. This led to much smaller amounts of attenuation occurring (Figure 6.34). Larger amounts of attenuation led to delayed but higher peak flows. Results of these simulations showed that much less flood peak stage reduction downstream, caused by the smaller amount of change in the two tributaries (Table 6.22). Both tributaries offered similar amounts of stage reduction downstream, with a maximum of 0.015 m.



a) Upper Eden *b) Eamont*

Figure 6.34 *Input hydrographs for a) Upper Eden, and b) Eamont for attenuation scenarios of varying degrees by approach 2.*

Factor	Change in stage (m)
Eamont 0.3	-0.010
Eamont 0.34	-0.015
Upper Eden 0.35	-0.008
Upper Eden 0.55	-0.015

Table 6.22 *Results of attenuation effect on downstream peak stage at Sheepmount.*

6.5. Summary of Spatial Downscaling

Both the statistical and hydraulic modelling spatial downscaling methods showed that the Upper Eden and the Eamont sub-catchments were the most important in determining downstream peak stage. Tables 6.23 and Table 6.24 summarise the most important results from the hydraulic modelling and statistical analysis approaches respectively. It is important to note that the changes of the two approaches are not directly comparable. This is because the baseline for each approach was different due to the different errors associated with each approach. The hydraulic modelling method indicates that the impact of changing the timing or magnitude of either tributary is significantly greater than the statistical downscaling approach. However, in percentage terms, the effect of both methods are similar in terms of the effect of a 25% reduction in discharges, with the Upper Eden causing a 2.4-2.0% reduction in peak stage magnitude downstream in Carlisle and the Eamont a 1.7-1.6% reduction in peak stage in Carlisle. It is clear that large changes in sub-catchment hydrographs result in only a modest change in downstream peak stage. However, the impact of the timing of the flows from these two tributaries on peak stage downstream varies considerably between the two methods. The numerical modelling approach indicates that changing the timing of the flows from each tributary has an effect of the same order of magnitude as changing the magnitude of the flows. The statistical method indicates that the effect of timing is much lower than the hydraulic modelling method. An 8 hour delay of the Upper Eden causes a 2.3% reduction in peak stage in Carlisle through the hydraulic modelling approach, and only a 0.6% decrease through the statistical approach. Even more significant is that the effect of the Eamont differs between the two methods in terms of the direction of change downstream. The hydraulic modelling approach shows that delaying the Eamont decreases peak stage downstream, while the statistical method indicates that delaying the Eamont causes peak stage to increase by 0.5% in Carlisle.

One of the main differences between the two approaches is that the statistical approach investigated a range of flood events of different magnitudes, while the hydraulic modelling approach just looked at a single event, the extreme January 2005 flood. Saghafian and Khosroshahi (2005) found that for higher return period flood events the spatially distributed response of the catchment and channel routing processes become less important and the whole catchment responds in a more homogeneous manner. However, this study has found that changes to individual sub-catchments can still have a significant effect on downstream flood magnitudes, even for extreme events.

There are similarities between the results of the two downscaling approaches. Both approaches indicate that the Upper Eden is more important than the Eamont, both in terms of the magnitude and timing of the flows. Furthermore, both approaches show that these two tributaries are significantly more important in influencing downstream flooding than the other sub-catchments: the Irthing, Petteril and Caldew, while the difference between the two sub-catchments themselves is not that large. Also generally both approaches show that the effect of changing the magnitude is greater than changing the timing of the flows. There is one exception to this finding, with the hydraulic modelling approach indicating that delaying the Eamont by 8 hours has a greater effect than reducing the flow magnitude of the Eamont by 25%.

Scenario	Change in Stage (m)	% Change in Stage
Magnitude 25% decrease Upper Eden	-0.331	-2.4%
Magnitude 25% decrease Eamont	-0.219	-1.6%
Timing 8 hour delay Upper Eden	-0.323	-2.3%
Timing 8 hour delay Eamont	-0.274	-2.0%

Table 6.23 *Summary of results from the hydraulic modelling spatial downscaling approach*

Scenario	Change in Stage (m)	% Change in Stage
Magnitude 25% decrease Upper Eden	-0.15	-2.0%
Magnitude 25% decrease Eamont	-0.12	-1.7%
Timing 8 hour delay Upper Eden	-0.05	-0.6%
Timing 8 hour delay Eamont	0.04	0.5%

Table 6.24 *Summary of results from the statistical spatial downscaling approach*

Overall there are important similarities between the two methods, indicating that these approaches do have potential to prioritise the optimum sub-catchment to focus on. Using these approaches allows a greater understanding of flood generation in large catchments, especially in terms of sub-catchment interactions (Prohaska et al., 2008). Furthermore, this understanding, especially in terms of the timing of the flows from different sub-catchments, can be used to improve flood forecasting and warning systems. The most important similarity is that both methods highlighted the importance of the Upper Eden and Eamont out of the five Eden sub-catchments. However, there are significant differences between the two methods in terms of the magnitude of the changes in peak stage. The following section discusses and justifies which of these sub-catchments have been chosen to focus land management scenario testing.

6.6. Justifying Chosen Sub-Catchment

The spatial downscaling results indicated that the optimum sub-catchment to focus on to deliver the greatest amount for flood hazard mitigation downstream in Carlisle was the Upper Eden, closely followed by the Eamont. It has been decided that the sub-catchment which will be focussed on for the rest of this thesis will be the Eamont. The reasons for this are outlined below.

The overall aim of this thesis is to test the hypothesis that land management has an impact on catchment scale flood risk. The methodology used to do this is through numerical modelling. This approach has several requirements, for example data inputs and model validation data. When assessing which of the Upper Eden and Eamont met these requirements, it was concluded that the Eamont was most suitable. First, the Eamont has 21 gauging stations of either river stage or discharge (Figure 6.35), while the Upper Eden only has 5 gauging stations (Kirkby Stephen, Great Musgrave, Appleby and Temple Sowerby on the Eden and Cliburn on the Leith tributary).

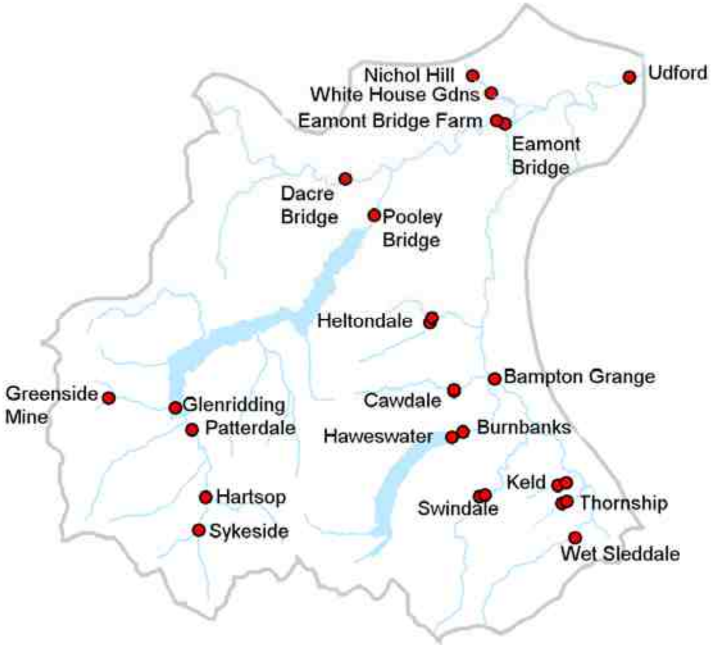
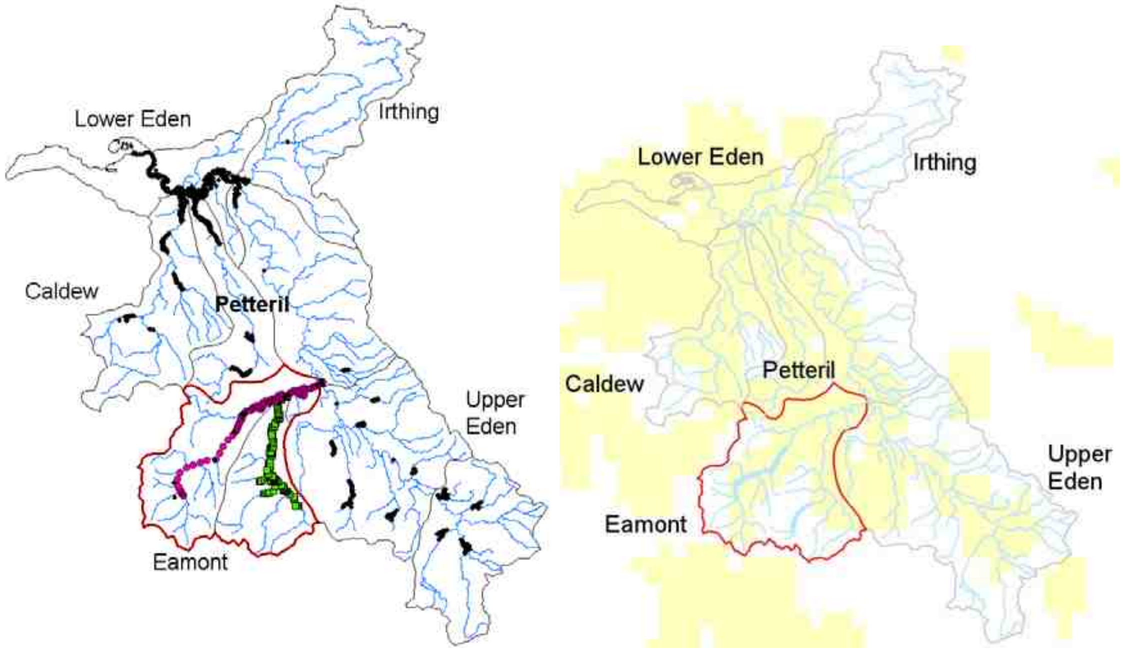


Figure 6.35 *Gauging stations in the Eamont sub-catchment*

Furthermore, the Upper Eden is considerably larger than the Eamont (616 km^2 compared to 396 km^2). Catchment size will affect the resolution and run-time of any models that are developed. Additionally, the Eamont has 17 tributaries, of which only 7 are downstream of Ullswater, while the Upper Eden has 26 tributaries. The fewer number of tributaries makes hydraulic modelling easier, especially as only one of the Eden tributaries has a gauged record, while many of the Eamont tributaries have a gauging station. Another requirement of hydraulic modelling is channel cross sections and floodplain topography data. As both of these river systems are large, it would be very labour and time intensive to survey them. Therefore, an assessment of existing hydraulic models of the Eden catchment is shown in Figure 6.36a. This showed that most of the Eamont/Lowther system is covered, while only very small reaches of the Upper Eden have been modelled in the past. Figure 6.36b shows the LIDAR coverage of the Eden catchment. A higher proportion of the Eamont sub-catchment has coverage, with the main Eamont and Lowther having data. The main Upper Eden channel is covered, but few of the major tributaries have data.



a) Hydraulic model *b) Lidar*

Figure 6.36 *Data coverage of the Eamont sub-catchment*

An additional reason why the Eamont is a favourable sub-catchment to focus on is that there is a flood risk problem within the sub-catchment. Figure 6.37 shows widespread flooding in the Eamont sub-catchment in January 2005. One of the worst effected settlements was Eamont Bridge (Figure 6.37 b, c, d, k), where 35 houses were flooded. Eamont Bridge was again flooded in the Novemeber 2009 floods, one of just a few areas in the Eden catchment (Figure 6.38). Further upstream, the villages of Bampton and Bomby have also experienced flooding in recent years. An in-depth study by Wade et al., (2008) concluded that the management of Haweswater reservoir contributed to flooding. There is a flooding problem in the Upper Eden, although the worst effected settlements such as Appleby have hard temporary flood defences.

In conclusion, it has been decided that the Eamont sub-catchment will be used in the rest of this thesis to test the hypothesis that land management has an impact on catchment scale flood risk. The justification for this decision is that it has been shown by the spatial downscaling analysis that the peak flow magnitude and timing of the Eamont has one of the greatest impacts on downstream flood risk, and that there are sufficient data for this catchment to test land use change scenarios.

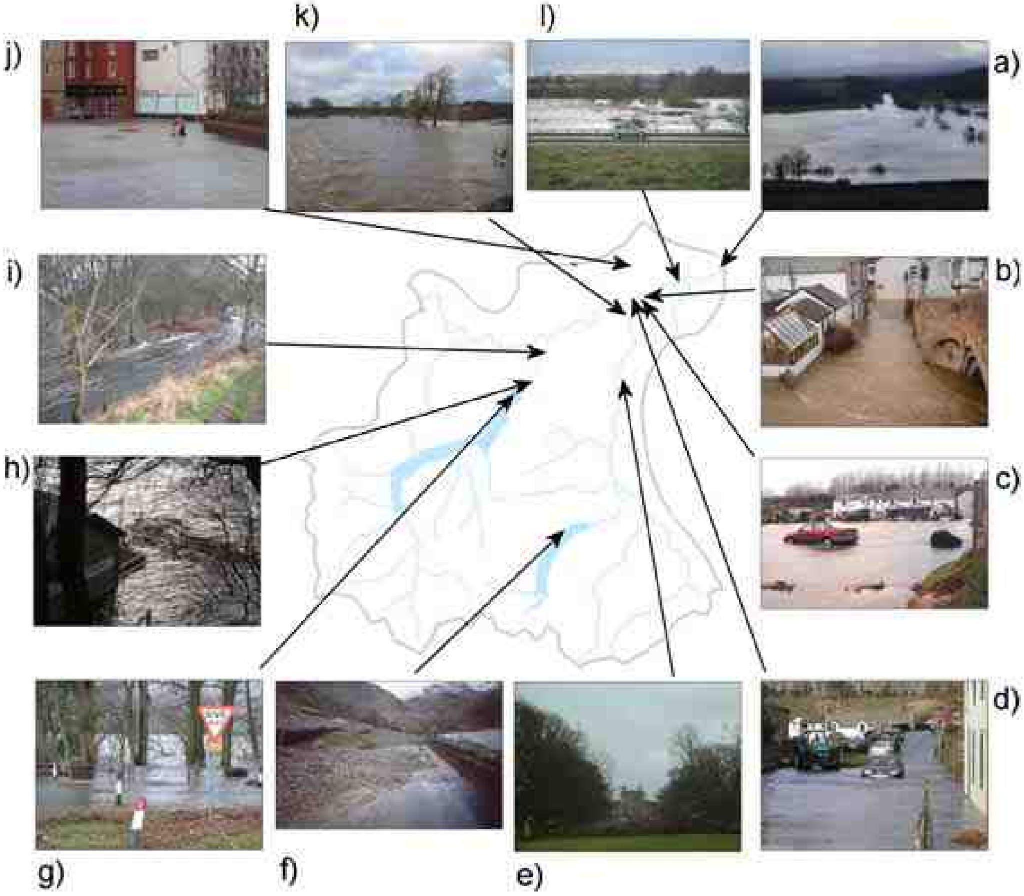


Figure 6.37 *Photographs of flooding throughout the Eamont sub-catchment in January 2005. a) Eden-Eamont confluence; b) Eamont Bridge; c) Eamont Bridge; d) Eamont Bridge; e) Lowther estates; f) Haweswater reservoir; g) Ullswater; h) Ullswater boat shed; i) A592 along side Ullswater; j) Penrith; k) Brougham; and l) Eamont along side A66.*

Figure 6.38 *Photographs of flooding in the Eamont sub-catchment in November 2009. a) Brougham; b) Eamont Bridge; c) Eamont Bridge; d) Ullswater; and e) Brougham.*

6.7. Chapter Summary

This chapter has reported the results of the two spatial downscaling methodologies developed in Chapter 5. There are three key conclusions from this work. First, it has been shown that both the magnitude and timing of the peak flows from contributing sub-catchments exhibit a critical influence on downstream flood magnitude. The relative importance of the tributary peak flow magnitudes (49.4%) is higher than the relative timing (34.0%) of the peak flows from the different sub-catchments, although this shows that timing is an important secondary factor to consider. The hydraulic modelling spatial downscaling approach also showed that shifts in the timing of the tributaries hydrograph had a significant effect on flood peak stage in Carlisle. It was shown that the effect of a 25% reduction in flow magnitude was comparable to an 8 hour delay in timing in terms of the impact on peak stage downstream for the Upper Eden and Eamont sub-catchments.

Second, it has been shown that considerable changes to the flows from the sub-catchments are needed to have a significant impact downstream in Carlisle. A delay of 8 hours of the Upper Eden results in 0.32 m peak stage reduction downstream. A 25% reduction in flow magnitude of the Upper Eden leads to a 0.33 m decrease at Sheepmount. Smaller changes in both magnitude and timing result in smaller amounts of change downstream. It was also shown that only these large upstream shifts produce peak stages that are below the bankfull when accounting for the error of the model.

Third, the spatial downscaling approaches have been shown to be able to be used to prioritise sub-catchments in terms of their effects downstream. The results from the statistical and modelling approaches were comparable, highlighting the importance of the Upper Eden and Eamont sub-catchments in controlling downstream flood risk. Taking both the results of the spatial downscaling and the data needs of models used to test land use changes into account, it has been concluded that the Eamont sub-catchment will be focussed upon for the rest of this thesis.

Chapter 7

Stakeholder Participation in Deciding What Scenarios to Test

"Tell me and I will forget, show me and I may remember,
involve me and I will understand" *(Confucius, c. 450 BC)*

7.1. Chapter Scope

Chapter 2 summarised the impact of land use changes on flooding at the local and catchment scales. Chapters 5 and 6 determined that the optimum sub-catchment to focus on for the rest of the thesis was the Eamont sub-catchment. This chapter addresses the choice of land management scenarios to be tested in the rest of this thesis. This will be done through an approach that combines scientific and local knowledge through active stakeholder engagement. Active engagement allows for the two way exchange of information, while passive engagement allows stakeholder just to provide information to the scientists (Grimble and Wellard, 1997; Rowe and Frewer, 2000).

This chapter starts by introducing different models through which stakeholders have been involved in doing science. The advantages and limitations of each approach will be assessed, with reference to previous flood risk studies. This is followed by a discussion of which stakeholders were included in this study. Finally, the methodology used will be outlined, in which a series of workshops were held with all the stakeholder organisations.

7.2. Need for Stakeholder/Public Involvement in Science

The classic definition of a stakeholder is those who affect or are affected by a decision or action (Freeman, 1984). Different stakeholders have different roles to play in flood risk science and have different opinions on whether or not rural land management could be used to reduce flood risk. The Environment Agency's role in flood risk science is concerned with the management of flood risk. Traditionally, it has focussed on engineered flood defences (Werrity, 2006), but both national policies and local practitioners are now considering alternative options, such as rural land management. Specifically for the Eden catchment, the Environment Agency had plans in place to upgrade flood defences before the flood event in January 2005. These were higher in elevation but to levels which would still have been exceeded by the 2005 event. After the January 2005 floods in the city of Carlisle, new flood defences, including embankments and flood banks have been extended and their elevation increased further. However, alternative options of land management are also being considered and researched within this thesis. The Environment Agency mostly commissions consultants or academics to do flood science research on their behalf (Lane, in press).

7.2.1. Models of Stakeholder Participation in Science

Lane *et al.*, (in press) use Callon (1999) to propose three approaches to think through how stakeholders and the public are and might be engaged in flood risk science. Callon (1999) classifies engagement into three types: (1) public education (PE); (2) public debate (PD); and (3) co-production of knowledge (CK), which are outlined and discussed in terms of flood risk science below.

The public education approach assumes that the stakeholders and the public are deficient in knowledge and tries to reduce this deficit. There is an assumption that stakeholders are scientifically ignorant and scientists need to enhance their scientific literacy. This assumes a hierarchy of knowledge, where scientific knowledge is positioned above lay knowledge. This authority given to science over other types of knowledge (Sturgis and Allum, 2002) means that communication of research takes the form of education rather than allowing any reflexive engagement with the science done. Furthermore, *a priori* framing of the problem by the scientists often means that the problem that matters to the stakeholders is not addressed. Intermediaries are used to transfer knowledge from the scientists to the public. The Environment Agency is a good example of an intermediary, as consultants do the science, while the Environment Agency communicates this information to the stakeholders. Often trust in these intermediaries breaks down, which makes the management of the problem harder to fulfil.

Sturgis and Allum (2004) called for a re-evaluation of the deficit model, as cross-transfer of information may lead to better theory and more successful decision-making. The public debate approach (Callon, 1999) considers that scientific knowledge should be viewed as provisional until the people who have a stake in it are consulted (Collins and Evans, 2002). Under this form of engagement, if "expert" findings conflict with local knowledge then debate should be allowed. Collins and Evans (2002) argue that this allows science to overcome the problems of legitimacy, by widening decision making beyond a core of certified experts. This is the classic approach to doing flood risk management research, where a scientist undertakes a modelling study, produces a report, and then embarks upon a public consultation. This is how the Environment Agency produced their Catchment Flood Management Plans (CFMP's). However, there maybe mis-trust between the public and the scientists, as the public do not fully understand how the "experts" calculated their results (especially the use of models) (Morton 1999). Furthermore these consultation exercises maybe just a box to tick before a scheme can go ahead and any feedback is unlikely to influence the outcome (Lane, in press). In a stronger form, the public debate approach may involve engagement earlier in the process, such as in defining the problem, but the role of the scientist as the provider of knowledge is left intact.

Simonovic and Akter (2006, p. 183) state that "real participation is more than consultation". This is because management options can be designed without participation, but cannot be implemented without it (Affeltranger, 2001). Thus, the final approach to stakeholder participation in science uses co-production of knowledge. This approach allows stakeholders to participate in the process of knowledge generation, rather than just deliberating over its findings. There are many different approaches to co-producing knowledge (e.g. participatory action research, (Kindon et al., 2007)). These vary in how non-scientists are identified and engaged in the process, the weight given to scientists and non-scientists, and the form of the engagement. However, they all share a key characteristic: a redistribution of the responsibility of conducting science, meaning that scientists are no longer given an exclusive position over others. Implicitly the co-production of knowledge approach repositions the stakeholder participation much earlier in the research process (Wynne, 2003; Ledoux *et al.*, 2005; Cockerill *et al.*, 2006). Lane *et al.*, (in press) recognise different types of expertise; process-expertise, which covers an understanding of the physical system and place-expertise (which is similar to what Collins and Evans (2002) called experience based expertise), which includes knowledge of the specific area and problem.

In this thesis, by actively engaging stakeholders in the framing of scientific questions to be assessed using mathematical models, the approach being adopted involves co-production. The level of participation is probably best described as “weakly” co-productive, as a substantial proportion of the science was conducted outside the stakeholder engagement. Rather, the stakeholders were actively involved in defining what land use management measures might work, where they should be tried, and how important they thought they might be. Furthermore, they were also actively involved in evaluating the research findings in a way more like the public debate approach.

7.2.2. Advantages and Challenges of involving stakeholders

Scientific studies involving stakeholder participation are increasing but are still uncommon. This is because although there are many benefits to co-producing knowledge with stakeholders, there are still many challenges that need to overcome before the approach is more widely adopted (Irvine and Stansbury, 2004). The purpose of including stakeholders in the process of doing science is to have mutual benefits for all involved. It is often stated that research carried out with stakeholders is more successful than without them (Horelli, 2002). This is because the inclusion of relevant stakeholders focuses the research on the important issues and therefore the outcomes are more relevant to the real world specific problem. Furthermore the stakeholders bring local knowledge to the study, as they often interact with the system on a daily basis and have a good understanding of the specific case study (Prell *et al.,* 2007). Participation often enhances the quality of any decisions that are made, as it is more representative of interested groups. Furthermore, these decisions are more likely to be accepted by the community, of which they are a part, making the outcome more sustainable. A key issue here is trust between the scientists, the practitioners and the public. This mutual trust (Bloomfield *et al.,* 2001; Ostrem *et al.,* 2003) leads to more confidence in the decisions made and more co-operation in their implementation. This follows the Trust-Confidence-Co-operation model of Earle and Siegrist (2006).

There are also benefits for the stakeholders that participate in the research. Under the public education approach, it is believed that stakeholders gain a greater understanding of the system and processes at work, along with possible options to improve the problem being researched (Pateman, 1970; Blackburn and Bruce, 1995). The public are often referred to as becoming citizen experts. The public debate and co-production approaches often give the stakeholders the opportunity to frame the research, and if involved at an early enough stage can define the problem investigated. This has been referred to as empowering the public and increasing their political influence in the decision making process. Also they feel a sense of ownership of the decision and these benefits are likely to make the project more successful.

However there are several challenges and limitations of doing participatory research. The first challenge is deciding which stakeholders to involve in the project. Groups are often categorised by academics in a subjective manner, as issues such as relative power and influence are considered (Mitchell *et al.*, 1997). These groups are often heterogeneous which means that the individual chosen to represent the organisations views is critical to the success of the project. Different people have different personalities and opinions and the person involved in the project often changes throughout the process due to its time intensive nature (Walker and Langan, 2004). This means that the stakeholder group dynamics change making the participatory process more difficult. Also the person chosen is often just representing their organisations views and has to consider many factors along with the one being focussed upon.

Another issue regarding the legitimacy of the participatory process is that the problem being researched may be chosen before the stakeholders who have an interest in it have been chosen. However, it is very difficult to overcome this dialectic between issue definition and stakeholder selection, meaning that the problem under investigation is decided in a top-down manner, with potential bias introduced from the very beginning of the engagement process (Dougill *et al.*, 2006). Therefore, stakeholders have less power than they often think as the process has already started before they become involved. This links to the challenge of trust, as by working equally together the project should benefit, but often the influence of the stakeholders may be less than they hoped for and this may lead to problems of mistrust and sceptism of the scientists.

Often participatory research is carried out as a marketing exercise, where stakeholders are guided towards the same decision that would have been made without them, but now it is more likely to be accepted (Rourke, 1984). Stakeholders lack research objectivity (Gass *et al.*, 1997) as they often have a particular perspective, hidden agenda or a preferred outcome in mind before the engagement begins. Even if this pre-determined decision is not the case, often decisions that stakeholders arrive at are not going to please all the participants.

There are also more practical challenges in doing participatory research such as transcending disciplinary boundaries, as often one person does not have all the skills needed to carry out the interdisciplinary project. Different academic fields use different methods and terminology and this makes working together more difficult. Also the cost of organising participatory research groups, often with multiple meetings is greater than if the science was done in isolation. Furthermore, these projects are often time intensive, which often leads to participants losing interest in the research over time and dropping out of the project (Cockerill *et al.*, 2006).

7.2.3. Use of Stakeholders in previous flood risk studies

Lane *et al*. (in press) describe the process of including stakeholders in flood risk studies as “doing flood risk science differently”. This is because most flood risk research is done by scientists or consultants with little, if any, stakeholder participation. There are two types of stakeholders involved in flooding research; (1) individuals who are present by virtue of their profession (e.g. Environment Agency employees); and (2) individuals who are present due to their personal experience of the problem. This section will outline a few studies that have used this approach, giving details of the methodology and the conclusions drawn.

Firstly the Lane *et al.* (in press) project focussed on the controversy of flood risk. Environment competency groups allowed collaboration between local residents and academic social and natural scientists. The approach used in this study was a series of meetings focussing upon developing new competencies with respect to flooding.

A second study investigating the potential for land use to reduce flood risk is Posthumus *et al.* (2008). This used a different type of stakeholders, as these group members belonged and represented an interested organisation (i.e. professional partners), such as policy makers, planners, land owners and non-governmental organisations. The format of the participation was in the form of interviews and workshops. One of the questions asked was about the causes of flooding in the catchment, and answers ranged from urbanisation to field drainage and lack of channel dredging. The tool used to structure discussions was the FARM tool (Floods and Agriculture Risk Matrix) (Hewlett *et al.*, 2004; 2008; Quinn, 2004), which related soil management and the processes of infiltration and storage to the landscape scale process of hydrological connectivity. The group suggested several land management options and assessed their impact using the FARM framework. These scenarios included reducing stock density, improving soil structure through adding organic matter, buffer strips, fencing and ponds. One of the most important priorities of farmers was to maintain hedgerows and stonewalls. Often the organisations involved in the project had multiple objectives in addition to reducing flooding, such as wildlife biodiversity and diffuse pollution.

Howgate and Kenyon (2009) studied community opinions on natural flood management in Scotland. A series of community meetings showed a lack of trust between the organisations responsible for flood management and the public. This was highlighted by comments such as “there is a lack of relevant paperwork for people in the valley to read” (p 336) and that the lack of consultation with local residents was due to “institutional lethargy”. This study also showed that the general public has an understanding of hydrological processes. This is illustrated by comments such as “water is running off too fast, so this [storage] will help” (p 337). Another finding in this study is that the public preferred natural solutions to flood risk, rather than hard engineering (Kenyon, 2007; Howgate and Kenyon, 2009). Furthermore there was a sense of obligation to reduce flood risk downstream. This solidarity was suggested to be related to the physical connection provided by the river. In terms of participation, it was felt that bottom-up approaches initiated by stakeholders were better than top-down studies, where residents felt pressurised into participating.

There are three key issues relating to past use of stakeholder participation in flood risk science. First, the types of stakeholders included in the study, either professional partners or flood experienced individuals, and the benefits each bring. Second, the place specific nature of each study, relating to both the types of management scenarios tested and the methods used to test them. Certain management options may be unfeasible in certain contexts and locations, knowledge that local stakeholders can bring to the research. Furthermore, certain processes may dominate in certain case studies, while other processes may be thought to be less important, meaning that models can include/exclude them in a parsimonious manner. Finally, the form of participation is important, ranging from individual interviews to group workshops, using a range of methods such as brainstorming and mapping.

7.3. Approach to combining Stakeholder Knowledge with Scientific Knowledge

This section starts by identifying the interested organisations in flood management and rural land use in the Eden catchment. This is followed by the participatory approach used in this thesis to determine land management scenarios to reduce flood risk in the Eamont sub-catchment of the Eden. This consisted of a brainstorming of ideas (Section 7.4.2), which were mapped on to a conceptual process-oriented framework, formulated through a review of the literature. This is important as different types of models are needed to test different parts of the process cascade. Then, these options were evaluated under five main criteria; relevance to catchment, scientific effectiveness, testability, robustness/uncertainty and feasibility of implementation (Section 7.4.3). This was then taken back to the steering group for them to discuss the suitability of each scenario. The options were then accepted or rejected for future consideration. These decisions were based both on scientific needs and expectations and local suitability and feasibility. The scenarios which were accepted were then ranked in order of priority (Section 7.4.4). The next stage of the participatory approach was a mapping workshop, whereby a map of the catchment was laid out and locations where each scenario could feasibly be implemented were identified (Section 7.4.5). As progress was made with the numerical testing of these scenarios, results and recommendations were reported to the stakeholders for their input and opinions. This feedback then informed further scenario testing. By maintaining close linkages between science and the organisations involved in managing the catchment, the scenarios tested and the overall outcomes should be more relevant and useful for all involved.

7.3.1. Which stakeholders to include?

Often stakeholders are selected on an *ad hoc* basis, which may marginalise important groups, bias results or potentially jeopardise the long term sustainability of the management practice (Reed e*t al.,* 2009). There are multiple stakeholders who have an interest in flood risk in the Eden catchment. These include both individuals (the general public) and organisations who both live and work in the area. It was decided that a steering group would be formed involving professional partners who manage the catchment and have interests in either rural land management or flood risk or both. The Eden Rivers Trust, who were one of the original members of the steering group, suggested several more professional organistations who had a stake in land management and flood risk management in the Eden catchment. This approach is known as snowball sampling. The organisations included can be classified by the following categories: (a) non-governmental organisations; (b) commercial; (c) statutory non-departmental public bodies; and (d) academic. Several interested organisations were excluded from the initial engagement, such as land owners, local authorities, angling clubs, and individuals who had experienced flooding. These groups will be involved in the latter stages of the project when management changes are being planned. The specific organisations involved in the project are detailed below (Table 7.1).

a) *Non-governmental organisations*

These stakeholders are charities which rely on fund-raising activities and external sources of funding to manage the catchment, but are independent of any regulation.

Eden Rivers Trust

The Eden Rivers Trust is a charitable organisation, founded in 1996, with two aims: (1) to conserve, protect and improve the River Eden, its tributaries and the flora and fauna in and adjacent to them; and (2) to increase public awareness of the importance of the River Eden and its catchment through education. The slogan the Eden Rivers Trust uses is: “Getting our feet wet; researching, conserving and educating” which alludes to the practical nature of their work. However, they have no statutory power or legal authority or responsibility. Rather, they focus on voluntary partnerships forming agreements with land owners and tenants over how they manage their land. They are restricted in the geographical area they focus on, to just the Eden catchment, which means that they can concentrate on restoring and conserving the area and focus their resources upon the areas in most need. They do this through a targeting approach, grounded in expanding scientific understanding through research.

Stakeholder	Why are they involved ?	Identification
Eden Rivers Trust	Manage Eden catchment with good links to land owners	Originally involved in project formulation
Association of Rivers Trust	National scale knowledge of similar projects and allows wider dissemination	Originally involved in project formulation
Royal Society for the protection of birds	Multiple benefits of many of the measures used to reduce flood risk	Eden Rivers Trust contact and site visit of Sandford wetland
United Utilities	Water resource management in the catchment	Originally involved in project formulation and funder
Environment Agency	Responsible for flood management in the catchment	Originally involved in project formulation and funder
Natural England	Fund land owners for schemes which can be used to reduce flood risk	Eden Rivers Trust contact
Lake District National Park Authority	Local knowledge of specific sub-catchment.	Identified after Eamont sub-catchment identified to focus upon.

Table 7.1. *Stakeholder groups involved in this project*

Association of Rivers Trusts

The Association of Rivers Trusts is the organisation representing all 30 rivers trusts in the UK (Figure 7.1). It was founded in 2001 and co-ordinates and increases information transfer between the individual rivers trusts. An advantage of their involvement in the project is that similar studies in other catchments can be highlighted and it will allow wider dissemination of the research outcomes of this study through national seminars and workshops.

Figure 7.1. *Map showing the locations of Rivers Trusts in the UK*

Royal Society for the Protection of Birds

The RSPB focuses on the conservation of bird populations, along with other wildlife and their habitats. It was founded in 1889 and gained Royal Charter in 1904. They own and manage 200 nature reserves in the UK, including Geltsdale and Haweswater in the Eden catchment. Land management advice is also provided to land owners, which enhance habitats and biodiversity. For example, wetlands are a key focus of the RSPB’s work (e.g. they manage Sandford Mire, near Appleby in the Upper Eden sub-catchment). The RSPB also promotes the protection and restoration of hedgerows which provide good habitat for nesting birds, while also having benefits for reducing hydrological connectivity and potentially flooding.

b) *Commercial*

Commerical companies are profit making organisations which provide a service or produce something. Their source of money is either the public or other companies.

United Utilities

United Utilities is a FTSE 100 company which provides the North-West of England with both energy and water services. It is the UK's largest water company, supplying water to 2.9 million households (6.7 million people) and businesses. It was privatised in 1989 and therefore is regulated in terms of economics (OFWAT – office of water service), the environment (Environment Agency) and drinking water quality (Drinking Water Inspectorate). The Environment Agency decides how much water can be abstracted from surface and sub-surface stores and sets and enforces standards for water quality in rivers.

United Utilities also own the Haweswater estate in the Eamont sub-catchment, which comprises 15 farms let to tenants and over 26,000 acres of agricultural land, woodland and reservoirs. This area is critical to the water supply to the whole of the NW of England, as explained in Section 1.4.6. As the sub-catchment chosen to be the focus of this thesis is the Eamont, it is important that the land management scenarios do not have negative effects on water resources and low flows. United Utilities under the SCaMP (Sustainable Catchment Management Programme) project are aiming to discover good land management practices to protect SSSIs, enhance biodiversity, improve water quality and ensure a sustainable water supply.

c) *Statutory Non-Departmental Public Bodies*

These are governmental organisations, but they are not an integral part of a government department and therefore act with little ministerial influence.

Environment Agency of England and Wales

The Environment Agency replaced the National River Authority in 1995, with the principal aim of "protecting and enhancing the environment, taken as a whole, as to make a contribution towards attaining the objective of achieving sustainable development" (Environment Act, 1995, p 2). The Environment Agency is responsible for a wide range of environmental issues in England and Wales, including flooding, droughts, water quality, the impacts of climate change, and outdoor recreation. In relation to flooding, the Environment Agency is responsible for "a general supervision over all matters relating to flood defence" (Environment Act, 1995, p 2). The Environment Agency has the role of setting standards and then making sure other organisations operate within that framework (Howgate and Kenyon, 2009).

The structure of the Environment Agency is based on different regions of England and Wales, with eight regional offices. The Eden catchment is within the North-West region. There are then twenty-two area offices across England and Wales, of which the Penrith office serves the Eden catchment.

Several members of the Environment Agency are involved in the project. Firstly, the North-West Area manager is involved and brings knowledge of nationwide strategic polices. Second, a member of the development control department is included, who has knowledge of the specific Eden catchment and the numerical models that consultants have developed. Third, a member of the pollution control department is part of the stakeholder group, which allows scenarios to be assessed for multiple catchment management issues, such as water quality. Finally, a member of the research department is involved, who brings knowledge of other similar projects.

Natural England

Natural England is the statutory government advisor on the natural environment. The remit of Natural England is "to ensure that the natural environment is conserved, enhanced and managed for the benefit of present and future generations, thereby contributing to sustainable development" (Natural Environment and Rural Communities Act, 2006, p 2). They have four broad strategies; 1) to maintain a healthy natural environment; 2) to inspire people to value and to conserve the natural environment; 3) to allow sustainable development of the landscape; and 4) to secure an environmental future. The Executive Board of Natural England aims to deliver clear frameworks and effective decision making, but also to provide transparency to stakeholders, partners and the public.

The responsibilities of Natural England are twofold. Firstly, they are required to manage agri-environmental stewardship schemes. There are two levels to these schemes; entry level and higher level. These schemes provide farmers with funding in return for managing their land in a certain environmentally friendly way. The primary aims of these schemes are to conserve biodiversity, to enhance the landscape character, to promote access to the countryside and to protect natural resources through improving water quality and reducing surface runoff. Flood management is only a secondary objective, although most of the land management options have benefits for reducing flood risk. Types of land management which are available under these schemes are hedgerow maintenance, arable reversion to grassland, wet grassland, wetland creation, buffer strips and pond creation. Secondly, Natural England is responsible for maintaining the designated SSSIs and SACs in a favourable condition. There are 103 SSSI's, 16 SACs, 2 Special Protection areas, 2 Ramsar sites, 2 areas of outstanding natural beauty and 11 national nature reserves in the Eden catchment.

Lake District National Park Authority

As the spatial downscaling results indicated that the Eamont sub-catchment was the optimum area to focus upon, and this area is entirely within the Lake District National Park, it was thought that the Lake District National Park Authority would be advantageous to include on the steering group. The Lake District National Park was established in 1951 and is 2292 km^2. The authority's role is to co-ordinate and to manage conservation efforts. The area's heritage, including dry stone walling and ancient woodland, needs to be protected and conserved. It relies on governmental and statutory bodies for funding to do this.

7.4. Stakeholder Engagement in Scenario Development

Van Der Heijden (1996) highlighted the advantages and benefits of including stakeholders in the scenario planning process. Participatory scenario development is thought to offer "*a good mix of data, scientific rigour, imagination and expertise from different perspectives*" (Volkery *et al.,* 2008, p. 460). The definition of a scenario is a "coherent, internally consistent and plausible description of a possible future state" (Nakicenovic *et al.*, 2000; Volkery *et al.*, 2008, p. 461). The key words here are "plausible" and "possible", and therefore scenarios do not have to be forecasts, predictions, former states or even probable futures. As project results should be relevant to the end-users, it would be optimal to include them as early in the research process as possible (Kaesmir *et al.,* 2003).

Volkery *et al.* (2008) identified two key issues which need to be considered in the participation process for scenario development. First, the advocacy-discourse dilemma looks at the composition of the stakeholder group. Diverse interested organisations may have conflicting views, often with hidden agendas, which does not result in open minded discussions, but does result in a wide range of contrasting scenarios. Conversely, homogenous groups can lead to agreement on only one future scenario. In this project, the stakeholder group consisted of a range of professional partners, with their main focus on a wide range of topics including; flooding, biodiversity, recreation, water quality, and aquatic ecology. Second, the science-policy dilemma looks at the difficulty of scientists and policy makers co-producing knowledge (Pahl-Wostl, 2002). Policy makers focus less on the quantitative modelling needs of research, while scientists avoid introducing factors which are difficult to measure or model. A key method in deriving future scenarios is producing a "storyline" (Volkery *et al.,* 2008), whereby different aspects of the system are explained sequentially in detail. However, a weakness of this approach is that it produces non-standardised data which is specific to a location and is also a time intensive approach (Fraser *et al.,* 2006).

7.4.1. Spatial Downscaling of flood risk

Chapter 6 presented the results from the two spatial downscaling approaches, which indicated that the Upper Eden and Eamont were both important in determining downstream flood hazard, in terms of their peak flow magnitudes and timings. The Eamont was recommended to be the focus sub-catchment, and this was proposed to the stakeholder steering group. The reasons for choosing the Eamont instead of the Upper Eden were based on both the spatial downscaling results, the relative size of the two sub-catchments, and the model needs to test land management scenarios. These reasons were outlined in Section 6.6. A report outlining this proposal was sent to the steering group who prepared responses to it.

There was wide agreement that one sub-catchment should be chosen to focus on both in terms of time available for the research and the resources available for implementation. However, there was some concern and worries over the choice of the Eamont, with one member stating "*that they had not seen enough evidence to convince me that the Eamont/Lowther is the correct choice of sub-catchment*", while another member commented that "*the paper strongly points to the Eamont as a good choice*". There were several reasons why some group members were concerned about the choice of the Eamont. First, the impact of Ullswater and Haweswater reservoir was highlighted as being an issue both in terms of how this regulation would be modelled and in terms of the area downstream of these features being too small for changes to have any impact, as the attenuating effect of the storage would outweigh the land management signal. To address this concern it was calculated that 218.2 km^2 (55.1%) of the total 396.2 km^2 is downstream of the lake and reservoirs in the Eamont sub-catchment. Also there are seven minor tributaries within this area.

However, the most important reason for the opposition to the Eamont was that the group had pre-conceived ideas about which sub-catchment to focus upon, the Upper Eden. One member said "*My reason for thinking the Upper Eden would be a more suitable place for the study are based mostly on my knowledge of the area and commonsense which is not a scientific approach so I may be entirely wrong*". Furthermore there was a perception that land management was worse in the Upper

Eden, "*much of which has been subject to intensive drainage projects over the past 30 years ... and loss of wetlands. There has also been a change in the nature of farming where grass used to be the main crop and now corn, maize and roots are grown ... I am anecdotally aware of the effect of this drainage. Floods that used to appear slowly and last for days now rise and fall dramatically quickly leading to severe erosion and siltation*" This highlights another characteristic of the stakeholders viewpoint, which was that restoring the catchment to its previous state is better than introducing new different land management to benefit flooding. This can be used to express the difficulty in making both stakeholder knowledge and scientist's knowledge equal in discussions. Furthermore, it shows how the stakeholders are aware of the impacts of land management and are considering multiple objectives.

However, the group also realised that to do flood risk research and modelling, data were needed, with one member saying that "*the level of information and data available for the Eamont and the size of this sub-catchment make it a preferable catchment to concentrate on*".

This stage of the stakeholder participation was more like the second model of participation, the public debate model, through consultation over a report. However, this process was still beneficial, as although the decision of which sub-catchment to focus upon was not changed, it meant that the stakeholders concerns and issues had to be thought through. Once the sub-catchment to focus on, the Eamont, had been agreed then the next stage was to formulate the specific land management scenarios that the stakeholder group thought were the best options to test for this area.

7.4.2. Brainstorming of ideas

Firstly a brainstorming exercise was carried out, where the stakeholder group suggested land management changes that could be used to benefit flood risk. This list of scenarios was also constructed bearing in mind the desire for an integrated holistic catchment scale management approach, with issues such as low flows, water quality, biodiversity and erosion considered. This process was initially quite difficult for the group to participate in, as they could not separate their opinions on the different options from identification of what the options might be. Several of the scenarios were opposed by many members of the stakeholder group, but the aim of the workshop was to generate a generic list of possible land management scenarios which could theoretically be tested and implemented.

These scenarios were then mapped onto a conceptual framework that was informed by a review of the literature. Prell *et al.*, (2007) combined stakeholder perceptions with peer-reviewed literature. Figure 7.2 highlights the sequence of processes which cause high and low river flows. These are: (1) climate; (2) partitioning of precipitation into surface and subsurface flows; (3) hydrological connectivity; (4) storage; and (5) channel conveyance. Extremes in precipitation are one of the main causes of hydrological extremes as it determines the water input to the system. Rainfall characteristics are most critical for flood generation, while a combination of rainfall and temperature (effective rainfall) control meteorological droughts, which may lead to hydrological droughts. Precipitation infiltrating into the soil has positive effects on both floods and droughts. Less overland flow means that more water is transferred through the potentially slower subsurface pathway to connect with the river channel, potentially reducing high flows. This also means that more water is stored in the soil and groundwater stores, which may buffer against low flows. The process of hydrological connectivity is critical for flood generation. The rate of overland flow delivery to the channel is important for the magnitude of peak flows. Surface storage is important for mitigating floods, through landscape features such as wetlands. These reduce the connectivity between floodplain and channel and attenuate peak flows. However, it is the subsurface storage which is most crucial for reducing low flow risk, through maintaining baseflow. The relative timing and sequencing of tributaries peak flows downstream determine the magnitude of high flows. Also the process of attenuation is crucial in the flood generation process. However, these processes are less important for drought risk. While each of these processes impact significantly upon extreme hydrological flows, it is only when the sequence of water transfers combine which produce the most severe events. This conceptual framework, although simplistic, was very useful in demonstrating the effect of the different land management scenarios.

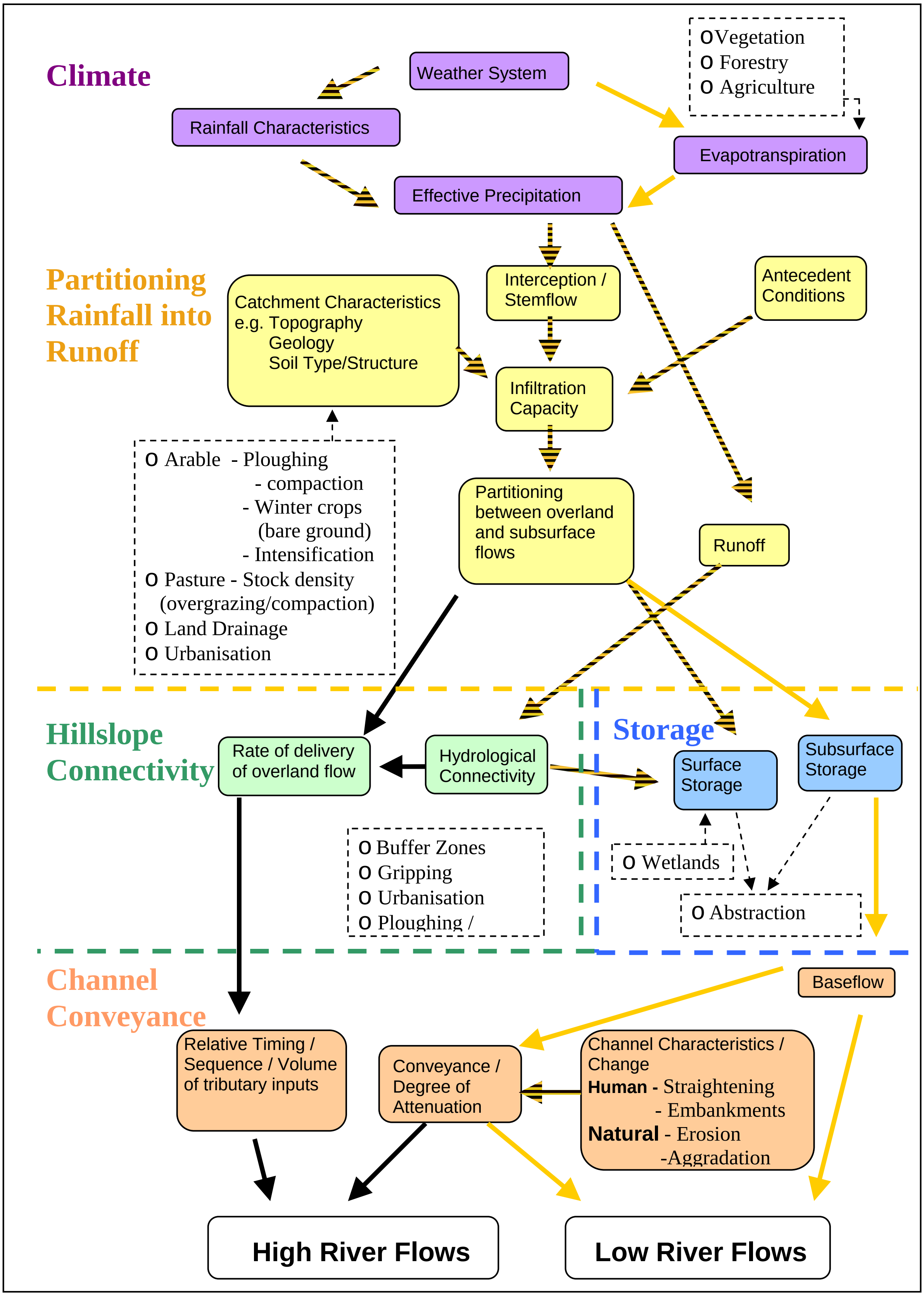


Figure 7.2 *Conceptual framework based on hydrological process that results in high and low river flows.*

Figure 7.3 shows the 28 scenarios that were suggested mapped onto the process oriented conceptual framework. Some example of land management scenarios suggested were stock density reduction, wet woodland, field size changes and channel naturalisation. Each scenario impacted different hydrological processes with some affecting more than one.

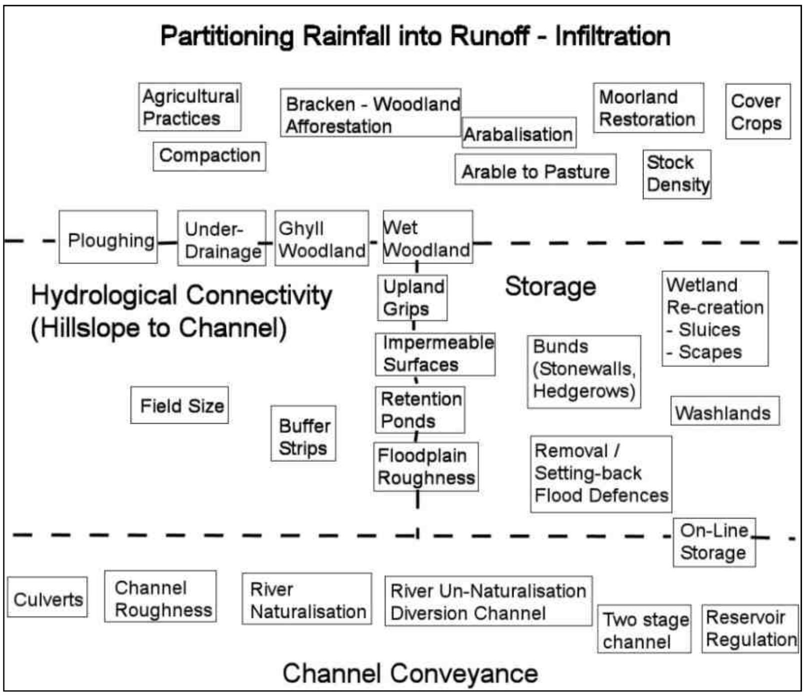


Figure 7.3 *Schematic of the Generic Land Management scenarios derived by the stakeholder discussion.*

7.4.3. Scenario Evaluation

The 28 scenarios were then evaluated against the following criteria. Firstly the scenario was assessed for its appropriateness and relevance to the specific sub-catchment being focussed upon, the Eamont. Secondly the effectiveness of the management practice at reducing flood risk was considered. This was done through a review of the literature. The third criterion considered the testability of the option with the models and resources available. Fourthly, the robustness of the technique for reducing downstream flooding was assessed. This considered factors such as the uncertainties of modelling results and also the agreement of past studies. The final criterion used was whether or not the land use change would be feasible to implement in the chosen sub-catchment. Using these five criteria an evaluation (Appendix B) was circulated to, and discussed by, the stakeholder steering group.

7.4.4. Scenario Prioritisation

It is important that the land management practices which are the most suitable to be modelled and implemented are chosen to be tested, so the steering group discussed their priorities and ranked the scenarios in order of which they thought were the best ones to test. This was just done through a discussion, but Simonovic and Akter (2006) highlighted the potential of using a fuzzy modelling approach to account for the great complexity caused by the number of stakeholders and their multiple objectives as an alternative approach. Figures 7.4 shows the decisions made by the stakeholder steering group, with 12 scenarios accepted, 8 identified as possible and 8 fully rejected for future analysis.

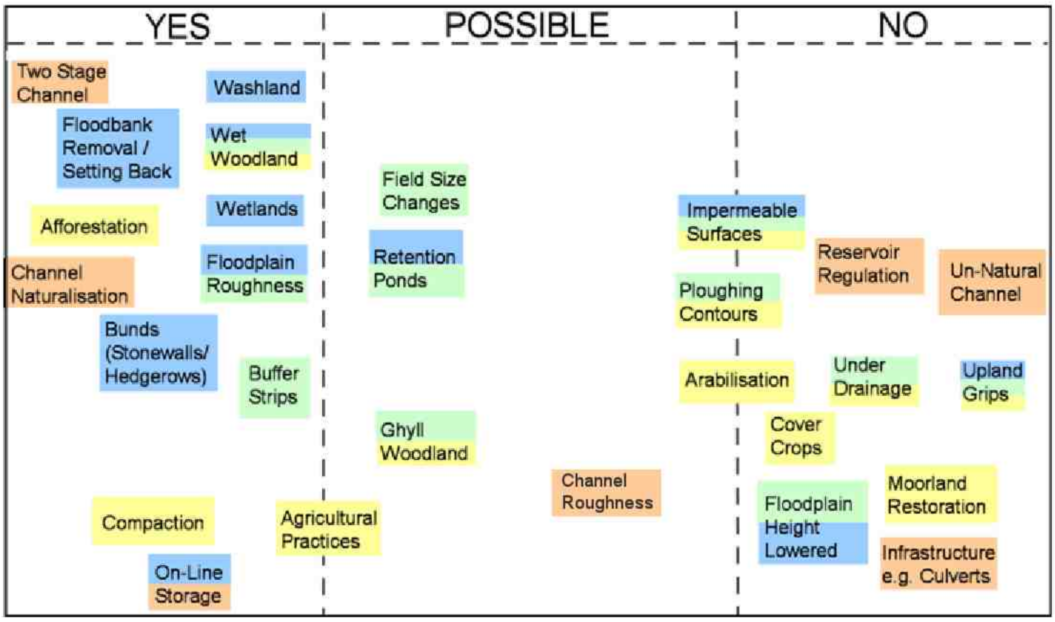


Figure 7.4 *Stakeholder prioritisation, including processes which scenario effects (colour coding relates to the hydrological process conceptual framework, with yellow representing partitioning rainfall into runoff, green representing hydrological connectivity, blue representing storage, and orange representing channel conveyance)*

Figure 7.4 shows which of the hydrological processes the land management change affects. The whole hydrological cascade is affected by the chosen scenarios. The accepted scenarios identified as possibly impacting on the partitioning of rainfall into runoff process, are afforestation and compaction. The chosen scenarios which may impact hydrological connectivity are wet woodland, buffer strips and floodplain roughness. The scenarios which may increase the storage of water on the floodplain are wet woodland, wetlands, floodplain roughness, bunds (hedgerows and stonewalls), on-line storage and flood defence removal or setting back. Finally the scenarios which might impact the process of channel conveyance are channel naturalisation, two stage channels and on-line storage.

