MORE FLOODS, LESS RAIN? CHANGING HYDROLOGY IN A YORKSHIRE CONTEXT

Stuart N. Lane
School of Geography
University of Leeds
LEEDS LS2 9JT

E-mail: s.lane@geog.leeds.ac.uk

Reproduced from

Atherden, M., 2003, (Ed.)
Global Warming in a Yorkshire Context

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School of Geography
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Introduction

November 2000 witnessed some of the worst floods on record to have affected our region; water levels in York were amongst the highest ever measured. Several individuals, including the Deputy Prime Minister, took these floods to be confirmation of a shift to a period of more frequent and higher magnitude storm events associated with climate change. The aims of this paper are: (1) to assess the extent to which floods in York are indeed becoming more frequent and high in magnitude; and (2), to identify and to hypothesise reasons for the patterns that emerge in answer to (1). The focus of the work is the River Ouse, at York, and the associated major contributing catchments (the Swale, the Ure and the Nidd). As such, it builds upon an earlier study by Longfield and Macklin (Longfield, 1998; Longfield and Macklin, 1999), that identified the need to explore land management issues as well as climate change in order to understand the York flood record.

Catchment characteristics for the tributaries of the Yorkshire Ouse upstream of York

The City of York lies on the River Ouse and receives inputs from three key sub-catchments (the Swale, the Ure and the Nidd), and two minor catchments (the Foss and the Kyle) (Figure 1a). Thus, the hydrology of the Ouse is heavily influenced by the behaviour of upstream river systems that extend into the South Pennines and the Yorkshire Dales. In addition to these upstream influences, the installation of Naburn Weir in 1759, at the downstream end of the study reach, resulted in a profound change in river behaviour. Prior to this installation, the Ouse from Myton-on Swale (the confluence of the Ure and the Swale) through York was affected by tidal cycles.

Each of the three main sub-catchments (the Swale, the Ure and the Nidd) rise on the Eastern edge of the Yorkshire Dales and Southern Pennines and enter relatively well-developed valley systems. The basin geology comprises: (1) millstone grits and carboniferous limestone in the upper catchment; (2) a piedmont zone consisting of Permo-Triassic magnesium limestone and mudstone; and (3) the Vale of York, comprising Quaternary glacial and alluvial deposits overlying Permo-Triassic Sherwood sandstone. The Kyle and the Foss, as shorter rivers that drain the Vale of York, have relatively under-developed and basic drainage networks. The main sub-catchments have drainage networks that reflect the overall relief of each sub-catchment. In the upper part of each catchment, these are strongly dendritic. Each river system follows the main valley. As it approaches the lower gradient sections of the Vale of York, the rivers start to meander, and notably the Swale and the Nidd. This characteristic has largely ended by the confluence of the Swale and the Ure, and the Nidd and the Ouse.

Law *et al.* (1997) provide an overview of the hydrology of the Humber catchment. Mean annual precipitation exceeds 1750 mm per year in the upper part of the Ure, and 1500 mm per year in the upper parts of the Swale and the Nidd. The rainfall decreases most rapidly in the Swale, followed by the Ure and the Nidd, with less than 750 mm per year in the Vale of York, including the Kyle and Foss catchments. This emphasises the importance of sub-catchment hydrological controls upon flows in the Ouse as this is where most precipitation falls. Whilst the Ouse flows through predominantly arable and pasture land use types, the three main sub-catchments are associated with a transition in land-use from moorland in the upper catchment, through pasture on well-drained upper slopes, at lower elevations on the valley sides and in the valley bottoms, through to arable where the valleys widen into the Vale of York. There is very little in the way of woodland cover in any of the catchments, with the exception of the Ure, where there is significant amount of woodland adjacent to river channels, especially in the lower catchment. The North-East part of the Swale catchment also has significant woodland cover.

The upper parts of the major sub-catchments are predominantly moorland or pasture, and are influenced by two key agricultural changes in recent history: (i) upland land drainage associated with gripping; and (ii) changes in stocking densities. The first of these really began from about 1944 and the introduction of grant in aid for land drainage that extended through to 1968 (Longfield, 1998). The major increase in stocking density begins around

1982, and it has been suggested that this resulted in a 40% increase in sheep numbers in the Yorkshire Dales to 1995 (Sansom, 1996). Both of these changes would result in greater volumes of runoff but also, and perhaps more importantly, change the relative timing of runoff. In the immediate future, there may be a reduction in the extent of gripping, associated with current moves to restore blanket peat bog to certain parts of the Yorkshire Dales. This is associated with 'Best Practice' projects, such as that in the Upper Wharfe, which is being co-ordinated by the Environment Agency (EA). In principle, this should reverse the hydrological consequences of grip introduction (i.e. it should reduce runoff magnitude and result in slower runoff generation). An EA project in the Upper Wharfe is investigating the downstream hydrological consequences of these changes, as the effects upon runoff generation of both grip installation and grip removal are still uncertain.