Discussions arising from the steering group meeting resulted in a number of points. Firstly, the scenario of reservoir regulation, which potentially had multiple benefits for both floods and low flows, was dismissed by United Utilities. This was because this stakeholder is a commercial business and their current reservoir operating state was optimised with respect to sustainable delivery of water supply and income. Furthermore, United Utilities did not want Haweswater reservoir to be used for flood storage. Other scenarios which were rejected were moorland restoration and upland grips. The stakeholder group thought these scenarios had potential, but due to the focus of the sub-catchment and the constraint of changing downstream of the reservoirs, there was very little of the upland catchment where these scenarios were relevant. Furthermore, there was no model to test the upland grip scenario and high uncertainty in the hydrological model to represent peat landscapes. There was full agreement on the wetland creation scenario because there was a perception that past wetland degradation and loss was a potential cause of increased flood risk. One group member gave the example of Udford, where the wetland has decreased in size in recent decades.

The next stage was to rank these twelve scenarios into order of stakeholders priorities. The accepted column in Figures 7.4 show this ranking, whereby scenarios at the top were the most favourable and the ones at the bottom least favourable out of the accepted scenarios. Overall there was wide agreement over the scenarios which were preferred, but a limitation of this approach was that some group members dominated the placing of land management scenarios in the list. The most favourable scenarios included the two stage channel, wetlands/washlands, wet woodland and the removal/setting back of flood defences. These were some of the more visible scenarios, with surface storage and channel modifications allowing stakeholders and the public to see that less water is getting into the channel. Other scenarios such as bunds and on-line storage were less popular, as they were seen as expensive options with issues for the reservoir act in terms of the size of these features. Finally scenarios such as compaction and buffer strips were also less popular, as there was greater uncertainty over their benefits, although afforestation was higher up the list in the stakeholder’s priorities as this has multiple benefits and may be seen as enhancing the landscape.

Once the scenarios that were viewed by the stakeholder group as feasible had been decided, specific locations for their implementation had to be determined. The scenarios were reducing compaction; afforestation; and floodplain roughness e.g. wet woodland. This was done through a combination of a stakeholder group mapping workshop, an analysis of historical maps, a survey of the catchment, and analysis of hydrological connectivity of the catchment from the SCIMAP model. These will be outlined in the next four sections.

7.4.5. Mapping Exercise

A modelling study into future change scenarios can gain relevance through involving stakeholders in the decision making process of determining where to try each land management practice. Opportunities for certain changes may be highlighted or constraints upon management implementation could be established. A stakeholder workshop was based around using Ordinance Survey maps to identify areas where chosen scenarios could be tested and implemented. Each scenario was considered in turn and stakeholders were asked to draw on the map potential locations for that land management practice. This was quite a difficult activity, as many stakeholders were not particularly knowledgeable about specific locations, as they did not often go out on site visits. However, they knew about land owners and boundaries for the land owned by United Utilities and the Lake District National Park.

Several suggestions were made on specific locations where each scenario could be tested. Afforestation was thought to be a possibility on the land owned by Lowther Estates e.g. Low Deer Park. The SCAMP project organised by United Utilities had potential for forestry in United Utilities land (Haweswater, Cawdale, Heltondale and the Upper Lowther). Ghyll woodland could be implemented on the many small tributaries of the Lowther, while wet woodland was a possibility in the Whale Beck and Knipe Moor area. There was a belief that compaction was an issue in the Sockbridge area of the Eamont. Wetlands were a possibility in the upper parts of Dacre Beck. This area has seen extensive drainage but is still quite saturated. It was also suggested that old channels in the Shap area could be used to store water during high flows (on-line storage). The feeling of the stakeholders was that there were limited options for arabilisation due to the steep relief of the catchment, although the area around Hornby

Hall (Lower Eamont) was a possibility. Finally locations where the channel could be re-naturalised were identified as the upper parts of Shap Beck, the Upper Lowther just downstream of Wet Sleddale, and Swindale Beck downstream of the weir. Figure 7.5 shows the locations suggested by the stakeholder group for the different interventions.

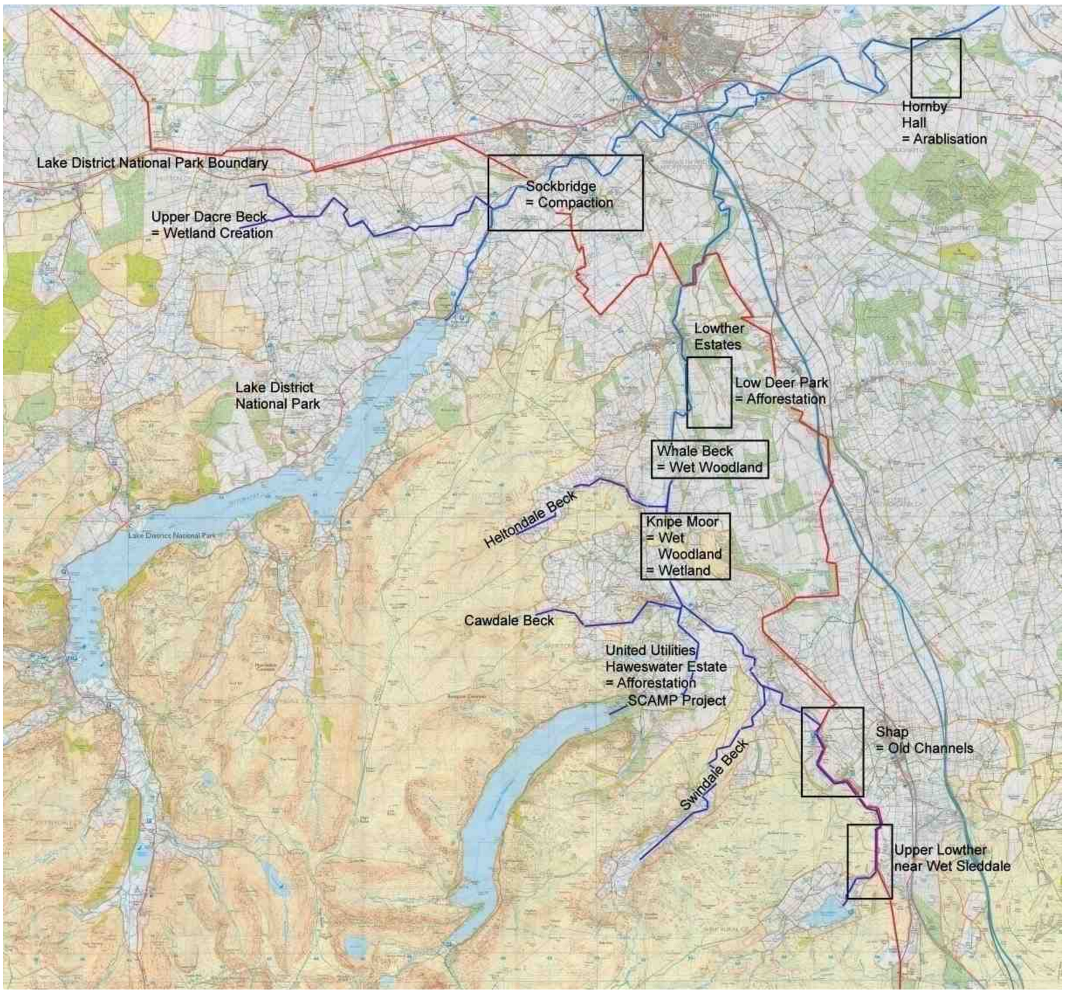


Figure 7.5 *Map showing potential land management scenario locations suggested by stakeholder group.*

7.4.6. Historical Map Evaluation

To investigate the changes in land use over the historical record, historical maps, from the 1860s, 1920s, and the 1950s, have been analysed and compared to modern OS maps. The Eden catchment is dominated by agriculture, with over 90% of the area being classified as this land use. Therefore it seems likely that any changes to the management of this agricultural land would have a significant effect on local runoff and potentially downstream flood risk. Chapter 2 showed how changes to both the arable and pastoral landscapes, such as compaction and intensification, could lead to increases in flooding. In the Eden, the management of the rural landscape has altered significantly over the past 150 years. Agriculture has become far more intensive, with sheep grazing migrating further into the uplands, while arable farming has increased in the lowlands. For example, the cropping of winter cereals and maize has expanded in the Howgill Fells of the Upper Eden.

The changes from the historical map analysis are summarised in Table 7.2 by ordinance survey tile. There are six major types of land use change over the past 150 years. The single largest change to the agricultural landscape has been the increased field size, whereby multiple fields have been joined together to form one large field. Figure 7.6 shows an example of this from the Eamont sub-catchment, near the settlement of Yanwath and Penrith. The 1860 and present day map both show exactly the same area, and the field density has decreased from 55.8 fields per km^2 to 22.3 fields per km^2. Furthermore, the average size of a field in this area has increased from 0.0167 km^2 to 0.0431 km^2. These statistics have been calculated using the area confined by the railway to the west, the road to the north and the river to the east. Also seen on Figure 7.6 is the development of infrastructure, with the road network being expanded, specifically the M6.

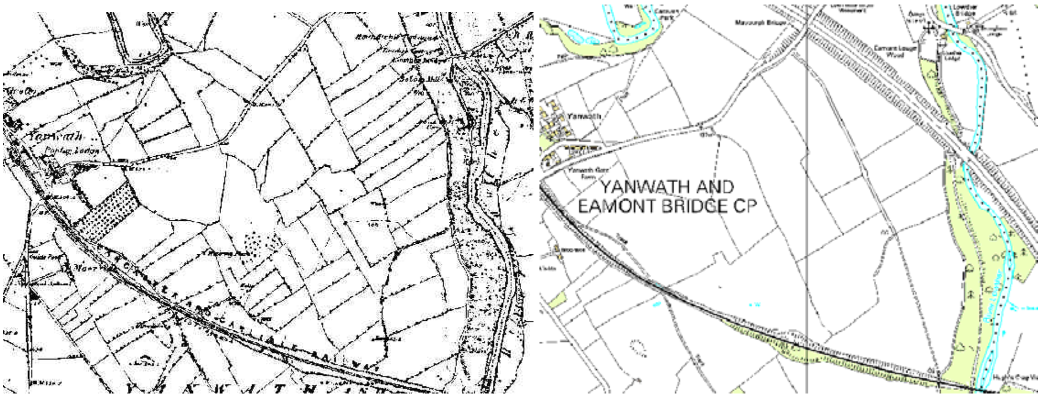
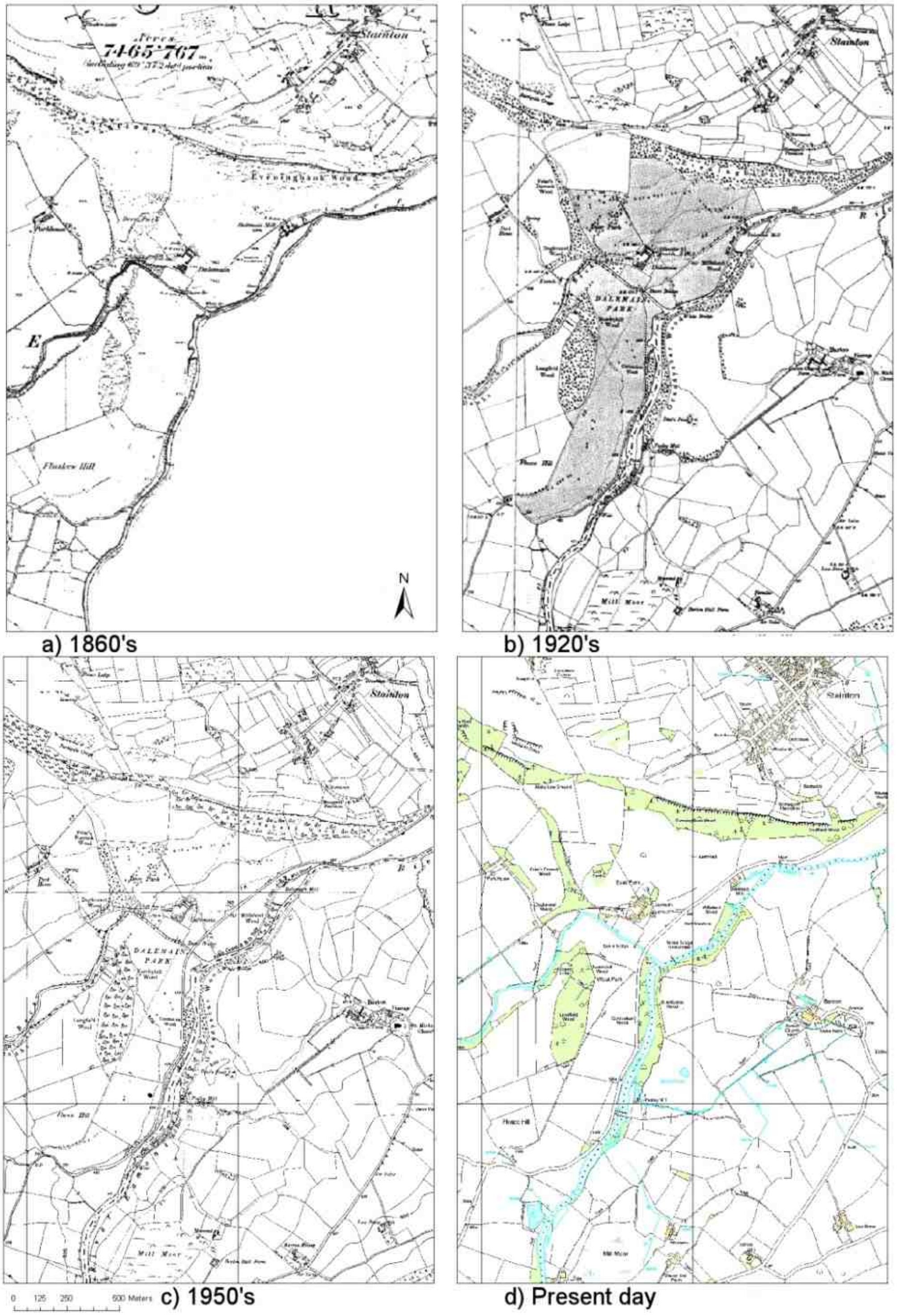


Figure 7.6 *Changes to field size from 1860s to the present day*

Another major change in the Eamont catchment is the loss of woodland, where large areas have been deforestated since the 1860s. An example of this is at Dalemain Park in the Dacre Beck sub-catchment. Figure 7.7 shows how this area has changed over time. Dalemain Park was established between the 1860s and the 1920s and consisted of a wooded area of approximately 1 km^2, which was reduced in area and into small patches, especially a buffer strip either side of the Dacre Beck by the 1950s.



a) 1860's
b) 1920's
c) 1950's
d) Present day

Figure 7.7 *Historical maps of the Dalemain Park area in the Dacre Beck sub-catchment.*

Another significant change in the Eden catchment over the last few centuries has been urbanisation. The town of Penrith is in the Eamont catchment and has developed from a town with 2,763 houses in 1921 to a settlement with 3,495 in 1961. The population has also grown slightly from 12,549 in 1911 to 14,756 in 2001. Figure 7.8 shows an OS map from 1876 and the modern day, and it is clear that the area of Penrith has increased considerably. The Castletown area of Penrith was developed in the 1920s, while the Pategill and Carleton areas were built by the 1950s. Newton Rigg was developed after the 1950s while the Gilwilly Industrial Estate was established between the 1920s and the 1950s.

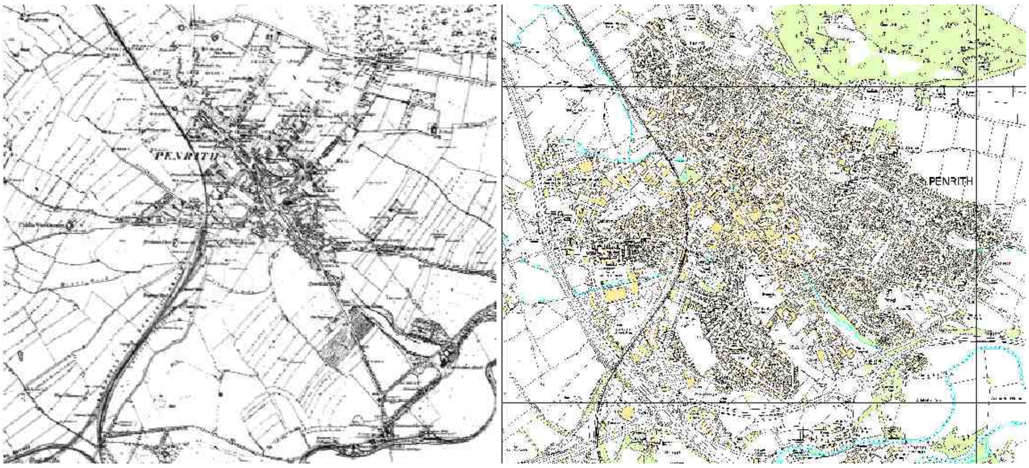


Figure 7.8 *Growth of Penrith from 1860s to present day.*

Along with catchment scale landscape changes, the river channel itself has also been modified and regulated. An upland, rural channel modification scheme is illustrated near Bampton in the Eamont sub-catchment. Figure 7.9 shows how the natural meandering channel was straightened between the 1880s and the present day. The channel length has decreased from 812 m to 477 m. This means that the sinuosity of the channel has decreased from 1.86 to 1.09, where a sinuosity of 1 is a straight channel. This has been calculated by dividing the channel length by the straight line valley length. Furthermore flood banks have been constructed on both sides of the straightened reach. This decouples the river channel from its floodplain. Other examples of channel straightening are the River Lowther near Helton, Naddle Beck and Carlsike Beck, which was modified to follow a field boundary rather than flowing through a field.

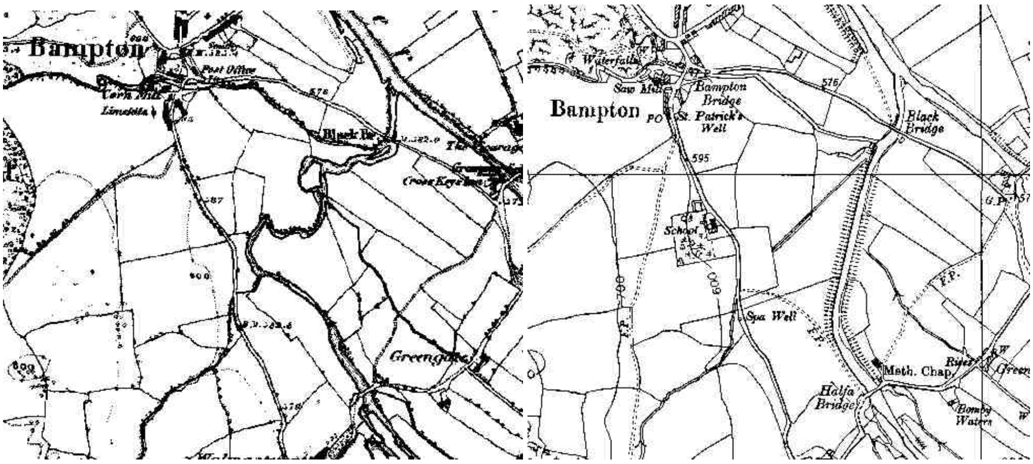


Figure 7.9 *Channel modification of Haweswater Beck.*

Another way in which the channel has been modified is through regulation. The Eamont sub-catchment is the most regulated with Haweswater reservoir and Wet Sleddale reservoir. Figure 7.10 shows the change in the Haweswater reservoir from the 1870s when it was a natural lake, approximately 4 km long, to an artificial impoundment, which is 6.7 km long. The development of the reservoir started in 1929 and was finished by 1935. The dam is 470 m long and 27.5 m high and raised the water level by 29 m, flooding the village of Mardale. The reservoir has a capacity of 84 billion litres.

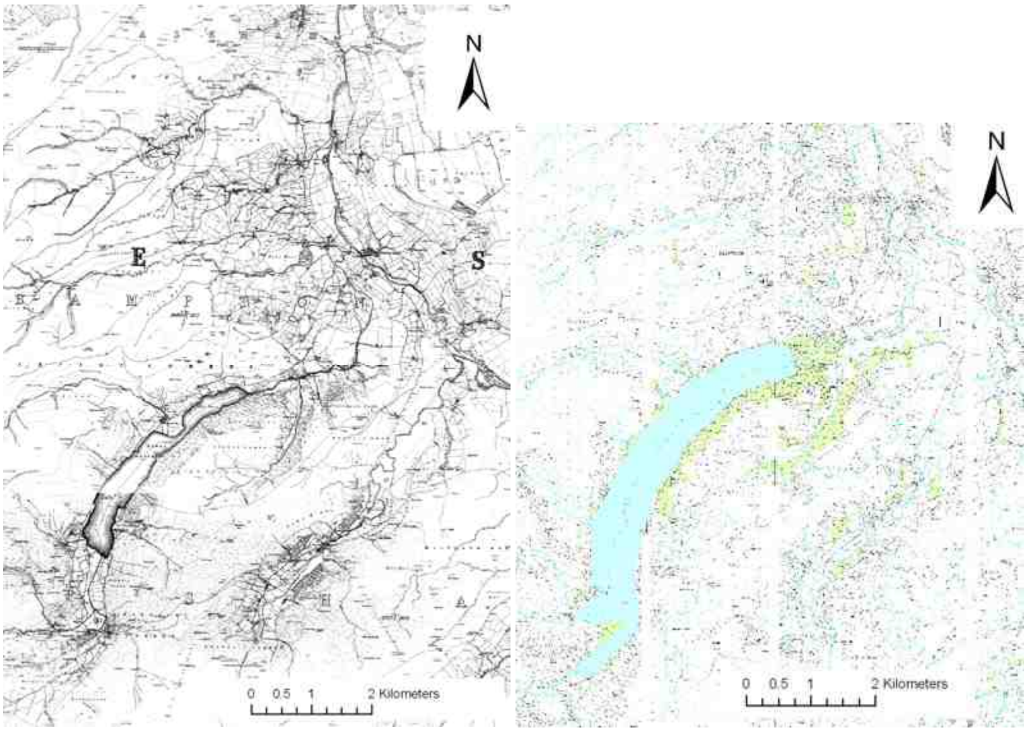
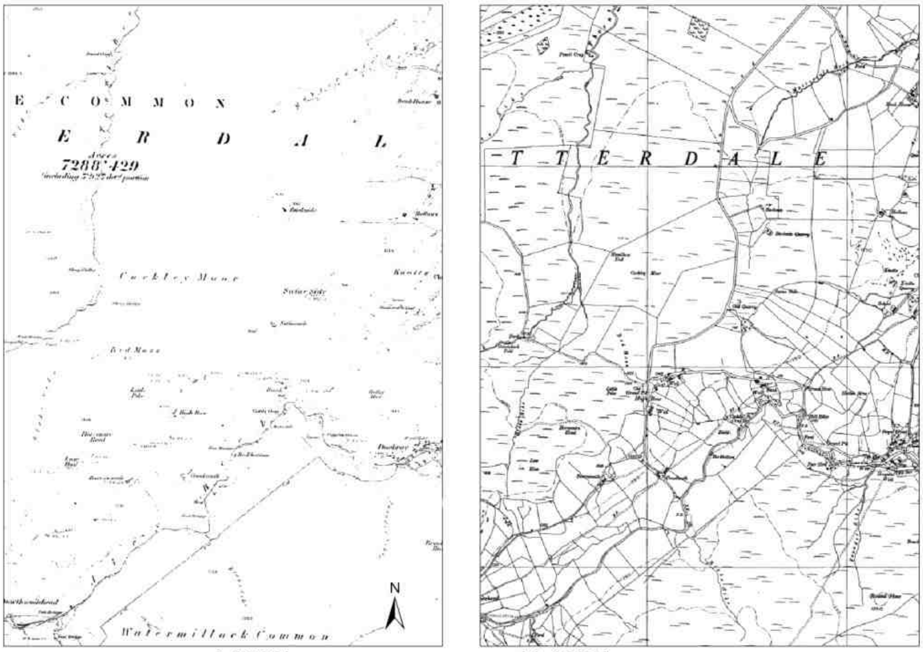
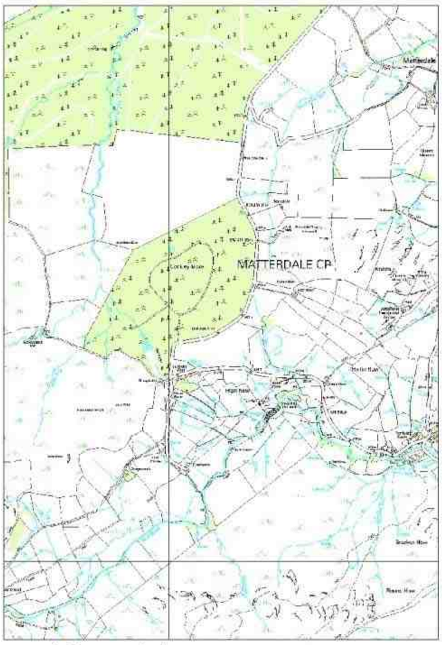


Figure 7.10 *Haweswater reservoir expansion from 1860s to present.*

The final common type of land use change over the past 150 years was drainage of both moorland and agricultural land. Figure 7.11 shows an area of the Dacre Beck sub-catchment. Before the 1950s the area consisted of mainly moorland with a thin strip of agricultural fields on the sides of the river. However, this area has been extensively drained since the 1950s, with Cockey Moor becoming an area of woodland and the area having lots of field drains installed. Other land covers in this area are moorland and rough pasture due to the soil being quite saturated.



a) 1860's b) 1950's



c) Present day

Figure 7.11 *Historical map of the Upper Dacre Beck sub-catchment*

Area	Land Use Change
52NW	• Penrith = Urbanisation since 1950s (M6/A66) and Wetheriggs area • Whinfell Sewage Works = Developed between 1860s and 1920s • Brougham Park = Woodland decreased especially between 1920s and 1950s • Yanwath = Field Size increased since 1860s • Carlsike Beck = Straightened to field boundary since 1920s • R.Lowther Left Bank = Field size increased since 1860s to 1920s • Clifton = Field size increased • High Dikes = Woodland decreased to 2 small patches since 1950s / field size increased • Etysian Fields = Caravan Park (Lowther) developed since 1950s / expansion of woodland.
52SW	• Heining Bank/Wood = Field size increased since 1950s • Hughs Garden = Developed between 1860's and 1920s • Askham / Gillriggs = Farm size increased since 1950s • Lowther leisure park = Loss of woodland since 1950s • Crookwath Bridge = Replacement of woodland with blocks of plantation since 1920s • Helton = Lowther bend straightened between 1920s and 1950s • Nelly's wood = Field size increased
53SE	• Eden-Eamont confluence = Mid channel bar in 1860s/1920s, gone by 1950s • Udford (North bank) = Large woodland away from river decreased in size by 1950s (rough pasture) and present day (agricultural land) • Udford = Near river fields 1920s patches of rough pasture, by present woodland buffer strips have appeared.
52NE	• South Udford Wood = Small field in 1860s, fewer/larger fields by 1920s • Winfell Forest = Small forest/rough pasture in 1860s , larger forest by 1920s, Holiday village by present • Church bank = Buffer strip (woodland) near river in 1860s, no strip by 1950s • Hornby hall = Fields in 1860s, buffer strips by 1950s
51NE	• Shap = Fields smaller in 1860s until after 1950s • Shap = urbanisation after 1950s
51SE	• South Shap East of Lowther = Farm size increased between 1860s and 1920s • Wet Sleddale = developed after 1950s • Shap summit wood = developed after 1950s from rough pasture
53SW	• Penrith = urbanisation throughout whole period – Gilwilly industrial estate after 1950s, Castletown after 1920s and Pategill/Carleton after 1950s • Brecon Hills woodland = loss of one large field after 1950s
51NW	• Butterwick Green = Channel straightening (Green Crook) gradual over time • Howes Moor (The Howes) = moor drained between 1860s and 1920s • Bampton (Haweswater Beck) = Straightened channel between 1860s and 1920s with flood embankments • Bomby = Field size increased after 1860s • Haweswater Dam/Reservoir = Developed between 1920s and 1950s
51SW	• Naddle Beck = Straightened between 1950s and present
50NW	NO CHANGES
43SE	• Blencow Quarry/Reservoir = Developed after 1950s • Newton Rigg = Urbanisation after 1950s / Field size increased
42NE	• Newbiggin = Field size increased since 1950s • Stainton = Urbanisation • Mill Moor = Pond developed since 1950s • Celleon = Broadrim wood decreased since 1860s and 1950s
42SE	• Salmonds Plantation = less woodland converted to rough pasture • Winter Green = Less rough pasture
41NE	• Hawewater reservoir = expanded between 1920s and 1950s
41SE	• Haweswater reservoir = expanded between 1920s and 1950s

40NE	NO CHANGES
43SW	NO CHANGES
42NW	• Greystoke Moor = coversion of some to woodland/plantation by 1950s • Barffs Wood/ Stafford Wood = deforestation between 1950s and present • Hutton / Tarn Moss = conversion of rough pasture to woodland post 1950s.
42SW	• Watermillock Common = conversion to agriculture between 1860s and 1950s • Swinburns Park = coversion of moorland to forestry between 1860s and 1950s
41NW	• Martindale Forest = Large area split into 2 small patches after 1950s
41SW	• Hayeswater reservoir = expanded after 1860s
40NW	NO CHANGES
32NE	NO CHANGES
32SE	• Dockray = Lots of drains (agricultural) constructed e.g. Thorneythwaite (large field with four drains)
31NE	NO CHANGES

Table 7.2 *Land use changes in the Eamont sub-catchment identified from historical maps*

7.4.7. Catchment Survey

The importance of a field visit for the modelling process cannot be underestimated, as it is essential to gain an understanding of the real world system to make sure it is adequately represented in the model (Lane, in review). The whole length of the rivers Eamont and Lowther were walked and surveyed to identify current land uses, potential for floodplain storage and channel characteristics. Furthermore some minor tributaries were also surveyed, including Dacre Beck, Swindale Beck and Haweswater Beck. Photographs were taken to provide a long term record and also so that stakeholders unfamiliar with parts of the catchment could be given an overview of what areas were like. A brief summary of catchment characteristics is shown in Figure 7.12 and the whole collection is in Appendix C.

A few of these areas are now expanded upon. First, Figure 7.12a shows the Udford wetland near the Eamont-Eden confluence, which many stakeholders commented had reduced in size in recent decades. Figure 7.12d shows a flood bank along the Eamont near Yanwath, which could be altered. Figure 7.12f shows the upper Dacre Beck landscape, which was saturated and mainly rough grassland with stock grazing. Figure 7.12k shows Knipe moor on the upper Lowther, which was a flat relief area, possibly with the potential to act as floodplain storage. Figure 7.12i shows Greengate floodbanks on Haweswater Beck, which could be removed or set back to re-couple the channel to its floodplain. Finally Figure 7.12m shows Crookwath meander on the Lowther, which was a flat area which could also act as floodplain storage.

Figure 7.12 *Photographic overview of the characteristics of the Eamont catchment. a) Udford wetland near Eamont-Eden confluence, b) Lower Eamont, c) Eamont-Lowther confluence, d) Flood banks on Eamont near Yanwath, e) Lower Dacre Beck, f) Upper Dacre beck, g) Upper Eamont near Ullswater, h) Ullswater, i) Kirkstone Beck upstream of Ullswater, j) Swindale Beck, k) Knipe moor on Upper Lowther, l) Flood banks at Greengate near Bampton on Haweswater Beck, m) Crookwath meander on Lowther, n) Lower Lowther*

7.4.8. Hydrological Connectivity

Another way in which locations for land management scenarios were identified was through investigating the hydrological connectivity of the Eamont sub-catchment. This is important because hydrological connectivity is one of the processes that are thought to affect the link between land use and catchment scale flood risk. The stakeholder group identified field size changes and buffer strips as high in their priorities and these are thought to effect the process of hydrological connectivity. If features, such as hedgerows, stonewalls and buffer strips can be placed strategically in locations of high flow convergence and connectivity then runoff input to the channel can be reduced. SCIMAP offers a modelling tool which identifies locations of high surface hydrological connectivity (Lane et al., 2006; Lane et al., 2009) and therefore identifies locations where these landscape features may be most beneficial.

The SCIMAP model determines catchment scale hydrological connectivity based upon the spatial pattern of soil saturation derived from the topography. For a unit of the landscape to be contributing runoff to the river, then it must be: (1) saturated; and (2) connected to the channel (Beven *et al.,* 2005). Cells are only connected to the channel if there is a complete flow path from hillslope to channel of saturated cells.

Lane *et al.* (2009) tested this by comparing the results from the network index (derived from the lowest value of the topographic index along a dominant flow path) with the results of a complex physically based hydrological model. It was found that spatial patterns of connectivity and the duration of this connectivity were well explained by the network index. It was also found that cells with a relative network index of less than 0.5 had only negligible connection durations, followed by an exponential increase for larger network indexes (Lane *et al.,* 2009). Within the SCIMAP framework, the network index is converted to a probability of connection by scaling between the 5th and the 95th percentiles and assigning values of 0 and 1 to either extreme, where 0 is no connection and 1 is full connection.

The relative network index was calculated firstly for the different sub-catchments of the Eden to see how the Eamont sub-catchment compared to other areas. Secondly, different areas of the Eamont were investigated further to determine if some reaches have greater hydrological connectivity than others.

Figure 7.13 shows that the Eamont sub-catchment (20.0%) has a higher percentage of the catchment greater than 0.5 than the whole Eden (19.4%). It has the third highest proportion of the major sub-catchments, behind the Caldew (26.7%) and the Petteril (25.2%) and above the Irthing (18.1%) and the Upper Eden (16.4%). The

Eamont has the highest relative network index percentage between 0.9 and 1.0, of 7.5%. However, it also has one of the highest proportions (17.3%) of disconnectedness (0.0-0.1).

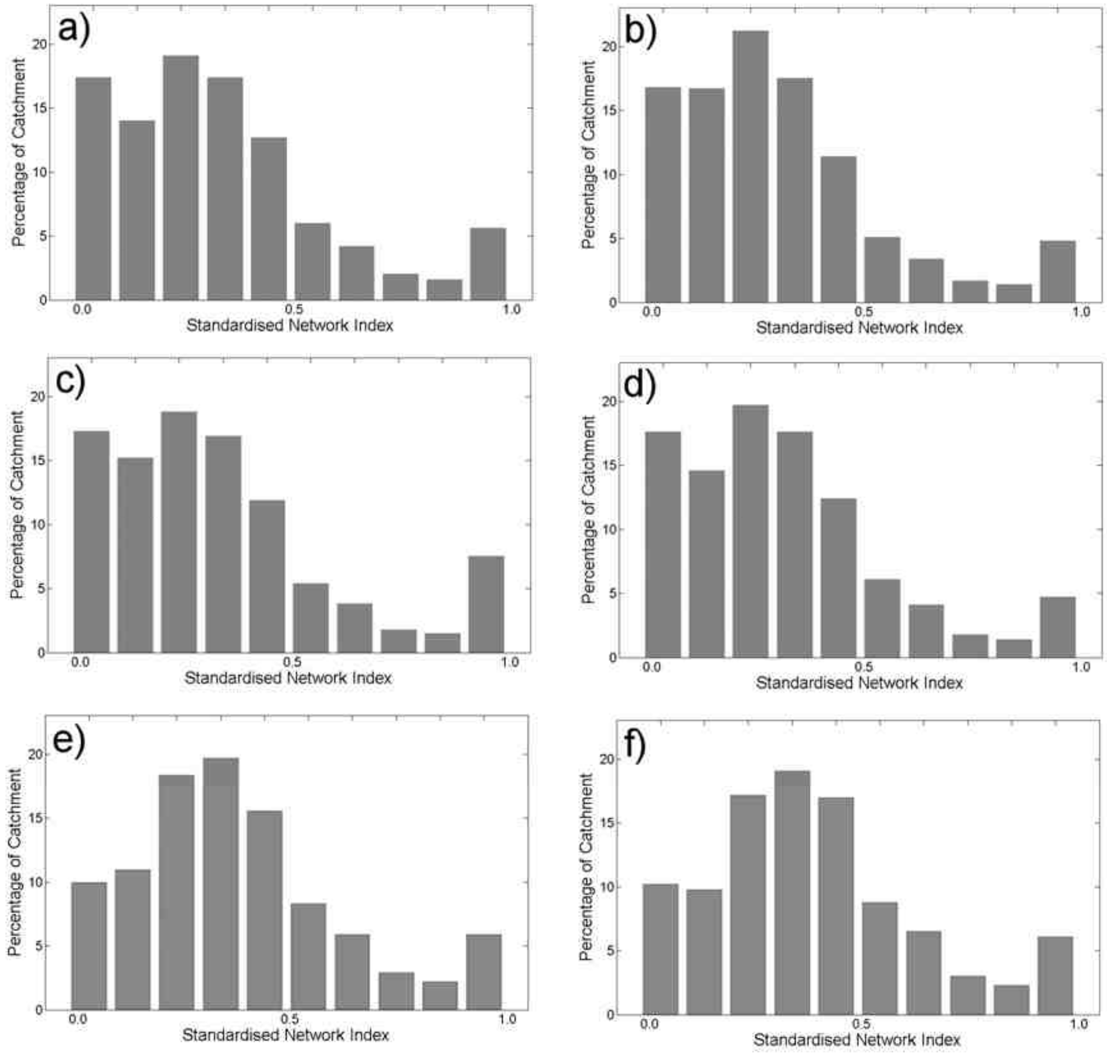


Figure 7.13 *Frequency distributions for the network index of various sub-catchments of the Eden a) Whole Eden; b) Upper Eden; c) Eamont; d) Irthing; e) Petteril; and f) Caldew*

Figure 7.14 shows the distribution of the highly connected areas and the disconnected parts of the Eamont sub-catchment. The red areas are connected to the channel network, while the green are disconnected cells. Figure 7.15 shows the Eamont catchment divided into contributing sub-catchments. Two main areas have been identified as being highly connected to the river network, Dacre Beck and the Middle River Lowther between Bampton and Askham. Particular areas within the Dacre Beck sub-catchment that are highly connected are the lower part of Dacre Beck (Dalemain), the upper part of Skitwath Beck and both the upper and lower reaches of Thackthwaite

Beck (Figure 7.16). Figure 7.17 shows the frequency distributions for the Dacre Beck sub-catchments, with the whole Dacre beck, Lower Dacre beck, Switwath beck and Thackthwaite beck having 20.9%, 19.9%, 24.0% and 19.2% relative network index greater than 0.5 respectively. This particularly highlights the high connectivity within the Switwath Beck sub-sub-catchment.

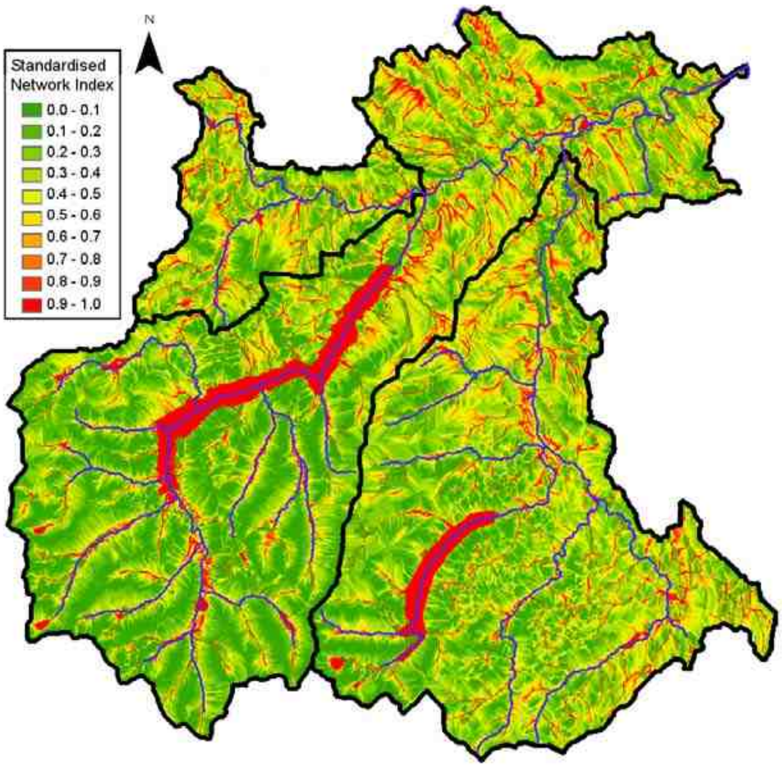


Figure 7.14 *Network Index of the Eamont sub-catchment*

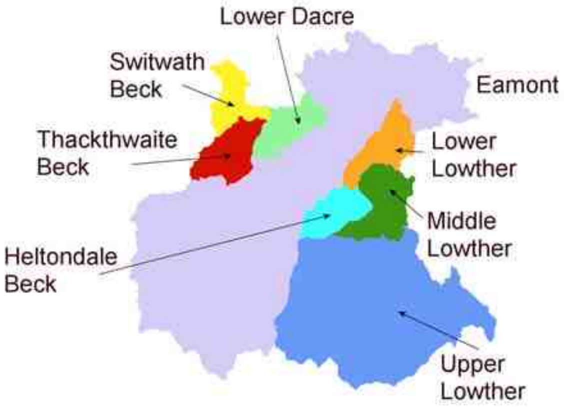


Figure 7.15 *Map of the Eamont Sub-catchment, showing sub-sub-catchments*

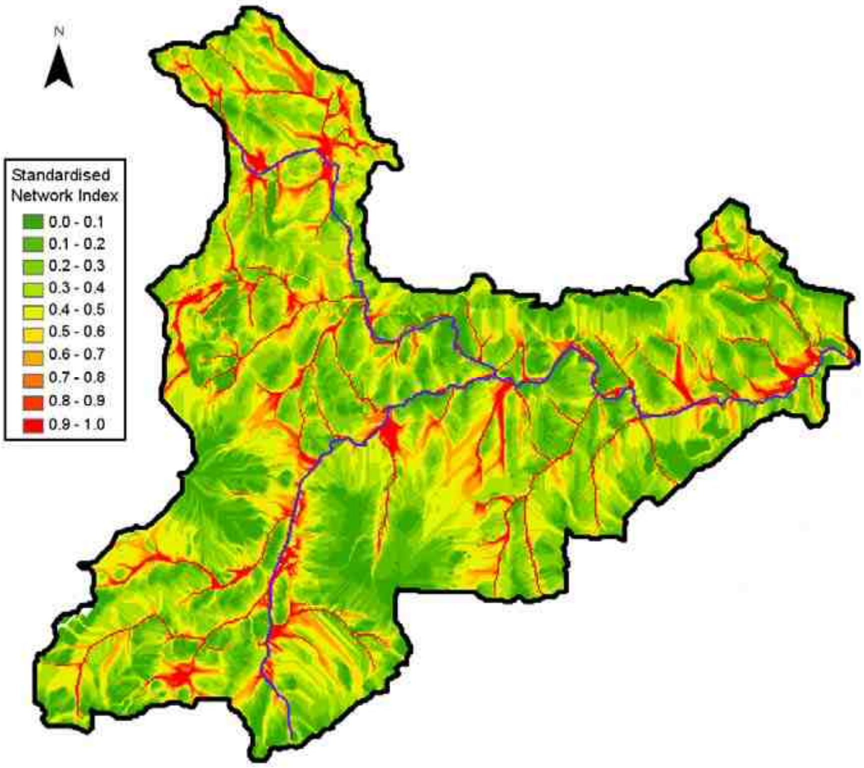


Figure 7.16 *Network Index of Dacre Beck*

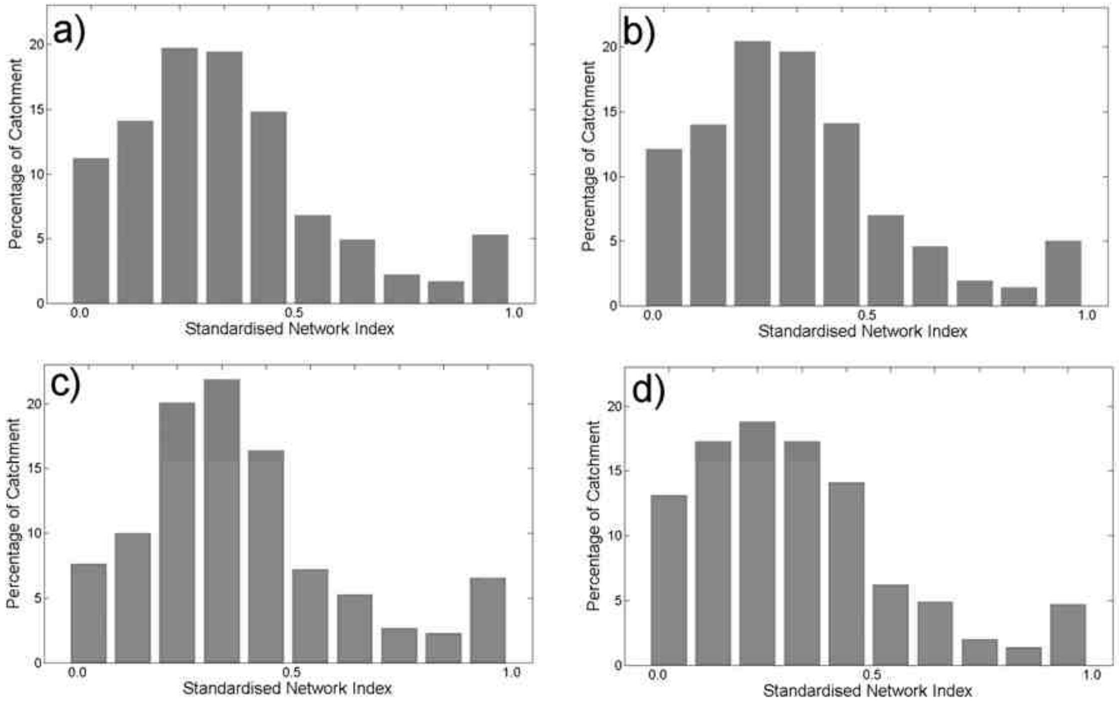


Figure 7.17 *Frequency distributions for the network index of various sub-catchments of Dacre Beck a) Whole Dacre; b) Lower Dacre; c) Switwath; d) Thackthwaite*

In the Lowther sub-catchment, the middle reach between Askham and Bampton (Figure 7.18) has relatively high network index values. The Middle Lowther has a high proportion of network index values greater than 0.5 (23.1%), while the Lower Lowther has 25.9%. Figure 7.19 shows how the upper part of Heltondale Beck is also an area with high hydrological connectivity to the landscape in the middle Lowther reach.

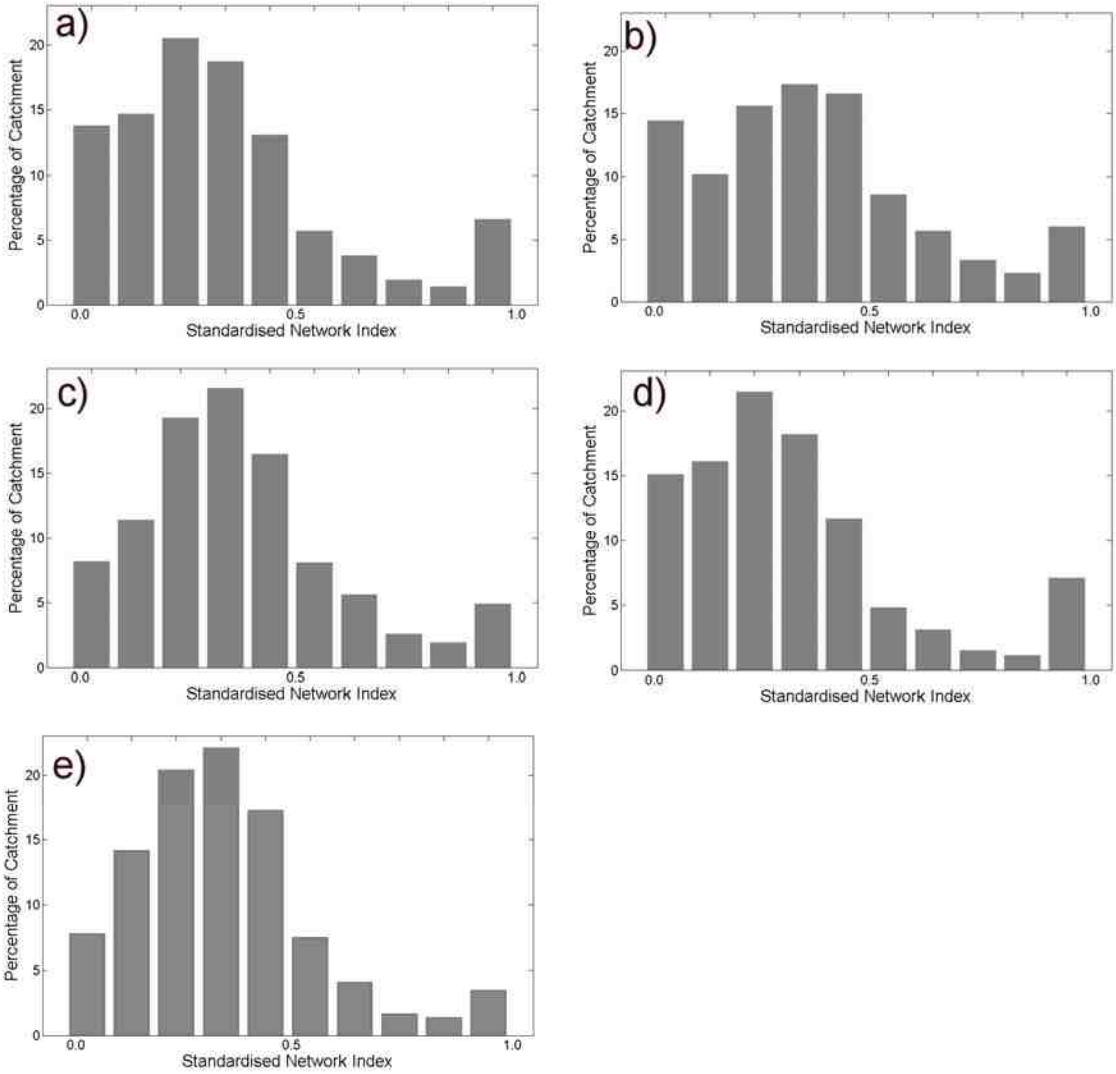


Figure 7.18 *Frequency distributions for the network index of various sub-catchments of the Lowther a) Whole Lowther; b) Lower Lowther; c) Middle Lowther; d) Upper Lowther; e) Heltondale Beck*

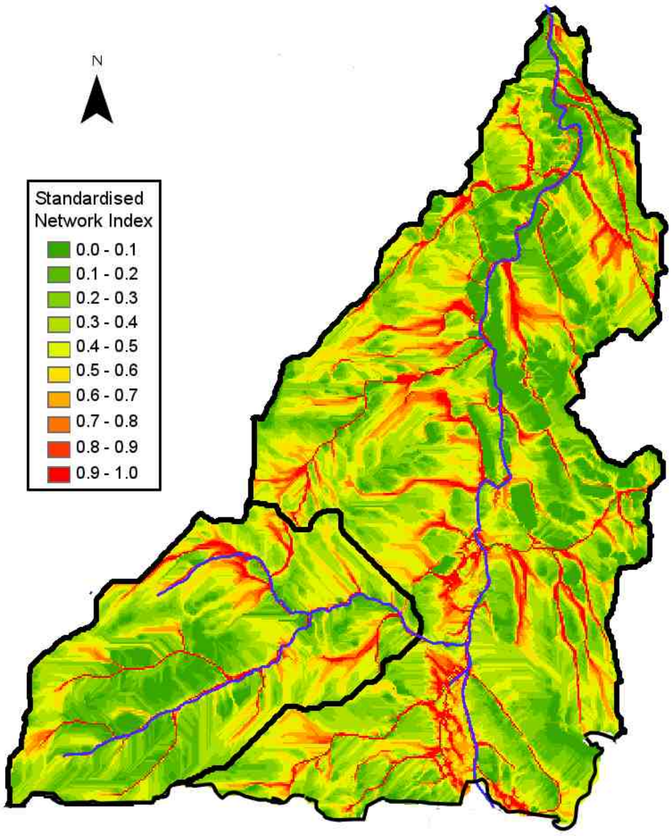


Figure 7.19 *Network Index of the Middle Lowther and Heltondale Beck*

7.4.9 Summary of Locations to Test Scenarios

The locations where the chosen land management scenarios could be tested were determined through using a combination of the stakeholder group mapping workshop, an analysis of historical maps, a survey of the catchment, and analysis of hydrological connectivity of the catchment from the SCIMAP model. It was decided that the Dacre Beck sub-catchment would be focussed on for the testing of the scenarios which affect the partitioning of rainfall into runoff processes. This includes the afforestation and compaction land management practices. This is because this sub-catchment has a wide range of current land uses and considering its size (37.9 km^2) is relatively important in determining flood hazard in the Eamont sub-catchment. It also has several characteristics that will make hydrological modelling more achievable, such as its area, which will make model computation demands manageable. Also there is a downstream gauging station at Dacre Bridge, which has a record of both stage and discharge since 1997. The stakeholder group raised the issue of the complicating presence of regulation in the Eamont catchment, and favoured the choice of Dacre Beck as this sub-catchment has no regulation. Analysis of historical maps showed that this catchment had undergone extensive land drainage (Figure 7.11). The catchment survey showed that agriculture dominated land cover in this catchment (Figure 7.12 e, f), which matches the type of scenarios to be tested. Dacre Beck was also shown to have high hydrological connectivity, especially in the Switwath Beck sub-sub-catchment (Figure 7.16, 17c).

The river channel and floodplain storage scenarios were also informed by these four approaches. Channel planform changes where re-meandering could be tested were identified by the stakeholder group on Shap Beck, the Upper Lowther and Swindale Beck. Analysis of historical maps showed straightened reaches on Haweswater beck, the River Lowther near Helton, Naddle Beck and Carlsike Beck. The survey of the catchment showed the extent of the artificial channel at Greengate on Haweswater Beck (Figure 7.12l). Furthermore, the height of the flood bank was surveyed, which were also identified on modern maps. Also flood banks on the River Eamont near Yanwath were also identified by survey (Figure 7.12d). Areas where floodplain storage may be possible were identified by stakeholders at Whale Beck, where a survey found a small wetland, and Knipe moor, which was found to be a large flat area (Figure 7.12k). Stakeholders thought that wet woodland would be a favoured option in this location. The survey also showed the potential of the area around Crookwath Bridge meander to be used as temporary floodplain storage (Figure 7.12m).

7.5. Chapter Summary

This chapter has combined scientific knowledge, from the literature reviewed in Chapter 2, with stakeholder participation, with elements of both Callon’s (1999) public debate and co-production of knowledge approaches. The reason for using this approach is that there are mutual benefits for both the scientists and the stakeholders from this form of engagement. The research gains local knowledge and experiences from people who manage the catchment and both the scientists and the stakeholders gain a greater understanding of the system and processes occurring in the catchment through the co-production of knowledge as individuals information is debated and discussed. Different types of stakeholders were involved in this research, categorised as NGO’s, commercial and statutory non-departmental public bodies. There organisations often had interests and objectives which differed from each others. However, the group discussions showed the multiple benefits of many of scenarios being considered, from flood risk to biodiversity.

So once the sub-catchment had been agreed it was then essential that the land management scenarios were achievable both through scientific testing and practical implementation. The process of deciding what land management scenarios to test, and where to test them, was the main purpose of the stakeholder group. This consisted of several steps. First, a brainstorming exercise was undertaken to derive a list a generic land use change options. Second, these were evaluated using both scientific and practical criteria. The stakeholder group then decided which scenarios to pursue and which to eliminate from future analysis. The accepted scenarios which impact the partitioning of rainfall into runoff process are afforestation and compaction. The scenarios which impact the hydrological connectivity process are wet woodland, and floodplain roughness. The scenarios which increase the storage of water on the floodplain are wet woodland, wetlands, floodplain roughness, bunds (hedgerows and stonewalls), on-line storage and flood defence removal or setting back. Finally the accepted scenarios which affect the process of channel conveyance are channel naturalisation, two stage channels and on-line storage.