In addition to upland land cover effects upon catchment hydrology, land cover changes in the lower parts of the sub-catchment will also affect runoff generation. In recent history, two are of importance (Longfield, 1998): (i) increases in the under-drainage of arable land; and (ii) increases in the cultivation of winter wheat. The former will result in more rapid runoff generation in particular. Increases in the cultivation of winter wheat were associated with expansion into lowland pasture in particular and will also increase the rate of runoff generation. As with gripping, this has been identified as starting in the 1940s (Longfield, 1998). As the non-tidal reach is affected by three major sub-catchments, its flooding characteristics could be strongly affected by changes in the timing of runoff generation in each of the sub-catchments. In theory, the different distances of catchment headwaters from the Ouse (Figure) mean that the Nidd should cause the Ouse to rise first, followed by the Ure and then finally the Swale. Processes that reduce the time to peak due to more rapid runoff will tend to increase the probability that these sub-catchments flood with a reduced separation time, so exacerbating the size of Ouse floods. Thus, these changes matter because of both their water balance affects and their rate of runoff generation effects. These are explored below.

Table 1. Summary of key reservoir impoundments for the sub-catchments. Data from Longfield (1998)

Catchment	*Number of Reservoirs*	*Average useable capacity (10^3 m^3)*	*Average catchment area (km^2)*	*Number of reservoirs with catchment area greater than 10 km^2*	*Number of Reservoirs with capacity greater than 2000 x 10^3 m^3*
Swale	3	218	4.46	0	0
Ure	3	2594	12.6	2	2
Nidd	7	3069	17.5	3	3

Reservoir impoundment will have both hydrological and sediment transfer consequences. The volume of water stored during a flood event will typically be small. For instance, consider a storm event with a constant peak discharge of 200 m^3s^{-1}, which lasts for 24 hours. This is a very small event as compared with the typical size of flood event that can be witnessed on the Ouse. It equates to about 17 x 10^6 m^3, or about 6 times the storage capacity in the Nidd. Thus, the size of reservoir storage will be small as compared to total runoff during a storm event, and impoundments will only affect flood storage during the earlier stages of a flood event, and before the reservoir is full. However, these impoundments may regulate river flows in relation to weir elevation and width. For a rectangular broad-crested weir, the total discharge across the weir (Q) is approximated as:

$$Q = C_D w g^{0.5}\left(\frac{2}{3}d\right)^{1.5} \tag{1}$$

where: C_D is the weir coefficient; w is the weir width, g is the gravity constant and d is the depth of water above the crest of the weir. Thu s, if we consider a reservoir impoundment:

$$Q_{in} \pm \frac{dV}{dt} = Q_{out} = C_D w g^{0.5}\left(\frac{2}{3}d\right)^{1.5} \tag{2}$$

where dV/dt is the rate of change of reservoir storage. Regulation of flow will occur whenever dV/dt is negative, or

$$Q_{in} > C_D w g^{0.5}\left(\frac{2}{3}d\right)^{1.5}$$

If the area of an impoundment is large, then the rate of change of d, the depth of water above the crest of the weir, will be small. Hence, with a large impoundment or for a small weir width, there is a greater probability that [3] is met and there is a large amounts of storage for a given change in d. This is a flow regulation effect that occurs regardless of how full the impoundment is and impoundments may have an important effect upon the regulation of flow release, especially in the River Nidd, where it would be expected to increase the time to peak discharge generation (i.e. delay peak flows).

The flood record at York

We are very fortunate to have one of the longest flood records in the U.K. in the form of the Viking record of water levels on the river Ouse in the City of York. This began in 1878. Although documentary records exist before this, they are incomplete and difficult to interpret. Before 1757, when Naburn Weir became operational, river flows at York were also affected by tidal influences, and comparison of flood records before this date with current water level records is especially unreliable. Water levels are of prime interest to flood managers as it is the water level associated with a given river discharge that results in a flood. Thus, the time series of 124 years of data now available represents one of the most valuable records of the changing magnitude and frequency of flood events in the U.K.

The commonest way to explore changes in flood magnitude frequency is to count the number of peaks over a particular threshold. For the Viking record of water level in York, this is commonly set to 8.058 m above Ordnance Datum (AOD). In identifying peaks, it is crucial to make sure that there is independence between peaks (i.e. two peaks within the same flood should not both be counted). This then provides a means of quantifying the number of flood events that occur. Commonly, this may be supported by the annual maximum flood series. This is the largest flood recorded in each hydrological year (which runs from 1 October to 30 September), and compliments the peak over threshold series by providing an indication as to whether or not there is any trend in the magnitude of the largest water level reached. Figure 1 shows the quite dramatic change in flood frequency (1b) and magnitude (1c) from 1881 to the present time.

It is clear from Figure 1b that there was a dramatic rise in the number of floods during two periods in the instrumental record: the 1940s; and the 1980s and 1990s. Not only are floods becoming more frequent, but also there is a general increase in their magnitude. Figure 1c shows the decadal mean and standard deviation of the largest annual flood, with a clear trend apparent from the start of the 20th century. It is clear that the number and size of floods are getting very much worse.

These results are interesting for a number of reasons. First, the length of the record is unusual. Long records are important: Robson (2002) notes the difficulty of interpreting flow records, many of which commenced in the 1960s and early 1970s, given that the records began during a period of low flows and which, when including the 2000 hydrological year, include an endpoint with exceptionally high flows. The shorter the series length, the greater the sensitivity to these sorts of edge effects. Second, Robson (2002) found no statistically significant trend in flood flows at the national level, or changes in the frequency of either summer or winter floods. When records were disaggregated to 30 separate flow records, only six sites showed a significant positive trend of which only two, both in Scotland, were thought to be reliable. The observation of positive trend in flood flows in Scottish rivers matches the findings of Black (1996). Most interestingly, Robson found no significant trend in the peak over threshold series for the Ouse, which must presumably be for the flow record at Skelton. The Viking record is at odds with this finding. This may be for a number of reasons, including the greater reliability that comes from a longer record, but also the problem that records of water level may be influenced by changes in conveyance that mean that they are only weakly indicative of changes in flow magnitude. Flow records themselves are not necessarily reliable: rating curves are inaccurate at peak flows (Robson, 2002) and there is evidence that the change to a continuous ultrasonic gauge at Skelton in 1992 produces different discharge estimates than those provided by stage-discharge relationships before that date. Third, the analysis presented here focuses upon both flood magnitude and flood frequency, the latter based upon a peak over threshold series.