Third, once the scenarios to be tested had been prioritised, the specific locations where they could be implemented needed to be identified. This process was greatly assisted by the local knowledge of those stakeholders who manage and work in the Eamont catchment. Four mechanisms were used to help identify suitable locations: (1) a stakeholder group mapping workshop; (2) an analysis of historical maps; (3) a survey of the catchment; and (4) an analysis of hydrological connectivity of the catchment from the SCIMAP model. An example of a scenario location identified through this engagement was that compaction was perceived to be an issue in the Sockbridge area of the Eamont. The historical maps identified that the channel of Haweswater Beck had been straightened and flood banks constructed since the 1860s and these could be removed or set back to re-couple the channel to its floodplain. The walkover survey of the catchment identified the area of Crookwath Bridge, where a low lying meander bend could be developed into a floodplain storage area. Finally, the SCIMAP hydrological connectivity modelling identified that the Dacre Beck sub-catchment was highly connected to the river network and therefore scenarios using buffer strips may be successful in this location. These four approaches were used in combination to decide where to test the specific scenarios. Often different methods showed that the same location was suitable for a certain scenario. An example of this was at Whale beck, where stakeholders thought wet woodland could be introduced and the catchment survey found a flat area, with a small wetland.

Overall the combination of scientific knowledge and stakeholder knowledge benefited this thesis, as the scenarios which will be tested in the rest of this thesis had both scientific potential to reduce downstream flood risk and could be feasibly implemented in the catchment. The next chapter goes on to identify how the scenarios decided to be tested in this chapter will be modelled and tested. Then Chapter 9 gives details of the results of these modelling simulations both for channel processes and landscape processes.

Chapter 8

Approaches to Testing Land Management Scenarios

8.1. Chapter Scope

Once the scenarios that will be tested had been decided (Chapter 7), it is important to determine how to assess the impact on downstream flood hazard. Numerical modelling will be used to test the land management change scenarios. From the literature review in Chapter 2, it is clear that different land use changes effect different parts of the hydrological cycle e.g. infiltration, connectivity or channel conveyance. These different processes are best simulated using different types of models. Section 8.2 reviews the scenarios which impact on surface or sub-surface soil processes, which are tested using hydrological models. Channel modifications or how the channel and floodplain are coupled are tested using hydraulic models (Section 8.3).

8.2. Hydrological Models

Hydrological models, sometimes labelled rainfall-runoff models, represent the catchment scale hydrological processes that partition rainfall into runoff and its connection to the channel. The following sections will review hydrological models of different complexity and explain how such models have been used to test land management impacts. It will then outline the hydrological model chosen for use in this thesis and its representation of hydrological processes.

8.2.1. Review of Hydrological models

Hydrological models are either lumped or spatially distributed (Beven, 2001). Lumped models simulate a spatially homogeneous catchment through assigning the same data inputs and parameter values throughout the whole catchment (e.g. FEH, 1999). Fully spatially distributed models divide the catchment area into a grid or mesh of a particular resolution with specific data inputs and parameter values for each cell or node (e.g. SHE Abbott, 1986a; 1986b; Bathurst, 1986). Such models may fit into a continuum. For instance, semi-distributed (multiple lump) models may split the catchment into a series of hydrologically similar areas (e.g. CLASSIC) (Crooks and Davies, 2001). Examples of these types of models are given in Section 8.2.2.

Beven (2001) outlined five major issues associated with this type of model: (1) non-linearity; (2) scale; (3) uniqueness; (4) equifinality; and (5) uncertainty.

First, the problem of non-linearity relates to the relationship between rainfall and runoff, which is non linear and scale dependent (Bronstert *et al.,* 2002). This is because runoff is not a linear function of rainfall volume, as it is also influenced by factors such as antecedent conditions and the partitioning of rainfall into surface and subsurface processes. As the spatial scale of the catchment increases, the deviation from a linear response increases (Clark *et al.,* 2008). Furthermore, non-linear systems are particularly sensitive to initial and boundary conditions which may be highly uncertain (Stephenson and Freeze, 1974).

Second, the problem of scale is particularly relevant for hydrological models (Bloschl and Sivapalen, 1995). This is because the scale at which the model requires inputs (grid cell resolution) is often larger than the scale at which these inputs can be measured. Bronstert (1999) emphasises that model results are highly dependent upon the accuracy of input data. There are two opposing views on this upscaling; (1) effective parameters can be derived which average the effect of the process parameter over the whole grid cell (e.g. Binley *et al.,* 1989); and (2) that upscaling is impossible and that modellers have to acknowledge that models, and particularly the parameters used are scale dependent (e.g. Beven, 1995; Bloschl, 2001). Armstrong and Martz (2008) found that reducing the spatial resolution of land cover data had a limited effect on hydrologic response at the outlet and that only an extreme shift to a homogeneous land cover changed the model output. Clark *et al.,* (2008) found that small scale heterogeneity of soil types were averaged out at the hillslope scale. Peters (2003) represented spatial heterogeneity by defining a few distinct landscape types and disaggregating the catchment into fractions.

A common problem emerges where equations are used at larger scales from the smaller-scale theory on which they are based. Furthermore, different processes emerge as being important at different scales (Kirkby, 1996). Grayson and Bloschl (2000) and

Naef *et al.* (2002) identified key or dominant processes at different scales. McDonnell (2007) argues that real progress will only be made in hydrological modelling when macro-scale laws are used, and suggests that catchment classification will facilitate this.

The third issue is the problem of uniqueness, which links closely to matter of scaling. Beven (2000b) noted that any catchment may have quite specific characteristics. Thus, a model constructed for one catchment may not be transferable to others. Where generic models have been calibrated (e.g. Seibert, 1999), parameterisations may have to be transferred, such parameters may be regionalised in the process (Heuvelmans, 2004): catchments with similar characteristics may be assigned a particular paramerer set. Another technique used is geographical regionalisation, where neighbouring catchments are assumed to have a similar hydrological response (Vandewiele and Elias, 1995).

The fourth problem is one of equifinality, which is the principle that a particular model output can result from several potential model simulations, normally parameter sets (Beven and Binley, 1992). This may be a result of poor data input. Equifinality is a problem because the cause of the changes in model output cannot be found, as multiple causes are possible. This may be demonstrated through a Monte Carlo experiment in a Generalised Likelihood Uncertainty Estimate (GLUE) framework (Beven and Binley, 1992), where randomly chosen parameter sets are tested. Hydrological models have long been based on the Freeze and Harlan (1969) blueprint, which was a conceptual physically-based hydrological model framework, which recommended certain equations to represent certain processes. However, due to the problem of equifinality, Beven (2002) proposed an alternative blueprint which allowed for the potential of equifinality in scale dependent model representations.

The concept of equifinality links closely to the final problem, uncertainty, which has been widely commented on in the literature (Beven, 2001; Ewen *et al.,* 2006; Todini, 2007; Sivapalen 2009). Sivapalen (2009) summarised the sources of uncertainty as; (1) model structure (Son and Sivapalen, 2007); (2) process representations; (3) parameter values (Beven and Binley, 1992; Eckhardt *et al.,* 2003); (4) numerical solutions (Lane, 2003); and (5) data inputs (Tetzlaff and Uhlenbrook, 2005). The first three of these issues are related by the concept of model complexity, which originates from perceptual and conceptual models (Daniell and Daniell, 2006) (Chapter 2). It has already been stated that different processes are important at different scales. There is a mis-match between sophisticated small scale process understanding and the completeness of the system understanding at the catchment scale (Clark *et al.,* 2008). As more of the local scale understanding is incorporated into models, the model becomes more complex. This makes hydrological models very demanding in terms of parameterisation and data inputs (Merritt *et al.,* 2003). This is what causes the problem of equifinality, as many different model realisations may give the same answer. Furthermore, the computational demand of the model increases, with model simulations taking longer to complete. This either implies that the timestep of the model needs to increase or process representation needs to be simplified. Jothiyangkoon, (2001), Eder (2003) and Mouelhi (2003) argue that the influence of the timestep is critical and that it is more important than the spatial resolution. This links to the fourth source of uncertainty, numerical solution uncertainty. This arises because model solutions are only approximate and not exact solutions. This is because methods used in numerical models use an iterative process to converge on the answer. Numerical instability can occur if the number of iterations exceeds a set threshold. Furthermore, numerical diffusion associated with the actual operation of the solver, can occur. Both these sources of uncertainty can be difficult to detect. It is essential that the timestep chosen can capture the dynamics of the catchment response (Lane *et al.,* 2009). However, Adams (1995) argues that the physical representation of the processes should always take preference to spatial and temporal discretisation. Another source of uncertainty in models is the data input (Bronstert, 1999). The availability of data is one of the main controls on what process representations are chosen for models, while the data quality influences the quality of the model results. Luis and McLaughlin (1992) note the importance of the data which is used to assess models with, as well as the data used within the model. The validation dataset has inherent measurement errors associated with it. Therefore the goodness of fit statistics includes both errors in the observed and predicted datasets.

8.2.2. Application of hydrological models to investigate land management impacts on high flows.

Globally, there are more than 100 rainfall-runoff models in current use, of varying complexity and resolutions (Singh and Frevert, 2002a; 2002b; Singh and Woolhiser, 2002; O'Donnell *et al.,* 2004). Table 8.1 outlines some of the most common models and indicate how they have been used to test land use change scenarios. It will be structured in terms of how complex they are, starting with the simplest models. This complexity relates to the spatial resolution and the process representation. Hydrological models range from empirical lumped conceptual models, like the Flood Estimation Handbook (FEH, 1999), to semi-distributed continuous simulation models, like CLASSIC (Climate and Land Use Scenario simulation in catchments) (Crooks and Davies, 2001) and ARNO (Todini, 1996), to physically-based distributed models, like CRUM3 (Reaney *et al.,* 2007) and SHE (Abbott, 1986a; 1986b; Bathurst, 1986). These model classifications were outlined in Chapter 2, and this section explains how these specific models have been applied to flood risk modelling.

Type of Model	Example	Rationale	Limitations
Lumped, Percentage runoff / unit hydrograph	FEH (1999)	- Based on loss of a certain percentage of rainfall - Depends on catchment characteristics (Bayliss, 1999)	- Overestimates flood peaks compared to the flood frequency curves derived from the statistical method
Deterministic, Lumped Conceptual model	ReFH	- Update of FEH - Consists of 3 sub-models (Loss / Routing / Baseflow) - Four parameters (Baseflow Lag = BL (hours), Baseflow Recharge = BR, Maximum soil storage capacity = C_{max} (mm), Unit hydrograph time to peak = T_p (hours	- No direct way to assess the impact of land use changes on flood risk. - Packman (2004) designed indirect approach, whereby % runoff and T_p adjusted to represent soil degradation.
Conceptual Lumped model based on Probability Distribution Function	Probability Distribution Model (PDM) (Moore, 1985)	- Represents different areas of catchment with different storage capacities (different soil depths) - 6 parameters	- None of the parameters are physically meaningful) (Moore, 1999; 2007). - Makes testing land use scenarios difficult (characteristics not

			represented explicitly) - Performs as well as more complex model with 19 parameters (Moore and Clarke, 1981).
Semi-distributed / Conceptual	CLASSIC (Climate and Land Use Scenario Simulation in Catchments)	- 3 modules (Soil water balance, drainage, channel routing) - Land cover maps from 1961 and 1990 used for Thames catchment. Flood frequency shown to be slightly effected.	- Simplistic representation of soils and land cover types makes testing land management scenarios difficult. - Coarse grid resolution (20 km^2), with multiple land covers per grid cell, but not spatially known.
Semi-distributed / Conceptual Distibution Function	ARNO (Todini, 1996)	- Divides catchment into sub-catchments. - Output driven by total catchment soil moisture storage related to dynamic contributing areas. - Some processes represented by physically based equations e.g. Rutter (1971) for interception, Penman Monteith for evapotranspiration.	- Lacks physical basis for deriving some of the parameters.
Semi-Distributed / Quasi-Physical model based on distribution function	TOPMODEL (Kirkby, 1975, Beven and Kirkby, 1976)	- Based on topographic index $\ln\left(\frac{a}{Tan\ b}\right)$ a = area (km^2); and b = slope gradient	- Land use changes cannot be represented explicitly.
Physically based spatially distributed	CRUM3 (Connectivity of RUnoff Model) (Reaney et al., 2007)	- Minimal parameter set for which values can be obtained from the literature. - Physically based process representation.	- Simplified process representation (e.g. interception just a container store)
Physically based spatially distributed	SHE (Systeme Hydrologique Europeen) (Abbott,	- Based on Freeze and Harlan (1969) blueprint. - Physically meaningful equations e.g. St. Venant equations for channel	- Several parameters and input data demands - Parameters lumped to grid scale, as they cannot be measured at

	1986a; 1986b, Bathurst, 1986)	flow, 1D Richards equation (1931) for unsaturated zone, Boussineq (1872) equations for saturated zone.	that scale (Beven, 1989) - Equations representing hydrological processes based on small scale theory applied at larger scale
Physically based spatially distributed	SHETRAN	- Development of SHE, coupling surface and sub-surface processes.	- Significant uncertainty in parameter estimates.

Table 8.1 *Summary of Hydrological models*

One of the main conclusions to come out of this review of hydrological models is that there is no consensus over which model, or even which type of model it is best to use. Furthermore there is a discrepancy between model development and model application (Buytaert *et al.,* 2008). Most of these models have undergone extensive evaluation and calibration, but scenario testing studies are in the minority. The small number of reported comparison studies (e.g. Bormann *et al,* 2007) suggests that the models produce a broad range of predictions.

However, the biggest problem remaining for hydrological modelling on determining the effect of land use changes on downstream flows is the problem of upscaling local changes in runoff to the catchment outlet. Jackson *et al.* (2006; 2008a; 2008b) have used data to inform their modelling approach. This thesis has taken a different approach to the scaling problem, using data to downscale the downstream flood magnitude to the upstream contributing sub-catchments. Data analysis and hydraulic modelling techniques have been used to determine which sub-catchment to focus the hydrological modelling on. This is because a major issue with hydrological modelling is the resolution of the model. As the total catchment area decreases, the resolution of the model can increase, meaning that processes can be represented more precisely. Also, a sub-catchment is more homogeneous than the whole Eden catchment, meaning that variables such as rainfall can be constant over the area. Furthermore, as the area decreases, the complexity of the model can be reduced, with fewer process included, and fewer uncertain parameters. Thus, as per Jackson *et al.* (2006; 2008a; 2008b) the focus of this research is use of a physically based model, to maintain a strong link to hydrological processes. This makes it easier to test land use scenarios with the model, as changes can be represented by changing physically meaningful parameters and land covers. The model that will be used in this thesis is CRUM-3 (Connectivity of Runoff Model) which is a fully spatially distributed, physically based hydrological model, developed by Dr. Sim Reaney. The justification for using this model is that it can be used to simulate the effects of land use change explicitly. Further reasons for using this model are given in the next section.

8.3. CRUM-3 (Connectivity of Runoff Model)

CRUM-3 takes an object oriented approach to model structure and was developed in C++. This has the advantage that the problem can be split into simple sub-routines, which can be solved in isolation (Reynolds and Acock, 1997). This allows related processes to be grouped, through the process of encapsulation, e.g. soil, groundwater, meaning parts of the code can be re-used in new forms of the model (Cox, 1986; Wegner, 1990).

As well as using an object oriented design, CRUM-3 also has two further important design features. First, the model aims to use a minimal parameter set, which can be obtained from the literature for any UK catchment. Second, the hydrological processes are represented in a physical meaningful way and are also spatially explicit. This is advantageous because the results of the model can be interpreted in terms of hydrology and can be used to test both climate and land use change scenarios. Furthermore, CRUM-3 is a continuous simulation model, meaning that several years of data can be modelled. The timestep of the model needs to be small enough to capture the dynamics of runoff generation, but large enough to prevent long model run times. CRUM-3 therefore uses a variable timestep, where if there is rainfall, then the timestep decreases to two minutes, but if there is no rainfall then it gradually increases to a maximum of six hours. This adaptive timestep maintains model stability in more computationally intensive parts of the simulation. CRUM-3 has been used in several catchments for both academic (Reaney *et al.,* 2007; Reaney, 2008; Lane *et al.,* 2009) and commercial (Conlan *et al.,* 2005) purposes.

8.3.1. Summary of process representation within CRUM-3

Figure 8.1 shows that the model structure is split into four categories, with a weather module, a one-dimensional vertical hydrological module, a landscape scale two dimensional module and a river channel module. For more details on the process representation of CRUM-3 see Reaney *et al.* (2009).

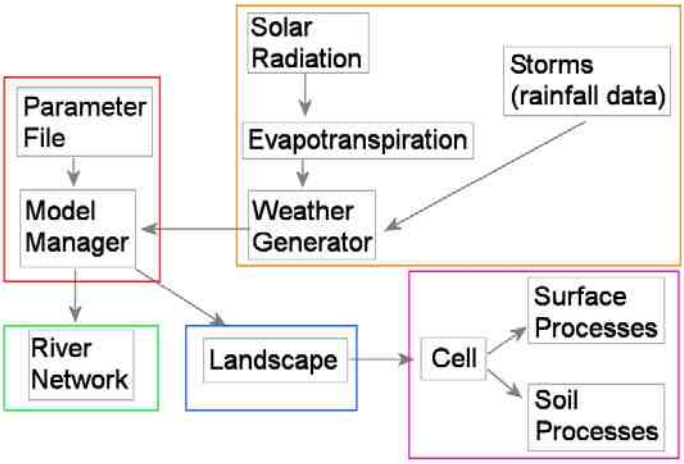


Figure 8.1 *Structural Framework of the CRUM-3 model*

a) *Weather*

The data inputs for CRUM-3 are rainfall and temperature data, at a daily resolution. For rainfall, a weather generator takes the input file with the daily timescale data, and assigns a proportion to individual storms through a Monte Carlo model parameterised from observed data for the UK. Then rainfall is distributed within individual storms to determine per-minute rainfall intensities. Finally these storms are distributed randomly within the timestep. The daily maximum and minimum temperature data is needed for CRUM-3. These values are then interpolated to per second temperatures ($t_{a(s)}$) using the equation below, then averaged to the needed timestep:

$$T_{a\,(s)} = \frac{\sin\left(\frac{d_s + td + (12 \times 60 \times 60)}{4 \times 60 \times 60}\right) + 1}{2} \times (t_{max} - t_{min}) + t_{min}$$

Where d_s is the current second of the day

td is the time between midday and the maximum temperature (seconds)

t_{max} is the maximum daily temperature (°C)

t_{min} is the minimum daily temperature (°C)

b) 1D Hydrological Processes

Figure 8.2 shows a conceptual model of the 1D hydrological module in the CRUM-3 model, and includes the hydrological processes of interception, evapotranspiration, infiltration and aquifer recharge in the vertical cascade. Stores of water in the system are vegetation, the earth's surface, the soil and the groundwater system. Precipitation can be directly evaporated to produce the effective rainfall, which then can either be stored on the vegetation canopy or reach the land surface. The precipitation that is intercepted can either drain to the surface or be evaporated. It is important to note that this calculation of the effective precipitation is carried out internally within the model, meaning that feedback mechanisms affect rainfall input. The water that reaches the land surface either infiltrates into the soil or is stored as depression storage. If this store overflows then runoff is initiated. Water that infiltrates into the soil is either stored, transferred laterally as throughflow, or drains to the groundwater stores.

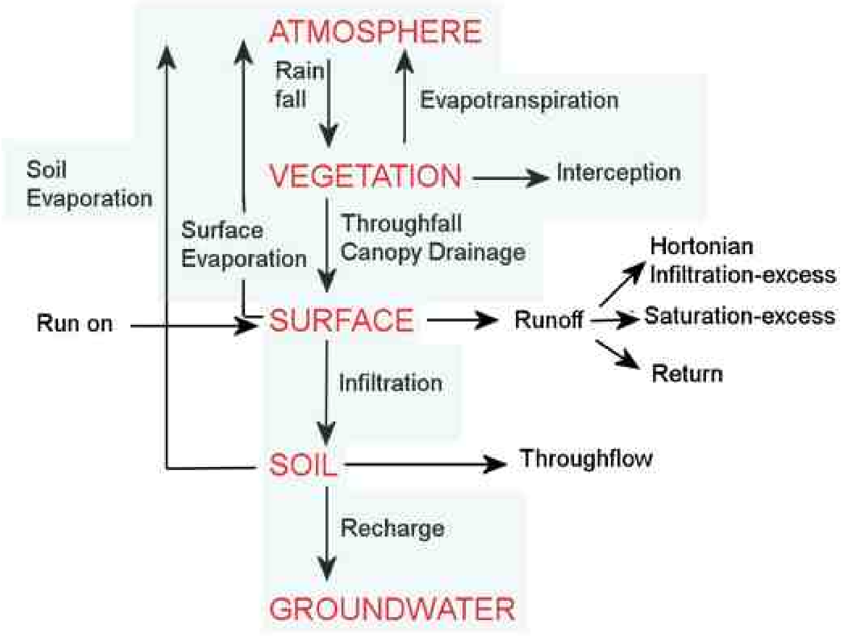


Figure 8.2 *Conceptual framework of the hydrological processes for the CRUM in individual cells (1D hydrological module cell shaded)*

Interception

Interception occurs when precipitation falls on surfaces other than the soil. Usually this is vegetation, although it can be urban features such as buildings. Interception reduces the amount of effective precipitation reaching the soil, as water is evaporated from interception stores e.g. a tree canopy. This is seen as an important hydrological process, as between 10 and 40% can be lost via interception and evaporation (Dingman, 1994). This decreases the effective precipitation input, meaning that the amount of water in the system is reduced, and flooding decreases. However, storms which cause floods are large and interception is not thought to be a significant process in reducing precipitation input. Factors which influence the process of interception are vegetation cover and climate of the catchment.

Vegetation type and growth stage determines the canopy density and the "gap fraction", which is the proportion of open canopy. Leaf Area Index is an important parameter for predicting interception loss. This is because it controls the rate of interception and evapotranspiration. These factors change through seasons and with species. Also rainfall characteristics, such as the magnitude, intensity, duration and type of precipitation influence the amount of interception (Crockford and Richardson, 2000). These two groups of factors are vulnerable to land use and climate change respectively.

CRUM-3 represents the process of canopy interception as a non-leaking store. Precipitation is partitioned between throughfall and canopy storage. Throughfall is the component of water that directly falls to the ground or drips off the canopy. Water stored on the canopy is either evaporated or is drained to the ground. The proportion of rainfall which is intercepted is determined by the gap factor of different vegetation species (Breuer *et al.,* 2003). The interception capacity of different species defines the quantity of water that can be stored in the canopy. Once this value is exceeded, and the canopy store overflows, the excess water drains to the land surface. This process representation is the same as used in the Pattern^{lite} model (Mulligan and Reaney, 2000) and the CASC2D model (Johnson *et al.,* 2000).

The parameters in CRUM-3 which control the process of interception are given Table 8.2. The interception depth or capacity is defined as the maximum quantity of rainfall that can be stored in the canopy without draining. The gap fraction quantifies the proportion of the landscape that is covered by the canopy and is expressed as a percentage. The growth temperature threshold (Grow$_{temp}$) defines when vegetation starts to grow. Growth proceeds at a constant rate ($Grow_{Rate}$) until the maximum height (H_{max}) is achieved.

Interception Depth	I_d
Gap Fraction	Gap Frac
Vegetation Maximum Height	H_{max}
Vegetation Growth Rate	$Grow_{Rate}$
Growth Temperature Threshold	$Grow_{temp}$
Sow Julian Day	Sow_{day}
Harvest Biomass	$H_{biomass}$

Table 8.2 *Land Cover parameters in CRUM3 which influence interception.*

Evapotranspiration

Water is lost from the system via the process of evapotranspiration, which has two main components, evaporation and transpiration (Smakhtin, 2001). Evaporation is the process by which water changes from the liquid state to the gaseous phase. Water stored in the interception store can evaporate and is lost from the system. Transpiration is the evaporation of water from within plant structures through stomata in leaves which open to allow CO_2 into the plant for photosynthesis.

Hydrological studies distinguish between potential evapotranspiration and actual evapotranspiration (Shuttleworth, 1993). Potential evapotranspiration is the maximum quantity of water which can be lost from a surface given available atmospheric conditions. Climatic variables which influence the rate of evapotranspiration are net solar radiation, temperature, humidity and wind speed. The characteristics of the surface also affect the potential rate of evapotranspiration, specifically the roughness. Wet rough surfaces (e.g. forests) have higher potential rates than smooth surfaces (e.g. water bodies). Actual evapotranspiration rates are controlled by the potential evapotranspiration rate and the amount of water available.

Factors which influence the process of evapotranspiration (Veihmeyer, 1964) are the climatic conditions, including the net radiation input to the system, air temperature, wind speed and humidity gradient. Characteristics of the land surface are also important, with the albedo of the land surface determining how much radiation is reflected back into the atmosphere. Other properties, such as heat storage capacity and aerodynamic roughness of the surface are critical factors to consider. These factors are affected by the vegetation cover of the land surface.

The preferred equation to represent the process of evapotranspiration is the Penman-Monteith (Penman, 1948; Monteith, 1965) equation (Dingman, 1994), as it is the most theoretically complete representation, but this is highly data intensive, with information on temperature, solar radiation, wind speed, relative humidity and vegetation characteristics required. Therefore CRUM3 uses the Priestley-Taylor (1972) equation.

$$PET_{PT} = \frac{\alpha_{PT}\Delta(R_n - G)}{\Delta\gamma}$$

where
α is the Priestley-Taylor Constant (1.26) (Jensen et al., 1990)
Δ is the Slope of the saturation vapour pressure temperature relationship from:

$\Delta = \left(\frac{4098 + e_s}{237.3 + T_a}\right)^2$ where T_a is the temperature (°C)
e_s is the saturated vapour pressure by the Clausius-Clapeyron equation (Wallace and Hobbs, 1977) where

$$e_s = 0.611\ exp\left(\frac{17.3 \times T_a}{237.3 \times T_a}\right)$$

R_n = Net radiation flux at surface (KJ / m^2 / s)

G = Soil heat flux (KJ / m^2 / s) from $G = R_n \times 0.1$

γ = Psychrometric constant from $\gamma = \frac{c_p \times P}{0.622\lambda}$ where

C_p = specific heat capacity of air
P = Atmospheric pressure
λ = Latent heat of vapourisation

This equation uses both temperature and net radiation to predict potential evapotranspiration. However, this equation does not consider the influence of wind speed on potential evapotranspiration rates, but data on this variable are not available for many catchments. Net radiation is thought to be the most important factor controlling potential evapotranspiration (Dingman, 1994). The net radiation is determined by considering the amount of energy input to the system, the transmission of energy through the atmosphere and the reflection of energy by the earth's surface. The amount of incoming radiation is determined by the position of the earth with respect to the sun, and the time of the year. Further details on how this input is calculated are given by equations in Dingman (1994). Radiation is scattered as it travels through the atmosphere, and is dependent upon the thickness of the atmosphere and particularly the amount of cloud cover. For cloud free days, the amount of incoming energy is halved due to the atmosphere effects. A further 50% is subtracted for cloudy days, which are all days with rainfall and a random selection of non-rain days. Finally, some of the incoming energy is reflected from the earth's surface rather than being absorbed. This can either be as shortwave or long wavelength radiation and are calculated from the following equations:

$$r_{sw} + R_{ES} \times a$$

Where r_{sw} is the amount of reflected short wavelength radiation

R_{ES} is the amount of solar radiation reaching the earth's surface

a is the albedo parameter (Geiger, 1950)

$$r_{lw} = e_{ms} \times (5.6696 \times 10^{-8}) \times (T_a + 273.15)^4$$

Where r_{lw} is the amount of reflected long wavelength energy

e_{ms} is the surface emissivity

Evapotranspiration occurs from many parts of the vertical cascade, including the surface, vegetation and soil stores. CRUM-3 evaporates water in the following order: (1) water intercepted by vegetation; (2) transpiration; (3) water in surface storage; and (4) water in the soil matrix. The rate of evapotranspiration from intercepted water and surface detention storage is at the same rate as the potential rate. Potential transpiration rates are calculated from the following equation (Scott, 2000)

$$t_p = PET_{PT} \times (-0.21 + 0.7^{LAI})$$

Where t_p is the transpiration rate

PET_{PT} is the potential evapotranspiration rate

LAI is the Leaf Area Index parameter

Actual transpiration rate is related to the rooting depth of the vegetation and the availability of water within the soil. Evaporation of water directly from the soil store is limited by the moisture retention characteristics of the soil, given by:

$$e_\theta = PET_{PT} \times \theta$$

Where e_θ is the soil moisture dependent evaporation rate

θ is the soil moisture content

However, the influence of soil moisture content upon evapotranspiration is debated, with Veihmeyer and Hendrickson (1955) indicating that soil moisture tension has little impact until the permanent wilting point is reached. Taylor and Haddock (1956) showed that the soil moisture tension restricts the availability of water and therefore its removal rate.

The parameters which control the rate of evapotranspiration are given in Table 8.3. Several of these parameters control the rate of interception as well and were explained previously. The additional parameters which control evapotranspiration include the albedo, which controls how much radiation is reflected and absorbed by the vegetation with high albedo values indicating a high reflectivity. The rooting depth controls whether or not the vegetation has access to a source of soil water for transpiration.

Albedo	a
Vegetation Maximum Height	H_{max}
Vegetation Growth Rate	$Grow_{Rate}$
Growth Temperature Threshold	$Grow_{Temp}$
Irrigation	I
Sow Julian Day	Sow_{Day}
Harvest Biomass	$H_{Biomass}$
Rooting Depth	RD_{max}

Table 8.3 *Land cover parameters which influence the process of evapotranspiration*

Surface Depression Storage

The depth of the surface depression store is determined from the surface slope and roughness using (Kirkby *et al.,* 2002):

$$\frac{dp}{\alpha} = 0.11\ exp\left(\frac{-\ 0.02\ \beta}{\alpha}\right)$$

Where dp is the surface depression storage capacity (mm)

α is the surface roughness

β is the slope gradient

Infiltration

Infiltration is the process by which water moves from the soil surface into the soil (Horton, 1933). Infiltration functions because of soil water gradients within the soil. There are two main soil zones when infiltration is proceeding at its maximum rate. The layer just below the surface is called the upper transmission zone. Gravitational forces act within this zone. Below this zone is a drier layer, which is separated from the upper layer by the wetting front. Across this boundary, there is a strong hydraulic gradient, meaning water is forced into the drier layer. This means that throughout a storm the wetting front migrates downwards, meaning that the infiltration rate decreases, until the capacity is reached, when the soil is fully saturated and infiltration can no longer occur.

Factors which influence the process of infiltration were summarised by Brakensiek and Rawls (1988). First, soil structure and texture is a key control on the rate of infiltration. Factors such as particle size influence the rate of infiltration, as coarser particles normally increase the rate (Rawls *et al.,* 1991). Also bulk density and organic matter content are important physical characteristics. Chemical properties influence the aggregation of particles and the chemical bonding with water. Second, soil surface characteristics are an important factor, especially slope and roughness. Bare soils often lead to formation of soil crusts due to raindrop impacts, which impede infiltration (Sumner and Stewart, 1992). Surface roughness (Zobeck and Onstad, 1987) and configuration also impact on infiltration (e.g. ploughing). Third, the saturated hydraulic conductivity controls the ease at which the liquid flows and the ease with which the soil medium allows it to flow through it when the soil is saturated (Klute and Dirkson, 1986). This is a key parameter in models of infiltration. Fourth, antecedent soil conditions control the depth of the wetting front at the beginning of the storm event

(Rawls *et al,* 1993). Finally, precipitation characteristics, especially intensity, are significant for infiltration rates. If rainfall intensity exceeds the infiltration rate, then infiltration-excess overland flow results. Rainfall duration and amount is also important because it controls the time it takes for the soil to become saturated. Other climatic factors, such as temperature are important, as <0°C temperatures lead to frozen ground and reduced infiltration rates (Lee, 1983).

Approaches to modelling infiltration can either be based in terms of time since the process began or in terms of the current soil water storage content. An advantage of the storage type equations is that they remain valid at the start of a storm when the infiltration rate (i_t) is less than the capacity rate, as the infiltration capacity is high. Some models have more than one layer to the soil structure (e.g. crust, horizons). A problem with most infiltration equations is that they do not account for macropores and their impact on infiltration (Beven and Clarke, 1986; Germann, 1989). CRUM-3 uses a storage type equation, rather than a time based equation and means that the model can be used for irregular time series. A simplified version of the Green-Ampt (1911) equation is used in CRUM-3, following Kirkby (1975; 1985)

$$i_t = a + \frac{b}{\theta}$$

Where a and b are the Green-Ampt a and b parameters and θ is the soil moisture content

The main advantage of using this equation is that it reduces the problem of scale dependence in parameters (Beven, 2000a). It allows the process of infiltration to be modelled over larger grid resolutions rather than at a point. A major control on the amount of water that can be stored within the soil profile is the soil depth. CRUM-3 categorises different geomorphological features, as this has been shown to relate to soil depth (Huggett and Cheesman, 2002). Soil depth is allocated in the following order for these different landscape units:

Channels > Plains > Ridges > Slopes

The full list of soil parameters are given in Table 8.4. The depth of the soil determines the total storage capacity, with deeper soils having greater storage capacities. However, it is the dynamic root layer which controls the near surface processes and the water content of this layer is what ultimately drives the generation of overland flow. The saturated hydraulic conductivity of this layer controls the rate of lateral throughflow in the topsoil layer and also the rate of transfer from the root soil layer to the main soil store. The saturated hydraulic conductivity parameter is a measure of the ability of the soil to transmit water through the soil (Klute and Dirkson, 1986). As the value of the saturated hydraulic conductivity increases, the ability of the soil to transfer water increases. This is demonstrated by the saturated hydraulic conductivity of a sandy soil being 1.76×10^{-4} m s^{-1}, while for a clay soil it is only 1.28×10^{-6} m s^{-1}. Table 8.5 shows typical values for the saturated hydraulic conductivity parameter for different types of soil. The porosity of the soil is related to the number of pores in the soil. Different soil textures have different porosities (Table 8.5), with finer grained soils having higher porosities due to the open arrangement of clay particles, while sand and silt particles are packed more closely together. This variable is closely related to the overall depth of the soil, as the volume controls the number and size of soil pores. Soil porosity often decreases with depth due to compaction and the biological activity near the surface. However, in CRUM-3 soil porosity is uniform across the whole soil depth, but the dynamic root layer b parameter, which is the pore size distribution index, allows the size of pores in the topsoil to be varied. Compaction will reduce the size of pores in the dynamic root layer.

Soil depth - Channels	d_c
Soil depth - Slopes	d_s
Soil depth - Ridges	d_r
Soil depth - Planes	d_p
Saturated Hydraulic Conductivity	K_{sat}
Dynamic Layer Saturated Hydraulic Conductivity	D_{Ksat}
Dynamic Layer depth	D_{depth}
Dynamic Layer b	D_b
Green Ampt A	A
Green Ampt B	B
Porosity	φ
Hydraulic Conductivity decay with depth	K_{decay}
Bedrock Conductivity	$K_{bedrock}$

Table 8.4 *Soil parameters which influence the process of infiltration*

Soil Type	**Saturated Hydraulic Conductivity (Ksat) (m s^{-1})**	**Porosity φ**	**Pore Size Distribution Index b**
Sand	1.76 ×10^{-4}	0.395 (0.056)	4.05 (1.78)
Loamy Sand	1.56 ×10^{-4}	0.410 (0.068)	4.38 (1.47)
Sandy Loam	3.47 ×10^{-5}	0.435 (0.086)	4.90 (1.75)
Loam	6.95 ×10^{-6}	0.451 (0.078)	5.39 (1.87)
Silt Loam	7.20 ×10^{-6}	0.485 (0.059)	5.30 (1.96)
Sandy Clay Loam	6.30 ×10^{-6}	0.420 (0.059)	7.12 (2.43)
Clay Loam	2.45 ×10^{-6}	0.476 (0.053)	8.52 (3.44)
Silty Clay Loam	1.70 ×10^{-6}	0.477 (0.057)	7.75 (2.77)
Sandy Clay	2.17 ×10^{-6}	0.426 (0.057)	10.4 (1.64)
Silty Clay	1.03 ×10^{-6}	0.492 (0.064)	10.4 (4.45)
Clay	1.28 ×10^{-6}	0.482 (0.050)	11.4 (3.70)

Table 8.5 *Soil infiltration parameter values (Clapp and Hornberger, 1978) (numbers in brackets are the standard deviation)*

Groundwater Storage and Recharge

The process of recharge to the groundwater store is determined by the minimum of the hydraulic conductivity at the base of the soil profile and the hydraulic conductivity of the bedrock. Factors which influence the process of groundwater drainage / recharge are: (1) geology; (2) climate; and (3) topography. Geology is important in terms of permeability and storage capacity of the rock type. Locations with low permeability bedrock often suffer from a flashy flood regime. Precipitation frequency and magnitude are important factors when considering the amount of water stored as groundwater. Groundwater stores delay the impact on hydrological systems, by acting as a buffer of low flows and extra storage to reduce floods. Topography is an important factor in determining whether climate or geology is the critical factor in controlling groundwater recharge. In regions of high topographic relief, climate is the dominant control, while in areas of low relief, geology is more critical.

c) Landscape scale processes

The spatial representation of the catchment is through a grid structure, with every cell in the model generating and receiving water from surrounding cells as runoff and throughflow (Figure 8.3). Overland flow occurs when the surface depression storage overflows. Run-on is the input to a cell from upslope. Sub-surface throughflow of water also occurs between cells.

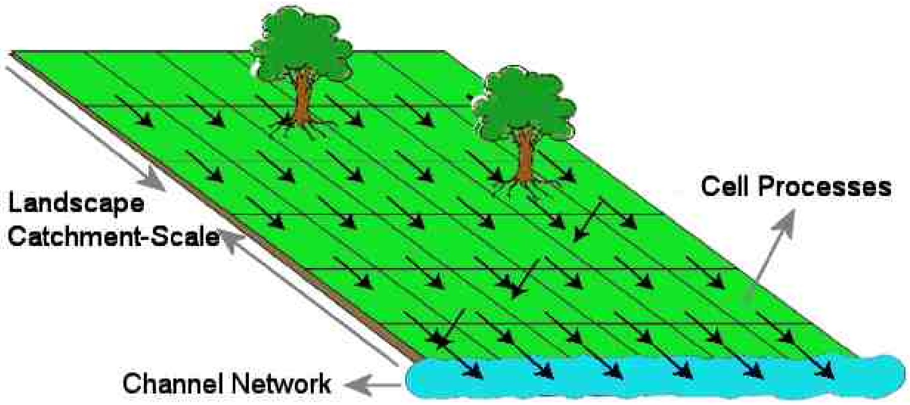


Figure 8.3 *Schematic of the landscape scale model structure (adapted from Reaney, pers comm.)*

Overland Flow – Runoff / Run-on

There are three type of overland flow: (1) infiltration-excess/Hortonian; (2) saturation-excess; and (3) return overland flow. Hortonian or infiltration-excess overland flow occurs when the rainfall intensity exceeds the rate of infiltration. Saturation overland flow occurs when the soil is saturated and therefore no more water can infiltrate whatever the intensity. Return overland flow or interflow occurs when water infiltrates into the soil upslope, flows laterally through the soil and exfiltrates downslope. These processes can be modelled simply by applying these conceptual definitions as a function of infiltration rate and precipitation rate. Overland flow may be either laminar, transitional or turbulent (Abrahams *et al.,* 1986) and therefore the Darcy-Weisbach equation is the most appropriate to determine the velocity (v) of overland flows (Baird, 1997).

$$v = \sqrt{\frac{8gRs}{ff}}$$

where g is the acceleration due to gravity

R is the hydraulic radius

s is the slope of the energy gradient

ff is the friction factor (Abrahams *et al.*, 1992)

Routing of overland flow from cell to cell is via the FD8 algorithm (Quinn *et al.,* 1991), which allows water to flow from one cell to multiple cells, meaning that water flow can be both dispersed and concentrated. This is thought to be more physically realistic to represent hillslope flow pathways that are both divergent and convergent (Freeman, 1991). The alternative flow algorithm (D8) assigns all the water from the upslope cell to a single downslope cell based on greatest slope (Band, 1986; Morris and Heerdegen, 1998). These two flow routing algorithms are illustrated in Figure 8.4. In the FD8 algorithm, the downslope flow of water is weighted on a slope gradient basis by (Quinn *et al.*, 1991):

$$F_i = \frac{\beta_i^v}{\sum_{i=1}^{8} \beta_i^v}$$

where β_i is the slope from the central cell to the neighbour i; and v is a flow concentration constant (Holmgren, 1994), with values 4-6 recommended

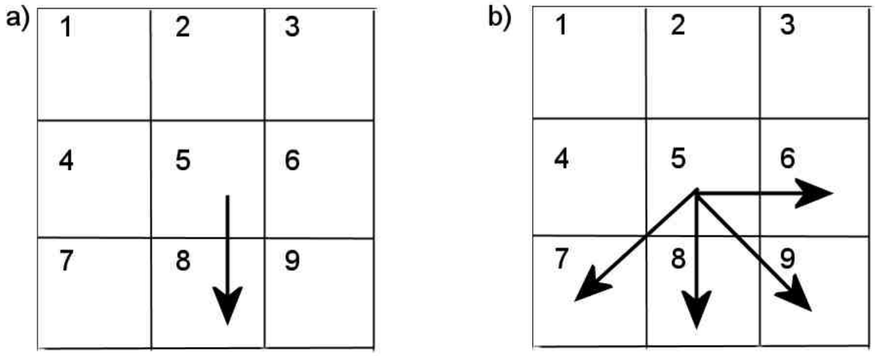


Figure 8.4 *a) Single flow routing algorithm (D8), b) FD8 Multiple flow routing algorithm*

The parameters which control the process of overland flow in CRUM-3 are given in Table 8.6.

Darcy-Weisbach Friction Factor	FF
Percentage of Cell with flow	Flow%

Table 8.6 *Parameters in CRUM3 which influence overland flow*

Throughflow

Throughflow is used to describe subsurface lateral water flows. Throughflow mainly occurs in the saturated soil layer, but relatively small rates of throughflow can also occur in the unsaturated zone. Lateral flows then occur and transfer water downslope under the force of gravity. Darcy's law is the basic formula used to model subsurface flows in the saturated zone:

$$tf_v = wt \times y \times K_d \times \frac{\delta h}{\delta x}$$

where tf_v is the throughflow volume per second; wt is the height of the water table above the bedrock; y is the width of the routing cell; and K_d is the soil conductivity at water table depth from :

$$K_d = K_{sat}\, exp\left(\frac{-d}{dc}\right)$$

where K_{sat} is the soil saturated conductivity; d is the water table depth; dc is the decay factor for changing conductivity with depth; h is the hydraulic head; and x is the horizontal distance between model cells.

However, lateral flows can also occur when the soil is not saturated, meaning that Darcy's law is no longer valid. Richard's equation can then be used to model lateral flows, which is a combination of the Darcy's law for unsaturated soil and the conservation of mass equation. However, CRUM-3 assumes that these flows are insignificant and therefore are not modelled.

d) *River Channel Network*

Routing of water within the channel network is represented using the Muskingham-Cunge equation (Section 5.3.1) (McCarthy, 1938; Cunge, 1969; Price, 1978).

This section has outlined how the physical hydrological processes, both at the plot scale and at the catchment scale are represented within CRUM-3.

8.3.2. How will the land use scenarios be tested using CRUM-3 ?

There are two land use change scenarios that will be tested using CRUM-3 are compaction and afforestation.

Scenario 1: Compaction

This section has two parts. The first describes the process of compaction and how it affects the soil characteristics. The second describes how the scenario of compaction will be tested by using CRUM-3.

Compaction reduces the infiltration rate of water into the soil. Compaction can be caused by both heavy machinery (Jansson and Johansson, 1998) and stock (Scholz and Hennings, 1995). The amount of compaction is dependent upon the characteristics of the load, including weight and the amount of time the soil is under load, and the characteristics of the soil, including its texture, water content and hydraulic conductivity. For instance, it has been found that low pressure tyres reduce the amount of soil compaction (Boguzas and Hakansson, 2001) and that rubber tracks cause compaction of the topsoil but less deep compaction (Febo and Planeta, 2000). The types and densities of stock are also important factors for pastoral fields. Betteridge *et al.* (1999) compared the effects of cattle and sheep on soil compaction and found that cattle cause soil disturbance through upward and downward movement, while sheep cause surface compaction. Godwin and Dresser (2003) estimated that 40 kg sheep, with a foot area of 0.0006 m^2, exert a pressure of 160 kPa when static, 320 kPa when walking and up to 480 kPa under dynamic conditions. Furthermore, stock reduces the vegetation cover, which leads to soil surface crusting and reduced overland flow resistance (Ferrero, 1991). Heathwaite *et al.,* (1989) found that 7% of rainfall was converted to runoff in ungrazed fields, while this increased to 53% in grazed fields. Furthermore, Heathwaite *et al.,* (1990) found that infiltration capacity was reduced by 80% on grazed areas compared to fields with no stock.

Compaction is known to modify the soil structure and decrease the depth of the soil and therefore increase the soil density, as the same mineralogical content is compressed into a smaller volume (Soane, 1980; Gupta *et al.,* 1989). Rauzi and Hanson (1966) found that the intensity of grazing affected these soil characteristics, with soil bulk density increasing significantly from lightly to moderately and heavily grazed plots (Table 8.7).

Grazing Treatment	**Bulk Density (g / cc)**	**Pore Space (% total volume)**
Heavy	1.29	7.7
Moderate	1.24	8.4
Light	1.17	10.6

Table 8.7 *Effect of different magnitudes of compaction on soil bulk density and pore space (Rauzi and Hanson, 1966)*

The porosity (φ) of the soil is related to the density through the following relationship:

$$\varphi = 1 - \frac{p_b}{p_m}$$

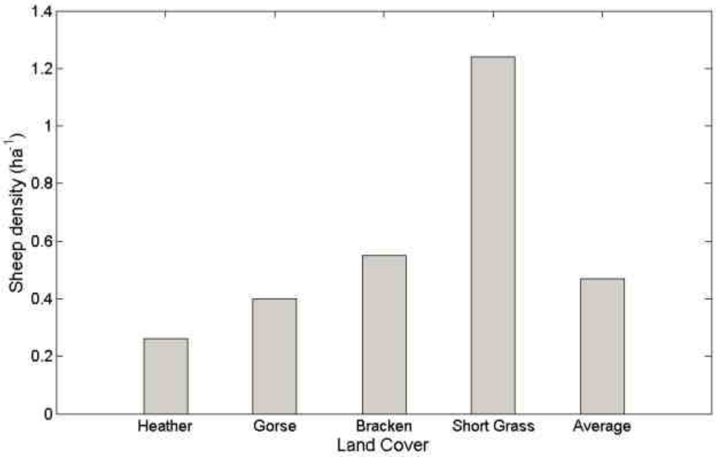
Where p_b $is\ the\ soil\ bulk\ density$

(peat = 0.7, clay = 1.1, sand = 1.6, compacted = ≥1.7)

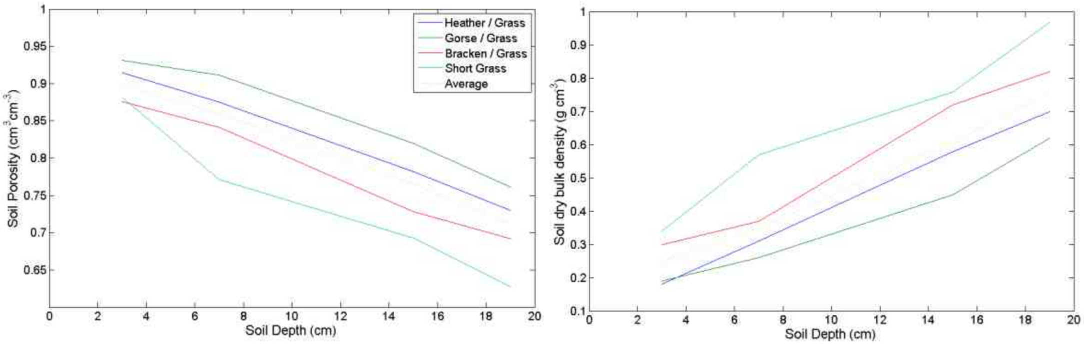
p_m $is\ the\ soil\ particle\ density = 2.65$ (quartz)

Therefore, soil porosity decreases as soils become compacted. Meyles *et al.,* (2006) found that the land cover the highest stock densities (short grass = 1.24 sheep / hectare) (Figure 8.5a) had the lowest soil porosities (Figure 8.5b) and the highest soil bulk density (Figure 8.5c) for all soil depths.

As there are fewer pore spaces within the soil the saturated hydraulic conductivity decreases. Servadio *et al.* (2001) studied the effects of compaction caused by heavy farm machinery on saturated hydraulic conductivity. The number of times the machinery passed over the land was found to be a critical factor (Bakker and Davis, 1995), with Servadio *et al.* (2001) finding that wheeled machinery reduced the saturated hydraulic conductivity from 18.5 mm h^{-1} to 3.3 mm h^{-1} with one pass and to 1.1 mm h^{-1} after 4 passes. A tracked vehicle reduced saturated conductivity less, with one pass resulting in a value of 11.2 mm h^{-1} and four passes 7.5 mm h^{-1}. A modelling study by Williams *et al.* (2004) decreased the saturated hydraulic conductivity from 1.5×10^{-5} to 1.5×10^{-7} to simulate the effect of compaction. Also they introduced an impermeable clay layer at 0.3 m depth to represent the effects of compaction in another approach.



a) Sheep densities for different land covers



b) Soil porosities with soil depth *c) Soil bulk density with soil depth*

Figure 8.5 *Soil Physical Properties under different land covers with different sheep densities (Meyles et al., 2006)*

The effects of compaction are thought to penetrate up to the depth of 60 cm (Flowers and Lal, 1998), although the greatest effects are seen in the top 10 cm. However, there is great debate over this issue, with Ferrero and Lipiec, (2000) and Vzzotto *et al.*, (2000) stating 20 cm and 5 cm respectively. This might be due to different soil types being more or less susceptible to compaction, with fine textured soils being more susceptible (Mwendera and Saleem, 1997). Also as the soil moisture content increases, the load that the soil can support decreases (Kondo and Dias Junior, 1999; Lipiec, 2002).

Compaction has been shown to affect the soil characteristics. This land management scenario will be tested through two approaches. First, a sensitivity analysis was carried out on the soil parameters. Second, scenarios of light, moderate and heavy compaction were used using parameter values from the literature.

The soil parameters were shown in Table 8.4 and the ones that are affected by compaction are: the Green Ampt parameters; A and B, the dynamic root layer saturated hydraulic conductivity; the dynamic root layer depth; the dynamic root layer parameter b; the soil porosity; and the main soil layer saturated hydraulic conductivity and depth. As the value of the Green-Ampt A and B parameters increase the rate of infiltration also increases. Therefore reducing the value of these parameters will simulate compacted soils, while increasing them will simulate improving soil structure. A range of 0 to 100 for each of these parameters will be simulated. The dynamic root layer is critical for the simulation of compaction, as compaction is greatest in the top few centimetres of the soil. Therefore, the process of compaction decreases the dynamic layer depth. A range of 0.5 m to 1.0×10^{-6} m will be used. The dynamic layer b parameter, which is the pore size distribution index, allows the size of pores in the topsoil to be changed. This affects the porosity of the top layer of the soil only. The review of the literature did not yield any information on how compaction affects this parameter, so a range of 0 to 16 will be used initially. From the literature, it has been shown that the effect of compaction on saturated hydraulic conductivity is to change the rate by at least two orders of magnitude. Therefore, for both the main soil saturated hydraulic conductivity and the dynamic layer saturated hydraulic conductivity, the range of the parameter will include typical values for un-compacted soils (Table 8.5) and two orders of magnitude beyond this. The range therefore will be from 1.0×10^{-2} m s^{-1} to 1.0×10^{-9} m s^{-1}. The porosity of a soil ranges from 0 (free draining) to 1 (no pores). Normal soils have a range from 0.395 (sand) to 0.482 (clay) (Table 8.5). Compaction has been shown to decrease the soil porosity. The range of porosities used in the sensitivity analysis is from 0 to 1. A full list of the range of soil parameters are given in Table 8.8.

Parameter	**Range**	**Number of Simulations**
K_{sat}	1.0×10^{-4} m s^{-1} to 1.0×10^{-9} m s^{-1}	37
D_{Ksat}	1.0×10^{-2} m s^{-1} to 1.0×10^{-9} m s^{-1}	25
D_{depth}	0.5 m to 1.0×10^{-6} m	32
D_b	0 to 16	25
A	0 to 100	12
B	0 to 100	12
φ	0 to 1	27
Soil Depth	-0.01% to -50%	31

Table 8.8 *Sensitivity analysis ranges for soil parameters*

To test the effects of soil compaction on the flow regime of Dacre Beck, soil parameter values were derived for different scenarios of the degree of soil compaction. The basis of these scenarios were from the data reported by Rauzi and Hanson (1966), shown in Table 8.7, for a lightly, moderately and heavily compacted soil. However, these values are for a different type of soil than the soil in the Dacre Beck sub-catchment. Therefore, the percentage changes to the bulk density were calculated (Table 8.9) and applied to the standard values for a loam soil, which is found in Dacre Beck. Soil bulk density and soil porosity are related through a negative linear relationship, meaning that percentage changes in both variables are the same, just the opposite sign. The standard soil porosity for a loam soil is 0.45 (Clapp and Hornburger, 1978). The soil porosity parameter value for CRUM3 is one minus this value, giving a soil porosity of 0.55. The effect of compaction on the soil bulk density, in percentage terms, was applied to this standard value of 0.55 giving a soil porosity of 0.515 and 0.492 for moderately and heavily compacted soils. The standard saturated hydraulic conductivity value for a loam soil is 6.95×10^{-6} and it is this value which is used for a lightly compacted soil. Williams *et al.,* (2004) used a change of two orders of magnitude to represent compaction. It was therefore decided that a heavily compacted soil would have a saturated hydraulic conductivity of 6.95×10^{-8} and a moderately compacted soil a value of 6.95×10^{-7}. In compacted soils it is the top few centimetres which experience the highest amounts of compaction. Therefore it was decided that the dynamic layer Ksat value would be lower than the main soil horizon value. A value of one order of magnitude lower was used. The soil depths were determined using the data collected by Rauzi and Hanson (1966) on the changes to the proportion of the soil volume taken up by pore spaces (Table 8.9). Compaction reduces the proportion of the soil that is air spaces, meaning that overall depth will be reduced. The standard values of 1.0 m, 0.5 m and 0.16 m for were used for the channel, floodplain/ridges and slopes soils respectively for the lightly compacted soil, as these were the depths used in the calibrated model for the Rye catchment in North Yorkshire (Lane *et al.,* 2009). Using the data from Rauzi and Hanson (1966), 10.6% of these depths is air space, i.e. 0.106 m, 0.053 m and 0.01696 m for the channel, floodplain/ridges and slopes soils respectively. These depths were then reduced by 21% and 27% for moderately and heavily compacted soils respectively, to calculate the depth of the soil of air space. These depths were then subtracted from the total depths to calculate the compacted soil depths. The same principle was applied to the dynamic layer depth. The soil parameter values for the lightly, moderately and heavily compacted soils are shown in Table 8.9. Several more compaction scenarios were derived by linearly interpolating between these scenarios, resulting in 17 compaction scenarios of varying degrees.