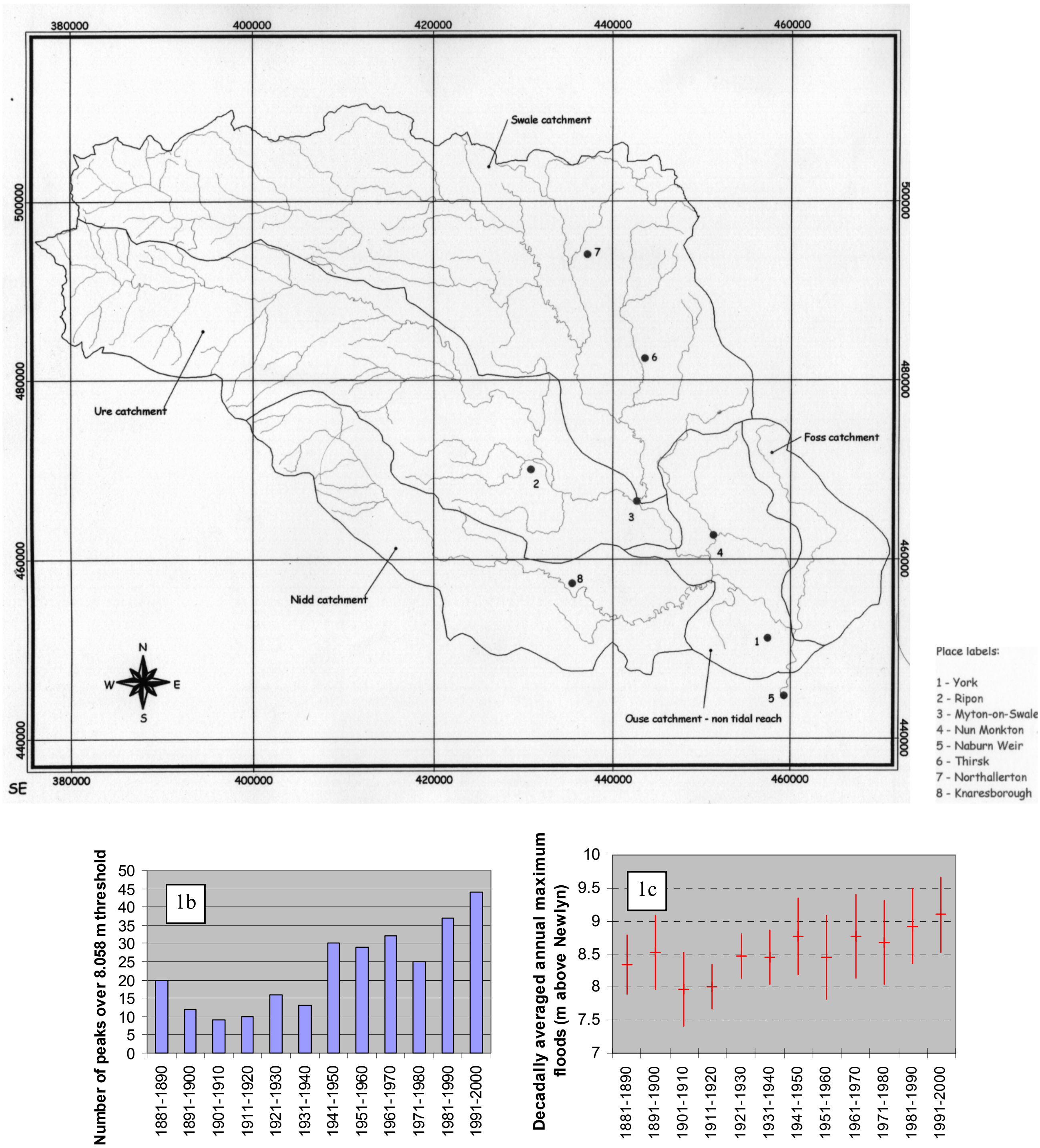

Figure 1. The location of sub-catchments influencing the flood record for Viking in the City of York (1a) and the number of floods above the 8.058m threshold per decade (1b) and the decadal mean and standard deviation of the annual maximum flood (1c) for the Viking record.

Hypotheses for change

The Viking data are records of water level and, as noted above, it is a high water level that leads to the occurrence of a flood. To assess what could be causing the patterns shown in Figure 1, it is necessary to recognise that two prime attributes control water level: (a) river discharge; and (b) river channel conveyance. River discharge is a direct function of the upstream contributing catchment area, and the way in which rainfall interacts with the catchment surface to produce runoff, which enters the drainage network to become river flow. Thus, the prime explanation of increasing discharge will be changes in rainfall characteristics. These may include both the amount and the intensity of rainfall. However, there are two other groups of controls that also need mention. First, it is important to consider the way in which this rainfall interacts with the land surface. The land surface controls the partitioning of rainfall into overland flow (which tends to lead to rapid runoff) and throughflow (which tends to lead to slower runoff), and it is the creation of rapid overland flow that is commonly associated with flood discharges. The prime conditions for overland flow generation are when the land surface is saturated. However, overland flow generation is not independent of the characteristics of a rainfall event: especially intense rainfall may result in overland flow generation even when there is no surface saturation through the mechanism of infiltration-excess overland flow. Second, flood generation can be a dynamic process, as a result of the effects of overland flow routing, initially across a hillslope, and eventually within the river channel. This is especially the case in larger catchments where the discharge associated with a given rainfall depends upon the timing of response of individual sub-catchments. In the context of York, the structure of drainage in the three main sub-catchments is such that the Nidd's flow should peak first in York, followed by the Ure and finally the Swale. It is commonly thought that if the Nidd peaks late or the Swale peaks early, there is a greater possibility that their flood peaks coincide with the Ure's peak at York, so producing a higher discharge. What causes these differences in timing is both the way in which a given rainfall event tracks across the sub-catchments, but also the speed with which water from the sub-catchments reaches the River Ouse.