Compaction	**Porosity**	**Ksat**	**Root Ksat**	**Soil Depth**			
				Channel	**Ridge / plain**	**Slope**	**Dynamic Layer**
Light	0.55	6.95 × 10^{-4}	6.95 × 10^{-5}	1.0	0.5	0.16	0.01
Medium	0.515	6.95 × 10^{-5}	6.95 × 10^{-6}	0.978	0.489	0.156	0.00978
Heavy	0.492	6.95 × 10^{-6}	6.95 × 10^{-7}	0.971	0.485	0.155	0.00971

Table 8.9 *Model parameter values for different levels of compaction*

Scenario 2: Afforestation

Vegetation covers, like afforestation, affect the soil and vegetation characteristics. This land management scenario was tested through two approaches. First, a sensitivity analysis was carried out on the vegetation parameters. Second, scenarios of different land covers, like arable and pastoral agriculture and deciduous and coniferous woodland were tested using parameter values from the literature.

The vegetation cover parameters in CRUM3 are: (1) the interception depth, which controls how much water can be stored in the canopy; (2) the albedo, which controls the amount of radiation which is absorbed into the system; (3) the vegetation maximum height; and (4) the gap fraction, which controls the proportion of the canopy that is open.

Table 8.10 provides a summary of the simulations for testing the scenario of afforestation. The maximum height of the vegetation will range from grass (0.005 m) to trees (15 m). Albedo ranges from 0.05 to 0.33, using values for grassland and forest vegetation species, taken from Bruer *et al.* (2003). Interception capacity ranges from 0 m to 0.011 m, using values from Bruer *et al.* (2003) for different vegetation species. The gap fraction represents the coverage of the canopy and this ranges from 0 to 1.

Parameter	Range of Values	Number of Simulations
H_{max}	0.0 m to 15 m	28
a	0.05 to 0.33	23
I_d	0 m to 0.011 m	22
gap frac	0 to 1	15

Table 8.10 *Sensitivity analysis ranges for Land cover parameters*

The vegetation cover scenarios were determined from using parameter values from existing literature. This is an under-represented aspect of the hydrological modelling literature. There are hundreds of hydrological models used worldwide (O'Connell et al, 2004; Singh and Woolhiser, 2002), although relatively few have been applied the problem of the effect of land use on catchment scale flood hazard, and even fewer report the parameter values used to represent such scenarios. This makes constraining parameter values particularly difficult, especially as all models have different parameters. One of the important benefits of CRUM3 is that the parameters used within the model all have a physical meaning (Lane *et al.,* 2009) and therefore it is easier to find literature relating to them, either field-based studies or other modelling investigations. However, through calibration model parameters may lose their physical definition as they are changed to become effective parameters.

Land cover scenarios will be derived by changing the soil and vegetation parameters to ones that represent the characteristics of each land cover. The way this was done was to conceptualise how woodland differs from a grassland area in terms of its hydrological response. First, a literature review of the effects land cover has on river flows will be reported, focussing on how parameter values can be derived. Second, the specific methodology used within this thesis to test land cover changes will be outlined.

First, the soil characteristics differ, with woodland soils being free draining, due to the higher organic content. The effect of land cover change on soil bulk density is debatable, with the studies in Table 8.11 showing the magnitude of the change. Table 8.12 shows the percentage change of different land conversions on soil bulk density used by Bormann *et al.* (2007).

Authors	Land Use Change	Change in Bulk Density
Bauer and Black (1981)	Grassland to Crops	5-20% increase (depth dependent
Bewket and Stroosnijder (2003)	Forest to Crops	13% increase
Breuer et al., (2006)	Crops to Grassland	No significant changes
Bronson et al., (2004)	Grassland to Crops	3-21% increase (depth dependent)
Franzluebbers et al., (2000)	Grassland to Crops	3-17% increase (depth dependent)
Murty et al., (2002)	Forest to Grassland Forest to Crops	9.5% (± 2%) increase 17% (± 2%) increase
Neill et al., (1997)	Forest to Grassland	0-27% increase
Strebel et al., (1988)	Crops to Grassland	15% increase (upper soil layer)

Table 8.11 *Review of how land cover change effects soil bulk density (Bormann et al., 2007)*

Land Use Change	Change in Bulk Density
Crops to Grassland	6.5% decrease
Crops to Forest	15% decrease
Grassland to Crops	7% increase
Grassland to Forest	9% decrease
Forest to Crops	17% increase
Forest to Grassland	10% increase

Table 8.12 *Review of how land use type effects bulk density (Bormann et al., 2007)*

From these studies it is likely that afforestation will lead to a decrease in bulk density by between 9% and 15% depending on the original land cover. The impact on soil porosity can be calculated using the bulk density. Afforestation leads to a higher soil porosity.

Also soils in woodland are deeper than agricultural field, especially the dynamic root layer, as there is the leaf litter and high organic content. Bruer *et al.*, (2003) gave a list of maximum rooting depths for various vegetation types, which could be used for this parameter. The response to soil depth would be slow, as soil development operates on centennial timescales.

Vegetation characteristics also differ in forests compared with other land covers, with higher interception losses caused by greater storage capacities of trees. Breuer *et al.*, (2003) provide parameter values for interception capacities of different types of vegetation. The amount of interception is greater because there is greater coverage of the area, which will be represented in the model through decreasing the gap fraction parameter. The rate of evapotranspiration of woodland is higher than other land uses, with higher vegetation and lower albedo factors, meaning that less radiation is reflected.

The specific methodology used within this thesis will now be outlined. For the scenarios of vegetation cover, both soil and vegetation parameters were needed to be determined. The vegetation parameters were determined from Bruer et al., (2003). These were for plant species that are representative of the four main groups of land cover; (1) Arable = Maize and Wheat; (2) Pasture = Rye grass; (3) Deciduous trees = Oak and Beech; and (4) Coniferous woodland = Spruce, Fir and Pine.

Interception capacity or depth is defined as either the canopy capacity or the maximum amount of water left on the canopy after a storm event. There are fewer studies where the interception capacity of shorter species has been measured, but more data available for tree species. However, there is a lack of data for seasonal patterns including leafed and unleafed periods. The general trend is that deciduous trees have a lower interception capacity than lower growing species, as their structure is designed to allow throughfall and stemflow. However, there is no standard value for each species and therefore several values were taken from the range of literature values to represent whole range of each main land cover type.

The albedo of a surface represents the proportion of reflected to absorbed radiation. The general findings have concluded that pasture, arable and deciduous land covers have similar albedo values between 0.15 and 0.30, while coniferous trees have a lower albedo, with values lower than 0.14. This is because of the different canopy artitecture, with the spectral reflectance of leaves and needles differing considerably. However, there is no accounting for seasonal variations in the reflectance of leaves. The maximum height of different vegetation covers varies considerably over several metres, with pasture landscapes having the lowest vegetation, followed by arable. Woodland species are considerably higher, with the average height of forests being about 20 m. The gap fraction parameter represents the proportion of the canopy that is open i.e. 0.1 = 10% open. This is normally the lowest for forest land covers due the multi-layer structure of these landscapes. However, a range of gap fractions were considered as this variable is quite easy to change due it being influenced by the density of the planting.

How soil characteristics change under different land covers is far more uncertain, with very few field based or modelling based studies focussing on soil parameters. After an extensive search of the literature on this subject, it was decided to use data from Gonzalez-Sosa *et al.,* (2010), which used similar land cover categories and gave measurements for porosity and saturated hydraulic conductivity (Table 8.13).

	Porosity	**Saturated Hydraulic Conductivity (mm s^{-1})**
Permanent Pasture	0.63 (0.05)	0.51 (0.75)
Cultivated Pasture	0.52 (0.11)	0.11 (0.08)
Crops (wheat stubble)	0.47 (0.01)	0.28 (0.10)
Crops (bare soil after ploughing)	0.41 (0.10)	0.13 (0.21)
Broad leaf forest	0.74 (0.05)	1.32 (0.57)
Coniferous forest	(0.73 (0.05)	0.23 (0.15)

Table 8.13 *Soil characterisitics under different types of land cover from Gonzalez-Sosa et al., (2010)*

However, a problem with this study in terms of using the values for these parameters was that it used a catchment with a different soil type. Therefore, the percentage difference between the measured values for the different land covers and the standard value for the soil type was calculated. This percentage change was then applied to the specific soil type in the Dacre Beck sub-catchment (loam) (Table 8.14). Another limitation of the Gonzalez-Sosa et al., (2010) study was that the measured parameters were based on relatively small sample sizes, ranging from 21 to 3. However, as there so few studies reporting parameter values this was thought be an acceptable initial attempt at simulating land cover changes through changing vegetation and soil parameters in a hydrological model. The parameters used in this scenario testing of different land covers are detailed in Table 8.15.

	Porosity			**Saturated Hydraulic Conductivity (m s^{-1})**		
	1-Value	**% change from standard**	**Loam value**	**Original**	**% change from standard**	**Loam value**
Permanent Pasture	0.37	-34.5%	0.36	0.00051	1369%	0.000102
Cultivated Pasture	0.48	-15.0%	0.46	0.00011	217%	0.000022
Crops (wheat stubble)	0.53	-6.2%	0.52	0.00028	706%	0.000056
Crops (bare soil after ploughing)	0.59	4.4%	0.57	0.00013	274%	0.000026
Broad leaf forest	0.26	-54.0%	0.25	0.00132	3704%	0.000264
Coniferous forest	0.27	-52.2%	0.26	0.00023	563%	0.000046
Standard Sandy Loam	0.565			0.0000347		
Standard Loam	0.55			0.00000695		

Table 8.14. *Application of literature values to standard loam soil to derive soil parameters for Dacre Beck.*

	Plant Species	**Int Depth (m)**	**Albedo**	**Max Height (m)**	**Gap Frac (%)**	**Root Depth (m)**	**Ksat ($m\ s^{-1}$)**	**Dynamic Layer Ksat ($m\ s^{-1}$)**	**Porosity**	**Soil Depth (m)**			
										Channel	**Ridge/ Plain**	**Slopes**	**Dynamic Layer**
1	Maize	0.0014	0.20	3.0	0.5	0.9	1.02×10^{-4}	1.02×10^{-5}	0.54	1	0.5	0.16	0.01
2	Maize	0.0025	0.20	2.5	0.45	0.9	1.02×10^{-4}	1.02×10^{-5}	0.54	1	0.5	0.16	0.01
3	Maize	0.003	0.20	1.5	0.4	0.9	1.02×10^{-4}	1.02×10^{-5}	0.54	1	0.5	0.16	0.01
4	Maize	0.006	0.20	1.0	0.3	0.9	1.02×10^{-4}	1.02×10^{-5}	0.54	1	0.5	0.16	0.01
5	Maize	0.0025	0.20	2.5	0.45	0.9	1.02×10^{-4}	1.02×10^{-5}	0.54	0.978	0.489	0.15648	0.00978
6	Maize	0.0025	0.20	2.5	0.45	0.9	1.02×10^{-4}	1.02×10^{-5}	0.54	0.971	0.4855	0.15536	0.00971
7	Wheat	0.0021	0.17	0.6	0.7	0.5	1.02×10^{-4}	1.02×10^{-5}	0.54	1	0.5	0.16	0.01
8	Wheat	0.0021	0.17	1.0	0.5	0.5	1.02×10^{-4}	1.02×10^{-5}	0.54	1	0.5	0.16	0.01
9	Wheat	0.0021	0.17	1.5	0.4	0.5	1.02×10^{-4}	1.02×10^{-5}	0.54	1	0.5	0.16	0.01
10	Wheat	0.0021	0.17	1.5	0.3	0.5	1.02×10^{-4}	1.02×10^{-5}	0.54	1	0.5	0.16	0.01
11	Wheat	0.0021	0.17	1.5	0.2	0.5	1.02×10^{-4}	1.02×10^{-5}	0.54	1	0.5	0.16	0.01
12	Wheat	0.0021	0.17	1.5	0.4	0.5	1.02×10^{-4}	1.02×10^{-5}	0.54	0.978	0.489	0.15648	0.00978
13	Wheat	0.0021	0.17	1.5	0.4	0.5	1.02×10^{-4}	1.02×10^{-5}	0.54	0.971	0.4855	0.15536	0.00971
14	Rye	0.0028	0.19	0.1	0.6	0.1	5.61×10^{-5}	5.61×10^{-6}	0.36	1	0.5	0.16	0.01
15	Rye	0.0028	0.19	0.3	0.55	0.2	5.61×10^{-5}	5.61×10^{-6}	0.36	0.978	0.489	0.15648	0.00978
16	Rye	0.0028	0.19	0.5	0.5	0.3	5.61×10^{-5}	5.61×10^{-6}	0.36	0.971	0.4855	0.15536	0.00971
17	Rye	0.0028	0.19	0.1	0.6	0.1	2.60×10^{-5}	2.60×10^{-6}	0.46	1	0.5	0.16	0.01
18	Rye	0.0028	0.19	0.3	0.55	0.2	2.60×10^{-5}	2.60×10^{-6}	0.46	0.978	0.489	0.15648	0.00978
19	Rye	0.0028	0.19	0.5	0.5	0.3	2.60×10^{-5}	2.60×10^{-6}	0.46	0.971	0.4855	0.15536	0.00971
20	Oak	0.001	0.20	18.0	0.5	1.3	2.64×10^{-4}	2.64×10^{-5}	0.25	1.5	0.75	0.24	0.03
21	Oak	0.0013	0.20	18.0	0.3	5	2.64×10^{-4}	2.64×10^{-5}	0.25	1.5	0.75	0.24	0.03
22	Oak	0.0013	0.20	18.0	0.1	9	2.64×10^{-4}	2.64×10^{-5}	0.25	1.5	0.75	0.24	0.03
23	Beech	0.0006	0.23	4.0	0.5	0.6	2.64×10^{-4}	2.64×10^{-5}	0.25	1.5	0.75	0.24	0.03
24	Beech	0.001	0.23	7.0	0.4	1	2.64×10^{-4}	2.64×10^{-5}	0.25	1.5	0.75	0.24	0.03

25	Beech	0.0015	0.23	10.0	0.3	1.25	2.64×10^{-4}	2.64×10^{-5}	0.25	1.5	0.75	0.24	0.03
26	Beech	0.002	0.23	15.0	0.2	1.5	2.64×10^{-4}	2.64×10^{-5}	0.25	1.5	0.75	0.24	0.03
27	Beech	0.0026	0.23	20.0	0.1	3.4	2.64×10^{-4}	2.64×10^{-5}	0.25	1.5	0.75	0.24	0.03
28	Spruce	0.0003	0.05	10.0	0.5	2	4.61×10^{-5}	4.61×10^{-6}	0.26	1.3	0.625	0.2	0.02
29	Spruce	0.0007	0.05	20.0	0.2	6	4.61×10^{-5}	4.61×10^{-6}	0.26	1.3	0.625	0.2	0.02
30	Fir	0.0021	0.09	15.0	0.4	0.7	4.61×10^{-5}	4.61×10^{-6}	0.26	1.3	0.625	0.2	0.02
31	Fir	0.0024	0.09	15.0	0.3	3.2	4.61×10^{-5}	4.61×10^{-6}	0.26	1.3	0.625	0.2	0.02
32	Fir	0.0031	0.09	15.0	0.4	3.2	4.61×10^{-5}	4.61×10^{-6}	0.26	1.3	0.625	0.2	0.02
33	Fir	0.0016	0.09	15.0	0.5	3.2	4.61×10^{-5}	4.61×10^{-6}	0.26	1.3	0.625	0.2	0.02
34	Pine	0.0003	0.11	15.0	0.5	1.5	4.61×10^{-5}	4.61×10^{-6}	0.26	1.3	0.625	0.2	0.02
35	Pine	0.0006	0.11	15.0	0.3	2.5	4.61×10^{-5}	4.61×10^{-6}	0.26	1.3	0.625	0.2	0.02
36	Pine	0.0007	0.11	15.0	0.2	6	4.61×10^{-5}	4.61×10^{-6}	0.26	1.3	0.625	0.2	0.02

Table 8.15. *Vegetation and Soil parameter values for different plant species for different land cover types, including arable, pasture, deciduous woodland and coniferous woodland.*

8.4. Hydraulic Models

Hydraulic models are representations of water flow within the river channel, which route water along the modelled reach. All hydraulic models are based on the Navier-Stokes momentum equation and the mass continuity equation. Chapter 5 gave a more detailed explanation of hydraulic models. This section will outline how hydraulic models have been used in the past to test the impacts of channel modifications and detail how the scenarios of wet woodland, wetlands, floodplain roughness, and flood defence removal or setting back will be tested in this thesis. These scenarios either alter channel dimensions or planforms or how the river interacts with its floodplain.

8.4.1. Application of hydraulic models to investigate channel/floodplain change impacts on high flows.

Several studies have investigated the impact of land use change and channel modification on flood hazard downstream using hydraulic models. To date most studies used an one dimensional hydrodynamic model, although floodplains were often represented by storage units.

Acreman *et al.,* (2003) modelled the effects of floodplain restoration on flooding. This study used iSIS for a 5 km long reach of the River Cherwell. This consisted of channel changes such as narrowing to pre-engineered dimensions and changing the interaction between the channel and its floodplain through removing embankments. Historical maps were used to extract the pre-engineered topography, while LiDAR was used for the current cross sections. The model was calibrated through adjusting the Manning's n parameter and the effects of these scenarios were assessed for four flood events. It was found that restoring the channel to pre-engineered dimensions reduced the peak flow downstream by 10-16%. Embanking the channel increased the flood magnitude downstream by 52-153%. However, the local scale effect differed depending on where the changes were made, where both scenarios led to water stage increasing, by 0.30-0.47m for the channel restoration and 0.53-1.59m after introducing embankments. It was found that the restored channel delayed the timing of the peak flow by 3 to 17 hours, as the shallower channel reconnected the channel to the floodplain, while building embankments made the peak flow occur earlier by 33 to 47 hours. This showed that the role of the floodplain was important in terms of attenuating high flows.

Bronstert *et al.,* (2007) studied the effects of river training on flooding downstream, using the SOBEK model (WL Delft Hydraulics, 1997). Scenarios of change related to changes in the channel bed through altering channel cross sections and the longitudinal profile, and storage effects of polders or floodplain inundation. Landscape land use changes were also simulated through changing the lateral inputs from tributaries, by altering the hydrograph. The model was calibrated and achieved a goodness of fit of ±10-20cm for the peak flow. It was found that retention of water within polders resulted in a 1-15cm reduction in peak stage along the whole modelled reach of the Rhine. A further study by Chatterjee *et al.* (2008) and Forster *et al*. (2008) investigated the effects of emergency storage areas further, especially circumstances where the retention and release of water is controlled. The MIKE11 1D model was used to represent the channel, which was linked to the MIKE21 2D model to represent the polders using a 50m resolution DEM. This was compared to a simple 1D model, with two storage areas defined by elevation-volume relationships. Chatterjee *et al.* (2008) found that there was very little difference between the two models in the peak flow magnitude, but they differed considerably in terms of timing especially of the emptying of the polders, which took 4 days for the 1D-2D model and 24 days for the 1D model. Forster *et al.* (2008) showed the steepness of the hydrograph determined how effective polders were in terms of reducing peak flow magnitudes downstream.

Further to floodplain inundation attenuating flows, changing the land cover of the floodplain can change the amount of attenuation as the roughness changes with different vegetation covers. JBA Consulting (2006) tested several scenarios relating to this concept for the Long Preston Deeps floodplain on the River Ribble in North Yorkshire. These consisted of creating wet woodland/grassland of different areas and locations. Wet woodland increases floodplain roughness due to rigid trees and thick undergrowth, while wet grassland has a greater flow resistance than shorter grass (e.g. grazed/cut). This project used the iSIS model and found that changing floodplain roughness has the greatest effect on shallower overbank flows. However the effects of these scenarios seemed to have little impact on peak flows, with a reduction of only a few cumecs (2.6 m^3s^{-1}) and a time delay of about 15 minutes. To have a significant effect on high flows downstream the whole floodplain width would have to be converted. Other scenarios considered within this project were breaching embankments to couple the channel to its floodplain and narrowing bridges to increase the blockage effect on flows.

Thomas and Nisbet (2007) studied the effects of floodplain wet woodland in more detail and found greater impacts. They also compared the results from a 1D model (HEC-RAS) and a 2D model (River2D). Scenarios tested included the baseline existing situation to allow comparisons with future changes. Also land cover was changed to broadleaf woodland on one bank and across the whole floodplain for a 500m reach. Mannings n parameter values were altered to simulate these land cover vegetation effects, with values of 0.04, 0.035 and 0.15 used to represent the channel, pasture and woodland respectively. Results showed that water level was raised by a maximum of 270mm, while floodplain storage was increased by 71%. Water velocity through the altered reach decreased by 60-70%, while peak flow timing downstream was delayed by 140 minutes. The results from both the 1D and 2D models were similar.

Finally, as part of the Ripon multi-objective project the effect of land cover changes on flooding were investigated (JBA, 2007). However, this study also applied a novel technique of altering the routing of water from the tributaries to simulate changes in localised runoff. This was done in an iSIS framework and indicated that upstream land cover changes which affected localised runoff had been attenuated by the time the flows reached the downstream gauging station.

This section has showed that several land use change scenarios, both in the channel and on the floodplain can be tested using hydraulic models. Thomas and Nisbet (2007) showed that 1D models are suitable for this purpose and that the increased process representation of 2D models does not improve hydrograph reproduction. Therefore the 1D model iSIS-Flow will be used in this thesis to test the land use scenarios which were decided in Chapter 7, namely channel modification, wet woodland, wetlands, floodplain roughness, and flood defence removal or setting back. The Environment Agency has already constructed an iSIS model for the Eamont catchment and it is thought that this is a suitable starting point to test land use scenarios.

The 1D iSIS-Flow model is fit for the purpose of assessing the impact of upstream channel and floodplain roughness on downstream peak stage. Firstly, the focus of this investigation was on downstream effects, and 1D models represent the propagation of the flood wave well. The effects on the changes in floodplain inundation at the location where the changes are made are not the focus of this study. It is acknowledged that 1D models will not be able to represent the floodplain inundation and processes as well as 2D hydraulic models (Stoesser *et al.,* 2003). The representation of roughness in 1D models, Manning's n lumps together several resistance processes e.g. form roughness, turbulence, multi-dimensional flow processes, and it is important to consider this when the sensitivity of the model to Manning's n is assessed either through calibration or scenario testing. Secondly, Horritt and Bates, (2002) and Thomas and Nisbet (2007) have shown that 1D models can accurately simulate gauged hydrographs and the effects of floodplain roughness, albeit after model calibration. Therefore, the parameters are being used to compensate for lack of process representation, and not just parameterising the surface roughness as is required. However, these studies have shown that 1D hydraulic models can be calibrated adequately using hydrometric data, which is all that is available in the chosen sub-catchment. Horritt and Bates (2002) stated that 2D models should be used when floodplains are wide and have complex topography, which is not the case in this sub-catchment, as the topography is relatively flat and the valley quite constrained. Thirdly, an existing iSIS-Flow model existed for the Eamont/Lowther sub-catchment and could be used without the need for channel cross section survey or time consuming DEM pre-processing. Finally, it was appropriate that the same model was used throughout the whole thesis, which aided upscaling of the scenarios to the catchment scale, as the output from the sub-catchment model was in the same form as what was required as an input into the catchment scale Eden iSIS model that was outlined in Chapter 5.

8.4.2. How will the Channel/Floodplain scenarios be tested using iSIS-Flow?

The River Eamont/Lowther iSIS model will be used to simulate the scenarios of wet woodland, wetlands/washlands, floodplain roughness and flood defence removal or setting back. These affect the processes of channel conveyance and attenuation through modification of the channel cross section or the extent of floodplain-channel coupling.

This approach is not to test all possible scenarios and locations, but to use the co-produced knowledge reported in Chapter 7 to test feasible scenarios.

It is thought that the 1D hydraulic model is fit for purpose as the focus of the study is on the downstream effect on peak stage. Therefore, it is essential that the model reproduces the propagation of the flood wave accurately.

The removal or setting back of flood banks can be simulated by changing the cross sections of the desired reach. The height of the channel banks can be reduced to pre-engineered elevations. Alternatively the flood embankment profile can be set back from the river by increasing the distance between the river channel and the flood levee. These two scenarios will be accompanied by a floodplain storage area represented in the model by a reservoir unit connected to the channel by spill units.

This floodplain storage can consist of various features, including wetlands, washlands or wet woodland. These areas can consist of different size storage features, with different storage capacities. These reservoir units are connected to each other by floodplain sections which simulate floodplain conveyance. These units have a roughness parameter which can be varied to represent different land covers. Wetlands are commonly wide shallow storage features, with rough grassland management. The Thomas and Nisbet (2007) modelling study used the Manning's n value of 0.035 for pastoral land cover. Wet woodland is a more resistant land cover, as trees and dense undergrowth reduce floodplain conveyance. A Manning's n value of 0.15 has been used in the past to represent wet woodland (Acrement and Schneider, 1990; Thomas and Nisbet, 2007).

8.5 Chapter Summary

This chapter has outlined the modelling approaches that will be used to test the land management scenarios what were decided upon through stakeholder participation in Chapter 7. There are two types of model that will be used to test these different scenarios; hydrological and hydraulic. First, hydrological models were reviewed and the problems of non-linearity, scale, uniqueness, equifinality and uncertainty were addressed (Beven, 2001). The approaches of how these models were used to test land management scenarios were then detailed, with the parameter values representing soil and vegetation characteristics being altered to simulate land cover changes. It was noted that hydrological models have different complexities, but it was decided that physically based hydrological models were the most appropriate for testing land use change scenarios. Existing hydrological models were assessed and it was decided that CRUM3 (Connectivity of Runoff Model) would be used as it represents hydrological processes in a physically meaningful manner, with a minimal parameter set, which can be obtained from the literature for any UK catchment. The process representation of the model was outlined, with the Priestley-Taylor (1972) equation representing evapotranspiration and the simplified Green Ampt equation (Green and Ampt, 1911; Kirkby, 1975; 1985) representing infiltration. The catchment scale processes of hydrological connectivity and throughflow are also represented within the model. The approaches used to test the scenarios of compaction and afforestation were outlined, with the sensitivity to the infiltration parameters used to test the scenario of compaction, and a land cover with different characteristics used to test afforestation.

The next section outlined how hydraulic models could be used to test land management change scenarios. Then it was explained how the chosen model, iSIS-Flow would be used to test the scenarios of wetland/washland creation, wet woodland, flood bank removal/setting-back and channel naturalisation. The scenarios, which are modifications of the channel, can be simulated by changing the channel cross sections, while the scenarios which re-connect the channel to its floodplain can be represented by adding spill and reservoir units. The roughness of the floodplain sections could be used to simulate different ecosystems e.g. wetlands, wet woodland. The results of the scenario testing of the land use changes through using the models outlined in this chapter are given in Chapter 9.

Chapter 9

Testing of Land Management options

9.1. Chapter Scope

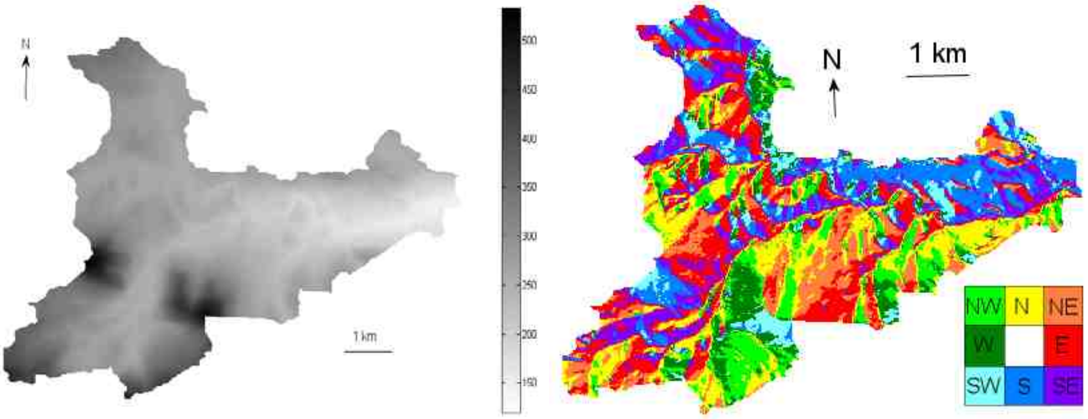
This chapter tests the hypothesis that land management changes impact peak flows. The scenarios to be tested were determined in Chapter 7 through stakeholder engagement, including possible locations to be tested. Chapter 8 outlined the modelling approaches used to test the land management scenarios, which can be divided into two main groups. First, landscape scale changes (Section 9.2), such as compaction (Section 9.2.2) and afforestation (Section 9.2.3) will be tested using a catchment scale, physically-based hydrological model, CRUM3. These scenarios will be tested in the Dacre Beck sub-catchment, as justified in Chapter 7. Second, channel scale changes (Section 9.3), including floodplain storage (Section 9.3.2) and channel and floodplain naturalisation (Section 9.3.3) scenarios will be tested in locations throughout the Eamont catchment using a hydraulic model, iSIS-Flow. The impacts of all these scenarios will be assessed at multiple spatial scales; (1) the reach scale; (2) the sub-catchment scale, (3) the Eamont catchment scale, and (4) the whole Eden catchment downstream at Carlisle, and for different geographical locations within the catchment.

9.2. Catchment Scale Landscape Changes

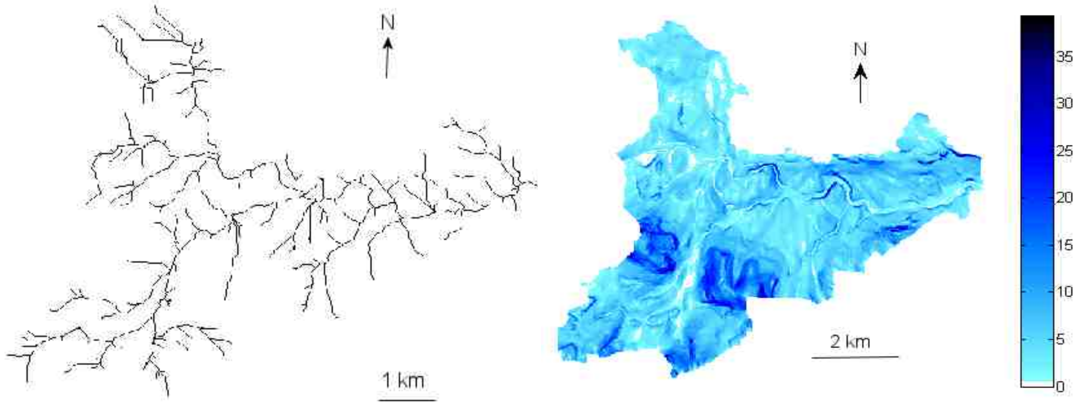
The landscape catchment scale changes of compaction and afforestation will be tested using the hydrological model, CRUM3, as outlined in Chapter 8. This section starts by outlining how the model, CRUM3, was applied to the Dacre Beck sub-catchment (Section 9.2.1). This is followed by analysis of sensitivity to the soil and land cover parameters, before testing the scenarios of compaction (Section 9.2.2) and afforestation (Section 9.2.3).

9.2.1. CRUM3 model development

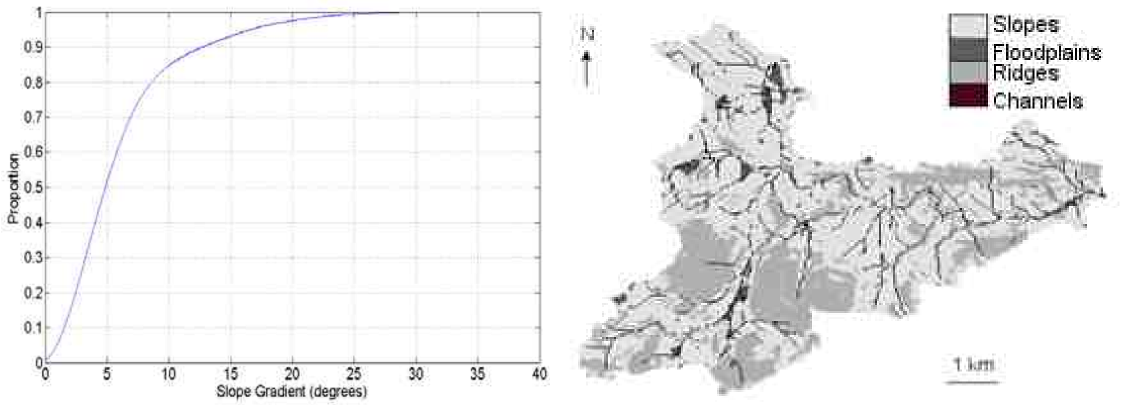
CRUM3 had to be developed for the Dacre Beck sub-catchment. The data needs for the model are the topography, from which the river network and other catchment characteristics can be derived, and climatic data, including daily rainfall totals and minimum and maximum temperatures, for use as boundary conditions. These data requirements will now be expanded upon and the process of model development will be explained. Figure 9.1 shows the digital elevation model (DEM) of Dacre Beck, which was acquired from NextMap. The DEM was resampled at 20m resolution, as it was thought this spatial resolution would capture field scale hydrological processes whilst still providing a reasonable run time for the model. A resampling scheme based on median of each cell was used, with the cells containing river channels using the channel elevation. The code for this resampling method was developed by Dr. Nick Odoni at Durham University, and included the pre-processing step of pit filling and preliminary channel definition. The relief of the Dacre Beck sub-catchment ranges from 550 m to 120 m AOD.



a) Digital Elevation Model (m) *b) Flow Direction*



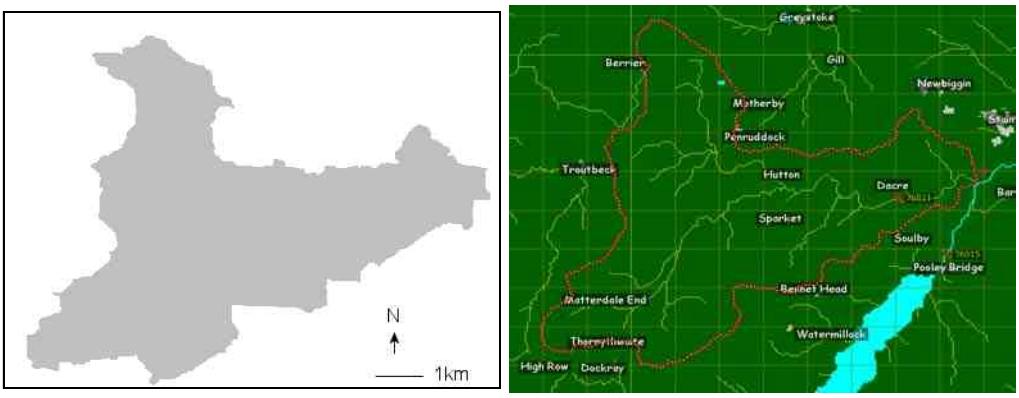
c) Channel Network *d) Slope gradients (°)*



e) Exceedance Plot of slope gradients *f) Topographic Classifications*

Figure 9.1 *Catchment characteristics for input into CRUM3 model*

The DEM was used to derive the flow direction of water flow throughout the catchment, using the FD8 flow algorithm (Quinn *et al.*, 1991) for diffuse hillslope flow and the D8 algorithm (Band, 1986) for channel flow. Figure 9.1b shows that flow in an easterly direction dominates. From this a flow routing algorithm was applied which defined the channel network. The criteria for defining a channel was that the discharge along a flow path should be greater than 0.02 m^3s^{-1} when a total of 0.05 m of rainfall is applied to the catchment in 24 hours. The channel network is shown in Figure 9.1c. The catchment boundary was then calculated by specifying the seed cell downstream and tracing the connected cells upslope. Figure 9.2a shows the catchment area produced by the code, while Figure 9.2b shows the actual catchment boundary from the Flood Estimation Handbook, which is calculated from a coarser (50 m resolution) DEM. The calculated catchment area is 37.90 km^2, which is very comparable to the actual contributing area of 37.98 km^2. The catchment shape is also very similar.

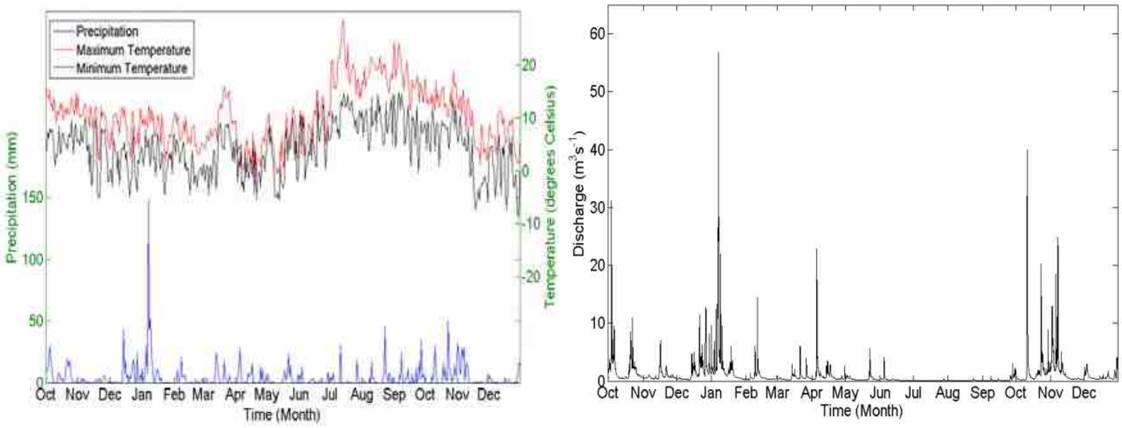


a) Modelled catchment outline *b) FEH catchment outline*

Figure 9.2 *Comparison of the catchment area from the modelling and FEH*

One of the data needs of CRUM3 are the landscape features, as parameters can be specified for different topographical features. These landscape classifications are made on the basis of slope. Figure 9.1d shows the slopes of each cell in the catchment, ranging from 0° to 39.4°. Figure 9.1e shows the probability exceedence plot of the slope distribution in the Dacre Beck sub-catchment, which was used to define the boundaries between topography features. Floodplains are defined as areas of the catchment with a slope less than 1°. Slopes were classified as the areas of slopes between 1° and 7°, with Ridges being defined as areas with a slope greater than 7°. Channels have already been defined by the flow routing algorithm. Figure 9.1f shows the spatial distribution of the different landscape features.

The other data requirement of the model is climatic data. These were extracted from the British Atmospheric Data Centre respository, using the Met Office MIDAS land surface observation stations. There is only one weather station in the Dacre Beck sub-catchment; Hutton Green Close Farm gauging station, which has a daily precipitation and temperature series extending from 2000 to present. The station has an elevation of 248 m, meaning it is in the lowland part of the Dacre Beck sub-catchment. Initial runs of the CRUM3 model found that discharges were significantly lower than the observed record. It was thought that this was caused by a rainfall series that was unrepresentative of the catchments rainfall. Therefore a nearby rain gauge at Shap was used instead, which is at a similar elevation (252 m) but records higher rainfall intensities and totals. For a catchment of this scale (36 km^2) it would have been preferable to use meteorological data on a 15 minute timestep, but data at this timescale were not available for gauges within the Eamont catchment. Section 8.3.1 showed how daily rainfall data can be downscaled to higher resolution data using a weather generator. This approach is not ideal, as the highest intensity events will probably be missed and the temporal correlation of the different data types will be incorrect, but is the only alternative when data is not available. Figure 9.3a shows the precipitation series for the modelled time period. A three month spin up period at the end of 2004, followed by a year of simulation (2005) was chosen. This was because 2005 included two main flood events, in January and October. The minimum and maximum daily temperatures for the same time period are also shown. Figure 9.3a shows that these two events were of similar magnitude in terms of the amount of precipitation, but Figure 9.3b shows that the January flood had a higher peak flow than the October event. This is probably due to antecedent soil moisture contents at different times of the year. Model simulations took between 8 hours and 3 days depending on the specification of the computer they ran on.



a) Meteorology Data *b) River Discharge data*

Figure 9.3 *Observed records for model input and validation for years 2004/2005*

<u>*Model Assessment*</u>

CRUM3 has previously been used in a hydrologically similar catchment, the Upper Rye in North Yorkshire (13.1 km^2) (Lane *et al,* 2009). The model was set up at the same resolution as for Dacre Beck, 20 m. This study concluded that CRUM3 captured "at least some of the elements of the landscape's hydrological response" (pp. 4), with a minimum Nash-Sutcliffe coefficient of 0.655, and a maximum Mean Absolute Error of 0.29 m^{3}s^{-1}.

In this thesis, CRUM3 was assessed by comparing the simulated and observed peak daily discharges. This is because the input rainfall data was at a daily resolution and then downscaled using a weather generator making within storm event comparisons unreliable: this weather generator randomly distributed rainfall throughout the day, meaning the timing of storm events was not accurate; and the model could not be expected to accurately predict the sub-daily hydrograph, but daily peak discharge might be expected to be more accurate. Figure 9.4a shows the comparison of the observed and simulated peak daily discharges for 2005. Overall, the performance of the model over the whole range of flows means that the model is fit for purpose. Model performance is better for the higher flows, which are the focus of this thesis. The accuracy of the model in predicting medium and low flows is not ideal but this will be taken into account when interpreting flow duration curves and low flow impacts. This is most likely due to the baseflow recession being poorly simulated due to the limited groundwater representation within the CRUM3 model. The Nash-Sutcliffe coefficient for the whole year is 0.31, with a mean deviation of -1.6 m^3s^{-1}, and an RMSE of 4.7 m^3s^{-1} (Table 9.1). However, from Figure 9.4a it is clear that the model performs much better in certain periods than others. The October flood is poorly simulated, with the largest events being missed and others being of much lower magnitude. This is likely to be caused by the rainfall input being not high enough to stimulate a hydrological response. Figure 9.3a shows that the rainfall for October is not higher than other months. This is caused by rainfall being highly spatially variable such that using a rain gauge from an adjacent sub-catchment may not be appropriate to accurately reproduce the observed hydrograph. This highlights the problem of the lack of data in complex catchments, making physically based hydrological modelling difficult. However, the January 2005 flood (Figure 9.4b), which has been the focus of this thesis, is simulated quite well, with an error of only -0.73% in the magnitude. The Nash-Sutcliffe coefficient for the month of January is 0.65, and improves to 0.74 around the 10 days of the flood. This shows that the performance of the model is good for flood events when the measured rainfall input is high enough to cause such a hydrological response. Other sources of uncertainty and error may be the soil hydrological response to this rainfall input.

The hydrological model has not been calibrated, meaning that the performance is not optimised. This has both benefits and limitations for investigating the impact of land management scenarios on flooding. As no calibration has taken place, the parameters in the model have a physical meaning and are not “effective parameters”. This takes the representation of changes more feasible in the model. However, the accuracy of the results could be improved. As stated, the performance for the January 2005 flood is good, and this event is the focus of the analysis. Therefore, more confidence can be taken for this event. Furthermore, the results for the hydrological processes, especially the soil moisture contents, match theoretical links between land management and flooding. This increases the level of confidence we can have in the results. The main factor limiting model performance is using a homogeneous land cover and not knowing what the current land management practices are throughout the catchment. It cannot be expected that the model simulation matches the observed record, if the parameterisation of the model is not for the current baseline conditions. However, the scenario which matches best with the observed record gives some indication of the current management of the catchment in terms of compaction levels and land cover. In the case of compaction, a scenario between light and moderate compaction fits the observed data best. As validation has proved difficult, it is important to investigate the sensitivity of the model output carefully. This is done in the following sections.

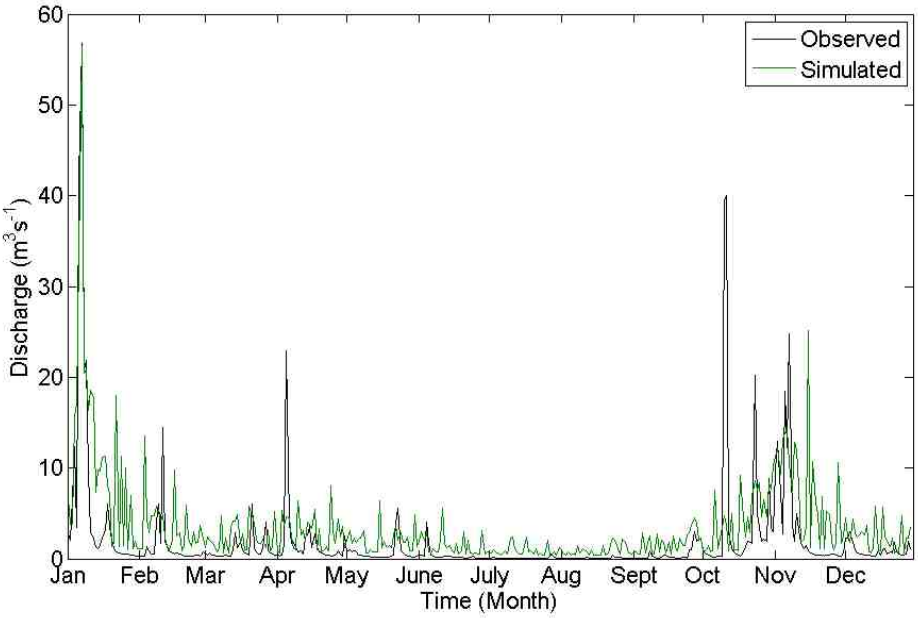


Figure 9.4a *Validation of CRUM3 for the year 2005, comparing simulated and observed discharges at Dacre Bridge*

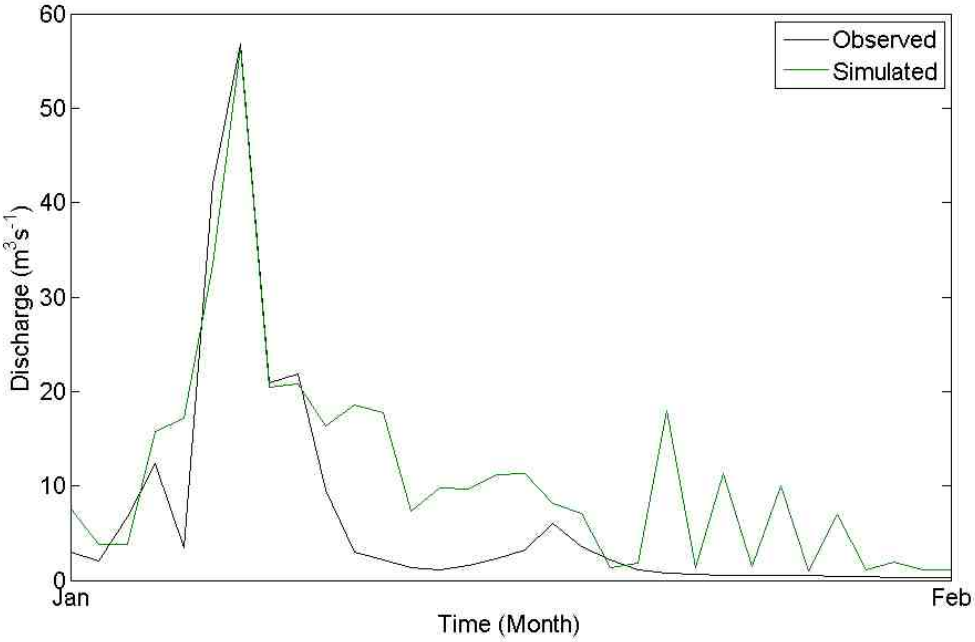


Figure 9.4b *Validation of CRUM3 for the month January 2005, comparing simulated and observed discharges at Dacre Bridge*

	2005	**January 2005**	**3^{rd}-13^{th} January 2005**
Mean Deviation (m^3s^{-1})	-1.58	-0.39	-0.13
Nash-Sutcliffe	0.31	0.65	0.74
Peak Magnitude Error (%)	-0.73	-0.73	-0.73
Peak Timing Error (%)	0	0	0
RMSE (m^3s^{-1})	4.66	2.18	1.53

Table 9.1. *Validation model assessment statistics for CRUM3 for different time periods*

9.2.2. Effect of soil compaction

Compaction affects soil characteristics. This land management scenario was tested through two approaches. First, a sensitivity analysis was carried out on the soil parameters. Second, scenarios of light, moderate and heavy compaction were used using parameter values from the literature.

<u>*Sensitivity Analysis*</u>

Saturated hydraulic conductivity (Ksat) controls the rate at which water passes through the soil. Values for typical soils range from 1.76 $\times10^{-4}$ m s^{-1} for sand to 1.28 $\times10^{-6}$ m s^{-1} for clay (Clapp and Hornburger, 1978). A range of 1.0 $\times10^{-3}$ m s^{-1} to 1.0

×10^{-9} m s^{-1} was included in the sensitivity analysis to cover the whole range of typical values for normal and compacted soils. The results of this sensitivity analysis are shown in Figure 9.5a. Percentage changes are expressed from a baseline of 4.2 ×10^{-4}, which was the calibrated value for a hydrologically similar catchment, the Upper Rye in North Yorkshire (13.1 km^2) (Lane *et al,* 2009). The catchment characteristics shown in Table 9.2 indicate that the Rye and Dacre Beck catchments are similar enough for the Rye parameters to be a suitable baseline and starting point (FEH, 1999).

	River Rye	Dacre Beck
Area (km^2)	131.7	36.0
Maximum Elevation (m)	450	550
SAAR (Average annual rainfall)	882	1428
BFIHOST (Baseflow index by HOST soil type)	0.422	0.457
SPRHOST (Standard % Runoff by HOST soil type)	43.1	36.5
PROPWET (Proportion of time when Soil Moisture Deficit <6mm)	0.34	0.64
FARL (Index of attenuation by lakes)	0.998	0.999
DPLBAR (Mean distance between nodes on IHDTM grid and catchment outlet)	11.54	9.16
DPSBAR (Mean of inter-nodal slopes)	145.45	100.2
URBEXT (Extent of Urban land cover)	0.0007	0.0005

Table 9.2 *Comparison of the characteristics of the Rye and Dacre Beck catchments*

Figure 9.5a indicates that the peak discharge is highly sensitive to this parameter. However, over the typical range of soil Ksat values (1.0 ×10^{-4} m s^{-1} - 1.0 ×10^{-6} m s^{-1}) the sensitivity is lower. There is a critical turning point in Figure 9.5a at 2.0 ×10^{-4} m s^{-1}, which has the lowest peak flow for any of the saturated hydraulic conductivity values. The value of this turning point is not accurate as the model has not been calibrated, but it is this point that would be the optimum to achieve and its specific value will differ for different catchments. However, it is significant that there is a turning point in the value of this parameter, meaning that that both really high and really low Ksat values produce higher peak flows. Beyond this turning point as Ksat decreases, the peak discharge in Dacre Beck increases. At Ksat values of 1.0 ×10^{-6} m s^{-1}, this effect diminishes and no further decreases in Ksat effect peak discharge. The Ksat parameter controls the ease of water transfer through the soil, which becomes slower at lower Ksat values leading to higher soil moisture contents. Therefore less precipitation infiltrates into the soil and there is faster and a greater quantity of surface runoff leading to higher river flows downstream.

The parameters which control the rate of infiltration are the Green-Ampt A and B parameters (Green and Ampt, 1911; Kirkby, 1975; Kirkby, 1985). This is the process by which precipitation enters the soil. Figure 9.5b shows the sensitivity of peak discharge to changes in these parameters, which influence the rate of infiltration in a co-dependent manner. Peak discharge is insensitive to changes in both the Green-Ampt A and B parameters, with the maximum change being a 1.2% decrease of peak discharge from the baseline simulation.

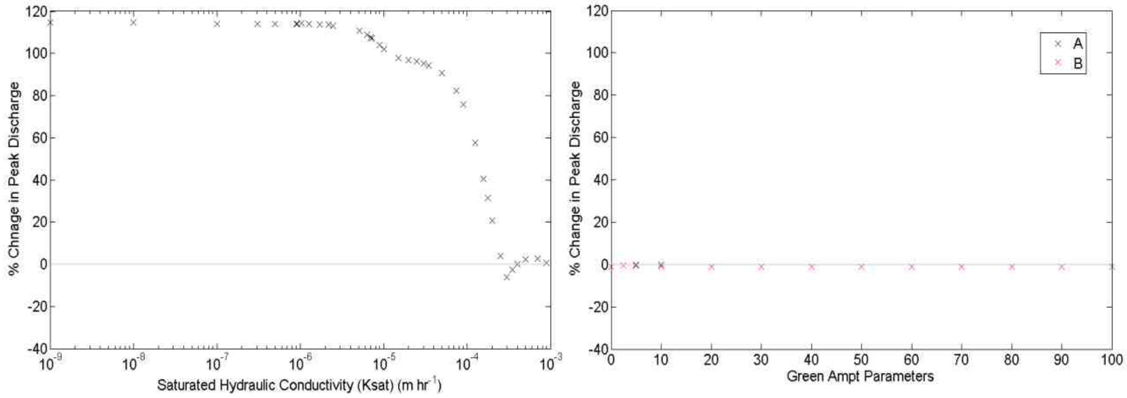
Figure 9.5c shows the sensitivity of peak discharge to changes in soil porosity. Soil Porosity varies on a scale of 0 to 1. The model represents soil porosity by deriving an effective storage depth of water from multiplying the porosity parameter by the soil depth. Furthermore, CRUM3 represents porosity in the opposite direction to the reported values in the literature, where in the model a porosity of 0 has no air space and a porosity of 1 has all air space. Therefore reported literature values have to be subtracted from 1 to derive the opposite proportion and the soil porosity for input in the model. Model output (peak discharge) is highly sensitive to changes in the soil porosity parameter, with decreases in porosity resulting in the peak discharge increasing. This is because lower soil porosities have less pore space for water to be stored in. This is represented in CRUM3 by the lower effective storage depths of soils with lower soil porosities. The effect of changing the soil porosity from 0.9 to 0.5 is to increase peak flow magnitude by approximately 35%. However, in the range of typical porosity values for soils (0.3-0.6) sensitivity is lower. Soil porosities lower than 0.3 also have a significant impact on peak discharges, with an even steeper gradient than the higher porosities. A soil porosity of 0.1 produces a peak discharge that is 92% higher than the baseline porosity of 0.45.

Figure 9.5d shows the sensitivity of the sub-catchment peak discharge to the soil depth. Soil depth is an important parameter as it controls the storage capacity of the soil. The model sensitivity to soil depth was tested by changing all four depths by a constant percentage change. The results indicate that the peak discharge is sensitive to changes in soil depth, but not to the same extent as previous parameters. A 50% change in the soil depth results in a peak discharge 9.5% higher than the original baseline soil depths. Peak discharge is linearly related to percentage changes in soil depth.

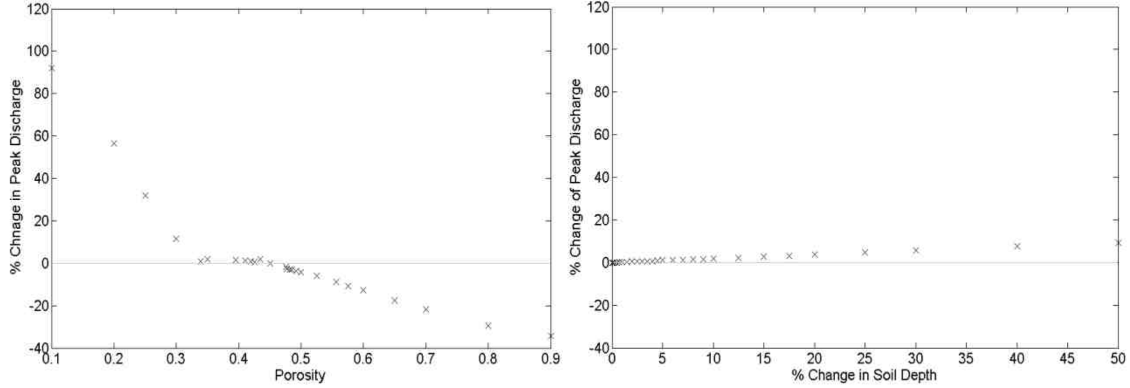
The saturated hydraulic conductivity of the dynamic layer controls the ease at which water is transferred through that horizon. The storage capacity of the dynamic layer is controlled by its depth. The importance of the dynamic layer was assessed through the sensitivity of the peak discharge to the dynamic layers depth and saturated hydraulic conductivity. Figure 9.5e shows that peak discharge is highly sensitive to changes in the saturated hydraulic conductivity of the dynamic layer. Dynamic layer Ksat values higher than 1.0×10^{-4} m s^{-1} have little impact on peak discharge. Decreasing the saturated hydraulic conductivity between 1.0×10^{-4} m s^{-1} and 1.0×10^{-6} m s^{-1} results in a slight increase in peak discharge of 12%. The saturated hydraulic conductivity of 1.0×10^{-6} m s^{-1} is a turning point in the graph, as between 1.0×10^{-6} m s^{-1} and 1.0×10^{-8} m s^{-1} peak discharge increases considerably by 110%. The important implication of this result is that the range of Ksat values where peak discharge is most sensitive (1.0×10^{-4} m s^{-1} to 1.0×10^{-8} m s^{-1}) is also the range of values for typical soils.

The peak discharge is also highly sensitive to the depth of the dynamic layer (Figure 9.5f). In scenarios when the depth is greater than 0.01 m, the sensitivity of the model output is low, with changes in depth only resulting in small increases (<2%) of peak discharges. Dynamic layer depths between 0.01 m and 0.001 m result in a rise in peak discharge of up to 14%. Between 0.001 m and 0.0003 m model sensitivity is low with a slight decrease down to an 8% change. Depths smaller than 0.0003 m result in significantly higher peak flows, with a depth of 0.00001 m experiencing a peak flow 110% higher than the baseline. This is because smaller dynamic layer depths mean that there is a lower storage capacity and the dynamic layer becomes saturated more quickly resulting in more overland flow.

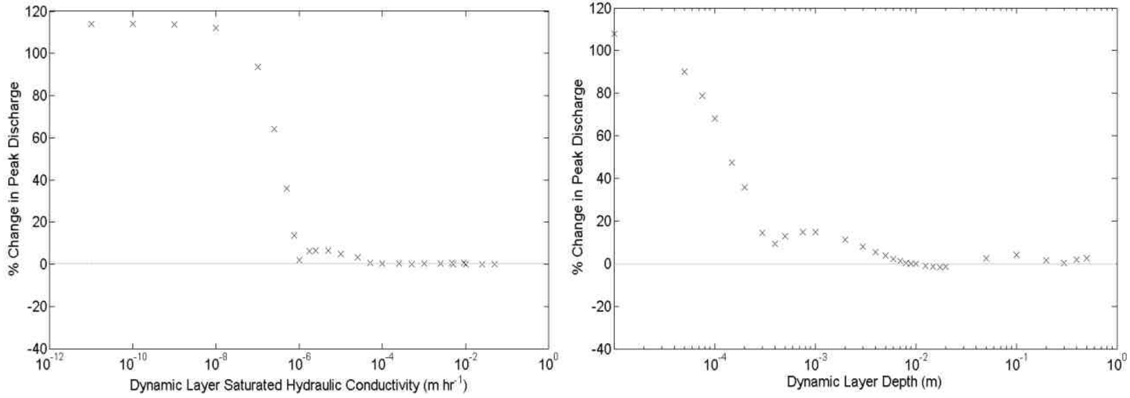
The dynamic layer b parameter which represents the pore size distribution in the dynamic layer, allows the porosity of the upper layer of the soil to be different to the main soil horizon. However, sensitivity analysis of this parameter has shown that sub-catchment peak discharge is insensitive to changes in the b parameters value (Figure 9.5g). Using a range of 0 to 16 (4x the baseline value) results in only a maximum of -1.0% change in the peak discharge.



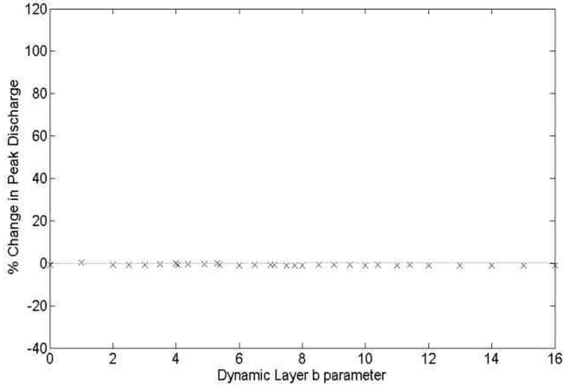
a) Saturated Hydraulic Conductivity *b) Green Ampt A and B*



c) Porosity *d) Soil Depth*



e) Dynamic Layer Ksat *f) Dynamic Layer Depth*



g) Dynamic Layer b

Figure 9.5 *Sensitivity of peak discharges to the soil parameters in CRUM3.*

The most sensitive parameters are the saturated hydraulic conductivity and soil porosity of the main soil layer and the saturated hydraulic conductivity and depth of the dynamic layer. Model output is fairly sensitive to the main soil layer depth. Model output is insensitive to the Green-Ampt A and B parameters and the dynamic layer b parameter. This indicates that changing the soil characteristics has an impact on flood hazard at the Dacre Beck sub-catchment scale, when the whole sub-catchment is managed in the same manner. To determine the importance of each parameter in influencing flows in Dacre Beck, the soil type and characteristics of this specific area need to be taken into account. However, often through model calibration sensitive parameters need to be changed, meaning they lose their physical meaning and become effective parameters. The soil type in Dacre Beck is predominantly loam. Standard values in the literature (Clapp and Hornburger, 1978) are shown in Table 8.5. A loam soil has a saturated hydraulic conductivity of 6.95×10^{-6} m s^{-1}. Figure 9.5a suggests that the peak discharge is not very sensitive to changes in the saturated hydraulic conductivity at this standard value. This is probably because the movement of water through the soil is already restricted, meaning that further decreases have little effect on peak flow. However, small increases in saturated hydraulic conductivity can result in smaller peak flows (e.g. changing Ksat by an order of magnitude can reduce peak flow by 11%). The sensitivity of the peak discharge to the dynamic layer Ksat value (Figure 9.5e) suggests that around the range of values for loam soils peak discharge is highly sensitive to changes in dynamic layer Ksat. It is this parameter which has been identified as the most sensitive parameter, especially in the range of loam soils. A loam soil has a soil porosity of 0.451 (standard deviation = 0.078). Therefore, the soil porosity parameter in CRUM3 is 0.55 (1 - 0.45). Figure 9.5c shows that the peak discharge is sensitive to the porosity parameter around this standard value, suggesting the soil porosity of the soils in Dacre Beck are important in effecting peak discharge, and that management to change the porosity by practically feasible amounts could result in significant changes in peak discharge. The effectiveness of rural land management changes on flood hazard depends on the soil, vegetation and topographic characteristics of the area. Land use changes will be most effective in areas where river discharge and surface runoff are highly sensitive to the soil-vegetation-topography complex.

The following part of this section will outline the results from compaction scenario testing. The main variable of interest is the discharge at Dacre Bridge, where there is a gauging station. Figure 9.6 shows a visual comparison of the three compaction scenarios of light, moderate and heavy levels of compaction. Parameter sets were chosen to represent each scenario from the literature as explained in Section 8.3.2 and all results presented here are dependent upon each scenarios location in the parameter space. It is important to note here that all the landscape scale scenarios tested in this chapter were tested for a homogeneous sub-catchment scale change. It is unlikely that managing the whole sub-catchment in the same manner would be possible, but it was thought an initial step in determining the link between land cover and high flows would be to see if a catchment wide change could have an effect. Further work could explore how much of the catchment needs to be changed to see the desired effect and also locations where changes should be made. Results indicate that the observed hydrograph is between the low and moderate compaction scenarios, suggesting that reducing compaction in the sub-catchment does have potential to reduced sub-catchment scale flood magnitude.

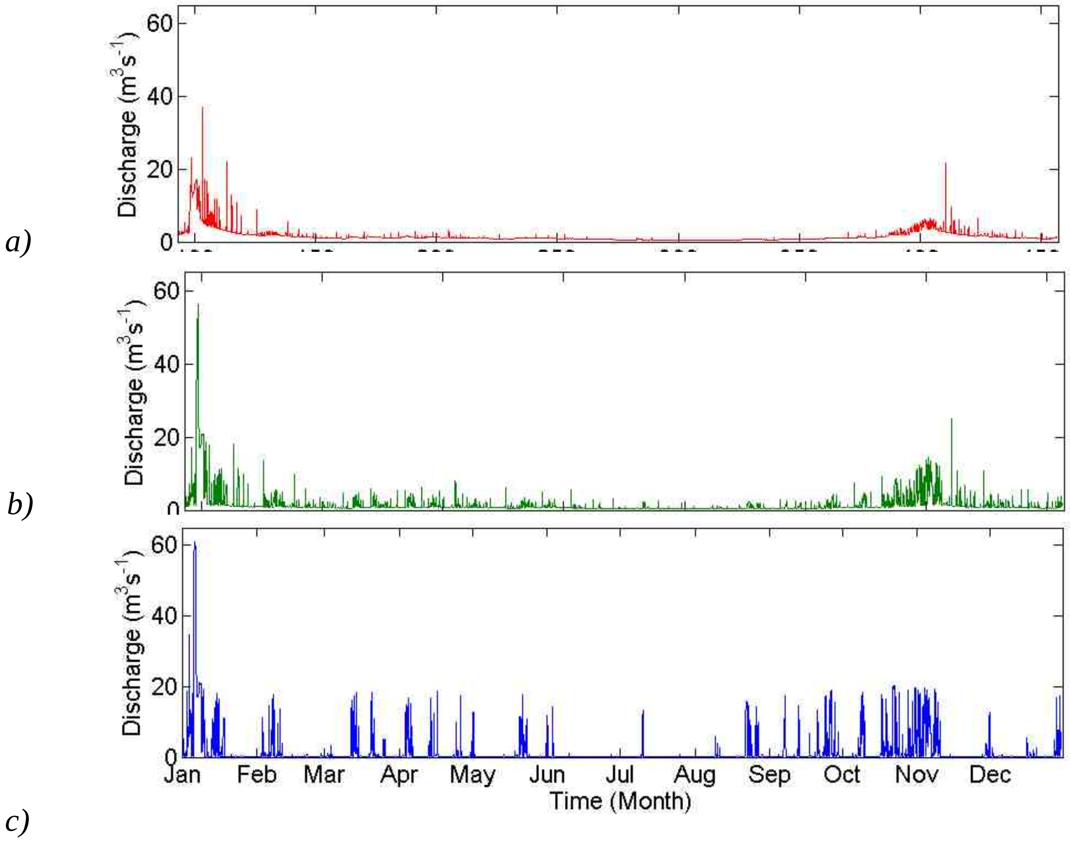
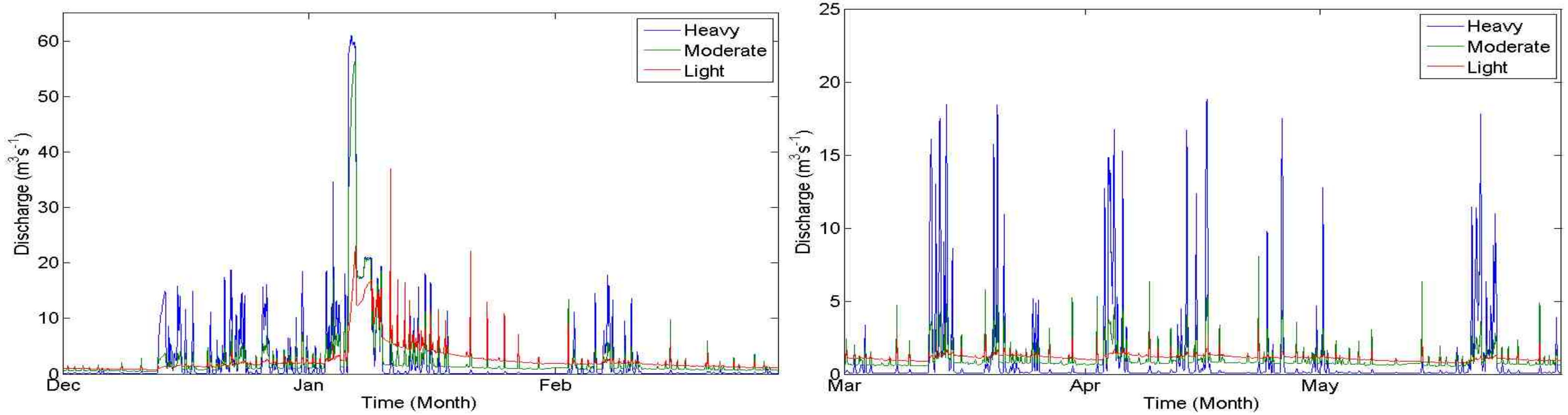


Figure 9.6 *Comparison of simulated light (a), moderate (b) and heavy (c) compaction scenarios.*

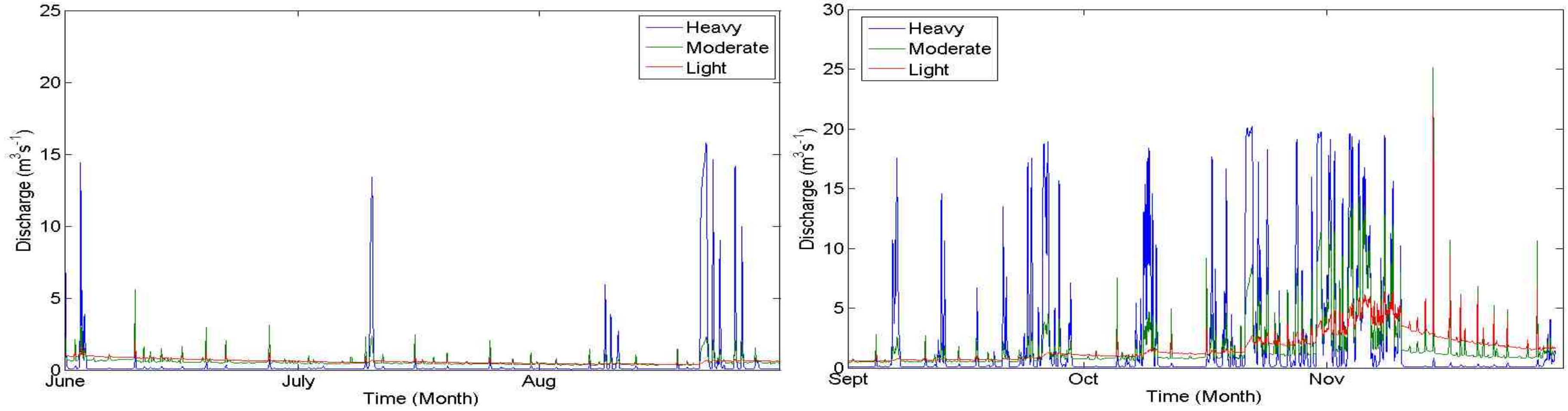
Seasonal Flows

Figure 9.7 divides the year into seasons (starting with winter as the December of 2004, January and February of 2005). The most notable event in the winter (a) was the January 2005 flood. As compaction level increases, maximum peak flow magnitude also increases. The simulated peak flows were 36.9 m^3s^{-1}, 58.7 m^3s^{-1} and 60.9 m^3s^{-1} for the light, moderate and heavy compaction scenarios respectively. Furthermore, the peak becomes longer in duration and the rising limb begins earlier. This suggests that heavily compacted soils result in more rapid runoff and therefore rivers peak earlier. Another significant difference between the effects of compaction scenarios on sub-catchment scale discharge is that there is a more flashy response of the more heavily compacted catchment, with a greater number of peaks and peaks with a higher magnitude. Higher peaks for the heavy compacted scenario occur earlier in the season, while for the moderately and lightly compacted scenarios there are peaks later in the season (around Day 100-130). The flows resulting from the different compaction scenarios in Spring (b) vary considerably. There are six main periods of high flow events, each over a couple of days. For the light compaction scenario, these peaks are barely visible as peaks, while for the scenario of moderate compaction these events have a magnitude of about 5 m^3s^{-1}. However for the heavily compacted catchment scenario these flood peaks are significantly higher at around 15-20 m^3s^{-1}. The difference between the heavy and moderate compaction scenario for the extreme January 2005 flood was not large, but for these lower magnitude high flow events the difference seems to be more important. Low flows occur in rivers during the Summer, and this is the main signal in the simulated discharge hydrograph for Dacre Beck (c). The highest levels of compaction result in the lowest flows. Therefore as compaction levels increase, the low flow magnitude decreases. However, the highest level of compaction also results in a few summer high flow events of approximately 15 m^3s^{-1} in magnitude. Moderate levels of compaction does result in some peaks but much lower in magnitude, while low levels of compaction does not produce any summer high flows. The trends seen in Autumn (d) are similar to the ones seen in Spring. Furthermore the occurrence of high flows in the first part of the season for the heavily compacted catchment and high flows in the latter part of the season for the moderate and light scenarios.



a) Winter (Dec 04, Jan, Feb 05)

b) Spring (Mar-May 05)



c) Summer (June-Aug 05)

d) Autumn (Sep-Nov 05)

Figure 9.7 *Seasonal discharges for the light, moderate and heavy compaction scenarios*

Summary Statistics

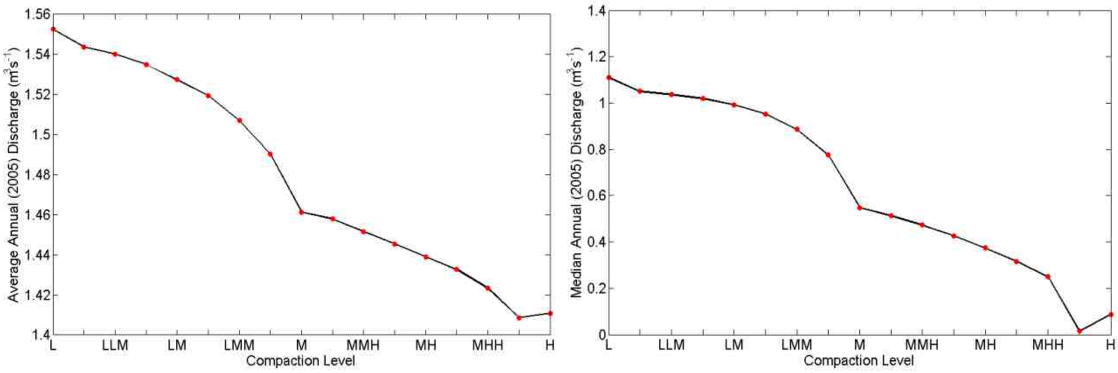
More detail on the effects of compaction can be discovered by looking at the whole continuum of the 17 model simulations. These ranged from light to heavy compaction, with the other scenarios being linearly interpolated between the two extremes. The descriptive statistics are shown in Figure 9.8. The average discharge decreases by 9.1% (0.1 m^3s^{-1}) from lightly compacted soils to heavily compacted soils. This is an unexpected result, as it was expected that increasing compaction would increase discharge. However, as has already been highlighted lower flows decrease. Lower flows are more frequent than the occasional flood event. Therefore the annual signal of runoff is dominated by the longer duration non-extreme flows, which have been shown to decrease, meaning that the change to lower flows dominates the annual signal, resulting in the mean discharge decreasing. The trend between compaction and mean discharge is linear, with the decline from light to moderate compaction being slightly greater than from moderate to heavy. This suggests that any amount of compaction decreases mean flows, and as compaction level increases the effect on mean flows decreases. The same trend is seen on the median flows, whereby as compaction increases, median flows decreases by more than 92%. Furthermore, median flows are lower than mean flows, due to the higher frequency of lower flows.

This thesis is most interested in the extreme flows, both high (floods) and low (droughts) discharges. Figure 9.8c shows the effect of compaction on peak flows, for the January 2005 flood event. This shows that as compaction level increases, peak flows increase considerably from 36.9 m^3s^{-1} to 58.7 m^3s^{-1} and 60.9 m^3s^{-1} for light, moderate and heavy compaction scenarios respectively. From a lightly compacted catchment to a heavily compacted catchment, peak discharge increases by 24 m^3s^{-1} (65%). The effect of going from a moderately compacted landscape to a heavily compacted catchment is not significant, with an increase of only 3.7% (2.2 m^3s^{-1}). There is a rapid increase in the peak discharge between the light-moderate (LM) scenario and the moderate (M) compaction scenario. It was expected that compaction would increase peak flows. Sullivan *et al.,* (2004) found that a 43% increase in stocking density, resulted in a 8.7% increase in median mean daily flows for the De

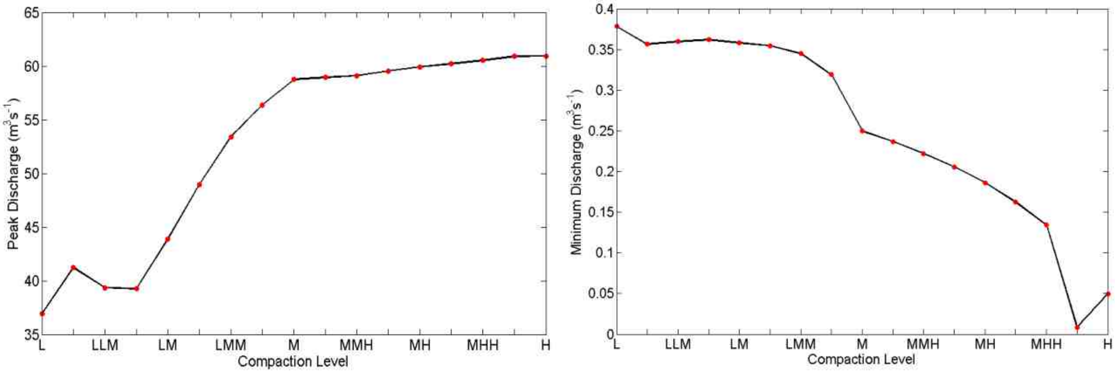
Lank river in Cornwall. A modelling study by Bulygina *et al.,* (2009; 2010) used regionalisation techniques of the Curve Number (CN) and Baseflow Index (BFI) to simulate the effects of compaction in the Pontbren and Hodder catchments. It was found that the median peak flow increased by 8% and 11% respectively when each catchment becomes heavily grazed. Compacted soils mean that precipitation is partitioned into surface flows rather than sub-surface flows (Holman *et al*., 2003, Lane *et al.,* 2007). The rate of water transfer is different in these two pathways, with overland flow being considerably faster than throughflow. This means that compacted soils lead to a greater proportion of the precipitation being delivered to the channel faster than for uncompacted soils. Evidence for this explanation comes from the proportion of runoff occurring through these two routes. A greater proportion of the runoff occurs as overland flows rather than throughflow (Figure 9.9b/c). The difference between lightly compacted soils and heavily compacted soils is large, with 74% of runoff occurring as throughflow for lightly compacted soils and only 1.8% for heavily compacted soils. This means that in heavily compacted soils nearly all runoff occurs as surface overland flow.

Figure 9.8d shows the effect of compaction on the minimum discharge throughout the year. It shows that as compaction increases, the lowest flow decreases. There is an 86.8% (0.3 m^3s^{-1}) decrease in the lowest flow between the light and heavy compaction scenarios. Heavily compacted soils prevent throughflow of water through the soil layers, meaning that baseflow is reduced. Lightly compacted soils have the highest low flows as throughflow occurs and maintains baseflow at a higher discharge. Sansom (1999) studied the effects of overgrazing on both flow extremes and found that both floods and low flows became more frequent and severe. Over a 13 year period there was a 40% increase in stocking density in the Yorkshire Dales. This period coincided with 4 large floods and very low flows in summer months. The impact of increasing the proportion of bare ground is thought to have increased runoff rates and reduced soil water storage capacity.

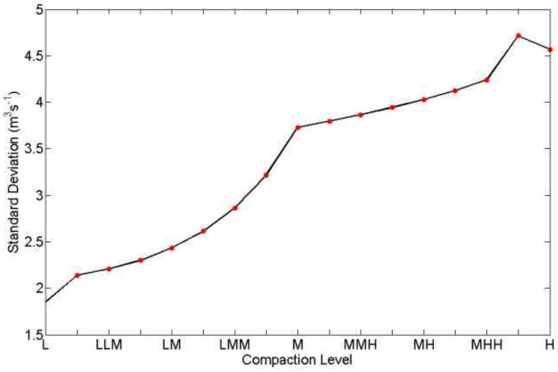
The final aspect of how compaction changes annual flows is the variability of flows over the year. Figure 9.8e shows that as compaction levels increase, the river flow magnitude becomes more variable, with a higher standard deviation which increases by 59.5%. This is a logical result if the flow extremes are becoming more extreme for heavily compacted soils.



a) Mean *b) Median*



c) Maximum *d) Minimum*

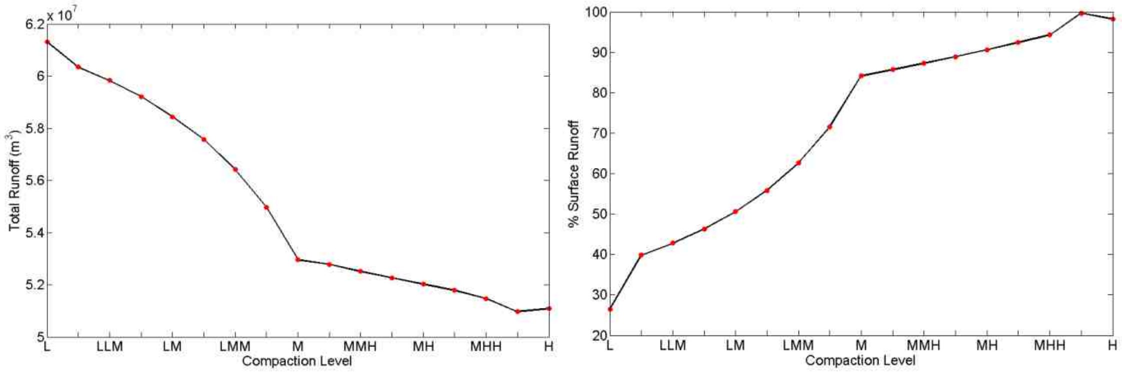


e) Standard Deviation

Figure 9.8 *Descriptive statistics for discharge simulated by continuum of compaction scenarios (where L = Light, M = Moderate, and H = Heavy compaction, and the rest are linearly interpolated e.g. LLM = Light Light Moderate)*

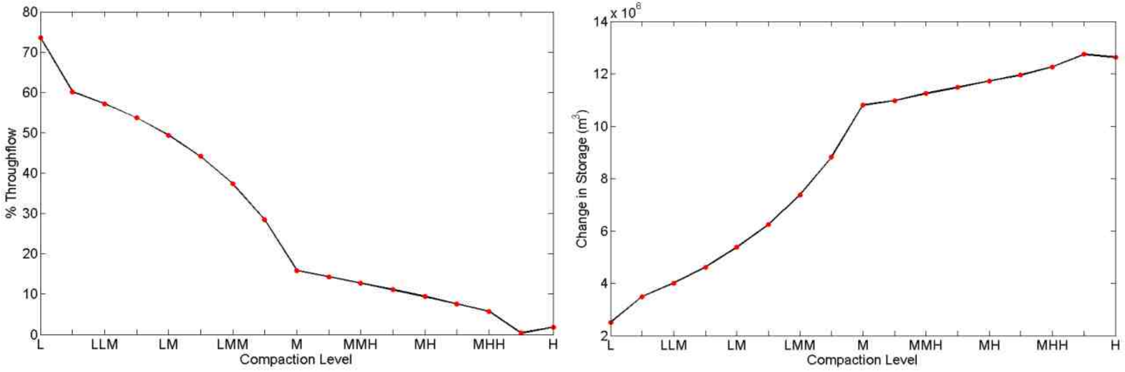
Effect of Compaction on Hydrological Processes

It is important to interpret these results for river discharge in terms of the hydrological processes which compaction may affect. Compaction decreases the amount of total runoff by 17% from the light compaction scenario to the heavily compacted soil scenario (Figure 9.9a). This is because the annual signal is highly affected by the more frequent low flows. Increased compaction increases the proportion of that runoff which occurs as surface overland runoff to the channel by 71.8% (from 26.4% for light compaction to 98.2% for heavy compaction) (Figure 9.9b/c). A comparison of this result with the field based study on which the parameters used in this thesis were derived indicates that the amount of surface runoff is 9 times higher between the light and heavily compacted scenarios (Rauzi and Hansen, 1966). Furthermore, the difference between the moderate and heavy compaction scenarios was 1.4 times. This finding is similar to the results of the modelling in this thesis where the difference between the moderate and heavy scenarios was much smaller than the difference between the light and the moderate scenarios. Other studies have found that ploughing, and the compaction caused by heavy machinery, can increase runoff by 30-100% (Kwaad and Mulligan, 1991). Evans (1996) found that a 50% increase in stock numbers coincided with a 25% increase in surface runoff in the Derwent catchment between 1944 and 1975. A modelling study by Jackson *et al.,* (2008a) found that introducing tree shelterbelts with no grazing decreased overland flow by up to 60%, resulting in peak flows decreasing by between 10% and 40%. Another key hydrological storage zone is water on the floodplain and slopes. Figure 9.9d shows that the more heavily compacted soil scenarios result in more water being stored on the land surface. There is an 80% increase in the amount of water stored in the landscape between the beginning and end of the simulation. This is a key finding as this increased surface storage is likely to increase the connectivity between the landscape and the channel. Figure 9.9e shows that there is a small increase in the amount of evapotranspiration for heavily compacted landscapes, although it is only a 0.4% increase. This is likely to be caused by the increased soil saturation levels meaning soil evaporation is more likely and also because of the increased surface water storage providing reservoirs (surface ponding) for actual evaporation. It is therefore more likely that potential evapotranspiration is not limited by the amount of water stored in the landscape for the heavily compacted scenario.



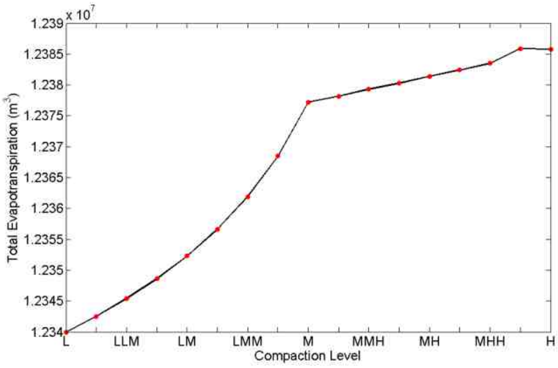
a) Total Runoff

b) % Surface Runoff



c) % Throughflow

d) Change in Storage



e) Evapotranspiration

Figure 9.9 *Effect of compaction on hydrological processes (where L = Light, M = Moderate, and H = Heavy compaction, and the rest are linearly interpolated e.g. LLM = Light Light Moderate)*

Figure 9.10 shows the proportion of the precipitation that is partitioned into the different hydrological processes. For all the compaction scenarios most of the precipitation is portioned into runoff to the channel (>60%). This proportion of precipitation decreases from 77% to 64.5% from light to heavy compacted soils. The breakdown of runoff into surface and sub-surface flows shows that throughflow decreases from 56% to 1%, while overland flow increases from 20.5% to 63%. The amount of precipitation that is stored in the landscape increases from 3.2% to 16% from low to heavy compaction. This is key for both causing more extreme floods and low flows. For floods, this increased storage on the hillslope increases the connectivity between the landscape and the river channel, meaning more water is delivered to the channel. For low flows, this increased storage is a result of decreased lateral flux caused by less free-draining soils meaning that baseflow decreases. A study by Holman *et al.*, (2003) found that soil structural degradation both reduces the storage capacity of the soil and the extent of vertical sub-surface flows. For the Ouse catchment, which was estimated to be 40% degraded, runoff increased by between 0.8% and 9.4% (Holman *et al*, 2003). The amount of precipitation that is partitioned into the processes of evapotranspiration or groundwater recharge does not change, with evapotranspiration being more important with 15% of rainfall being evaporated and 4% being percolated to groundwater. Lane (2003) stated that one of the effects of overgrazing was a loss of vegetation (biomass), which reduces the rate of evapotranspiration and therefore maintains soil wetness. This impact of overgrazing was not captured within these scenarios of compaction, and therefore the effect on soil saturation may be greater than what is predicted in these results.

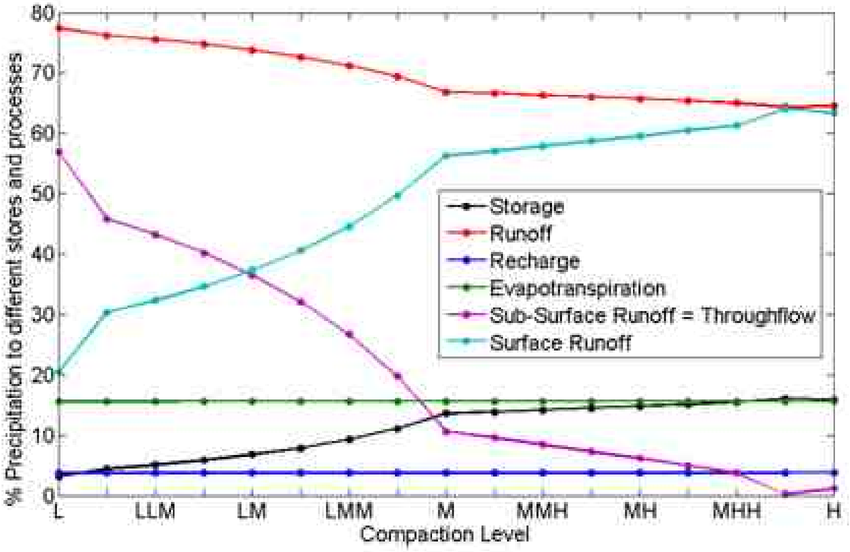
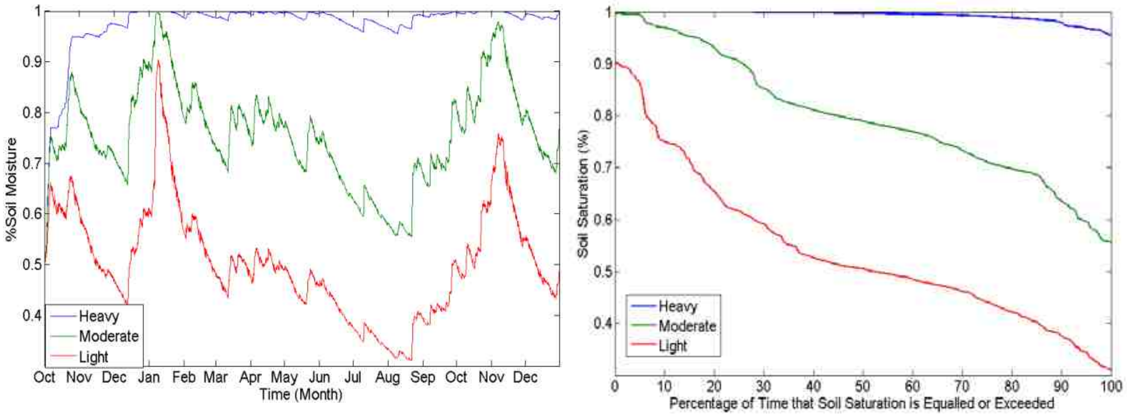


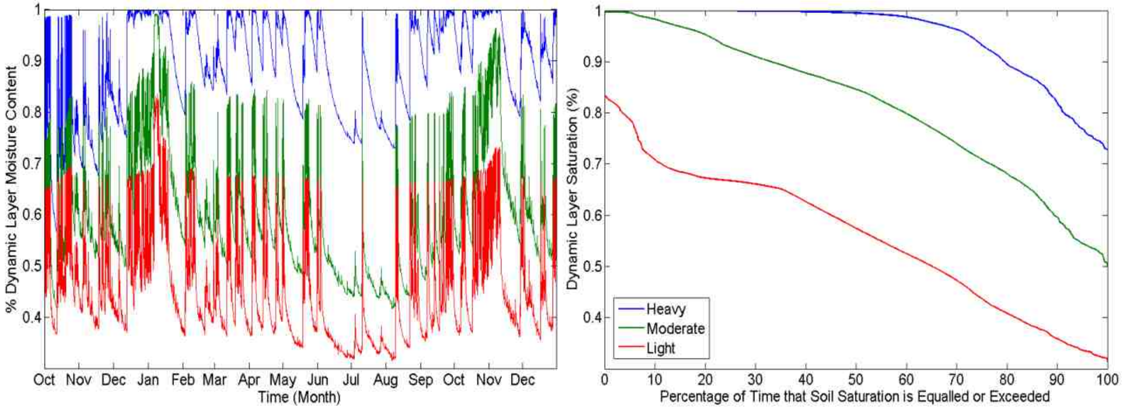
Figure 9.10 *Proportion of rainfall that is partitioned into different hydrological processes*

It is important to investigate the effects of compaction on these hydrological processes in more detail. This can be done by analysing the soil moisture content over time (Figure 9.11a-d). As previously explained the soil is represented by a two layered storage zone in CRUM3; the main soil layer and a thin dynamic layer near the surface. The most noticeable difference between the compaction scenarios in terms of the main soil moisture content is that for the heavily compacted soil, the main soil storage zone stays at saturation or very near saturation for the whole simulation period (Figure 9.11a). In fact, soil moisture content never falls below 0.95 (Figure 9.11b). For the moderate and light compaction scenarios soil moisture varies more over time. There are two main periods of flooding in this period, January and October. These two periods are clearly visible as peaks in soil moisture content. For the moderate compaction scenario soil saturation is reached for these two events, while for the light compaction soil saturation is never reached. This may explain why the difference between the peak flows for the heavy and moderate compaction scenarios only differs by 3.7%, while lower levels of compaction result in significantly lower peak flows. This highlights the importance of predicting soil moisture dynamics as a diagnostic tool for flood generation. Meyles *et al.,* (2006) found that changes to the physical characteristics of the soil (decreased organic content, increased bulk density, decreased porosity) caused the wetness threshold between dry and wet states was lower in heavily grazed area, as field capacity was reached more readily.

The dynamic layer is more easily saturated and results in saturation overland flow more often. It is clear from Figure 9.11c that the water content of the dynamic layer is more variable than the main soil layer. However, the heavy compaction scenario still results in the dynamic layer being at saturation for 60% of the time (Figure 9.11d). Moderate compaction only resulted in saturation of the dynamic layer for 6.5% of the time, which is predominantly the January 2005 flood event. Light compaction results in a maximum dynamic layer moisture content of 84%. Meyles *et al.,* (2006) found that it was the top 10 cm of the soil that were most important in controlling the time it took for overland flow to be initiated.



a) Soil Moisture over time *b) Exceedance plot of soil moisture*



c) Dynamic Layer moisture content *d) Exceedance plot of dynamic layer Moisture*

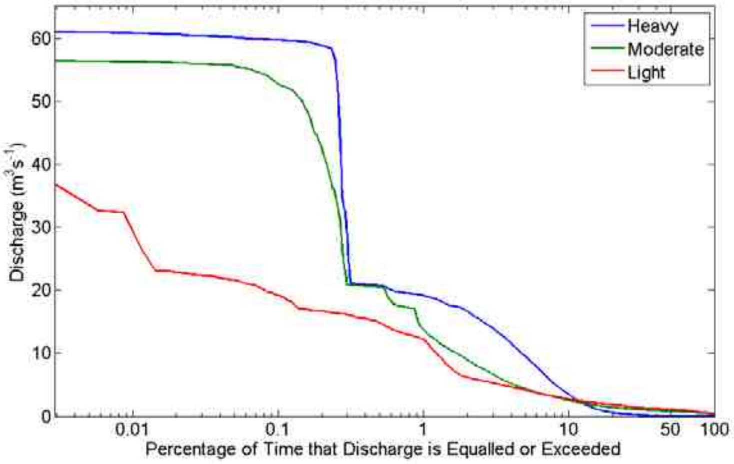
Figure 9.11 *Moisture content of the soil store, including both the main soil and dynamic layer.*

Flow Duration Curves

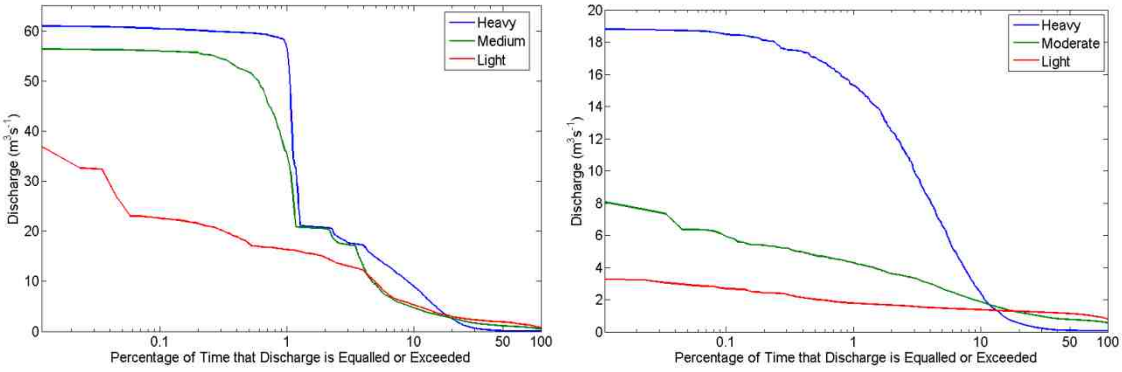
However, it is not just the flow extremes that are affected by soil compaction; the whole flow regime is altered. This impact can be assessed by looking at the annual (Figure 9.12a) and interannual (seasonal) (Figure 9.12b-e) flow duration curves. A useful statistic is the peak over threshold index (POT), which for Dacre Beck at Dacre Bridge has a threshold of 23.7 m^3s^{-1} (Environment Agency Hiflows). The proportion of time that flows exceed this threshold for the light, moderate and heavy compaction scenarios are 0.01%, 0.29% and 0.31% respectively. This shows the similarity of the moderate and heavy compaction scenarios. However, the discharges resulting from the heavy compaction scenario are slightly higher and maintained for a slightly longer duration. An explanation for the steep nature of the moderate and heavy compaction flow duration curves is that it represents two hydrological states of the catchment.

Extreme high flows are initiated by saturated catchments which result in high quantities of rapid overland flow, while less extreme flows and low flows are caused by unsaturated catchments where throughflow is the main source of runoff to the channel. The lightly compacted scenario doesn't ever reach full saturation so the gradient of the flow duration curve is less steep, as the amount of surface runoff is much lower than the other scenarios. For lower flows, the heavy compaction scenario produces the lowest flows, while the statistics for the moderate and light scenarios are similar.

The inter-annual (seasonal) flow duration curves are shown in Figure 9.12b-e. These show that Dacre Beck really exhibits two states throughout the year; an Autumn-Winter state and a Spring-Summer state. Autumn and Winter are the seasons when larger flood events occur, while low flows and flashy peaks occur in Spring and Summer. Heavy compaction seems to both increase the magnitude of peak flows but also increase their frequency and duration. In Winter, the shapes of the flow duration curves are very similar to the annual trend, with the gradient of the curve being quite steep, suggesting short periods of high flows and longer durations of the medium to low flows. The same trend is seen in Autumn, with the only difference being that the heaviest state of compaction doesn't result in the highest flow in terms of magnitude, but the duration of the high flows is much longer than the lower compaction scenarios. The difference in Spring and Summer is that the light to medium compaction scenarios do not produce high flows, meaning that the flow duration curves are very flat. However, the heavy compaction scenario does produce reasonably high flows of between 15-20 m^3s^{-1} for approximately 1% of the time.

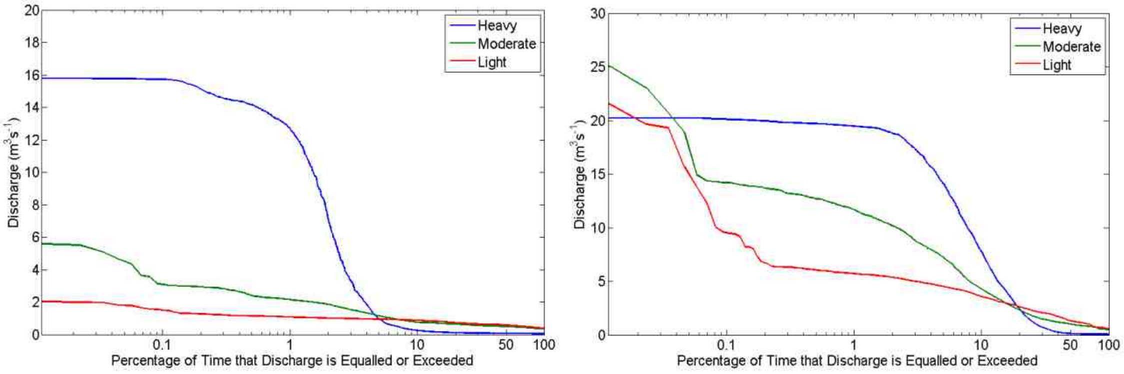


a) Annual flow duration curve



b) Winter FDC

c) Spring FDC



d) Summer FDC

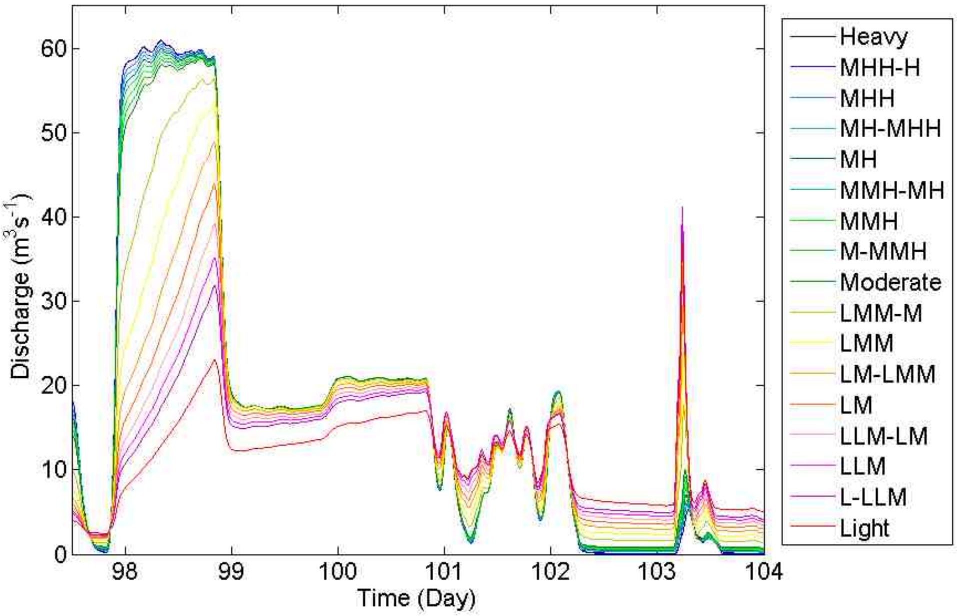
e) Autumn FDC

Figure 9.12 *Flow duration curves for different timescales including annual and inter-annual periods*

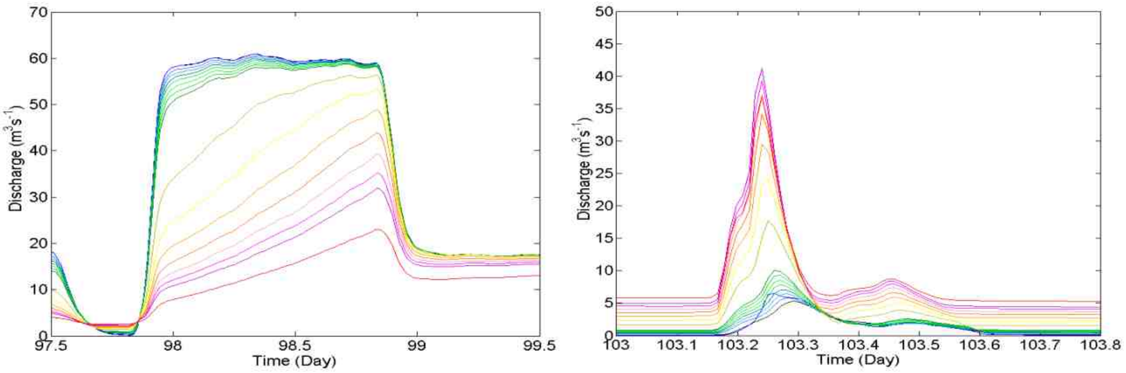
<u>*January 2005 Flood*</u>

Figure 9.13a shows the full continuum of compaction scenarios for the January 2005 flood event. For the main flood event (Figure 9.13b) the more compacted the catchment the greater the peak flow, with the relationship between the degree of compaction and the peak flow being positive. Furthermore, the duration of the peak increases considerably as the amount of compaction increases. This is the same relationship as explained earlier, but now with all 17 model simulations representing the continuum of compaction. However, what is interesting about this time period is that a few days later there is another peak flow, but this time the heaviest compaction scenario produces the lowest peak discharge and the light compaction scenario the highest peak (Figure 9.13c). A possible explanation for this is that the large flood event was caused by a large precipitation event, which increased soil moisture content considerably. The heaviest compacted soil scenario reached saturation for this peak. This meant that large

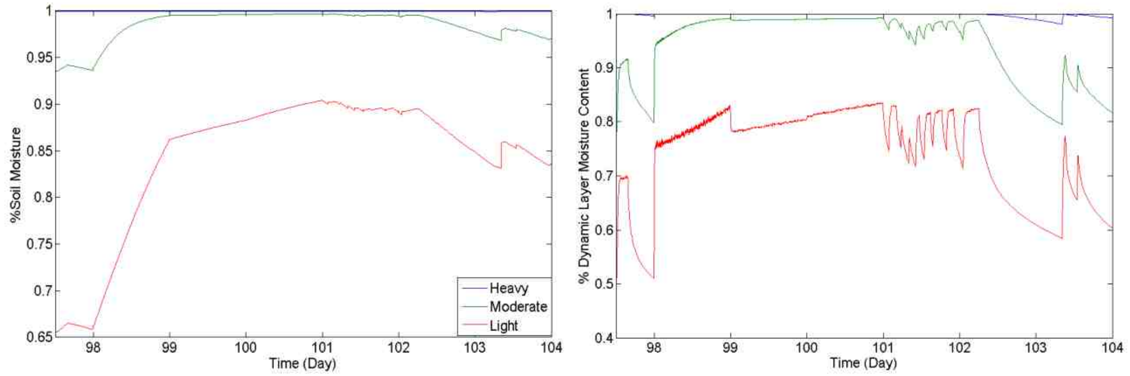
quantities of overland flow were initiated as infiltration into the soil store was not possible. This resulted in a high peak as previously explained. However, over the next few days less rainfall occurred, but this secondary flood peak still occurred in the moderate to light compaction scenarios. A hypothesis for this is that these soils still had high moisture contents and the less compacted structure of these soils meant that the amount of throughflow was greater and more rapid. This throughflow connected to the river channel and resulted in this secondary lower flood peak. The heavily compacted soils were even more saturated, but the compacted structure meant that little throughflow could occur and any water was just stored in the soil. During this period there was not enough rainfall to initiate overland flow meaning that the runoff from the most compacted soil was lower than the less compacted soils, as the amount of throughflow varied. Evidence for this hypothesis comes from the moisture contents of the main soil (Figure 9.13d) and the dynamic layer (Figure 9.13e) during this period. The most compacted soil scenario has a fully saturated main soil for the whole period. However, the dynamic layer has storage capacity (2%) during this secondary flood event, meaning that the little amount of rainfall that does occur can be stored rather than runoff as surface flow.



a) River discharge for the continuum of compaction scenarios for the January 2005 flood



b) River discharge for 1st flood *c) River Discharge for 2nd flood*



d) Soil Moisture content *e) Dynamic Layer moisture content*

Figure 9.13 River discharge and Soil moisture content for the continuum of compaction scenarios for the January 2005 flood

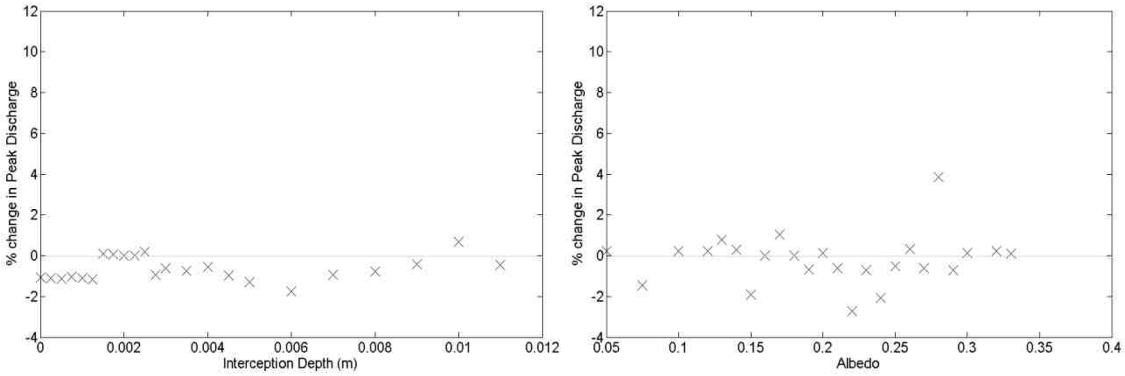
9.2.3. Effect of Vegetation Cover

Vegetation cover, like afforestation, affects the soil and vegetation characteristics. Its effects was explored through two approaches. First, a sensitivity analysis was carried out on the vegetation parameters. Second, scenarios of different land covers, like arable and pastoral agriculture and deciduous and coniferous woodland were tested using parameter values from the literature.

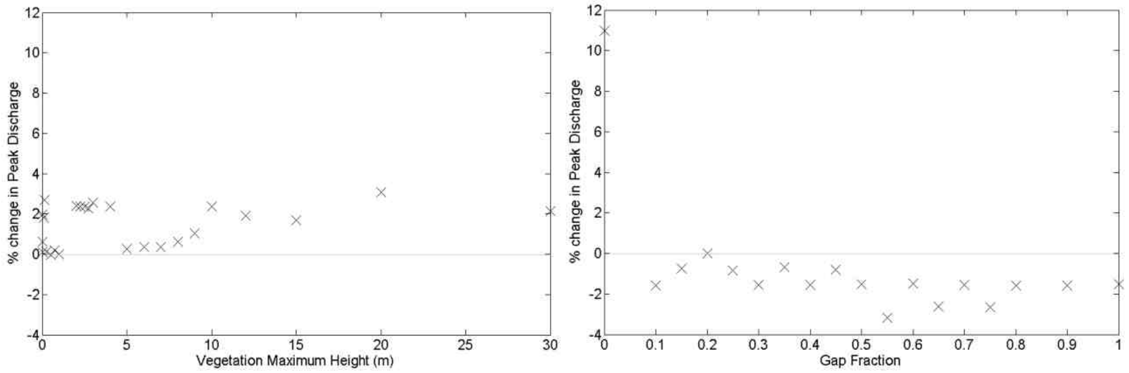
The vegetation cover parameters in CRUM3 are: (1) the interception depth, which controls how much water can be stored in the canopy; (2) the albedo, which controls the amount of radiation which is absorbed into the system; (3) the vegetation maximum height; and (4) the gap fraction, which controls the proportion of the canopy that is open.

Sensitivity Analysis

Figure 9.14 shows that peak discharge is not really sensitive to any of the vegetation parameters. Furthermore, there is no relationship between the parameters and their effect on peak discharge. This indicates that the vegetation characteristics are relatively unimportant in influencing peak discharges and high river flows. This is due to the hydrological effect of vegetation being minimal in large storm events. Firstly, during storms, the antecedent conditions mean that the canopy is often already at capacity, meaning little if any of the precipitation can be stored within the canopy (Robinson and Dupreyrat, 2005). Secondly, the evapotranspiration process is insignificant during storms, as precipitation greatly exceeds the rate of evapotranspiration, which is minimal due to the cooler, humid characteristics that occur during storm events. Therefore, if land cover and different vegetation types do have an effect on high river flows then it is probably due to their effect on the soil characteristics, that have already been shown to be important in influencing floods. However, the vegetation parameters may change the effect of the soil parameters, and potentially the effect of compaction. Furthermore, the best practical way to reduce compaction may be afforestation.



a) *Interception Depth* *b)* *Albedo*



c) *Maximum Height* *d)* *Gap Fraction*

Figure 9.14 *Sensitivity of peak discharge to the vegetation parameters*

The following part of this section will outline the results from land cover scenario testing. Figure 9.15 shows a visual comparison of the land cover scenarios of arable, pasture, deciduous and coniferous land covers. The deciduous land cover (Figure 9.15c) generally produces the least flashy regime, with fewer peaks than the other land covers. The coniferous land cover produces the highest flows, with several peaks throughout the year (Figure 9.15d).

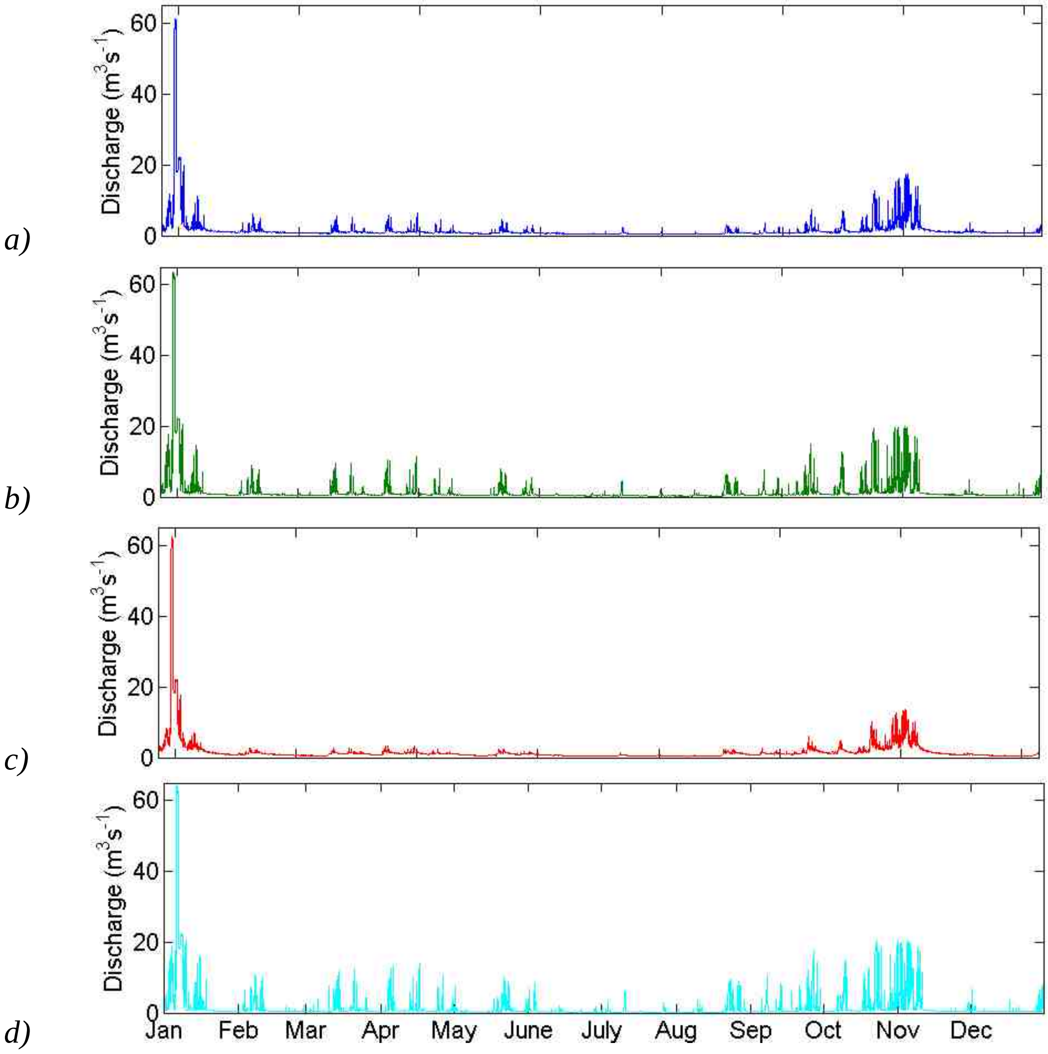
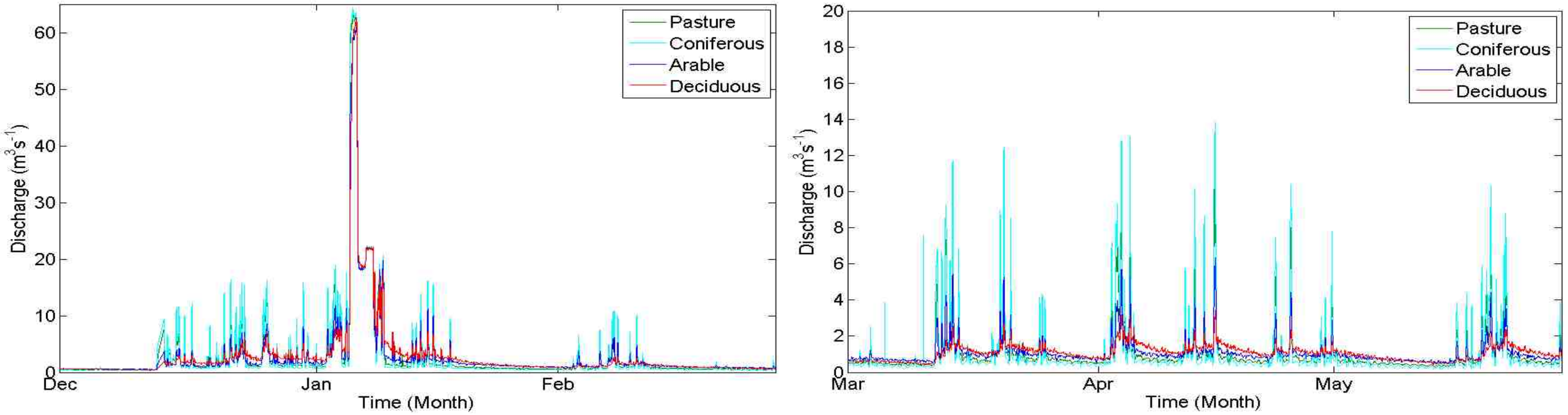


Figure 9.15 *Comparison of the land cover type scenarios (a) Arable; (b) Pasture; (c) Deciduous; d) Coniferous.*

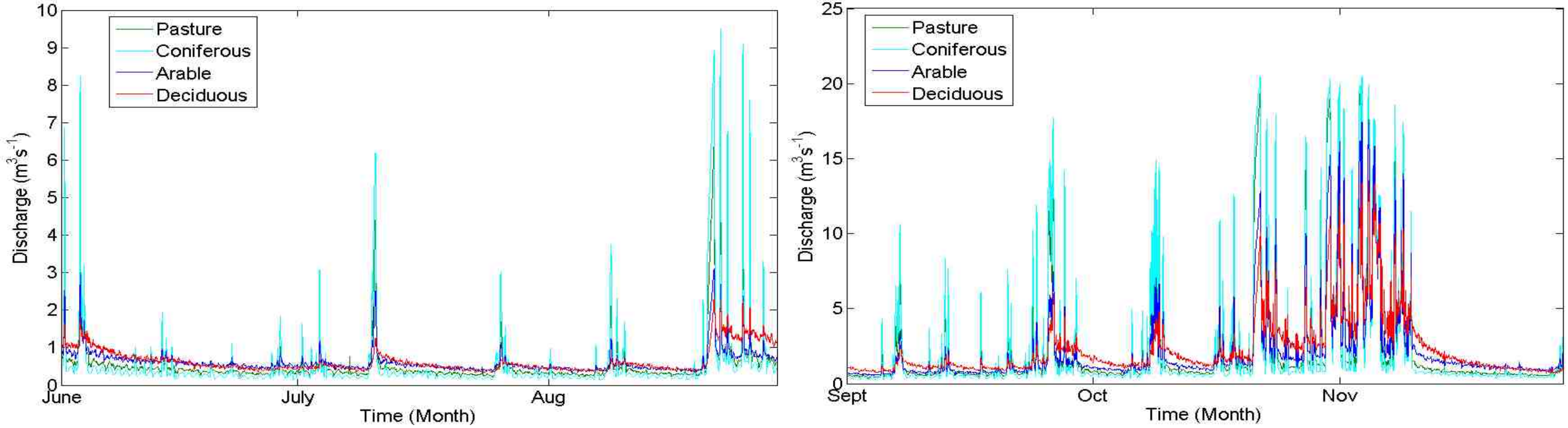
Seasonal Flows

Figure 9.16 shows the simulated results for the four different land covers for the different seasons. The extreme January 2005 flood event is simulated with a similar hydrograph shape for all four land covers, with the peak magnitude being comparable, although there are some differences. The highest peak discharge is for the coniferous woodland land cover (64.4 m^3s^{-1}). This is followed by the pasture (63.7 m^3s^{-1}) and the deciduous woodland (62.6 m^3s^{-1}), with the lowest peak magnitude being for the arable agriculture land cover (61.3 m^3s^{-1}). There is a 5.1% difference between the highest and lowest peaks for the coniferous and arable land types, which given parameter uncertainty is very low. Similar trends are seen for other flood events throughout the year. Arable agriculture has a lower peak flow than pastoral farming. This is hypothesised to be caused by the management of these two land uses, whereby arable fields are frequently ploughed, meaning the soil structure is improved and has better drainage. Pastoral fields often are heavily compacted meaning infiltration rates and capacities are lower and overland flow is more likely. This runoff connects to the channel faster than the sub-surface pathway leading to higher peak flows. Deciduous woodland land cover results in a lower peak flow than coniferous forest. This may be caused by both the soil and vegetation characteristics of these two types of woodland. Deciduous trees produce large amounts of leaf litter which improves the infiltration rate of the top few centimetres of the soil (dynamic layer in model), meaning that rainfall is partitioned into the slower sub-surface pathway resulting in lower peak flows (Carroll *et al,* 2004). Furthermore deciduous trees have larger leaves, with higher interception capacities than the needles of coniferous forests (Fohrer *et al.,* 2001). This means that more rainfall is stored in the canopy of a deciduous forest than one consisting of coniferous trees. For the low flows, especially in summer, the coniferous has the lowest flows, with the pasture land cover being similar. Flows produced by the deciduous and arable land covers are similar to each other but slightly higher than the pasture and coniferous woodland. Previous research has shown that afforestation has the largest absolute effect on winter flows (rainfall highest), but the greatest proportion reductions in flows occur in the summer low flow season (Scott and Smith, 1997).



a) *Winter*

b) *Spring*



c) *Summer*

d) *Autumn*

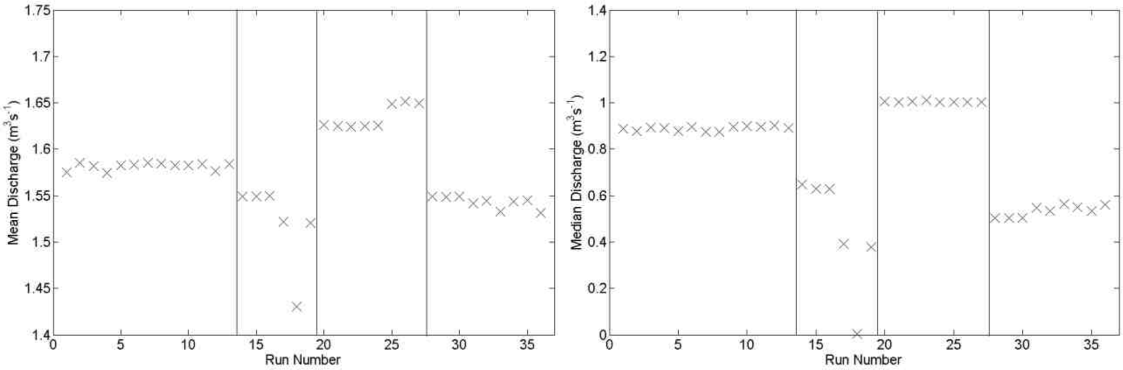
Figure 9.16 *Seasonal discharges for the four land cover types.*

Summary Statistics

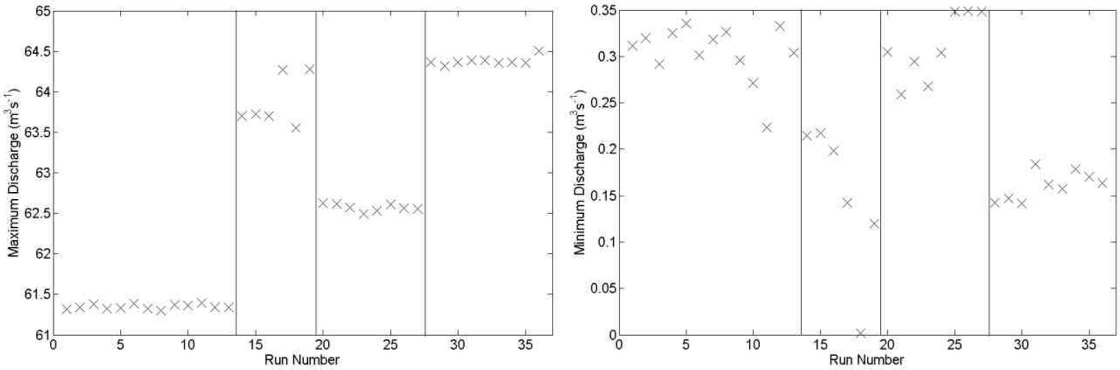
A single simulation was chosen to represent each land cover type throughout much of this analysis (arable = 12, pasture = 14, deciduous = 22, coniferous = 28). More detail on the effects of land cover can be discovered by looking at the whole range of simulations for each land cover type. The descriptive statistics are shown in Figure 9.17. The first and most important observation from all of these is that the intra-category variation is significantly less than the inter-category variation. This means that a single simulation is suitable to compare the different types of land cover. This suggests that the soil characteristics are the most important factor in driving flooding rather than the vegetation characteristics. This may be because canopy interception and evapotranspiration are relatively unimportant hydrological processes in large flood events, as antecedent conditions means canopies are at capacity, and rainfall significantly exceeds evapotranspiration. The mean discharge (Figure 9.17a) for arable land cover is 1.6 m^3s^{-1}. Pasture mean values are a little more variable ranging from 1.5 to 1.4 m^3s^{-1}, which is similar to the mean values for the coniferous woodland simulations (1.5 m^3s^{-1}). Mean values for the deciduous woodland land cover type range are the highest at 1.6 m^3s^{-1}. The trends in the median values are similar (Figure 9.17b), although values are typically lower than the mean (arable = 0.9 m^3s^{-1}, pasture = 0-0.6 m^3s^{-1}, deciduous woodland = 1.0 m^3s^{-1}, coniferous woodland = 0.50-0.6).

This thesis is most interested in the extreme flows, both high (floods) and low (droughts) discharges. Figure 9.17c shows the effect of land cover type on peak flows, which are for the January 2005 flood event. The peak flows vary little within each category, with arable agriculture ranging from 61.3 to 61.4 m^3s^{-1}, pasture from 63.6 to 64.3 m^3s^{-1}, deciduous woodland from 62.5 to 62.6 m^3s^{-1} and coniferous woodland from 64.3 to 64.5 m^3s^{-1}. Bosch and Hewlett (1982) concluded from a review of past studies that coniferous woodlands cause the largest increase in annual water yields of 40 mm, with deciduous land covers being associated with an increase of approximately 25 mm. Further evidence for this opinion comes from Robinson *et al.*, (2003) which concludes that coniferous forests have the greatest effects on flows. The minimum flows produced by the arable and deciduous land cover simulations were similar with a magnitude of

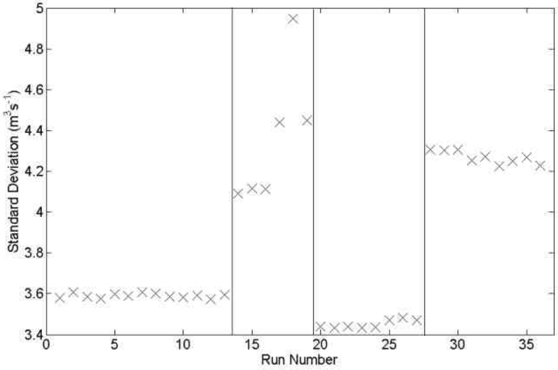
0.3 m^3s^{-1}. The minimum discharge for the pasture land cover was ranged from 0.002 m^3s^{-1} to 0.2 m^3s^{-1}, while coniferous woodland had a minimum discharge of 0.2 m^3s^{-1}. This matches the general consensus that forest growth decreases baseflows. Finally, the standard deviation indicates that the intra-category variation is very low, except for the pasture land cover type, where the standard deviation ranges from 4 m^3s^{-1} to 5 m^3s^{-1}.



a) Mean *b) Median*



c) Maximum *d) Minimum*



e) Standard Deviation

Figure 9.17 *Descriptive statistics for the whole range of land cover types (simulation numbers 1-13 represent arable, 14-19 = pasture, 20-27 = deciduous woodland, 28-36 = coniferous woodland.)*

Effect of Land Cover Type on Hydrological Processes

It is important to interpret these results in terms of the hydrological processes which the land cover type may affect (Figure 9.18). Deciduous woodland has the highest annual runoff proportion of the annual precipitation at 79-81%. The proportion of the rainfall partitioned into runoff for the other land cover types was 74-75% for coniferous woodland, 70-73% for pastoral agriculture and 72% for arable farming. However, what is critical for the generation of high flow events is the proportion of this runoff which occurs as surface flow, which connects to the river channel faster than sub-surface throughflow. For most land cover types it was found that annual surface flow exceeds throughflow contribution. This included arable where surface runoff was 59-67%, pasture where surface runoff was 76-99%, and coniferous woodland was 79-90%. However, the proportion of runoff as surface flow for the deciduous woodland was lower than the throughflow proportion, where surface flow ranged from 43-63% and throughflow from 36-56%. This indicates that the importance of surface flows in deciduous woodland is lower than other land covers, and that throughflow is more important. This provides a possible explanation for why the peak flows are some of the lowest simulated and why the low flows are some of the highest. Carroll *et al.,* (2004) highlighted the importance of forest landscapes in partitioning rainfall into the slower sub-surface flow pathway. Land cover type also has a slight impact on the amount of evapotranspiration, with deciduous woodland having a lower rate than the other land covers at 10.7% of annual precipitation. This is lower than field studies have show, with Johnson, (1991) finding that 25-30% of precipitation was evaporated in forest landscapes. The other land cover types have rates of 13.0%, 14.1% and 13.8% for arable, pasture and coniferous woodland respectively. A possible reason for this is that deciduous woodland vegetation has lower interception capacities and higher albedo values, meaning that less water can be stored on the canopy and more solar radiation is reflected.

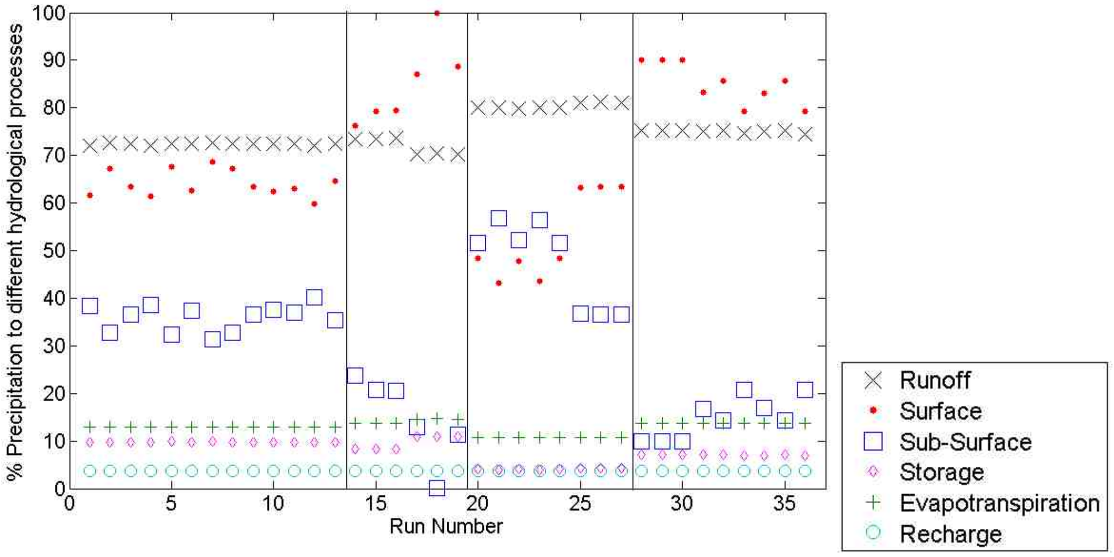
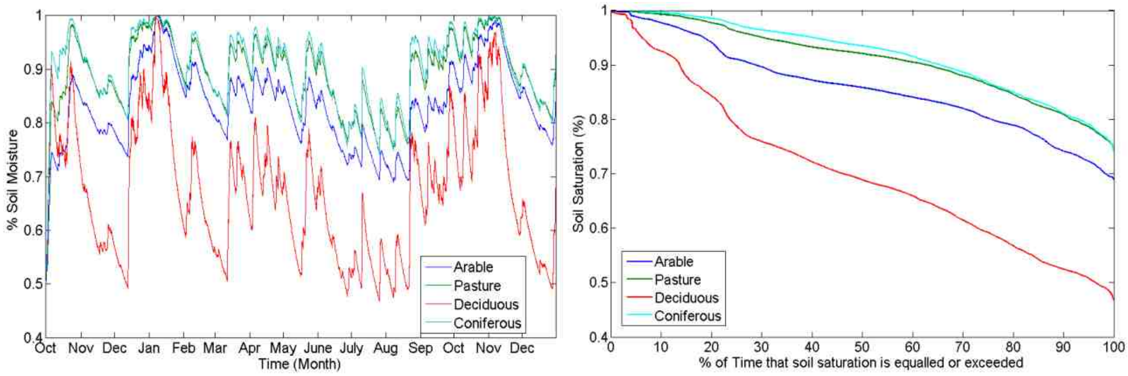


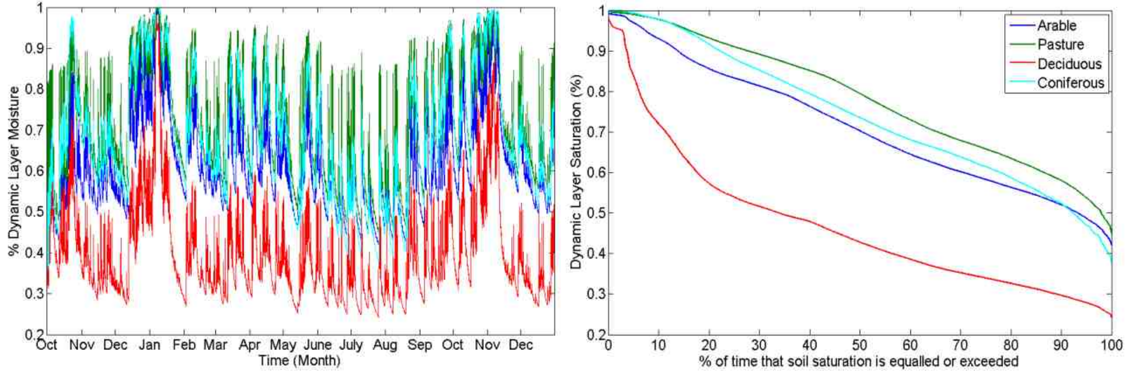
Figure 9.18 *Proportion of precipitation that is partitioned into different hydrological processes*

It is important to investigate the effects of land cover type on the process of runoff generation in more detail. This can be done by analysing the soil moisture content over time (Figure 9.19a-d). It is clear that the soil of the deciduous woodland is less easily saturated than other land cover soils (Figure 9.19a). Only 13.7% of the year has a soil moisture content of higher than 0.9 (Figure 9.19b). Hudson (1988) found through field experimentation that soils are drier under forest than grass. The arable land cover has a soil saturation of 0.9 for 28.7% of the year. The other land covers (pasture and coniferous woodland) have much higher soil moisture contents with 62.8% and 65.4% of year being above 0.9 respectively.

The dynamic layer is also critical for the generation of overland flow. Figure 9.19c shows that the saturation of this thin layer at the top of the soil is far more variable than the main soil store. Again, the deciduous woodland soil has the lowest saturation levels, with only 3.7% of the year being higher than 0.9 (Figure 9.19d). Furthermore, the soil under pasture has a saturation level of 0.9 for 27.7% of the year and the coniferous soil for 22.1% of the year. This indicates that the pastoral soil is more easily saturated in the upper layer than the soil under coniferous woodland land use. This is probably because the process of compaction, as already discussed, affects the top few centimetres of the soil the most.



a) Soil Moisture over time *b) Exceedance plot for soil moisture*

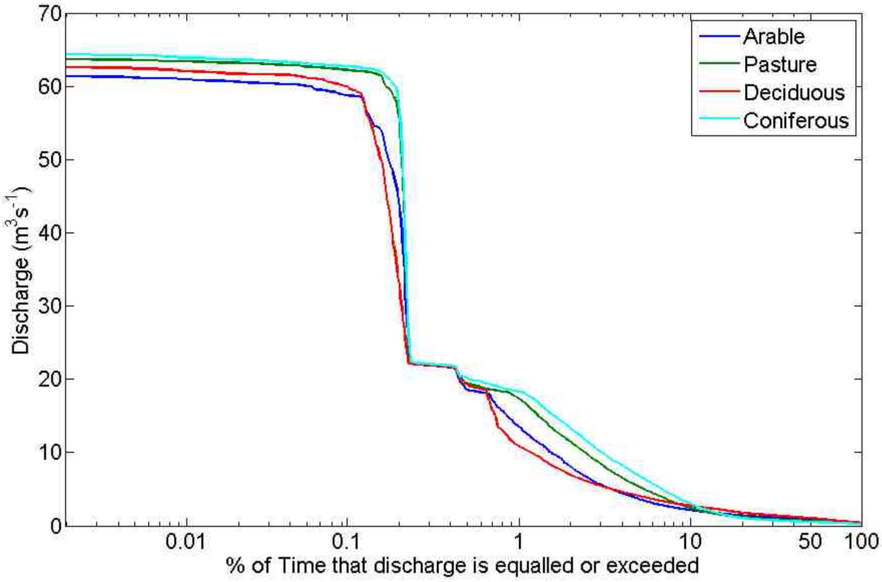


c) Dynamic layer moisture content *d) Exceedance plot for dynamic layer moisture content*

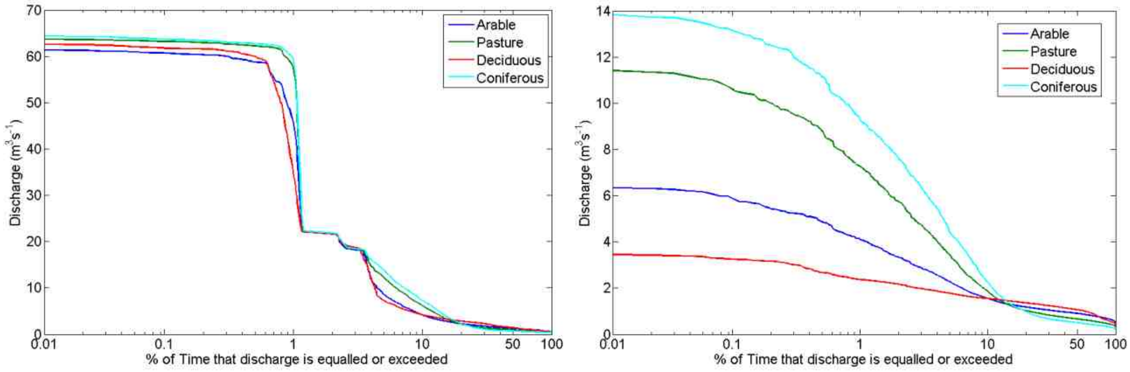
Figure 9.19 *Moisture content of the soil store, including both the main soil and dynamic layer.*

<u>*Flow Duration Curves*</u>

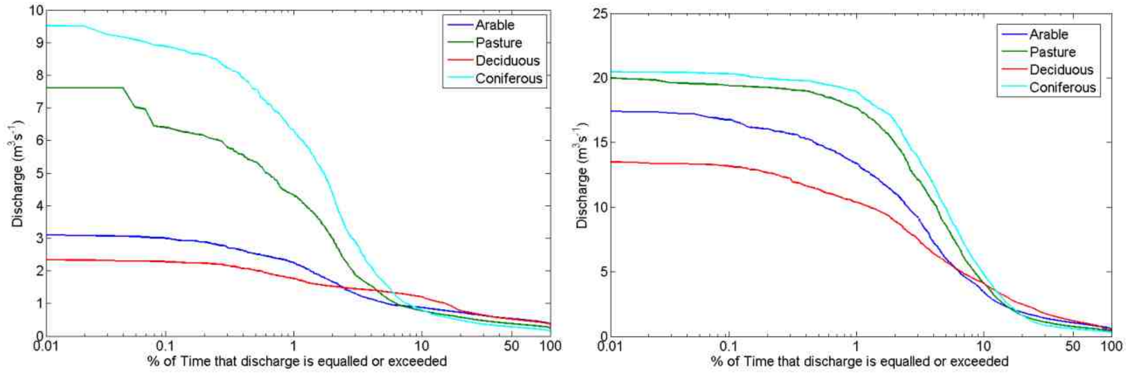
However, it is not just the flow extremes that are affected by land cover; the whole flow regime is altered. This impact can be assessed by looking at the annual (Figure 9.20a) and interannual (seasonal) (Figure 9.20b-e) flow duration curves. Again the peak over threshold index (POT) of 23.7 m^3s^{-1} (Environment Agency Hiflows) will be used to compare the scenarios, with only 0.2% of the time being higher than this discharge for all land cover types. This indicates that the differences between the different land covers is relatively small for the high flow regime. Q1 values are a little more variable, with coniferous woodland having the highest at 18.3 m^3s^{-1}, followed closely by pastoral agriculture at 17.3 m^3s^{-1}. Arable (13.5 m^3s^{-1}) and deciduous woodland (10.8 m^3s^{-1}) land covers have lower Q1 values. The seasonal flow duration curves from these simulations again suggest a two phase annual system, with Autumn-Winter and Spring-Summer. In winter, the duration of the higher flows is longer, while in summer any high flow events are more flashy. The difference between the pasture and coniferous scenarios and the arable and deciduous land cover scenarios is larger in the spring and summer.



a) Annual flow duration curve



b) Winter FDC *c) Spring FDC*

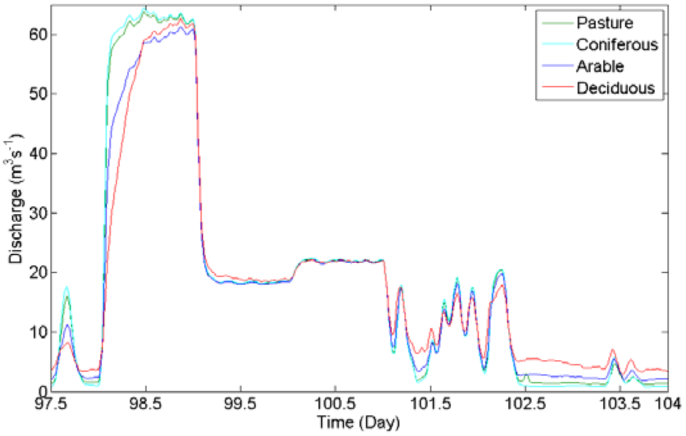


d) Summer FDC *e) Autumn FDC*

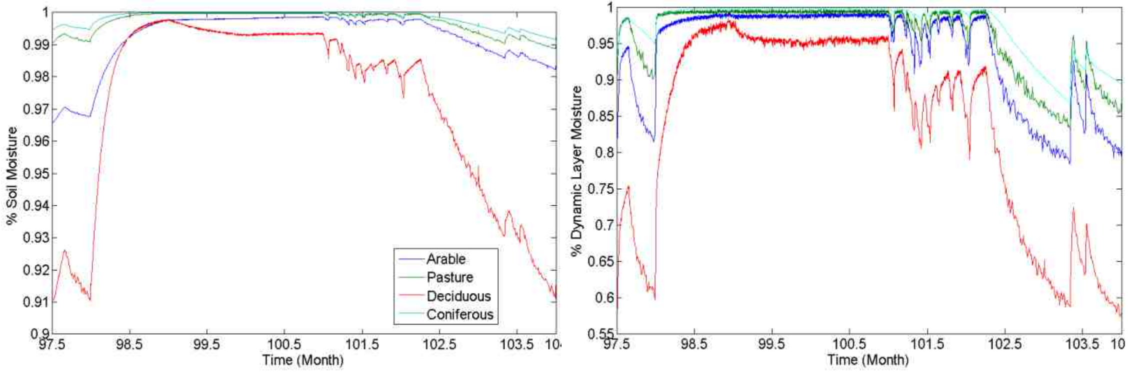
Figure 9.20 *Flow duration curves for different time periods, including annual and inter-annual periods.*

January 2005 Flood

Finally, the January 2005 flood event will be analysed in more detail, looking both at the discharge and soil moisture contents. Figure 9.21a shows the discharge simulations at Dacre Bridge. This shows that the peaks generated by the coniferous and pastoral land covers produce both the highest peak flows, but also that these events are longer in duration. The arable and deciduous land covers produce less steep rising limb hydrographs and shorter duration peaks. This is because the soils under coniferous woodland and pastoral agriculture are at saturation, in terms of both the main soil (Figure 9.21b) and the dynamic layer (Figure 9.21c) for a longer period of time. The main soil layer is always nearly saturated (above 0.9) for the whole time period, but the dynamic layer's saturation level varies much more. The saturation of the deciduous forest soil is much lower than the other land covers for the duration of this event, especially in terms of the dynamic layer.



a) River discharge for the January 2005 flood for the four land cover scenarios



b) Soil moisture content *c) Dynamic layer moisture content*

Figure 9.21 *River flow and soil saturation levels for the January 2005 flood for the four land cover scenarios.*

9.2.4. Land Management Scenario Summary

The hydrological model, CRUM3 was used to test the land management scenarios of compaction and afforestation. This model has previously been used for a hydrologically similar catchment, the Upper Rye in Yorkshire (Lane *et al*, 2009). Lane *et al.* (2009) found that CRUM3 simulated general hydrological patterns and had a Nash-Sutcliffe co-efficient of 0.655 and a Mean Absolute Error of 0.29 m^3s^{-1}. In this study, for Dacre Beck, the model was assessed on peak daily discharges for the year 2005, with a Nash-Sutcliffe coefficient of 0.31. However, the model performed much better for the January 2005 flood event, which is the focus of this thesis. The Nash-Sutcliffe coefficient was 0.65 for the month of January and 0.74 for the 10 days around the flood. The error on the peak discharge magnitude was -0.73% for the January 2005 event.

First, a basic sensitivity analysis of each individual parameter was carried out. It was found that peak flows are sensitive to the soil parameters, including saturated hydraulic conductivity, porosity, dynamic layer depth and dynamic layer saturated hydraulic conductivity. Peak flows were not sensitive to the vegetation parameters (interception depth, gap fraction, albedo and maximum height).

Second, the sensitivity of river discharges to the level of soil compaction was assessed. Scenarios ranged from light to heavy compaction using parameter values derived for a loam soil from the literature. It was found that peak flows are highly sensitive to compaction, with an increase of 65% in maximum discharge when compaction is increased from light to heavy. However, the difference between moderate and heavy compaction scenarios was only 3.7%. It was found that increased compaction decreases annual runoff due to the dominance of unextreme events. However, the proportion of this runoff which occurs as overland flow increases from 20.5% for light compaction to 63% for heavy compaction. This is because heavily compacted soils are saturated for the whole time period, with the dynamic layer (which drives saturation overland flow) being saturated for 60% of the time. These findings match field studies which have found that localised runoff may increase due to compaction (Heathwaite *et al.*, 1989; Heathwaite *et al.*, 1990). Other studies have hypothesised that compaction has increased high flows at the catchment scale (Lane, 2003; Sullivan *et al.*, 2004), as increases in stock densities have coincided with increases in flooding. However, as Lane (2003) highlights this correlation cannot be used to prove that compaction caused by stock and machinery has caused increased flooding at the catchment scale. This thesis has used the effects compaction has on the physical soil characteristics to model the effects compaction has on catchment scale discharges. It has shown that increasing the level of compaction increases peak flows in this sub-catchment (Dacre Beck). Orr and Carling (2006) highlighted the potential importance of the effects stock have on river flows, as 30% of the Britain is both classified as uplands (>300 m) and grazed by sheep. This means that the effects stock has on river flows may be widespread.

Third, the sensitivity of the flow regime to the land cover type was investigated. Scenarios of arable and pastoral agriculture, and deciduous and coniferous woodland were simulated. There was a 5.1% difference between the highest peak flow under coniferous woodland and the lowest peak flow under arable agriculture. It is difficult to compare these findings with previous quasi-experiments as the implementation of afforestation involves many stages, such as drainage, planting, growth and canopy closure (Archer, 2003). This modelling work really only simulates the latter of these. Furthermore, in catchments there is often a mosaic of trees at different stage of maturity. It was found that deciduous woodland had the highest annual runoff total (79-81% of precipitation), but significantly similar proportions of this occurred as overland flow and throughflow. This means that high flows are less extreme as more rainfall is partitioned into the slower sub-surface pathway, and low flows are buffered against by higher baseflow contributions. It was found that deciduous woodland had the lowest soil saturation levels of the four land cover types.

9.3. Channel Modification / Floodplain Storage.

The floodplain management scenarios were tested using the hydraulic model, iSIS-Flow. Section 9.3.1 will outline the development of the model used and assess its performance. The specific scenarios to be tested are floodplain storage (Section 9.3.2.), floodplain land cover and channel naturalisation, through the use of the roughness parameter (Section 9.3.3).

9.3.1. iSIS model development

The Environment Agency and Consultants had developed an iSIS-flow model for the Lowther tributary (Atkins, 2007). This Lowther model included the Lowther from Keld to the just downstream of the confluence with the Eamont at Brougham Bridge. The Lowther iSIS model used in this thesis was developed from the one constructed by Atkins (2007).

First, the Lowther iSIS model was developed, using the gauging station at Bampton Grange as the upstream boundary condition. The downstream boundary condition was at Eamont Bridge. This is so that the boundary conditions of the model are at gauging stations with monitored data for input and model validation. Figure 9.22 shows the observed gauged record against the simulated stage and discharge hydrograph at Eamont Bridge. It is clear that the shape of the hydrograph is well reproduced by the model. However, the magnitude of the peak stage during the first flood is not as well simulated, with the error being about -0.5 m (0.43%) corresponding to a -73.8 m^3s^{-1} (37.7%) error in discharge. Although the error on the discharge is quite high, it is thought that the model is suitable to use as the main variable of focus will be stage. This is because it is the water level which determines whether water goes over-bank and causes flooding. Furthermore, converting stage to discharge via the rating curve introduces more potential errors. The Nash Sutcliffe coefficient is good at 0.83 for the stage and 0.70 for the discharge, and an RMSE of ±0.029 m and ±25.5 m^3s^{-1}. The timing of the first peak flow is reasonable as well with an error of 1.75 hours (3.45%). The errors on the smaller second peak is -0.427 m (-0.37%) corresponding to a 50.5

m^3s^{-1} (37.9%) error in discharge and 1 hour (1%) in terms of timing. Further measures of model assessment are shown in Table 9.3.

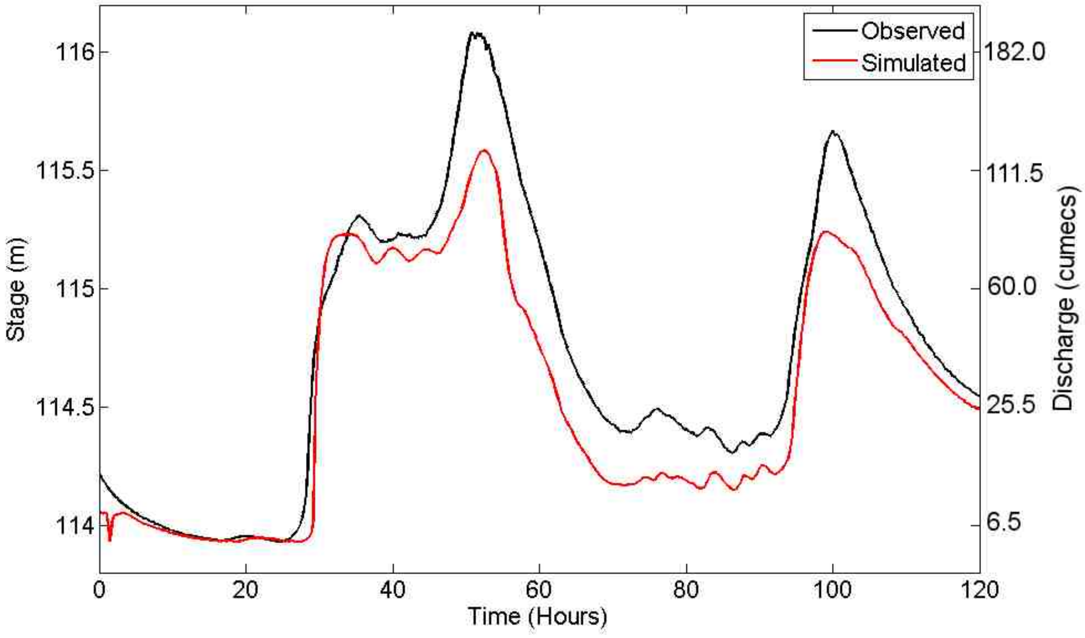


Figure 9.22 *Lowther iSIS model assessment for January 2005 flood at Eamont Bridge.*

	Stage errors	Discharge errors
Sum of Squared Residuals	28.3	312581.0
Sum of Absolute Residuals	86.0	6215.0
Nash-Sutcliffe Model Efficiency	0.83	0.70
Normalised Objective Function	0.0003	0.5
RMSE	0.029	25.5
Reduced Error Estimate	0.084	0.54
Proportional Error of Estimate	0.001	-
Standard Error of Estimate	0.0296	25.5
% Error in Peak Stage	-0.43 (-0.501 m)	-37.7 (-73.8 m^3s^{-1})
% Error in Peak Time	3.45 (1.75 hours)	3.45 (1.75 hours)
% in Stage Mean	-0.16	-25.5
Area for Observed	13810.4	5758.4
Area for Simulated	13788.9	4233.2
% Error in Volume	-0.16	-26.5
Variance	0.059	649.9
Mean Deviation	0.18	12.9

Table 9.3 *Model assessment statistics for Lowther iSIS models in terms of stage and discharge.*

9.3.2. Effect of removing/setting back floodbanks and increasing floodplain storage

There are several approaches for representing floodplains in 1D hydraulic models; (1) reservoir units connected to the channel via spill units; (2) extended channel cross sections; and (3) parallel channel cross sections. It was decided to use the first of the approaches to simulate floodplain storage. Existing data for the Bampton Grange area was available in the Lowther iSIS-flow model developed by Atkins (2007). These hydraulic units were added to the model developed outlined in the previous section.

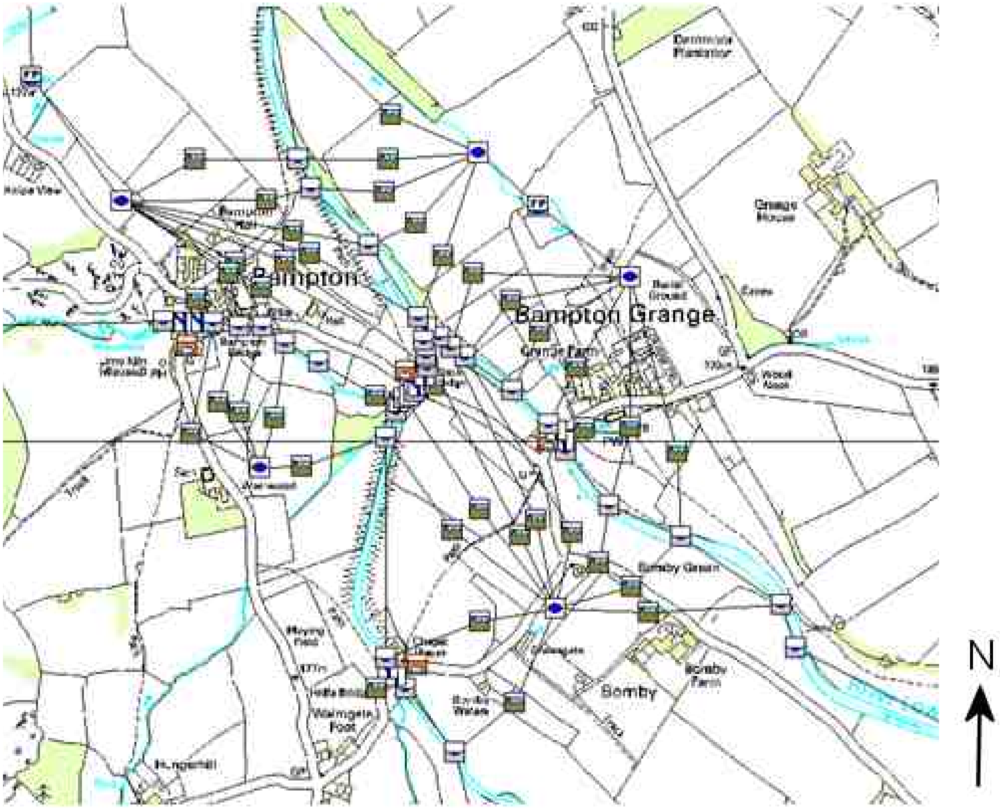


Figure 9.23 *Schematic of the Lowther iSIS model structure at Bampton showing floodplain representation through reservoir units*

The 1D-Storage cell approach works by the channel being connected to a reservoir storage unit by a spill unit. A schematic of the model structure is shown in Figure 9.23. The height of the spill controls the spilling and draining of water between the river channel and the floodplain. Reservoir units describe the capacity of the floodplain by an area-elevation relationship. Seven reservoir units were introduced in the model at Bampton and the area-elevation relationships for these are shown in Figure 9.24. The area-elevation relationships of the reservoir units show that significant changes in elevation (tens of centimetres) are needed to result in significant increases in the storage area. This is due to the topography of the reach being relatively steep.

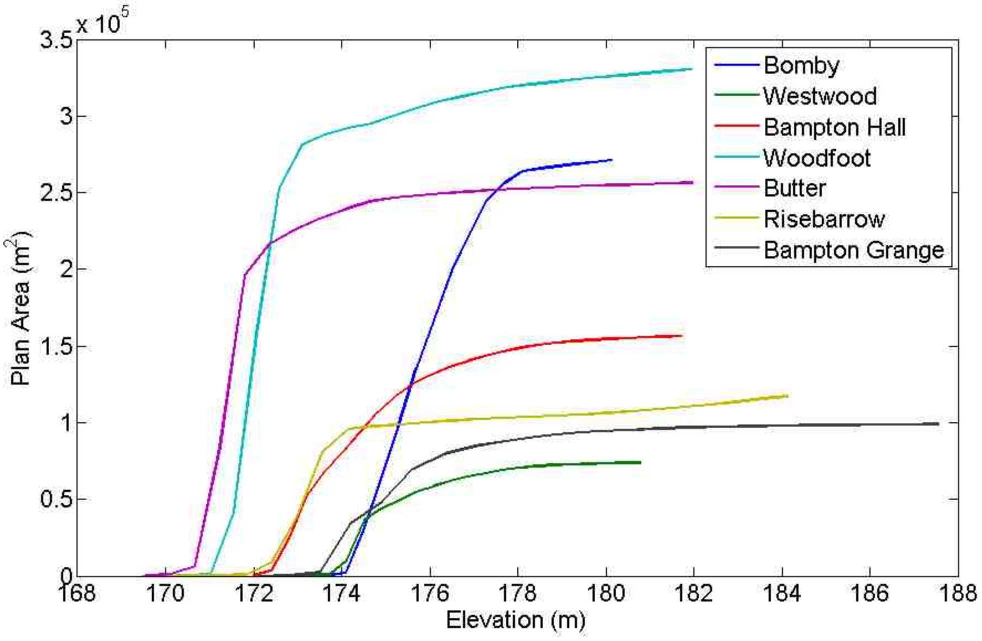


Figure 9.24 *Elevation-Area relationship for different reservoir units in iSIS model.*

It is expected that as the spill height changes, the timing of storage starting and the amount of water being stored on the floodplain will change. If the spill height is increased, then water storage will be delayed. This will mean that there is greater capacity on the floodplain to capture the flood peak and the flood wave will be attenuated and the peak flow downstream both delayed and reduced in magnitude. However, Figure 9.25 demonstrates that this is not the case. The flood hydrograph downstream is hardly affected by the upstream change in spill height. This indicates that the model is not simulating the effect of floodplain storage in the expected manner. Therefore the dynamics of the floodplain reservoir and spill units was investigated further to determine why this was the case.

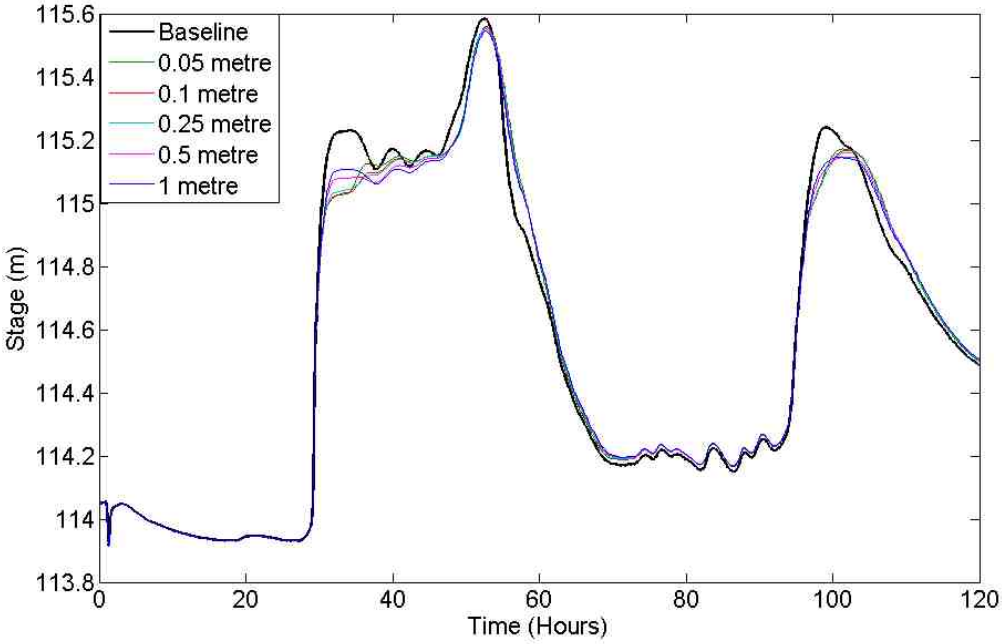


Figure 9.25 *Effect of changing spill height on the downstream hydrograph at Eamont Bridge (where the baseline represents the actual levee heights)*

It was found that the input of water to the floodplain is equal to the output of water from the floodplain back into the channel. This therefore results in very little if any storage of water on the floodplain, as water leaves the channel it flows straight back into the channel downstream. The way in which storage is represented in the iSIS-flow model is that water spills out of the channel and fills up reservoir units from their base. Water is stored in these units until the height of water storage exceeds the height of the spill to the next cell. Therefore this observation indicates that water is flowing instantaneously between the reservoir and channel, meaning that water is not stored. This process probably increases the speed of the flood wave as water is bypassing the channel and flowing over the floodplain. The reason why water flow across the floodplain is rapid is that the topography of the reach is so steep that water level in storage units quickly exceeds spill height. A similar observation was made by Tayefi *et al.*, (2007) for the Upper Wharfe in Yorkshire. A sensitivity analysis of channel and floodplain roughness was carried out by Tayefi *et al.*, (2007). It was expected that as channel roughness increases, then downstream peak discharge is decreased and delayed. This is because where roughness is increased; water stage is increased meaning that more water is stored on the floodplain. This expected result did not occur in the 1D-Storage model due to rapid floodplain conveyance. Tayefi *et al.*, (2007) concluded that

1D-Storage approaches should not be used for complex upland floodplains without carefull design of cells. This is because floodplain storage is represented in the 1D model by storage cells connected to the channel via spill units. Figure 9.26 shows that representing floodplains in this way is not a problem for shallow floodplains (low slope), and water is stored within the reservoir units (floodplain), but for steeper floodplains it may be more problematic with rapid flow of water over the steep floodplain. Furthermore, previous studies have raised concerns over the use of 1D hydraulic models in simulating situations with out of bank flows (Sellin *et al.*, 1993; Bates and Anderson, 1993), as the topography may significantly impact localised flow processes. These types of problems would not occur if a 2D hydraulic model was used, as these include inertia and advection terms which improve the representation of the floodplain processes and storage (Horritt and Bates, 2002).

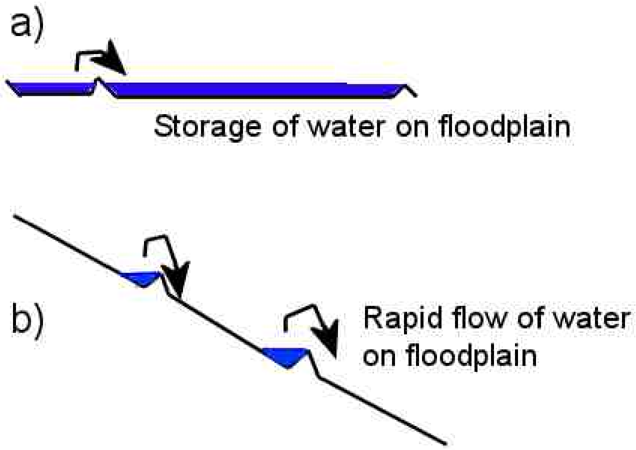


Figure 9.26 *Schematic of the effect of floodplain topography on floodplain storage and flow.*

It was therefore decided to use another approach to represent the floodplain in iSIS-flow, based upon extended cross sections. This approach may still be susceptible to some of the concerns and potential errors stated above, but the focus in this study was on the downstream effect of changing the roughness of the channel and floodplain, rather than the specific inundation of the local floodplain where the management scenario is tested. What is important in this study is that the model simulates the propagation of the flood wave well. Extended river cross sections were applied in four reaches. First, from Bampton to Green Crook (1.5 km), second from Green Crook to downstream of Whale Beck (2.0 km), third from Whale Beck to Crookwath Bridge (1.6

km) (Figure 9.27a/b) and finally the combined reach from Green Crook to Crookwath Bridge (3.6 km). Extended cross sections were extracted from LIDAR data, which has a 2 m resolution. Data were supplied in the form of a Digital Surface Model (DSM) and a Digital Terrain Model (DTM), with the vegetation and buildings filtered out. Supervised classification and filtering routines were carried out by the Environment Agency to form the DTM, which is a “bare earth elevation model”.

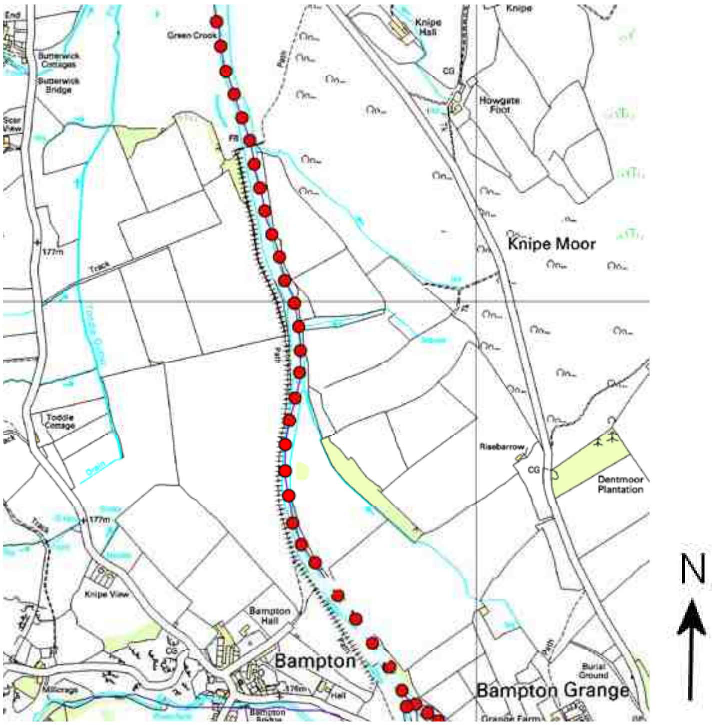
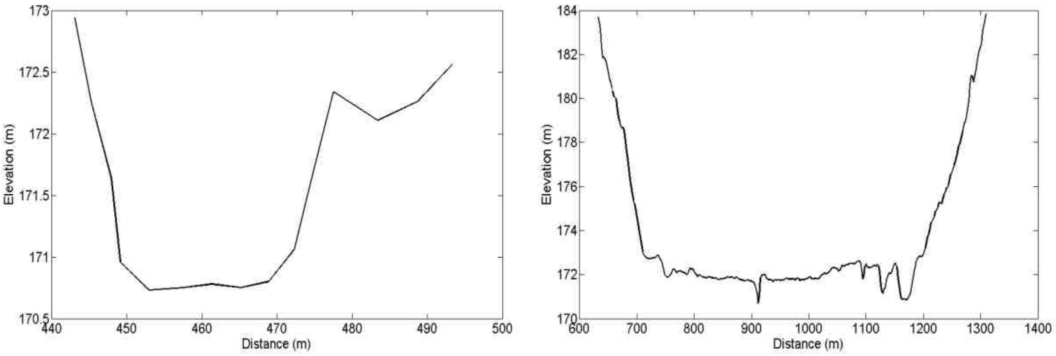


Figure 9.27a *Map of the Bampton to Green Crook reach showing cross section locations (red dots show locations of extended cross sections)*



a) Channel only   *b) Extended cross section for floodplain*

Figure 9.28 *Cross section of the Knipe Moor channel*

Figure 9.28 shows an example of the same cross section (Knipe Moor) for just the river channel and the extended floodplain cross section. It is clear that there is little floodplain on the right bank, but an extensive floodplain on the left bank.

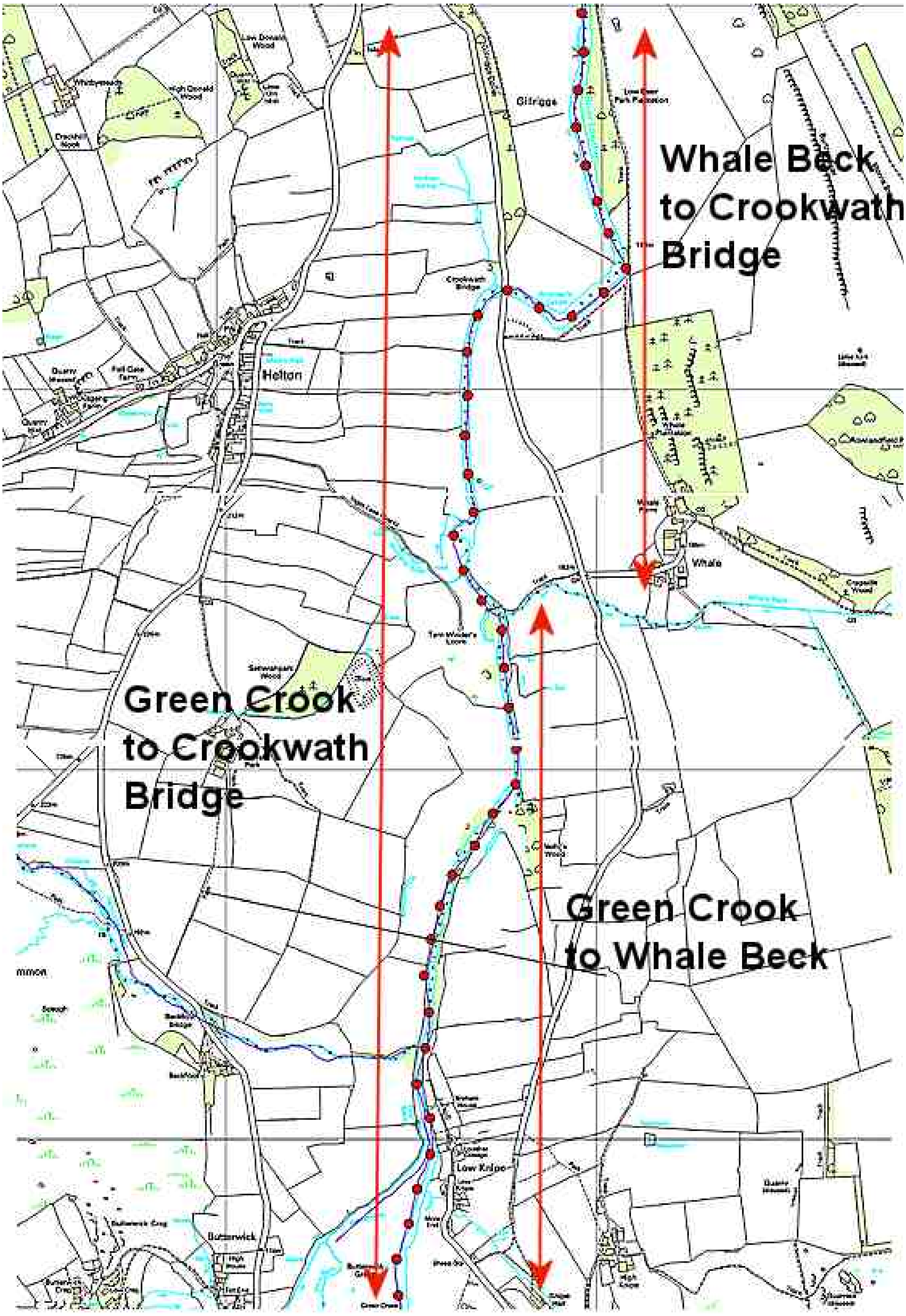


Figure 9.27b *Map of the Green Crook to Crookwath Bridge reach showing locations of cross sections.*

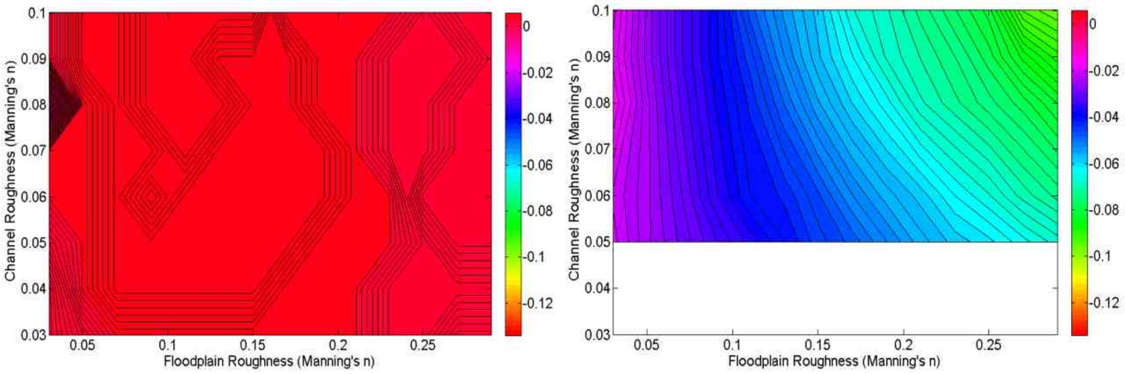
9.3.3. Effect of changing floodplain roughness

Different Manning's n values were chosen to represent the roughness of the channel and the floodplain. For the channel, values from 0.03 to 0.1 were used at a 0.01 interval, while for the floodplain values of 0.03 to 0.29 at an interval of 0.02. It has been suggested that Manning's n values of 0.03 for the channel represents a typical river channel and 0.05 for the floodplain represent a grassland or arable land cover (Chow, 1959). The maximum value of 0.1 was chosen for the channel, to represent a complex multiple channel stream structure with debris dams. The maximum value of 0.29 was chosen for the floodplain as this represents wet woodland, with a particularly dense understory and fallen trees (Thomas and Nisbet, 2007; Nisbet and Thomas, 2008). These values of Manning's n represent a wide range of roughness values, which may be particularly difficult to implement in practice.

The results of the analysis of the sensitivity of sub-catchment peak stage magnitude and timing to channel and floodplain roughness are assessed in the following section. The effects at various stations along the Lowther were assessed, both upstream of the changes at Bampton Grange and directly downstream of these changes at Askham and Eamont Bridge. The results at the sub-catchment scale are first described at the downstream end of the Lowther at Eamont Bridge. Contour plots show the impact of a range of roughness contributions, with the discussion concentrating on the maximum roughness scenario (Channel = 0.1, Floodplain = 0.29). As the maximum roughness scenario may be difficult to achieve in practice, it is useful to consider the whole continuum of roughness scenarios shown in the plots.

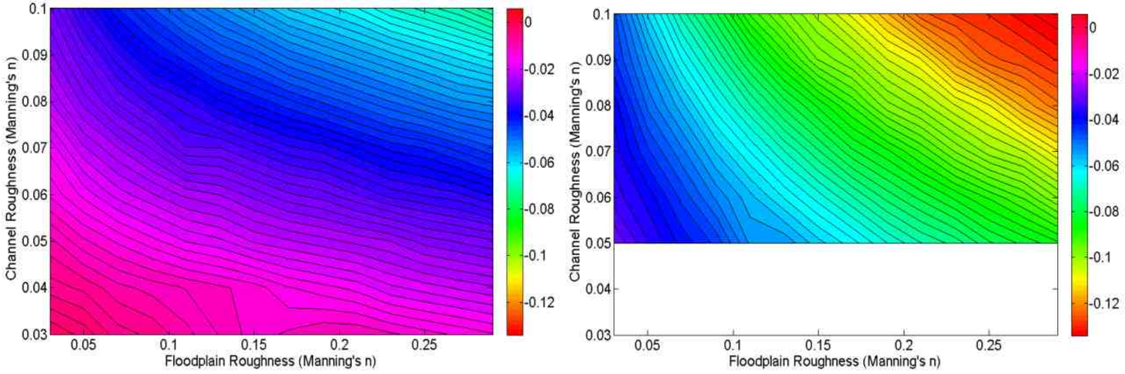
The impacts on the first and larger of the two flood events at Eamont Bridge varied considerably depending on where the channel/floodplain modification scenarios were implemented in the model. The reach from Bampton Grange to Green Crook had a minimal effect (less than 6mm) on downstream peak stage at the sub-catchment scale (Figure 9.29a). Furthermore, the introduction of rougher channel and floodplains in this reach made downstream flood peaks higher, although the peak flow was delayed by up to 15 minutes (Figure 9.30a). The second reach from Green Crook to Whale Beck could only be tested for channel roughness values from 0.05 to 0.1 (Figure 9.29b), as the model was unstable and did not run with lower channel roughness parameterisations. This reach was significantly more effective in affecting the downstream peak stage than the previous reach. The roughest scenario (channel 0.1, floodplain 0.29) resulted in a 0.10 m reduction in downstream peak stage. It was found that the downstream stage was more sensitive to the floodplain roughness than the roughness of the channel, although as the floodplain roughness increased the effect of the channel roughness became greater. The same roughest scenario led to a 90 minute delay of the peak stage downstream (Figure 9.30b). The third reach from Whale Beck to Crookwath Bridge (Figure 9.29c) was less effective than the second reach but more than the first. Lower channel roughness values had a minimal effect on downstream peak stage (less than -0.01 m), while the roughest scenario reduced peak stage at Eamont Bridge by 0.07 m. Furthermore, this reach delayed the flood wave less than the previous reach, with a maximum time delay of the peak flow of 55 minutes (Figure 9.30c). The last reach to be tested was the second and third ones combined. This reach had the largest effect on both the magnitude of the downstream peak stage and its timing. The roughest scenario resulted in a 0.13 m reduction (Figure 9.29d) and a 130 minute delay (Figure 9.30d).

Previous studies have shown that changing floodplain roughness to represent land covers such as wet woodland can have significant effects on the timing of the flows. Thomas and Nisbet (2007) found that a 50 hectare plot of woodland caused a time delay of 30 minutes and the whole floodplain in a 2.2 km reach (133 hectares) caused a time delay of 140 minutes. This latter scenario is only 2% of the catchment by area, indicating that changing relatively small areas can have significant impacts on the downstream flood hydrograph.



a) Bampton to Green Crook

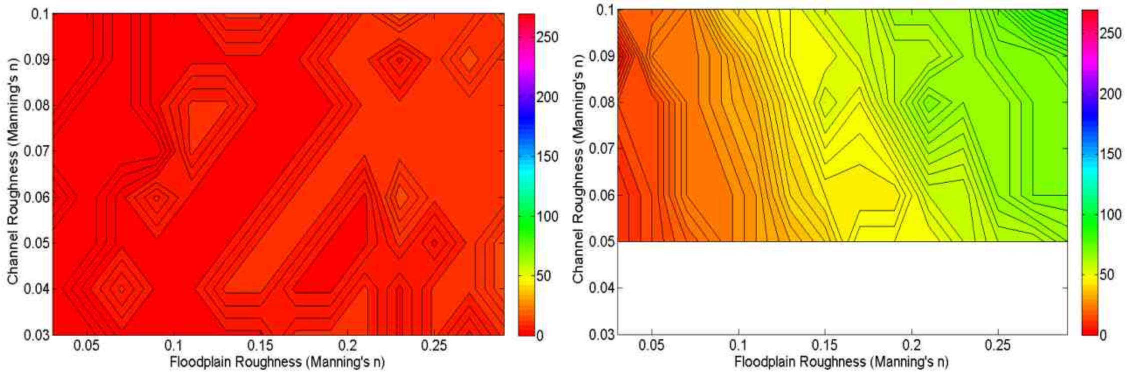
b) Green Crook to Whale Beck



c) Whale Beck to Crookwath Bridge

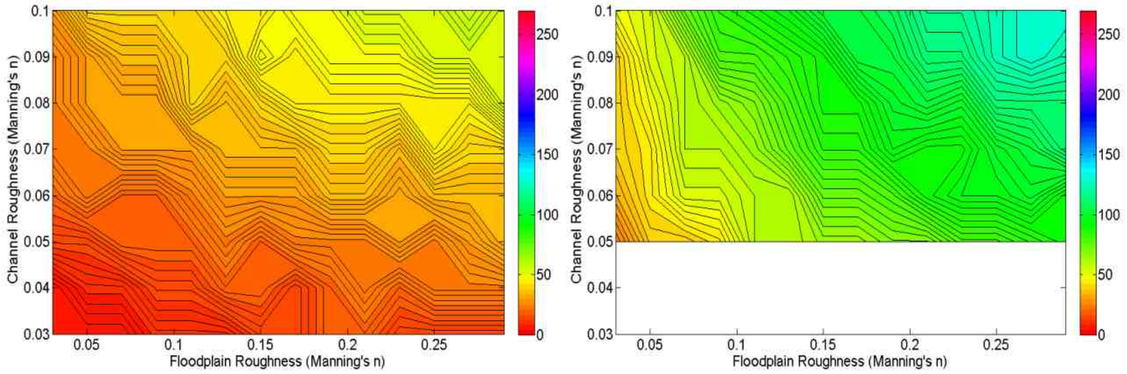
d) Green Crook to Crookwath Bridge

Figure 9.29 *Impact of roughness modification on sub-catchment scale (Eamont Bridge) flood magnitude for the 8th January 2005 flood event. Units are Stage in metres, where negative values are decreases.*



a) Bampton to Green Crook

b) Green Crook to Whale Beck

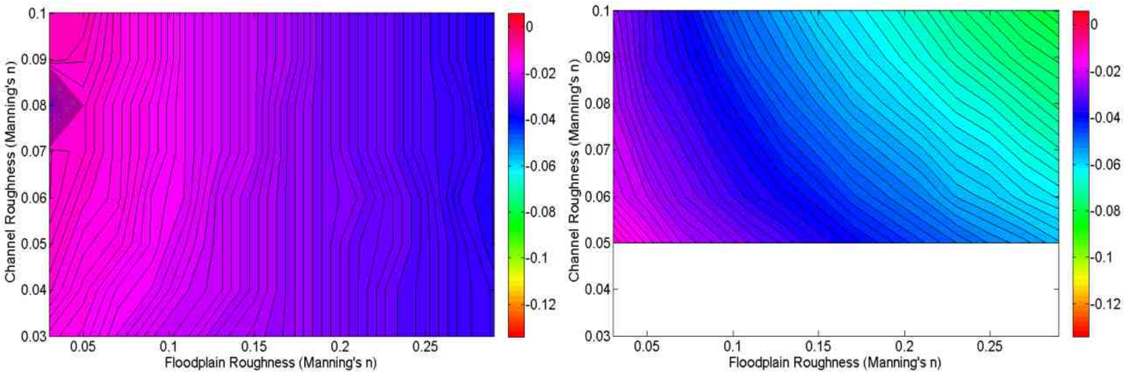


c) Whale Beck to Crookwath Bridge

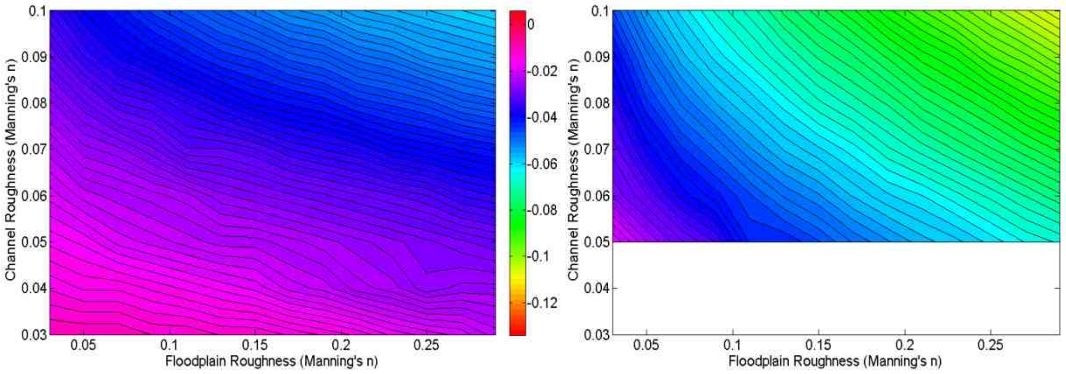
d) Green Crook to Whale Beck

Figure 9.30 *Impact of roughness modification on sub-catchment scale (Eamont Bridge) peak flow timing for the 8th January 2005 flood event.*

The effect of the same four reaches was then assessed on the second, slightly smaller flood a couple of days later. The Bampton to Green Crook reach had some effect on the smaller flood, with a maximum 0.037 m reduction in peak stage at Eamont Bridge (Figure 9.31a) and a 155 minute time delay (Figure 9.32a). The Green Crook to Whale Beck reach reduced the peak stage downstream by a maximum of 0.081 m (Figure 9.31b) and delayed it by 250 minutes (Figure 9.32b). The Whale Beck to Crookwath Bridge reach was less effective, with a maximum 0.059 m reduction in peak stage (Figure 9.31c) and a 170 minute time delay (Figure 9.32c). The combined reach from Green Crook to Crookwath Bridge had the largest effect on sub-catchment scale peak stage magnitude with a 0.107 m decrease (Figure 9.31d) and a 270 minute delay (Figure 9.32d). The only reach to have a greater reduction in downstream peak stage for the second smaller flood was the Bampton to Green Crook reach. All the other reaches had a greater effect on the larger flood event on the 8th January (Table 9.4). However, the channel and floodplain roughness scenarios had a greater effect in terms of the timing of the peak flow for the second smaller flood for all reaches. Figure 9.33 shows the stage hydrograph for the roughest scenarios in each of the four reaches compared to the baseline condition at Eamont Bridge.



a) Bampton to Green Crook *b) Green Crook to Whale Beck*

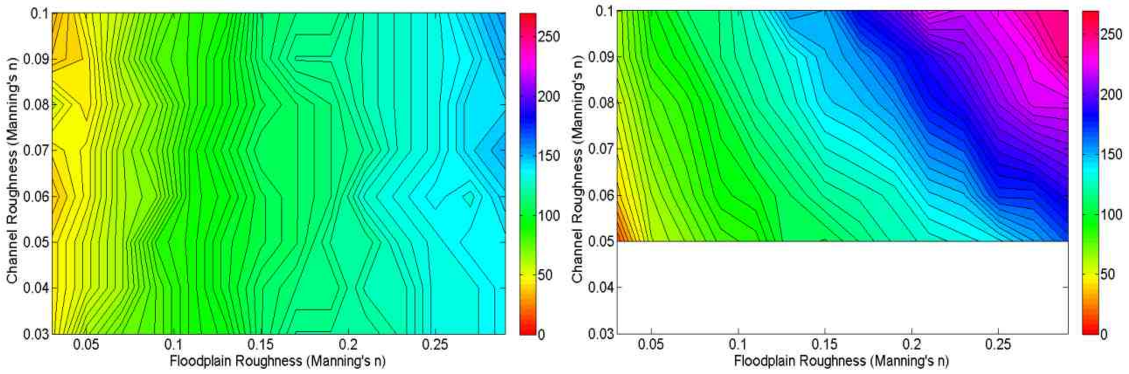


c) Whale Beck to Crookwath Bridge *d) Green Crook to Crookwath Bridge*

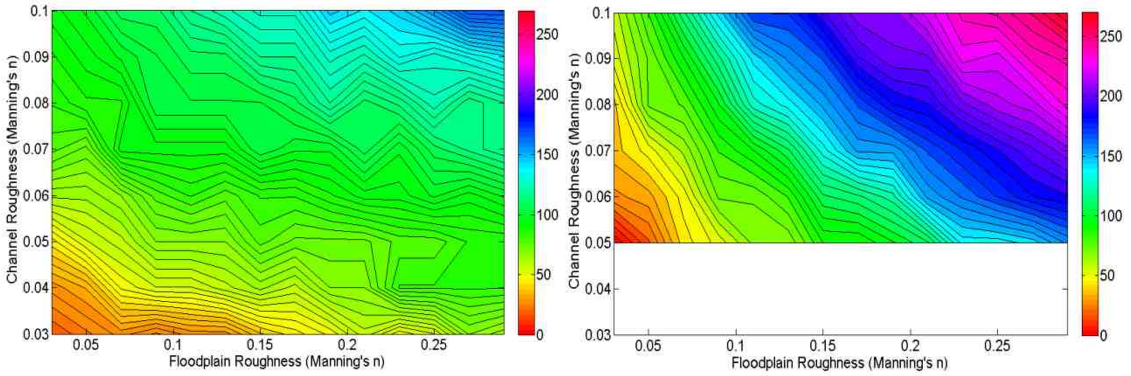
Figure 9.31 *Impact of roughness modification on sub-catchment scale (Eamont Bridge) flood magnitude for the 10th January 2005 flood event. Units are Stage in metres, where negative values are decreases.*

	Magnitude (Stage)		Timing (Hours)	
	1st Flood	**2nd Flood**	**1st Flood**	**2nd Flood**
Bampton-Green Crook	0.002 (0.002%)	-0.037 (-0.03%)	15	155
Green Crook - Whale Beck	-0.095 m (-0.08%)	-0.081 m (-0.07%)	90	250
Whale Beck - Crookwath Bridge	-0.072 m (-0.06%)	-0.059 m (-0.05%)	55	170
Green Crook - Crookwath Bridge	-0.134 m (-0.12%)	-0.107 m (-0.09%)	130	270

Table 9.4 *Comparison of the impact of the roughest scenario (channel 0.1, floodplain 0.29) for the four different reaches on the magnitude and timing of the peak stage for two floods at Eamont Bridge*



a) *Bampton to Green Crook* *b) Green Crook to Whale Beck*



c) Whale Beck to Crookwath Bridge *d) Green Crook to Crookwath Bridge*

Figure 9.32 *Impact of roughness modification on sub-catchment scale (Eamont Bridge) peak flow timing for the 10th January 2005 flood event.*

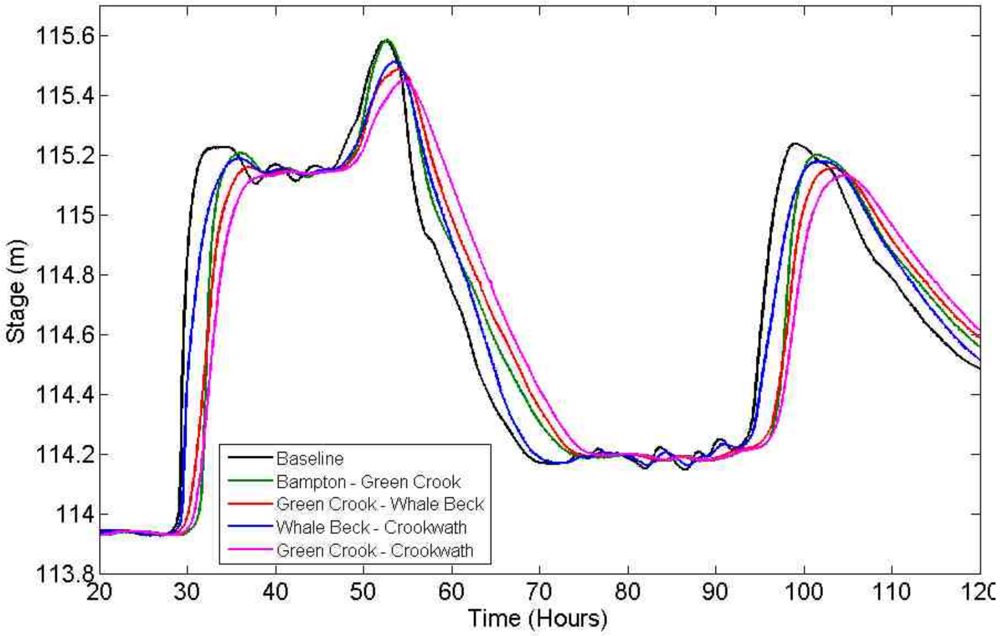
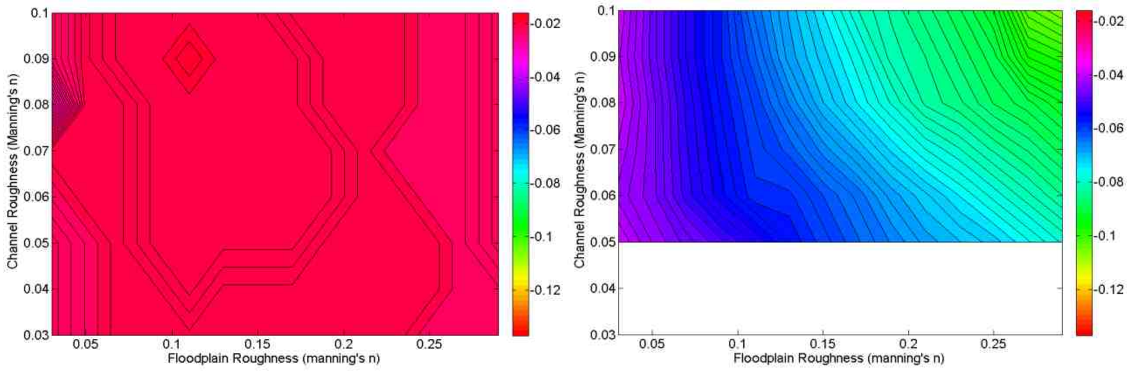


Figure 9.33 *Effect of the roughest scenario (channel 0.1, floodplain 0.29) for the four different reaches on stage hydrograph at Eamont Bridge*

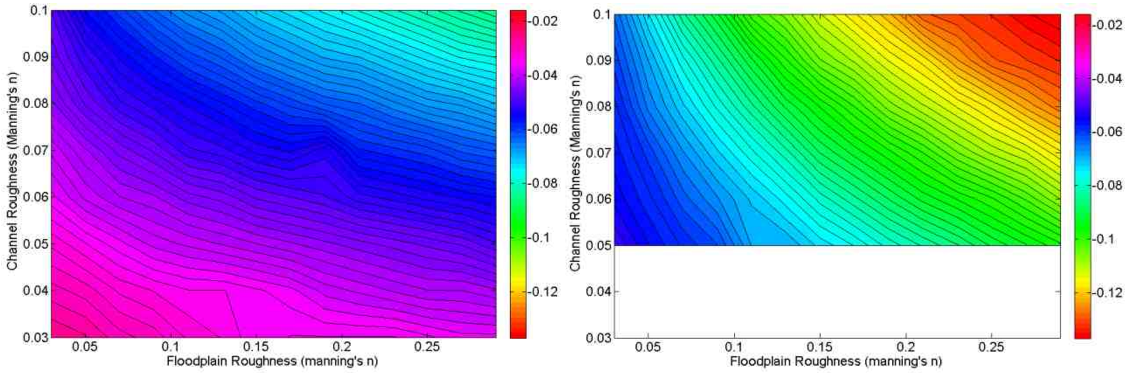
The effect of changing channel and floodplain roughness also needs to be assessed at other important settlements throughout the Lowther catchment. First, the village of Askham is looked at, which is just downstream of the reaches that are changed. This section takes the same structure as the analysis for Eamont Bridge above, with the timing and magnitude of the peak flow being assessed for the two flood events. The flood peak on the 8th January will be considered first. The Bampton to Green Crook reach reduced the peak stage at Askham by ~0.02 m (Figure 9.34a). However, it is interesting to note that by the time the flood wave reaches Eamont Bridge this effect has decreased to almost nothing, although the timing of the peak flow is not affected between Askham and Eamont Bridge, with the delay at Askham being 10 minutes (Figure 9.35a). The effect of increasing the roughness of the Green Crook to Whale Beck reach is to reduce the peak stage at Askham by 0.105 m (Figure 9.34b) and delay it by 85 minutes (Figure 9.35b). The third reach, Whale Beck to Crookwath Bridge, reduces the peak stage at Askham by 0.085 m (Figure 9.34c) and it is delayed by 1 hour (Figure 9.35c). The effect of combining these last two reaches, Green Crook to Crookwath Bridge has the greatest effect, with a 0.137 m (Figure 9.34d) decrease and a 130 minute delay (Figure 9.35d) of the peak stage at Askham.

The effect on the second smaller flood was greater than the larger flood for the Bampton to Green Crook reach, but smaller for the other three reaches. Furthermore, the order of which reach is most effective in changing downstream flooding is the same as for the first flood. The most effective at reducing downstream peak stage magnitude is the Green Crook to Crookwath Bridge reach, which causes a 0.109 m reduction in peak stage (Figure 9.36d), followed by the Green Crook to Whale Beck reach (-0.084 m) (Figure 9.36b). The third most effective reach is the Whale Beck to Crookwath Bridge (-0.064 m) (Figure 9.36c). The least effective is the Bampton to Green Crook reach (-0.042 m) (Figure 9.36a). In terms of the timing of the peak stage at Askham, all the modified reaches have a greater effect on the smaller flood than the first one. It has been shown that this can be up to 5.33 hours (Figure 9.37d) when the longest reach is altered to the roughest channel and floodplain (Table 9.5). Figure 9.38 shows the impact of the roughest channel/floodplain scenario in the four reaches on the stage hydrograph at Askham.



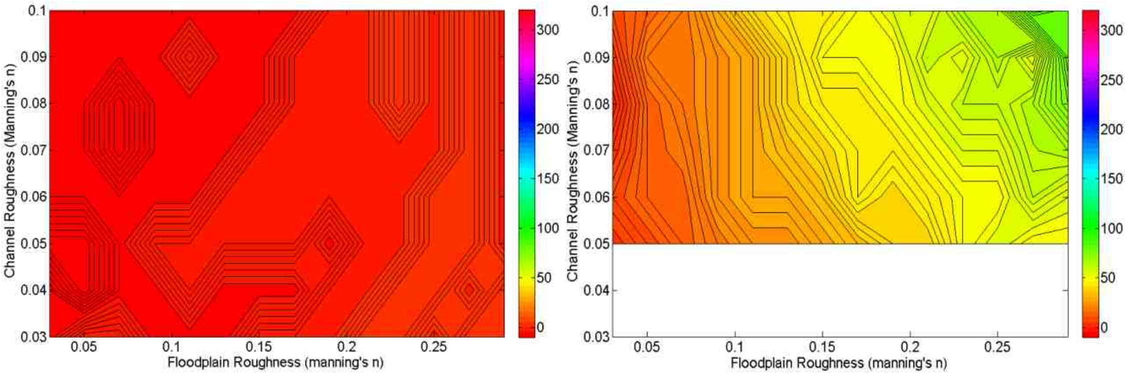
a) Bampton to Green Crook

b) Green Crook to Whale Beck

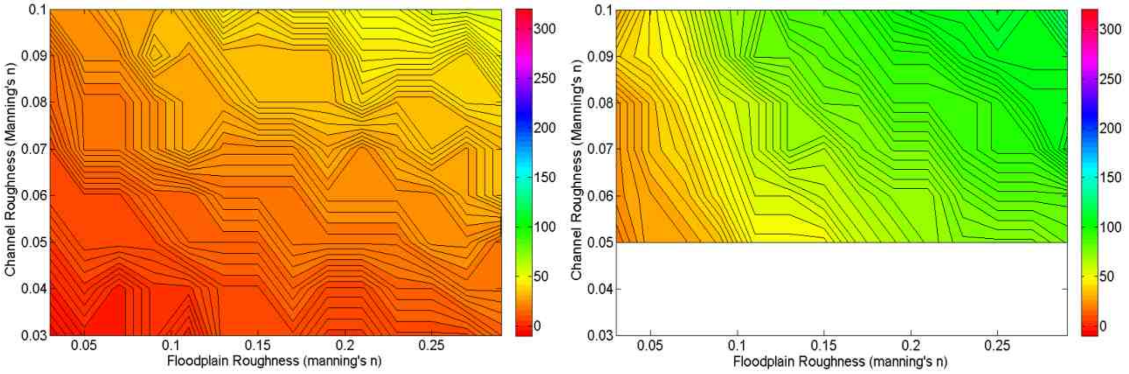


c) Whale Beck to Crookwath Bridge *d) Green Crook to Crookwath Bridge*

Figure 9.34 *Impact of roughness modification on sub-catchment scale (Askham) peak flow magnitude for the 8th January 2005 flood event. Units are Stage in metres, where negative values are decreases.*



a) Bampton to Green Crook *b) Green Crook to Whale Beck*



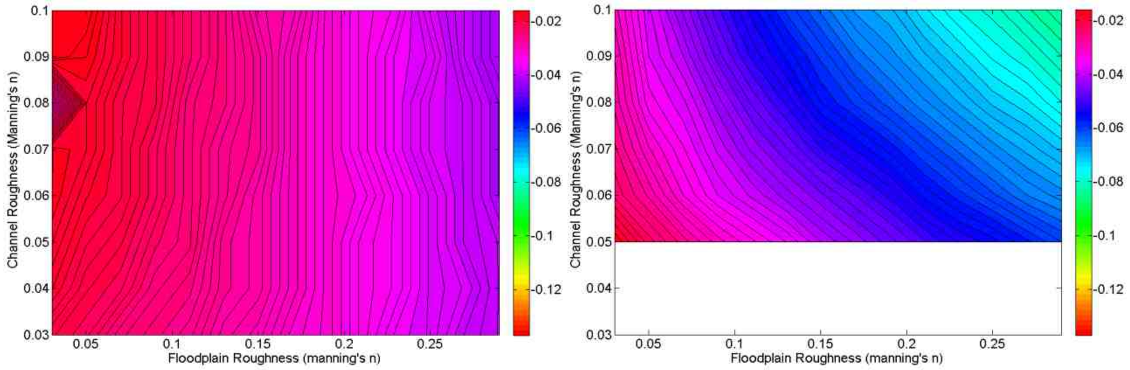
c) Whale Beck to Crookwath Bridge *d) Green Crook to Crookwath Bridge*

Figure 9.35 *Impact of roughness modification on sub-catchment scale (Askham) peak flow timing for the 8th January 2005 flood event.*

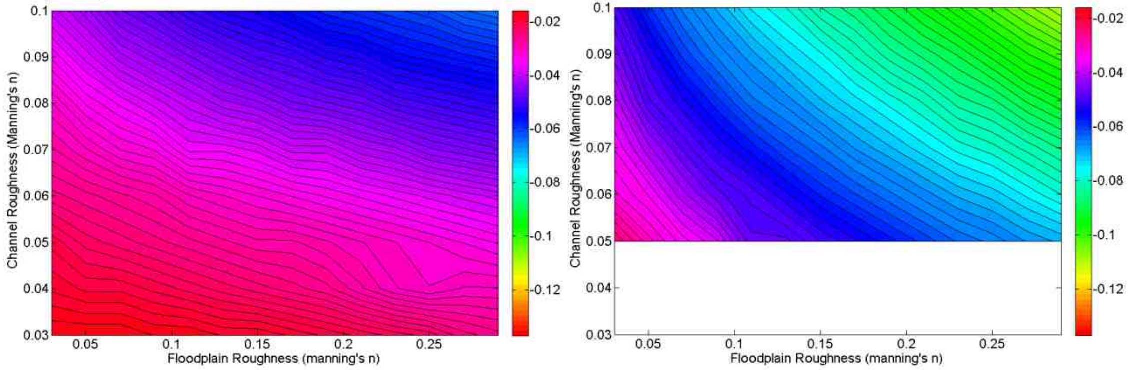
	Magnitude (Stage)		**Timing (Hours)**	
	1st Flood	**2nd Flood**	**1st Flood**	**2nd Flood**
Bampton-Green Crook	-0.023 m (0.01%)	-0.042 m (-0.03%)	5	150
Green Crook - Whale Beck	-0.105 m (0.07%)	-0.084 m (0.05%)	85	255
Whale Beck - Crookwath Bridge	-0.085 m (0.05%)	-0.064 m (0.04%)	60	160

Green Crook - Crookwath Bridge	-0.137 m (0.09%)	-0.109 m (0.07%)	130	320

Table 9.5 *Comparison of the impact of the roughest scenario (channel 0.1, floodplain 0.29) for the four different reaches on the magnitude and timing of the peak stage for two floods at Askham.*



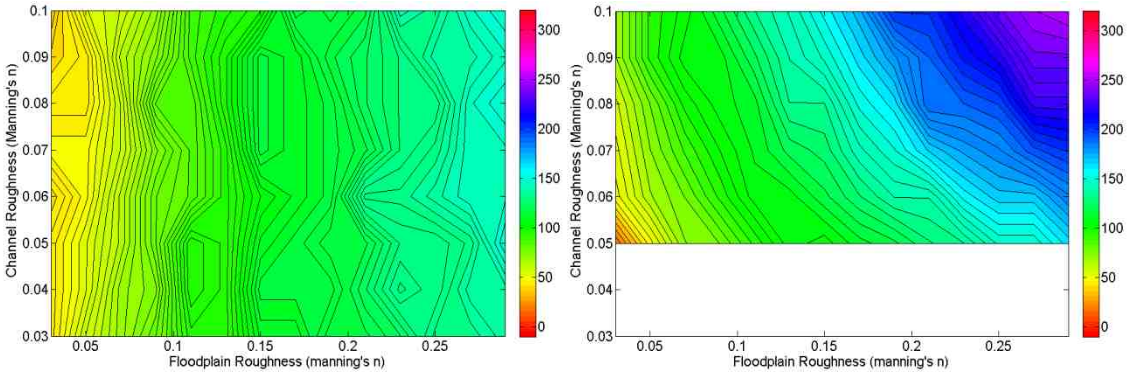
a) Bampton to Green Crook *b) Green Crook to Whale Beck*



c) Whale Beck to Crookwath Bridge *d) Green Crook to Crookwath Bridge*

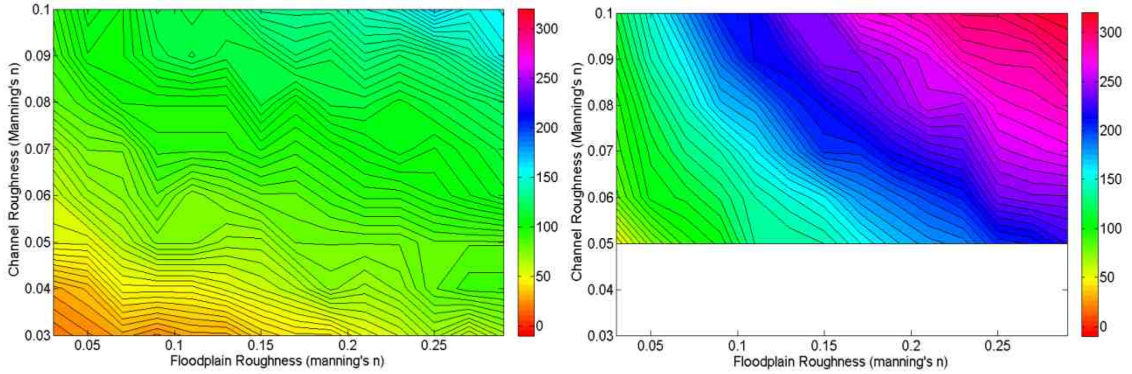
Figure 9.36 *Impact of roughness modification on sub-catchment scale (Askham) peak flow magnitude for the 10th January 2005 flood event. Units are Stage in metres, where negative values are decreases.*

It is interesting to compare the effect at Askham (just downstream of changes) and Eamont Bridge (sub-catchment outlet) to determine how the effect of the changes is attenuated and reduced as the flood wave travels downstream. It is impossible to compare these stations in terms of the effect upon the magnitude of the peak flow, as stage is a cross-section specific variable, and there is no rating curve to convert stage to discharge at Askham. However, the timing of the peak flow can be compared. Overall, the time delay at Askham is similar to the time delay at Eamont Bridge. This suggests that the effect of the land management change is not reduced as the flood wave travels downstream. The main reason why the flood wave is not affected between Askham and Eamont Bridge is that there are no major tributary inputs and the flow is contained within the channel for most of the time and reach. The only considerable change is for the second smaller flood for the Green Crook to Crookwath Bridge scenario, where the time that the peak stage is delayed by reduces from 320 minutes at Askham to only 270 minutes at Eamont Bridge.



a) Bampton to Green Crook

b) Green Crook to Whale Beck



c) Whale Beck to Crookwath Bridge

d) Green Crook to Crookwath Bridge

Figure 9.37 *Impact of roughness modification on sub-catchment scale (Askham) peak flow timing for the 10th January 2005 flood event.*

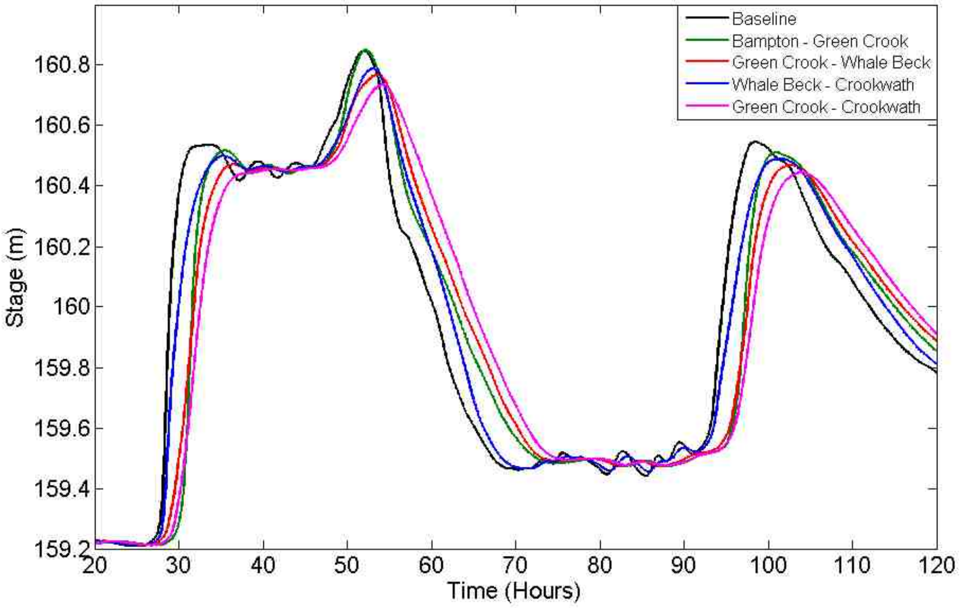
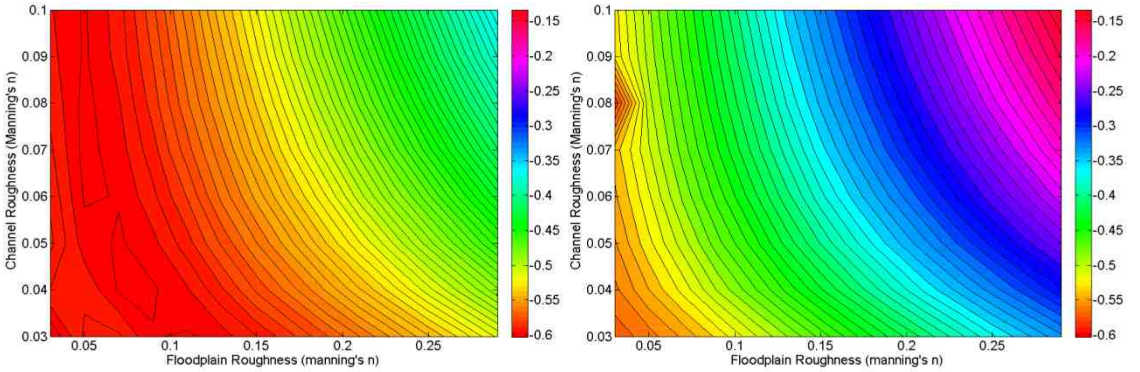


***Figure 9.38** Effect of the roughest scenario (channel 0.1, floodplain 0.29) for the four different reaches on stage hydrograph at Askham*

It is also important to assess the impact of the land management scenarios on locations upstream of the implementation. Bampton Grange is a village upstream of the four reaches where roughness has been increased. It has been shown that the reaches between Green Crook-Whale Beck, Whale Beck-Crookwath Bridge and Green Crook-Crookwath Bridge have no effect on the peak stage at Bampton Grange. Furthermore, the timing of the peak stage is not affected either. This is because the affected reaches are a sufficient distance downstream that the effects do not propagate upstream to Bampton Grange. However, the Bampton to Green Crook reach does affect flows at Bampton Grange as it is directly downstream of the settlement. However, peak stage is reduced in Bampton Grange by up to -0.603 m. This is because there is increased storage capacity for floodplain storage directly downstream of the village. As the roughness of the channel and floodplain increase, the amount by which the peak stage decreases in Bampton Grange reduces. The effects are greater for the first flood (Figure 9.39a), with peak stage being affected less in the smaller second flood (Figure 9.39b). This is different to a study by Thomas and Nisbet (2007) which found that local stage increased by 50-270 mm and the backwater effect propagated 400 m upstream of the where the floodplain roughness was changed. This difference is probably caused by the topography of the reaches, with the steeper topography in this study meaning that water does not build up and be stored causing no backing up of the flow.



a) 8th January flood *b) 10th January flood*

***Figure 9.39** Impact of roughness modification on upstream (Bampton) peak flow magnitude for the January 2005 flood events. Units are Stage in metres, where negative values are decreases.*

9.3.4. Summary of Floodplain management scenarios

The iSIS 1D hydraulic model has been used to test the floodplain management scenarios. The model was validated and was found to have a Nash Sutcliffe coefficient of 0.83 and a RMSE error of ±0.029 m for stage. The error on the magnitude of the peak stage was -0.5 m (0.43%) or -73.8 m^3s^{-1} (37.7%), with a timing error of 1.75 hours (3.45%). Firstly, reservoir cell units were used to represent storage on the floodplain. However, this was found to be problematic in this location as it was found that changing spill height had no effect on the downstream hydrograph. This was because there was no floodplain storage as water spilled from the channel onto the floodplain and immediately flowed back into the channel due to the steep topography of the area. This problem was also identified by Tayefi et al., (2007) for the River Wharfe in Yorkshire. Therefore, extended cross sections were used to represent the floodplain, with topographic data extracted from Lidar. Management scenarios such as wet woodland on the floodplain and debris dams in the channel were tested by changing the Manning's n values in the model. This was done for four reaches; (1) Bampton Grange to Green Crook; (2) Green Crook to Whale Beck; (3) Whale Beck to Crookwath Bridge; and (4) Green Crook to Crookwath Bridge. The largest downstream (at Eamont Bridge) reductions in peak stage were 0.107 to 0.134 m, by altering the Green Crook to Crookwath Bridge reach. A time delay of the peak flow by 130-270 minutes was also achieved by the scenario. However, these effects are only produced with large changes in channel and floodplain roughness. It was found that the greatest reductions in peak stage were for the larger of the two events simulated. Downstream peak stage was not affected by the Bampton to Green Crook reach, which is where the reservoir units were introduced originally. The downstream effect was similar to the localised effect in terms of the time delay on the flood peak. This implies that there was little attenuation of the flood wave as it propagated downstream, as there are no tributary inputs between the upstream and downstream gauging stations. The key conclusion from this scenario is that the downstream effect is highly dependent upon where the floodplain management scenario is implemented.

9.4. Upscaling the effects to the Catchment Scale

In this section the effects at the sub-catchment (Dacre Beck and Lowther) scale are upscaled to the sub-catchment (Eamont) and the catchment (Eden) scale. To fulfill the aim of determining the effect of land management scenarios at the catchment scale, a set of spatially nested models were developed (Figure 9.40). This consisted of the hydrological model, CRUM3, developed for Dacre Beck (sub-catchment), and hydraulic models developed for the Lowther (sub-catchment), Eamont (sub-catchment) and Eden catchments. This spatially nested approach works by inputting the simulation output from the prior, smaller scale into the next iSIS model.

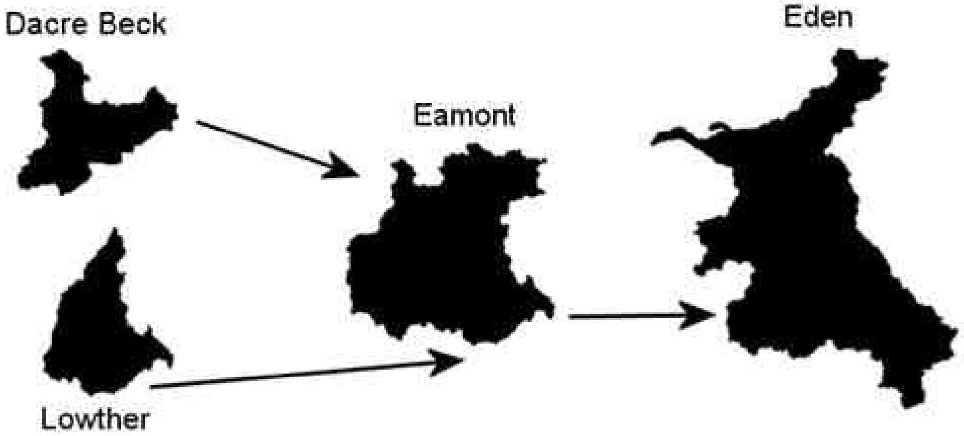


Figure 9.40 *Conceptual diagram of spatially nested modelling approach*

The Eamont model used the data from Mott MacDonald (2000), but excluded Lake Ullswater. This meant that the model started at Pooley Bridge gauging station and ended at the Eamont-Eden confluence. The output of the Lowther iSIS model is the input into the Eamont model. Other boundary conditions for this model include the outflow from Lake Ullswater at Pooley Bridge and Dacre Beck, along with other minor tributaries whose hydrographs were derived through using the Flood Estimation Handbook (FEH). Figure 9.41 shows the performance of the model, with the overall shape of the observed hydrograph being simulated by the model well. The magnitude of the peak flows are poorly predicted, with an error of -0.58% (-0.547 m) for the first peak and -0.41% (0.379 m) for the second flood peak in terms of stage (Table 9.6). When the rating curve is used to convert stage to discharge the peak errors are -139.3 m^3s^{-1} (35.1%) for the first peak and 78.9 m^3s^{-1} (29.7%) for the second peak. In terms of timing the peaks are quite well predicted, with an error of 0.5 hours (0.93%) and -0.25 hours (0.25%) for the first and second peaks respectively. The Nash-Sutcliffe coefficient of the Eamont model is 0.81 and the RMSE is ±0.034, which are within recommended limits found in the literature (Roughani *et al.* 2007; Wu and Johnston, 2008). Values of >0.65 are thought to be acceptable in hydraulic and hydrological models (Rouhani et al, 2007; Wu and Johnston, 2008).

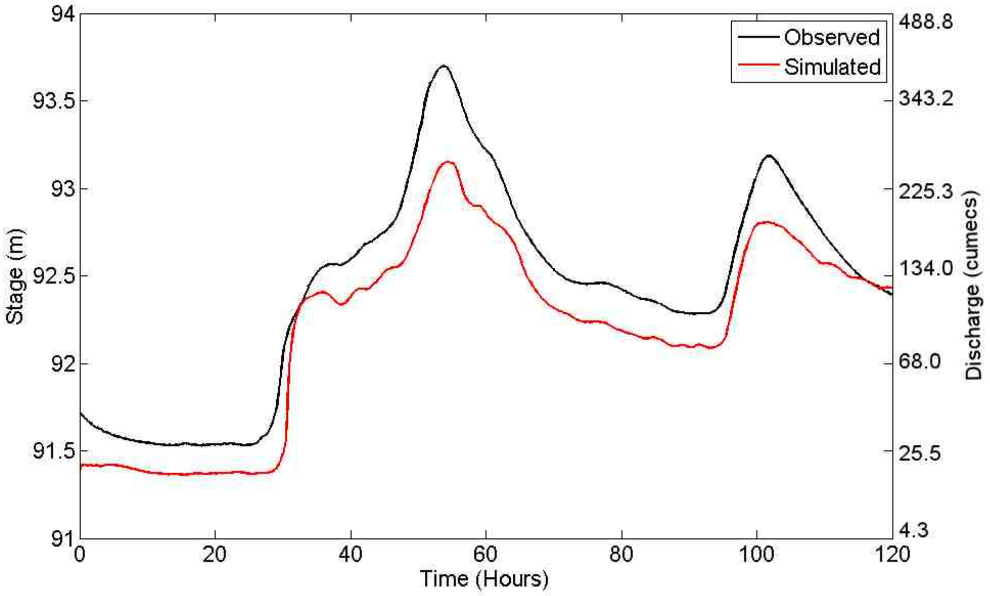


Figure 9.41 *Eamont iSIS model assessment for January 2005 flood at Udford*

	Udford Stage
Sum of Squared Residuals	32.4
Sum of Absolute Residuals	110.4
Nash-Sutcliffe Model Efficiency	0.81
Normalised Objective Function	0.0004
RMSE	0.034
Reduced Error Estimate	0.096
Proportional Error of Estimate	0.002
Standard Error of Estimate	0.034
% Error in Peak Stage	-0.58 (-0.547 m)
% Error in Peak Time	0.93 (0.5 hours)
% in Stage Mean	-0.25
Area for Observed	11126.2988

Area for Simulated	11098.7621
% Error in Volume	-0.25
Variance	0.067
Mean Deviation	0.23

Table 9.6 *Model assessment statistics for Eamont iSIS models.*

For the compaction and land cover scenarios, the outputs of the hydrological model (CRUM3) are inputted into the Eamont iSIS model as the Dacre Beck boundary condition. For the channel and floodplain roughness scenarios, the output of the Lowther iSIS model are inputted into the Eamont iSIS model as the Lowther boundary condition. The Eden iSIS model was outlined in Chapter 5.

9.4.1. Compaction

The results in this section cannot be compared to the actual gauged record at Udford as the errors involved in the hydrological modelling were too great to accurately reproduce the Dacre Bridge discharge hydrograph (Section 9.2.1). However, the results of the different levels of compaction can be compared relative to each other. The results in Table 9.7 and Figure 9.42 indicate that compaction in Dacre Beck makes a significant difference to the peak stage in the Eamont sub-catchment at Udford. The difference in peak discharge between light and heavy compaction in Dacre Beck was 24 m^3s^{-1} (65%). However at the sub-catchment (Eamont) scale the difference in peak stage is 0.168 m (0.18%) and the effect on peak discharge at Udford is 36.3 m^3s^{-1} (16.4%). This means that the effect of the compaction in Dacre Beck has been “diluted” by the effects of the other sub-catchments, but still makes a significant impact on sub-catchment flows. A possible reason why the effects of Dacre Beck are decreased at the Eamont scale is that Dacre Beck has a relatively small upstream contributing area (36 km^2). It was found in Chapter 6 that a 15% decrease in the magnitude of the flows from the Eamont sub-catchment reduced the peak stage at Sheepmount in Carlisle by -0.138 m. This converts to a 49.9 m^3s^{-1} decrease in peak discharge, which a 3.46% decrease.

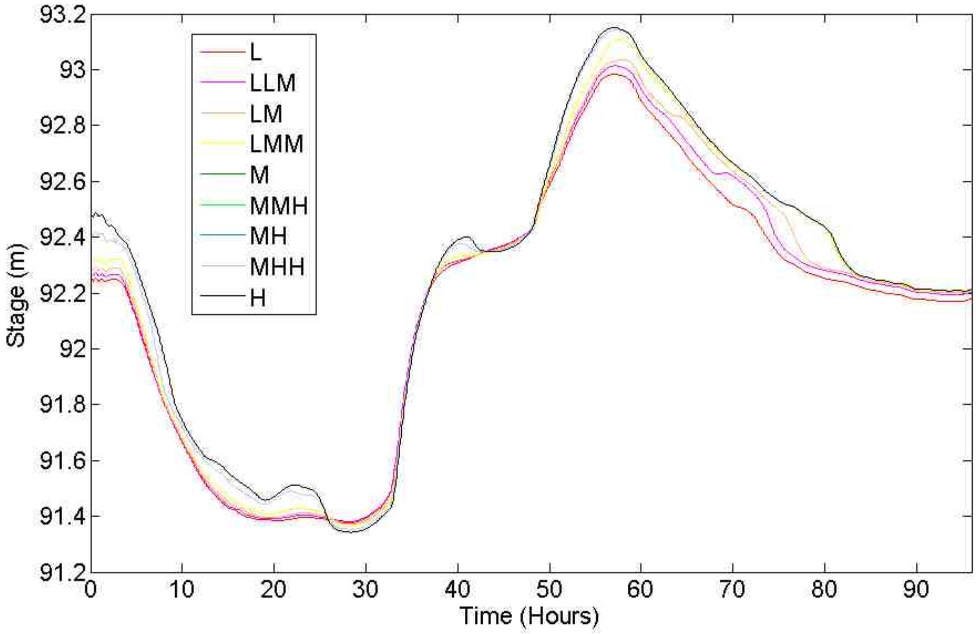


Figure 9.42 *Effect of compaction on peak stage at the sub-catchment scale (Eamont at Udford)*

Compaction	**Peak Stage (m)**	**% effect on sub-catchment scale peak stage**	**Peak Discharge (m^3s^{-1})**	**% effect on sub-catchment peak Q**
L	92.983	0.0	221.9	0.0
LLM	93.014	0.03	228.3	2.9
LM	93.035	0.06	232.8	4.9
LMM	93.107	0.13	248.4	11.9
M	93.142	0.17	256.1	15.4
MMH	93.142	0.17	256.1	15.4
MH	93.142	0.17	256.1	15.4
MHH	93.142	0.17	256.1	15.4
H	93.151	0.18	258.2	16.4

Table 9.7 *Effect of compaction on peak stage and discharge at the sub-catchment scale (Eamont at Udford)*

9.4.2. Land Cover

The results of the different types of land cover can be compared relative to each other. The results in Table 9.8 and Figure 9.43 indicate that land cover in Dacre Beck makes a significant difference to the peak stage in the Eamont sub-catchment at Udford. Arable land management was found to produce significantly lower flows than the other types of land use. The other three types of land cover were reasonably similar in terms of their effects on flows at the sub-catchment (Eamont) scale. Furthermore, it was found that converting from coniferous or pastoral land cover to arable land use saw just slightly less a reduction in peak discharge as reducing the level of compaction from heavy to light.

The effect of land cover on the timing of the peak flow was found to be quite small (up to an hour). The land cover which produced the earliest peak flow was the arable land cover, followed by the other three types of land cover which all peaked 0.66 hour later. This size of delay reduces the peak stage in Carlisle by between 0.011 m and 0.044 m. This corresponds to a 4.0 m^3s^{-1} (0.23%) to 15.9 m^3s^{-1} (1.1%) decrease in peak discharge. Bulygina *et al.*, (2009) found that afforestation delayed the peak flow by 15 minutes, while soil degradation (compaction) had no effect on the arrival time of the peak flow.

Land Cover	**Peak Stage (m)**	**% effect on sub-catchment scale peak stage**	**Peak Discharge (m^3s^{-1})**	**% effect on sub-catchment scale peak Discharge**
Arable	92.985	0.0	222.3	0.0
Pasture	93.13	0.16	253.5	14.0
Deciduous	93.113	0.14	249.7	12.3
Coniferous	93.137	0.16	255.0	14.7

Table 9.8 *Effect of land cover type on peak stage and discharge at the sub-catchment scale (Eamont at Udford)*

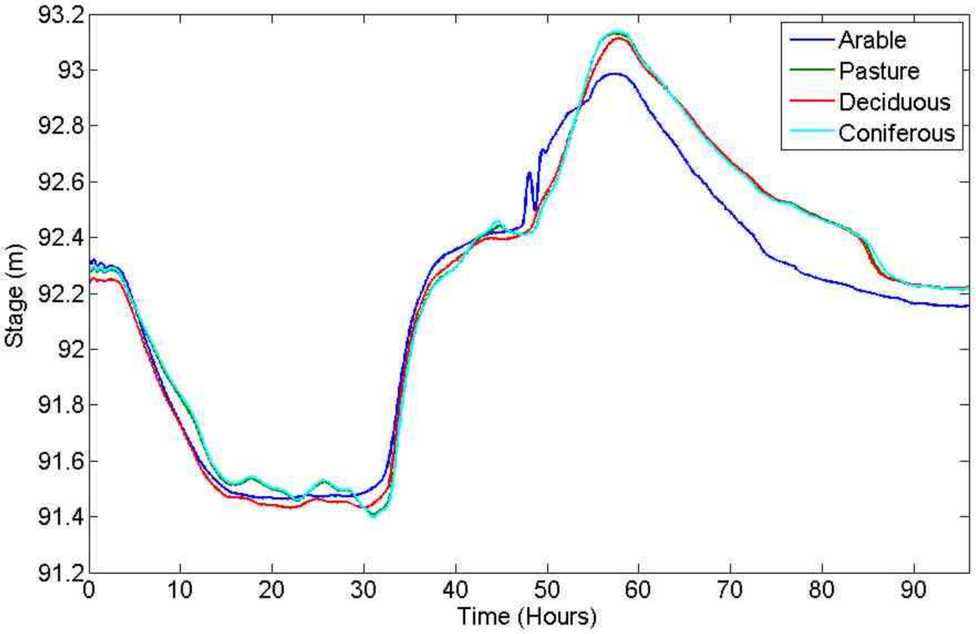


Figure 9.43 *Effect of land cover type on peak stage at the sub-catchment scale (Eamont at Udford)*

9.4.3. Channel and Floodplain Roughness

A selection of roughness scenarios were selected from the whole population to represent the whole range of possible environments, from wet grassland to wet woodland to really dense wet woodland, and hydraulically smooth channels to channels with debris dams and multiple channels. The results of these scenarios at Udford are shown in Table 9.9. Furthermore, the results of roughest scenarios in the four reaches are shown in Figure 9.44. The first observation is that the effect on peak stage magnitude is minimal (maximum of -0.052 m) (-0.056%). The scenario which resulted in this maximum was the roughest channel and floodplain in the Green Crook to Crookwath Bridge reach. This scenario resulted in a 0.107 m decrease (0.09%) in peak stage in the Lowther at Eamont Bridge. This suggests that as the scale of the catchment increases the effect on the peak stage decreases, due to propagation effects including sub-catchment interactions. However, the time delay for this scenario increases from 270 minutes at Eamont Bridge to 295 minutes at Udford. It was found in Chapter 6 that a 5 hour delay of the Eamont sub-catchment resulted in a peak stage reduction of between 0.167 m to 0.232 m at Sheepmount in Carlisle. This corresponds to a 60.3 m^3s^{-1} (4.18%) to 83.5 m^3s^{-1} (5.78%) decrease in peak discharge in Carlisle. Therefore, this highlights the importance of the timing of the peak flows in controlling downstream flooding. Using floodplain management scenarios to delay the peak flow has several potential benefits, including increasing the time for flood warnings to be issued and desynchronising flows from different tributaries. However, there are also potential implications of this, as flood peaks will be longer in duration and therefore may have consequences for consecutive events.

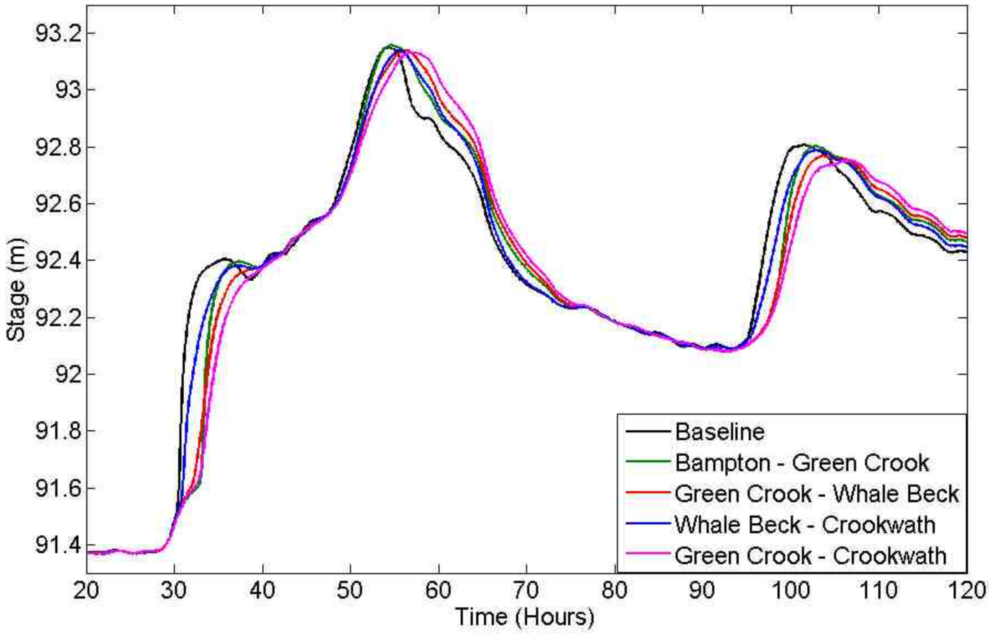


Figure 9.44 *Effect of channel/floodplain roughness modification on peak stage at the sub-catchment scale (Eamont at Udford)*

	0.03 0.03	0.03 0.15	0.03 0.29	0.05 0.09	0.05 0.21	0.06 0.03	0.06 0.15	0.06 0.29	0.08 0.09	0.08 0.21	0.1 0.03	0.1 0.15	0.1 0.29
Bampton- Green Crook	0.004	0.006	0.007	0.006	0.007	0.004	0.007	0.007	0.006	0.007	0.004	0.007	0.007
Green Crook-Whale Beck				-0.003	-0.002	-0.005	-0.003	-0.004	-0.003	-0.004	-0.002	-0.003	-0.009
Whale Beck-Crookwath	0.001	0.002	0.002	0.002	0.001	0.001	0.001	-0.001	-0.001	-0.003	-0.001	-0.005	-0.01
Green Crook-Crookwath				0	-0.002	-0.002	-0.001	-0.006	-0.003	-0.008	-0.003	-0.011	-0.017

Impact on peak stage (m) of the January 8th flood at Udford

	0.03 0.03	0.03 0.15	0.03 0.29	0.05 0.09	0.05 0.21	0.06 0.03	0.06 0.15	0.06 0.29	0.08 0.09	0.08 0.21	0.1 0.03	0.1 0.15	0.1 0.29
Bampton- Green Crook	10	5	15	5	10	5	10	15	5	10	10	5	15
Green Crook-Whale Beck				50	80	25	60	95	50	85	25	75	110
Whale Beck-Crookwath	0	35	35	40	45	30	50	55	50	60	45	70	75
Green Crook-Crookwath				70	85	50	85	115	75	120	60	110	160

Impact on peak time (minutes) of the January 8th flood at Udford

	0.03 0.03	0.03 0.15	0.03 0.29	0.05 0.09	0.05 0.21	0.06 0.03	0.06 0.15	0.06 0.29	0.08 0.09	0.08 0.21	0.1 0.03	0.1 0.15	0.1 0.29
Bampton- Green Crook	0.003	0.003	-0.003	0.005	0.001	0.004	0.004	-0.003	0.006	0.001	0.004	0.004	-0.004
Green Crook-Whale Beck				0	-0.009	0	-0.007	-0.02	-0.005	-0.019	-0.002	-0.017	-0.039
Whale Beck-Crookwath	0.001	0.002	0.001	0.002	0	0.001	0	-0.004	-0.003	-0.008	-0.004	-0.011	-0.017
Green Crook-Crookwath				-0.002	-0.015	0.001	-0.013	-0.033	-0.014	-0.035	-0.008	-0.037	-0.052

Impact on peak stage (m) of the January 10th flood at Udford

	0.03 0.03	0.03 0.15	0.03 0.29	0.05 0.09	0.05 0.21	0.06 0.03	0.06 0.15	0.06 0.29	0.08 0.09	0.08 0.21	0.1 0.03	0.1 0.15	0.1 0.29
Bampton- Green Crook	25	50	70	40	60	25	55	80	40	65	25	50	80
Green Crook-Whale Beck				40	65	20	55	100	60	95	30	90	130
Whale Beck-Crookwath	15	15	30	35	35	25	45	50	50	55	45	80	90
Green Crook-Crookwath				60	95	50	90	125	90	135	75	125	295

Impact on peak time (minutes) of the January 10th flood at Udford

Table 9.9. *Effect of channel/floodplain roughness on peak stage magnitude and timing at the sub-catchment scale (Eamont at Udford)*

9.5. Chapter Summary

This chapter has used numerical models to test the land management scenarios identified in Chapter 7. The landscape scale scenarios were tested using the hydrological model CRUM3. This was applied to the Dacre Beck sub-catchment at a spatial resolution of 20m for the time period October 2004 to December 2005. The Nash-Sutcliffe efficiency for the whole year is 0.31, with a mean deviation of -1.58 m^3s^{-1}, and a RMSE of ±4.66 m^3s^{-1}. However, the model performs much better for the January 2005 flood event with an error of -0.37% on the peak magnitude, and a Nash-Sutcliffe coefficient of 0.74 for the 10 days around the flood. The peak discharge was found to be most sensitive to the soil parameters including the saturated hydraulic conductivity; the porosity; the soil depth and the depth and the saturated hydraulic conductivity of the dynamic layer. The peak discharge was not particularly sensitive to the vegetation parameters. The scenario of compaction was tested, with heavy compaction producing a peak discharge 65% higher than light compaction. However, the difference between moderate and heavy compaction was quite small (3.7%). It was also found that as compaction levels increase, the low flows decrease, with the difference between the minimum flow between light and heavy compaction being 86.8%. These trends were explained in terms of the hydrological processes. It was found that runoff decreased by 17% between light and heavy compaction scenarios. The throughflow contribution of this runoff was 74% for lightly compacted soils, but decreased to 1.8% for the heavily compacted soil scenario. This can be explained by saturation of the heavily compacted soil never falling below 95%. The moderately compacted soil only reached saturation during the intense storm events, and may explain why the peak discharges of the moderate and heavy compacted soils were similar, as floods seem to be driven by overland flow in this sub-catchment.

The land cover scenarios found that the coniferous forest produced the highest peak flow (64.4 m^3s^{-1}), which is 5.1% higher than the lowest peak flow simulated by the arable agriculture land use. It was also found that the coniferous woodland and pastoral farming land covers produced the lowest minimum flows and well as the highest maximum flows. Runoff was found to be highest in the deciduous forest scenario (79-81%), but the throughflow contribution was sometimes greater than the surface runoff.

This circumstance did not occur for any other land cover type. This was caused by the deciduous woodland soil being at 90% saturation for only 13.7% of the time, compared to 28.7%, 62.8% and 65.4% for arable, pasture and coniferous land covers respectively.

The channel and floodplain roughness scenarios were tested using the hydraulic model iSIS, which was developed for the Lowther sub-catchment. The model was assessed and had a Nash-Sutcliffe coefficient for stage of 0.83, a RMSE error of ±0.029 m. However the error on the peak magnitude was -0.5 m (-73.8 m^3s^{-1}). Floodplain storage was first implemented using reservoir units. However, due to the steep topography, water flowed out of the river onto the floodplain and straight back into the channel downstream. Therefore the floodplain was represented by extended cross sections which were extracted from Lidar data. Channel roughness (Manning’s n) values of 0.03 to 0.1 were used to represent the whole range of channels from smooth channels to ones with multiple channels and debris dams. Floodplain Manning’s n values of 0.03 to 0.29 were used to represent floodplain land uses including wet grassland to dense wet woodland. Four reaches of the Lowther were tested. The maximum peak stage reduction at the sub-catchment scale was found to be 0.134 m from the maximum roughness scenario in the Green Crook to Crookwath Bridge reach. It was found that there was little attenuation of the flood wave between Askham and Eamont Bridge, as the time delay is similar in both locations. Furthermore, there is little impact upstream of the land management changes in the village of Bampton Grange. An important finding from this hydraulic modelling is that the location where the scenario is implemented significantly affects the impact it has both locally and at the catchment scale.

The sub-catchment scenario impacts were then upscaled to the intermediate scale (Eamont) and large catchment scale (Eden) using a nested modelling approach. The outputs of the sub-catchment models already summarised were inputted into the Eamont iSIS model. The assessment statistics for this model include a Nash-Sutcliffe coefficient of 0.81, an RMSE of ±0.034 m and an error of 0.58 m on the peak stage magnitude at Udford. The transition from light to heavy compaction increases the peak discharge at Udford by 36.3 m^3s^{-1} (16.4%). Converting from an arable land cover to a pastoral, coniferous or deciduous land cover increases peak discharge by 14.0%, 14.7% and 12.3% respectively. It was found in Chapter 6 that a reduction of the Eamont flow hydrograph by 15% resulted in a decrease in the peak stage at Sheepmount in Carlisle by 0.113 m. These landscape scale scenarios result in the peak discharge being delayed by up to 0.66 hours, which results in a decrease in the peak discharge in Carlisle by 0.011 m to 0.044 m. The channel/floodplain scale modification scenarios only result in a minimal effect on peak stage at the catchment scale at Udford (maximum of -0.052). However, the roughest scenario in the Green Crook to Crookwath Bridge reach results in a 295 minute delay of the peak stage at Udford. It was found in Chapter 6 that a 5 hour delay of the Eamont flood wave results in a 0.167 m to 0.232 m decrease in the peak stage at Sheepmount in Carlisle at the whole Eden scale. Therefore overall this Chapter has shown that local scale land management changes, such as compaction, land cover conversion and channel/floodplain roughness can impact flood hazard at a whole range of spatial scales, from the sub-catchment (Dacre Beck, Lowther) scale to the intermediate (Eamont) scale to the whole catchment (Eden) scale. Furthermore, the effect has been shown to not necessarily decrease as the spatial scale increases due to the relative timing of the peak flows from the sub-catchments playing a significant role in determining peak flow magnitude downstream.

Chapter 10

Conclusions

10.1 Chapter Scope

This chapter summarises the findings of this thesis and revisits the main thesis aims and objectives. The overall aim of this thesis was: *to investigate the potential impact of rural land management for catchment scale flood risk reduction.* To achieve this aim and to increase the likelihood of finding a link between land use changes and catchment scale flooding two complementary approaches have been used. The first identifies those areas to be most important in determining downstream flood magnitude, recognising that this is a challenging task because a number of variables (e.g. tributary peak flow magnitude; relative peak flow timing) may interact in complex ways. The second identifies which management practices are scientifically testable and practically feasible in the specific area identified. Previous research has shown that the effects of different land uses have different effects in different areas. It is therefore key that the questions of “where to focus on?” and “what to do there?” are answered simultaneously through the question “Where to focus and what to do there?”. Therefore, the main conclusion of this thesis assesses whether it is possible to identify particular locations in large complex catchments where land management measures might reduce flood hazard across a range of spatial scales.

The first part of this thesis (Chapters 4, 5 and 6) answered the first part of this question, while the second half of the thesis answered the second part (Chapter 7 and 8) and the question as a whole (Chapter 9). This chapter is structured around the answers to these two parts of the question and the whole question, focussing on the objectives outlined in Chapter 1

10.2 Where to focus efforts? - Spatial Downscaling of Flood Risk

The potential of downscaling the downstream problem, (i.e. flood risk), to the upstream causes (i.e. sub-catchments) was tested in Chapters 3 to 6. However, this approach relies on there being a downstream problem of flood risk. This was the focus of objective 1 and was addressed in Chapters 3 and 4.

1) *To assess the problem of flood risk in the case study catchment (River Eden) including how the frequency and magnitude of flooding has changed over different spatial and temporal scales, and the potential drivers of these changes.*

Firstly, the data on which a large amount of this thesis is dependent upon was evaluated. It focussed on the discharge data and concluded that for the chosen gauging stations the quality of the gauged flows at high flows is good enough for the analysis to be worthwhile. Therefore the gauged data were analysed for flood trends in terms of flood frequency and magnitude at different spatial and temporal scales. The most notable flood event of recent decades was the January 2005 extreme flood in Carlisle. This event, when put into a longer term context, was found to be significantly larger than any previous flood event on record. It was calculated that there is an average of 4.2 flood events at Sheepmount in Carlisle every year, where the definition of a flood used the Q1 value as the threshold. The frequency of floods in the Lower Eden was found not to change significantly over time. Furthermore, it was found that flood magnitude has not changed significantly over the last 30 years. However, some sub-catchments experienced more events than others. For example, the Upper Eden at Kirkby Stephen, the Irthing and Caldew all had more frequent floods than the other sub-catchments. Flooding in the Eden catchment was found to be a winter phenomenon, with 60% of floods occurring between December and February. Furthermore, the highest magnitude events occurred in January and February.

To put these short term trends, or lack of trends into a longer timescale context, documentary evidence was used to construct a flood record since 1770, although the beginning of this record may be unreliable due to uncertainties over the reliability and completeness of evidence. It is clear that there are distinct flood rich and flood poor periods throughout the record for the Eden at Carlisle. Flood rich periods have been defined as 1873-1904, 1923-1933 and 1994 to present. Possible explanations for this finding were explored, including climate change, assessed through Lamb weather types, and land use change. It was found that 5 weather types (Cyclonic, Westerly, South-Westerly, Cyclonic Westerly, Cyclonic South-Westerly) were responsible for 90% of the floods in Carlisle over the last 30 years. Furthermore, 51.4% of these events had one of these flood generating weather types on the previous two days as well as the day of the event, highlighting the importance of antecedent conditions. The link between these so called flood generating weather types and long term flood frequency was explored and it was found that there was a strong correlation between flood rich periods and a higher proportion of the year being one of these weather types. Previous studies have shown a link between flood rich periods and the North Atlantic Oscillation being in a strong positive phase (Wilby *et al,* 1997). Others have shown a link between the NAO and the frequency of Westerly weather types (Jones *et al,* 1997). Therefore this research has completed the "Chain of Causality" (Lawler *et al.,* 2003) and shown a link between weather types and flooding. The alternative hypothesis of land use change has in previous research proved elusive. Trends in such change have been strongly correlated with flood risk (Lane 2003), but causation has not been proved (Lane *et al,* 2007). This is because it is difficult to separate the land use signal from the climate change signal in the flood record. The Defra FD2120 study could not find any trends in UK flood series which could be attributable to land use changes, but conclude that this absence of a trend does not necessarily indicate that land use does not affect flood risk. Therefore, it was decided that this thesis would use a numerical modelling approach rather than using observed data to attempt to find a link between land management and flooding at the catchment scale.

Once the extent of the problem had been assessed the spatial downscaling approach could be developed and applied to the Eden catchment: Objective 2.

2) *To determine which areas (sub-catchments) of the catchment are the most important in explaining downstream flood risk in terms of both the magnitude and timing of the flows.*

    a) *To develop methodologies that are able to achieve this*
    b) *To apply these approaches to the Eden catchment*

There are three main benefits of adopting such an approach; (1) the optimum sub-catchment which explains downstream flooding the most can be identified; (2) the optimum sub-catchment can be focussed upon, meaning efficient use of time and resources; this is particularly relevant to hydrological modelling, where the size of the catchment and spatial resolution influence data demands and model run time; and (3) targets can be determined for how much the flow from each sub-catchment need to be changed to have the desired impact downstream.

Two approaches have been developed to downscale catchment scale flood magnitude to the contributing sub-catchments. The first is a statistical method, whereby the magnitude and timing of the peak flow are extracted from gauged data for several events. Principal components analysis is used to simplify the sub-catchment interactions and stepwise regression is used to predict downstream flood magnitude from them. Approaches have also been developed to assess the uncertainty of these predictions. The second approach uses numerical modelling, specifically the hydraulic model iSIS-flow. The approach consists of a sensitivity analysis of downstream flood peak stage to the magnitude and timing of the flows from the contributing sub-catchments. The Eden iSIS model was re-written based upon a previous model supplied by the Environment Agency. The model was calibrated using the January 2005 flood event and optimised for the peak stage. The performance of the model was assessed using statistics, with a Nash Sutcliffe coefficient of 0.85, and a RMSE of ±0.67 m. The error on the peak stage was -1.45% (0.208 m) and 3.25% (1 hour) in terms of magnitude and timing respectively. It was decided that this was within the limits of previous research using hydraulic modelling and therefore the model could be applied to the downscaling purpose (Roughani *et al.,* 2007; Wu and Johnston, 2008).

The results of the statistical approach showed that 83.4% of downstream peak flow magnitude could be predicted using the magnitude (49.4%) and timing (34.0%) of the peak flows from each of the contributing sub-catchments. This highlights the importance of the relative timing of the peak flows from each of the tributaries and how the peak flows interact. However, 16.6% of downstream flood magnitude could not be predicted from the peak flow magnitudes and relative timing of the sub-catchments. There are several reasons why this might be the case. First, and obviously, something is not being captured in the inputs to the regression analysis. This could be caused by input data being restricted to the instantaneous peak flow, rather than accounting for the whole flood event. Other reasons could be that flooding characteristics other than the magnitude and relative timing of the peak flows influence downstream flood magnitude.

These could be the duration of the event or the shape of the storm hydrograph. These factors are considered within the second hydraulic modelling approach.

It has been found that the Eamont sub-catchment is the most important in explaining downstream flood magnitude, accounting for 19.3%. Of this 11.2% is explained by the magnitude of the peak flow and 8.1% by the timing of the peak flow. However, there is a complex relationship between downstream flood magnitude and the timing of the flows, with the effect of delaying and speeding up the flow having a different effect. The result is that delaying the Eamont by 8 hours decreases downstream flood magnitude by 1.1%. The other sub-catchments are ranked in the following order of their effect on reducing catchment scale peak flows; Upper Eden (18.7%), Petteril (16.3%), Caldew (15.3%) and Irthing (13.8%). The importance of the Eamont is made even clearer when the results are standardised by catchment area. However, the proportion of downstream flood magnitude a sub-catchment explains is not the same as how changes to that sub-catchment influence downstream flood magnitude. Therefore a sensitivity analysis was carried out and it was found that changes to the magnitude of the Petteril had the greatest effect on catchment scale flood magnitude, while the timing of the Upper Eden was the most important. This is because the Petteril magnitude is important to both principal components, while the Upper Eden does not contribute to component 2. In the regression equation principal component 1 is more important than principal component 2, but the influence of the Petteril magnitude overall is more important than any other sub-catchment

The results from the second approach, using hydraulic modelling, also showed that the Upper Eden and Eamont were the most important sub-catchments. In terms of magnitude changes, a 25% decrease of the flows from these sub-catchments resulted in a 0.33 m and 0.22 m decrease in peak stage at Carlisle respectively. An 8 hour delay of these sub-catchments caused a 0.32 m and 0.27 m decrease downstream respectively. This shows that a 25% decrease in hydrograph magnitude is comparable to an 8 hour delay of the hydrograph. Scenarios when changes were made to both sub-catchments simultaneously resulted in a larger change downstream than if the shifts had been made separately, especially for the less extreme changes. A delay of the Upper Eden and Eamont by 8 hours each resulted in a 0.45 m decrease in peak stage at Carlisle. However, a delay of both tributaries by 4 hours each resulted in the same effect downstream as delaying just the Eden by 8 hours. Overall, this approach highlighted the importance of the Upper Eden as being the most effective sub-catchment. However, the flows from this sub-catchment are significantly higher than the others due to the large contributing area.

The results from the two approaches are comparable, although there are important differences between them, with the importance of the Upper Eden and Eamont being identified by both techniques. The effect on downstream stage by changing the magnitude of the flow of the upstream sub-catchments was very similar, while the modelling approach showed that the effect of timing was greater than suggested by the statistical approach. The importance of the timings of the peak flows and therefore how different sub-catchments interact with each other to determine downstream flood hazard is significant. It highlights another way in which land management change can be used to impact catchment scale flooding.

Overall, these approaches have been crucial in determining which area of the Eden catchment to focus upon. Changes to the Upper Eden and Eamont were found to have the greatest effect downstream. However, due to the significantly different areas of these sub-catchments, the Eamont has a greater effect per kilometre squared and was chosen for further study. This conclusion was supported by the data requirements of the modelling work. The Eamont had greater data availability in terms of discharge gauged data, river channel cross sections and Lidar, although it was less well-covered by rainfall data especially as compared with the Upper Eden. Furthermore, there is a flood problem within the Eamont at Bampton/Bomby and Eamont Bridge. Therefore, the effect of land management changes could be assessed at different spatial scales, both within the Eamont sub-catchment and at the whole Eden catchment scale.

Once the optimum area to focus upon had been identified, where changes to the sub-catchment output hydrograph would have the greatest impact on downstream peak flows, it was important to determine what land management practices can be used to achieve the targets set by the downscaling approaches.

10.3 Land Management Scenarios – What to do?

The possibility that land management practices might be used to reduce catchment scale flood risk remains unresolved. An often overlooked element of the debate is, regardless of the effectiveness of the measure, whether that measure can be delivered. Thus, stakeholder engagement was used to further increase the likelihood of delivery, combining scientific and local knowledge. This was the focus of Objective 3.

3) *To compile a list of potential land management scenarios which are both scientifically testable and practically feasible through stakeholder participation.*

Participatory scenario development is thought to offer "*a good mix of data, scientific rigour, imagination and expertise from different perspectives*" (Volkery et al., 2008, p. 460) and this was used to generate the land management scenarios that would be tested. This started with a brainstorming of ideas, which were then mapped on to a theoretical framework based on hydrological processes derived from the literature. The list of potential scenarios were then evaluated under five criteria; (1) relevance to the Eamont sub-catchment; (2) effectiveness at reducing downstream flood risk; (3) testability using models available; (4) robustness of techniques used to test them and the uncertainties associated with the results; and (5) the feasibility of actually being able to be implemented in the chosen areas. The stakeholder group considered this report and accepted certain scenarios and rejected others. Scenarios were rejected for different reasons, either relating to difficulties with scientific testing or past research findings or practical issues of implementation. The accepted scenarios were then ranked in order of the stakeholder groups priorities. This is a difficult task as different stakeholders have different primary interests, although it was found that several land management options had multiple benefits for the both high and low river flows, water quality and biodiversity, and hence were of appeal for many stakeholders.

The scenarios that were seen as high priority by the stakeholders were a mixture of both catchment scale landscape management changes (afforestation and compaction) and channel and floodplain scale scenarios (Channel/Floodplain roughness, Wet woodland, Channel naturalisation). Once the scenario to be tested had been decided it was important to determine the best location to test them in. Four approaches were used to do this; (1) a mapping workshop; (2) historical map evaluation; (3) a catchment walkover survey; and (4) an assessment of catchment hydrological connectivity through numerical modelling. It was decided that the Dacre Beck sub-catchment would be focussed on for the testing of the scenarios which affect the partitioning of rainfall into runoff processes. This was because of the types of land use in this sub-catchment and also the high hydrological connectivity between slopes and channel. The Upper and Middle Lowther were highlighted as being suitable for the testing and implementation of channel scale modifications. This was because of the current landscape uses; the remnants of old channel meanders and engineering of parts of the channel in this reach.

How these scenarios would be tested was then determined. The models chosen had to fulfil several criteria. Firstly, they had to be able to be set up for the chosen area with the data available. Secondly, they had to be able to simulate the land management changes chosen by the stakeholder group. Thirdly, they had be process based so that the effects of flooding could be explained in terms of actual hydrological processes. This was so that Objective 4 could be achieved.

4) *To determine the relationship between these land management practices and the different hydrological processes which influence downstream high flows, including*

   a) *Partitioning rainfall into runoff*
   b) *Hydrological Connectivity*
   c) *Storage*
   d) *Channel Conveyance*

The impact of each land management scenario was assessed in terms of the hydrological processes it affected. It is important to note that the hydrological model, CRUM-3, used to test the land management scenarios had quite considerable errors associated with it and therefore caution must be taken when interpreting the results. Compaction was found to influence the process of infiltration, runoff, storage and connectivity. Increasing the level of compaction from light to heavy decreases the amount of precipitation that is partitioned into runoff annually, and particularly affects the proportion of which flows through the surface and sub-surface pathways. Heavy compaction results in 17% less runoff than lightly compacted soils, although for the heavy compacted scenario 98% of this runoff occurs as rapid overland flow. This means that in heavily compacted soils, less water can be stored in the soil, and therefore saturation is more easily reached and initiates overland flows generating high peak flows. Furthermore, the lack of soil water storage means that low flows are less buffered, meaning that heavily compacted soils also result in lower minimum flows. It was also found that as the level of compaction increased, the amount of storage of water on the slopes increased. This suggests that hydrological connectivity between the landscape and the river channel would increase, further resulting in high flows.

The different land cover type scenarios also influenced the processes of infiltration, runoff, storage and connectivity. It has been found that deciduous woodland has the highest annual runoff rates (79-81% of precipitation), compared to arable farming that only leads to 72% of rainfall being partitioned into runoff. However, it has been found that a greater proportion of the runoff occurs through the slower throughflow pathway in deciduous woodland compared to any other land use. In fact sometimes a higher proportion of annual runoff occurred as throughflow than as overland flow. This means that deciduous woodland has lower high flows and higher low flows than the pastoral and coniferous land covers. Deciduous woodland also has a slightly lower rate of evapotranspiration than the other land uses. Furthermore, it has been shown that soil saturation levels are lower for the arable (28.7% of time above 0.9) and deciduous (13.7% time above 0.9) land covers than for pastoral (62.8%) and coniferous (65.4%) land uses.

Channel and floodplain roughness modification influences channel conveyance and floodplain storage. It has been shown that increasing the roughness of the floodplain has a greater effect than increasing the roughness of the channel. Increasing roughness has been shown to both decrease the peak stage magnitude by up to 0.134 m, but also significantly delay the peak flow by up to 5 hours. This is through the transfer of water to the floodplain, where the rate of conveyance is slower than in the channel. It is the effect on the timing of the flow which is most significant, as a similar quantity of water reaches the downstream outlet, just over a longer time period. The spatial downscaling approaches identified that it is the timing of the peak flows from each of the different sub-catchments, as well as the overall magnitudes of the peak flows that determine catchment scale flooding. The floodplain management scenarios have shown that these practices influence the timing of the peak flows more than they do the overall magnitudes of them. Therefore, the effectiveness of a land management technique on reducing downstream flooding may be more dependent upon how much it delays the flood wave, rather than reducing its magnitude. This highlights the importance of where land management scenarios are implemented for two reasons; 1) local scale factors such as topography and soil type effect whether a certain land management practice has a local scale effect or not; and 2) the spatial location where each land management scenario is implemented with respect to the channel network and each other determines how the different measures propagate downstream. However, the importance of the timing of the flows complicates the use of land management as a flood mitigation technique. This is because the timing of the flows is not just dependent on how the catchment filters the rainfall through it, but also on the timing of the rainfall in the first place. The spatial-temporal patterns in precipitation therefore means that the catchment scale effect of the same land management practice, in the same location could have two different impacts on downstream flooding. Furthermore, delaying flood wave propagation from tributaries may increase the time for flood warnings to be issued. However, a potential problem of delaying and attenuating peak flows from certain tributaries is that multi-day events may become more frequent and severe due to water levels being maintained at higher levels for longer periods, although this research has not shown this to be the case for the January 8th and 10th 2005 floods either in the Eamont sub-catchment or the whole Eden catchment.

5) *To establish the cumulative impact of different land use management practices on high flows, including the scales at which those impacts can be identified*

The cumulative effect of the land management scenarios at the sub-catchment, intermediate catchment and catchment scale have been determined. The landscape scale scenarios were tested in Dacre Beck. It was found that peak discharges varied from 36.9 m^3s^{-1} to 60.9 m^3s^{-1} for light and heavy compaction scenarios respectively, an increase of 65% (24 m^3s^{-1}). This shows that compaction has a significant effect on sub-catchment (36 km^2) flood hazard. At the intermediate Eamont scale, the difference between light and heavy compaction is 36.3 m^3s^{-1} (16.4%), with higher compaction levels producing higher peak flows. When upscaled to the whole Eden catchment this difference decreases to 3.5%. The conversion of arable land to coniferous woodland results in an increase in peak discharge by 5.1% in Dacre Beck. At the sub-catchment scale (Eamont), this effect increases to 14.7%, due to sub-catchment timing effects. Therefore the effects of converting from arable to coniferous woodland are similar to increasing the level of compaction from light to heavy at the intermediate sub-catchment and catchment scale. These landscape scale changes also result in a maximum time delay of less than an hour at the sub-catchment scale, which corresponds to a 4.0 m^3s^{-1} (0.23%) to 15.9 m^3s^{-1} (1.1%) decrease in peak discharge at the Eden catchment scale. Therefore it is the impact of these land management scenarios on the quantity of water which affects downstream flooding rather than the timing of the flows from Dacre Beck and the Eamont.

The effect of the channel/floodplain roughness scenarios resulted in a maximum decrease in peak stage in the Lowther sub-catchment of 0.134 m and a time delay of 4.5 hours. These resulted from the roughest scenario in the Green Crook to Crookwath Bridge reach. However, when this effect is upscaled to the Eamont sub-catchment, the effect on peak stage magnitude is minimal (maximum of -0.052 m, 0.06%). However, the peak stage is delayed by up to 5 hours (295 minutes) at Udford. A time delay of the Eamont results in a peak stage reduction of between 0.167 m to 0.232 m at Sheepmount in Carlisle. This corresponds to a 60.3 m^3s^{-1} (4.2%) to 83.5 m^3s^{-1} (5.8%) decrease in peak discharge in Carlisle.

Thus local scale land management changes, such as compaction, land cover conversion and channel/floodplain roughness can impact flooding at a whole range of spatial scales, from the small (Dacre Beck, Lowther) scale to the intermediate (Eamont) scale to the whole catchment (Eden) scale. Furthermore, the effect has been shown to not necessarily decrease as the spatial scale increases due to the relative timing of the peak flows from the sub-catchments playing a significant role in determining downstream peak flow magnitude. The most effective land management measure in reducing flooding at the catchment scale is the development of dense wet woodland in the Green Crook to Crookwath Bridge reach of the River Lowther, which can decrease peak discharge in Carlisle by up to 5.8%.

10.4 What to do and Where to do it?

A key finding of this thesis is that the same land management change has a significantly different effect depending where it is implemented. This was firstly shown by the differing effects of the different sub-catchments on downstream flood hazard, whereby the spatial downscaling analysis showed that the Upper Eden and the Eamont sub-catchments were the most important sub-catchments. However, it has further been demonstrated that changing the channel and floodplain roughness in different reaches of the same river can have significantly different impacts. The Bampton to Green Crook reach had only a minimal impact on sub-catchment peak flows, while the Green Crook to Crookwath Bridge had a far greater effect. The landscape scale scenarios of compaction and land cover conversion were tested for the whole Dacre Beck sub-catchment. However, there are problems in terms of applying the physically based hydrological model; CRUM3, to this catchment. This catchment was chosen due to the spatial downscaling methods identifying its importance in determining downstream flooding. Furthermore, stakeholders favoured the choice of this catchment due to the potential to implement land management practices there. However, there is a conflict between where it is best to do hydrological modelling in terms of research needs and in terms of where data availability meets modelling requirements. In this case, the rainfall gauged record has only a daily resolution. Daily rainfall was downscaled using a weather generator, but this approach is not ideal. The weather generator was developed for use in a semi-arid climate rather than the UK, and therefore does not stimulate sub-daily storms accurately in terms of their timing. This makes it impossible to stimulate sub-daily discharges using the hydrological model. This highlights the broader need for better monitoring of UK catchments in terms of both meteorological and hydrological variables. Furthermore, parameterisations of hydrological models limits there applicability as there is very little land use data at the same scale as hydrological models are developed i.e. at the field scale. Therefore it is unclear from this research whether the whole catchment has to be changed to have an impact on river flows, and if not what proportion needs to be managed and specifically which areas of the catchment. CRUM3 could easily be used to investigate these questions by using spatially distributed land cover parameters. However, there is a broader question of what values are given to the parameters to represent different land management practices. Through, extensive literature reviews for this thesis there was very little information on what values to give to the different soil and vegetation parameters to simulate land uses. Therefore, there is a need for better parameterisations of hydrological models.

6) *To produce a series of recommendations for what land management practices can be used to reduce downstream flood risk, and where to implement them.*

First, reducing the level of compaction can have beneficial impacts on both high and low river flows in the Dacre Beck sub-catchment. Second, different land cover types have been found to have different effects on river flow. Arable agriculture has the lowest peak flows, followed by deciduous woodland, pastoral agriculture and coniferous woodland. Finally, the most effective land management measure has been to increase the channel and floodplain roughness of the Green Crook to Crookwath Bridge reach of the River Lowther. This would involve restoring a more complex channel network, with multiple channels with debris dams and dense wet woodland on the floodplain. However, the scenarios which were favoured by the stakeholders and then found to have an impact on flooding at various spatial scales, such as floodplain management, reducing compaction and afforestation, have few incentives for land owners in terms of implementation. The main source of land management funding is from DEFRA in terms of their Environmental Stewardship schemes. Some of the relevant practices to this thesis are listed in Table 10.1. All these schemes are not specifically flood-oriented but do have multiple benefits. The scheme for livestock exclusion would be beneficial to flood hazard as soil compaction would be reduced. However, the arable to grassland conversion incentive may not have benefits for flooding, as this thesis has shown that pastoral fields produce a higher peak flow than arable agriculture. The wet grassland floodplain management scheme has been shown to have some beneficial impacts on flooding, but there are no incentives for introducing wet woodland on floodplains, which has a greater effect.

Management Scheme	**Financial Incentive**
Hedgerows	£27 / 100m
Woodland Restoration	£100 / ha
Livestock Exclusion	£100 / ha
Fallow plots	£80 / ha
Arable to Grassland conversion	£210 / ha
Wet Grassland	£335 / ha
Buffer Strips	£300 / ha

***Table 10.1**. Land Management practices included in Higher Level Stewardship offered by DEFRA*

10.5 Critical Evaluation of Methods and Results

This section critically reviews the problems with the methods used within this thesis and the limitations associated with the results obtained. Data was a crucial aspect of this thesis and there are the obvious errors associated with its measurement (Salas, 1993). As no data was collected specifically for this thesis, the data used was obtained through secondary sources. This means that there may be unknown errors associated with it. Chapter 3 both used advice from the sources of the data and evaluated it separately to assess the reliability of the gauged data. A key aspect for discharge data, which was the main type of data used in this thesis, was the rating relationship between stage and discharge. Another problem with the gauged record was the gaps within it. This posed problems for the construction of long term flow duration curves and also for some of the floods used within the statistical downscaling method. The infilling of these gaps were through traditional methods (Matalas and Jacobs, 1964; FEH, 1999), although a critical threshold is when interpolation becomes unfeasible and cross-correlation has to be used. This was determined to be a day, but this will still have caused problems in terms of missing flood peaks. Further data related issues are concerned with the record lengths. Most records were approximately 30 years, which was considered to be long enough to assess trends in flood frequency and magnitude, although these would still be susceptible to edge effects (Robson, 2002). Therefore some attempt to put these shorter term changes into a longer timescale context was made through the construction of a long term flood record. However, this used secondary sources only and therefore the accuracy of some of them were not collaborated. Other problems with the data are related to how it was used. Flow duration statistics are most unreliable at the extremes of flow (Young, 2002), which is an important consideration, as the focus of this thesis has been high flows. Furthermore, some of the analyses were done on arbitrarily defined categories, such as different magnitude events and decadal trends.

There were also problems with the spatial downscaling methodologies that were developed. Firstly, the statistical approach used variables which exhibited a non-normal distribution. Several statistical tests require normality as a prerequisite, although, principal components analysis is not one of them. However, to determine the proportion of each of the original variables accounted for by each component requires correlation, which does require variable normality. However, Lane (2003) states that analysis can precede but results should be interpreted with caution. The stepwise regression explained 83.4% of downstream flood magnitude from the sub-catchments peak flow magnitudes and relative timings. Furthermore, only 40% of these predictions are within the 95% confidence limits. This means that some variables that explain downstream flood peak magnitude are not included in the analysis. These could be the duration of the event, the flux of water through the system, or data from previous time steps (as this analysis just includes the peak flow).

There are also issues relating to the hydraulic modelling downscaling approach. The main problem relates to the uncertainties and errors associated with the Eden iSIS model. These have been quantified at three gauging stations: Great Corby; Linstock; and Sheepmount. Model calibration was mainly optimised for the downstream station of Sheepmount, which was used in further analysis. However, the model performance also needs to be assessed internally. This is because Lamb *et al.* (1998) and Clark *et al.* (2008) have shown that a model optimised at the catchment outlet does not necessarily guarantee correct within catchment response. Assessment especially at the Linstock gauging station suggests that sub-catchment interactions may not be correct for the upper catchment. Kuczera and Mroczkowski (1998) state that multiple types of data in different parts of the network would improve model validation. Another aspect of this is how model performance is assessed. In this study multiple assessment statistics were employed, although model performance was optimised for the flood peak. The criteria used introduce bias into the model calibration process (Johnstone and Pilgrim, 1976).

A comparison of the statistical and hydraulic modelling approaches showed that although general patterns were similar (i.e. that the Upper Eden and Eamont were the most important in determining downstream flooding), there were distinct differences in the findings of the two approaches. This raises some uncertainty over the conclusions drawn from this downscaling approach. Furthermore, it is important to consider whether the results would have been the same for different flood events, especially ones of different magnitude.

Further limitations of this research are related to the scenario testing methodologies, using hydrological and hydraulic models. The main limitation is that there was not time within this study to carry out a full uncertainty analysis of the models used. This was because this would have taken hundreds of model simulations, which was not feasible within the time constraints. Therefore, it is not possible to determine whether the predicted changes caused by the scenarios are distinguishable from the noise associated with model uncertainty. This means that results of the scenario testing should be viewed with caution, especially for the hydrological modelling. Another problem relating to the hydrological model was the rainfall input to the model. This was on a daily timescale and was downscaled using a weather generator that was not really suitable for the catchments climate. However, there was no better gauged rainfall data available, so this was the only option. However, this raises the wider issue of whether the quality and quantity of gauged data in UK catchments is high enough to support the data intensive physically based hydrological modelling that is used within this thesis, and many other studies. This is particularly important as the dialectic between where land management scenario testing would be most beneficial (as shown by spatial downscaling approaches and stakeholder engagement), and where there is data to support such research, is problematic. A broader problem with land management scenario testing studies relates to parameter uncertainty (Beven and Binley, 1992; Eckhardt *et al.*, 2003). This raises the issue of the physical meaning of model parameters and what the actual changes being simulated are. There is very little literature on the choice of model parameters for model use. Furthermore, it is debatable whether to make models effective and accurately simulate observed patterns, the physical meaning of parameters is lost and therefore makes land use change testing difficult.

The final limitation relates to the hydraulic modelling used to test the scenarios of floodplain roughness. A 1D hydraulic model was used for this purpose, as existing models were available and resources and time were not available to develop new ones. It was thought that using the iSIS model was suitable for its purpose, as it is believed that it could capture conveyance effects and accurately simulate downstream flows. However, it would have been beneficial to check findings with a more complex 2D hydraulic model, which have a better representation of the floodplain.

10.6 Concluding Remarks

This thesis has investigated the effect of land management on flooding at various spatial scales. By reversing the traditional approach to catchment hydrological research from upscaling local scale changes to the catchment scale, to downscaling the downstream flood risk problem to identify the most important contributing upstream causes (sub-catchments), it has made establishing a link between rural land management and catchment scale flood risk more likely. The first approach, a statistical methodology, confirmed the findings of a previous study by Lane (2003) that the peak flow magnitude and relative timing from the major sub-catchments explained a high proportion of downstream peak flow magnitude (>80%). Both downscaling approaches have highlighted the importance of the timing of the flows. Lane (2003) concluded that timing was a secondary critical factor to consider, and this thesis has confirmed and even corroborated the importance of this result. These downscaling approaches highlighted the importance of upstream sub-catchments in explaining catchment scale flooding which is the same as previous studies which found that the proximal sub-catchments to the outlet were the least important (Saghafian and Khosroshahi, 2005; Roughani *et al.,* 2007). This strengthens the possibility of using upstream rural land management as a possible option in mitigating downstream flood risk.

Stakeholder participation was used to derive the land management scenarios to be tested, along with specific locations for them to be tested in. This makes the numerical modelling approach more feasible along with scenario delivery in the catchment. This follows previous studies (Posthumus et al., 2008; Lane *et al.,* in press) where knowledge has been co-produced. The benefits for both the science researched and the management of the landscape have been shown to exist.

Both landscape scale changes, such as compaction, and local floodplain management do have an effect on high river flows at multiple spatial scales from the sub-catchment scale to the whole Eden catchment scale. The results from this study confirm previous modelling (Sullivan *et al.,* 2004; Bulygina et al., 2009; 2010) and field based studies (Evans, 1996; Orr and Carling, 2006) that have found that increasing the level of soil compaction increases localised runoff and flows. The magnitude of this effect has been shown to be large, which confirms Heathwaite (1989) which found that the amount of precipitation that was converted to runoff increased from 7% for an ungrazed field to 53% for a grazed field, compared to 20.5% to 63% respectively in this study. Few previous modelling studies have focussed on the effect compaction has on the hydrological processes that result in high river flows, and this thesis has shown the benefits of using a physically based hydrological model for this purpose. First, the level of confidence in the model predictions is strengthened, and second the reasons why compaction results in increased flooding can be analysed. This helps go beyond the correlation link between compaction and floods (Lane, 2003), and ascribe causation. It has been shown that the soil moisture content is a key control on flood generation, which confirms previous work by Holman *et al.,* (2003).

The land cover scenario, showed that both arable agriculture and deciduous woodland produced the lowest peak flows. However, it was shown that the differences in the soil characteristics under these different land covers was more important than the vegetation characteristics. This contradicts the conclusions of Lahmer *et al.,* (2001) who found that arable reversion had only a small impact on runoff, but influenced evapotranspiration and interception more. Bormann *et al.,* (2007) highlighted the uncertainty over the effects of land cover conversion. A possible reason for this is that there are many stages of development when land cover is changed which may have different effects. This has been most clearly shown by the work of Robinson (1998) and Archer (2003) in terms of the effects of afforestation. Therefore it is difficult to compare field based results with the modelling results in this thesis, as these scenarios represented a homogenous mature land cover, while in catchments there is a mosaic of areas at different stages of development.

Reach scale channel and floodplain roughness modifications also have a significant impact on all scales of flood hazard. However, the specific reach where changes are made determines the magnitude of the effect downstream. This conclusion is strengthened by contrasting results of previous work by JBA Consulting (2006) and Thomas and Nisbet (2007). JBA Consulting found that wet woodland scenarios resulted in a reduction in peak flows by only a few cumecs and small time delays. Thomas and Nisbet (2007) found that although reductions in peak stage were minimal at the reach scale, the effects on the time delay of the peak flow could be up to 140 minutes. The results of this thesis are the same as the Thomas and Nisbet (2007) study.

Furthermore, it has been shown that the relative timings of flood peaks from different sub-catchments are important in determining the magnitude of floods at the catchment scale. It is the effect of channel and floodplain roughness on attenuating the peak flow by up to 5 hours which sees the greatest peak stage reduction in the city of Carlisle.

The importance of relative timing of the flows from different sub-catchments means that the effect of land use on catchment scale flooding may not be as simple as initially thought. The conceptual model of Bloschl *et al.,* (2007) (Figure 2.7) shows that as catchment scale increases, the impact of land use on flooding decreases. The results of this thesis contradict this model, in that the effect of wet woodland at the sub-catchment scale in terms of decreasing peak stage was less than the effect at the whole catchment scale. This can be explained by the land use change causing a significant time delay of the peak flow at the sub-catchment scale, which means that the sub-catchment where the change was made interacts with the other sub-catchments differently, reducing downstream flood levels. Therefore the link between land use and catchment scale flooding is both spatially and temporally dependent i.e. the same land management practice has different effects depending on where it is implemented, and when implemented in the same location has different effects on different flood events.

In conclusion, the approaches used within this thesis sort: (1) to identify which sub-catchment to focus land management scenario testing in for optimum impact on downstream flood risk; and (2) to upscale localised effects on high flows to the catchment scale for transfer to different catchments. A potential future research aim to see how transferable these techniques are, as they are highly dependent on data availability. Other potential future research objectives resulting from work done in this thesis are:-

- Exploring the impact of the landscape and floodplain management scenarios on floods of different magnitudes. It has previously been thought that land management signals can only be found for smaller events. This thesis has shown that land management practices can have some impact on extreme events like the January 2005 flood provided they are properly targeted.

- Placing the current state of the catchment in the context of the findings of the land management scenarios. This would be done by asking questions such as: how compacted is the catchment?; and what proportion of the catchment is under each land cover type? This would be done through field experimentation to assess the soil characteristics. However, this assumes that point soil measurements are the same as the values needed to make hydrological models effective.
- Determining what proportion of the catchment needs to be managed in a certain way to see an effect at the catchment scale. This thesis has found that if the whole sub-catchment of Dacre Beck compaction level was reduced then downstream flood risk would be reduced. Furthermore, as the importance of the location where measures are implemented has been highlighted as being significant, then where in the catchment should land management be changed to have optimum effects?
- Determining the real effect of the different land management scenarios on real surface runoff and river flows. This would be done through monitoring of the catchment at several spatial scales (i.e. field, small sub-catchment, intermediate sub-catchment, catchment) both before and after implementation of the land management scenarios. Experimental design would have to be clearly thought out to try and overcome problems of natural variability in quasi-experiments.
- Improving parameterisation of hydrological models for testing land management scenarios. This would be done through measurement of soil properties under different types of management. Furthermore, the ecological literature and collaboration with ecologists may yield useful ways forward in parameterising hydrological models.

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