In addition to river channel discharge, river channel conveyance is also an important parameter. Clearly, an increase in discharge will lead to an increase in water level. However, the relationship between discharge and water level also depends upon river channel conveyance, which essentially describes the ease with which water is transferred through the river network. Commonly, if the conveyance of the river is reduced, then the water level associated with a given discharge may be increased. Hence, it is possible for more floods to occur without an increase in discharge, if river channel conveyance is reduced. River channel conveyance is controlled by: the shape of the channel; the resistance to flow associated with the roughness of the channel boundary and the level of vegetation in the channel; and downstream water surface levels. For instance, if there is aggradation of the river-bed, due to sediment delivery, then the magnitude of the water level reached for a given flow may be greater. Similarly, if the amount of bank or in-channel vegetation increases, then the water level associated with a given flow will commonly be higher. It is for this reason that many U.K. rivers are actively managed to maintain conveyance. Similarly, engineering for flood defence can affect the relationship between discharge and water level, and it is a common requirement of a flood defence scheme to demonstrate that water levels will not increase as a result of any associated changes in river channel conveyance. These are local changes. However, conveyance may affect larger parts of the drainage network: an increase in conveyance in one part of the drainage network may reduce discharge attenuation leading to higher water levels downstream. This has to be assessed as part of any plan to manage a particular river reach in order to reduce the magnitude and frequency of flooding.

This brief review allows us to identify three broad groups of explanations for the increasing magnitude and frequency of flooding observed at York and shown in Figure 1: (1) there has been a progressive change in flood conveyance, either associated with an increase in conveyance upstream which has reduced discharge attenuation, leading to higher water levels at York, or a local decrease in conveyance which has increased water levels associated with a given discharge; (2) there has been a change in rainfall patterns, resulting in either an increase in the amount of rainfall associated with individual extreme rainfall events, or an increase in the frequency of extreme rainfall events; or (3) there have been changes in land use management which affect the partitioning of rainfall between rapid overland flow and slower throughflow. These are each investigated in turn.

Changes in conveyance and the York flood record

The first major hypothesis for explaining the patterns shown in Figure 1 relates to a change in the relationship between discharge in the Ouse and the water levels associated with that discharge, with higher water levels being associated with a given discharge. I do this by comparing the estimated discharge record at Skelton upstream of York with the water level record for Viking in the centre of York. Exploring this aspect of flooding is not straightforward because of the way in which we measure discharge. First, over the last 10 years, we are fortunate to have seen the development of much more sophisticated discharge measurement devices, which measure discharge directly and most importantly continuously, using ultrasonic gauging methods. Before then, discharge was commonly inferred from a continuous record of water level. Discharge would be measured discretely in time, using one of a range of methods. These measurements would then be matched to associated water level records to form a stage-discharge relationship. Application of the stage-discharge relationship to the continuous record of water level allows water levels to be turned into discharge estimates. In the Ouse, up until the early 1990s, water level was measured continuously in the City of York (The Viking record) and also at Skelton, upstream of York. Discharge was measured discretely at Skelton, combined with water level data at Skelton to create a stage-discharge relationship, and then combined with the continuous water level record at Skelton to get a continuous discharge record. Thus, the analysis here is essentially an assessment of the extent to which water levels at York have increased as compared to those recorded at Skelton.

Second, after the early 1990s, an ultrasonic gauge was installed at Skelton, which changed the way in which discharge was estimated. Evidence suggests that this has resulted in different discharge estimates to those obtained from the stage-discharge method. Thus, if we are interested in whether the Skelton(discharge)-Viking(water level) relationship has changed, it is important that our measurement methods are constant throughout the duration of study. Thus, I restrict consideration to the period from the late 1960s (for when estimates of discharge for Skelton are available) to the late 1980s. All of the peak discharge data associated with the peak over threshold results in Figure 1a were identified and the results are shown in Figure 2a. As expected, there is a linear trend. However, there is scatter about that trend suggesting differences in water level at York of up to 1.0 for floods estimated to have the same magnitude. This is not surprising in a plot of peak discharge against maximum water level: water levels will not be controlled by just the size of the discharge peak, but also the duration of that peak. For instance, the November 2000 flood was especially serious because of both its peak and its duration. Of particular interest here is whether or not there has been any change through time in the water levels associated with a particular flow. If the water levels by the end of the 1980s were higher for a given flow than those in the late 1960s, then this would suggest that there had been a long-term trend towards reduced conveyance, explaining the increased frequency of flooding in York. This can be explored by fitting a linear trend line through the scatter of datapoints in Figure 2a and then looking at the residuals that result. This was done using ordinary least squares regression as the interest is in deviation in water level from the trend line. It should be noted that the sampling theory for this analysis is weak as the water level are not normally-distributed and the data are probably heteroscedastic (i.e. the variance of the data points around the relationship changes as a function of discharge.

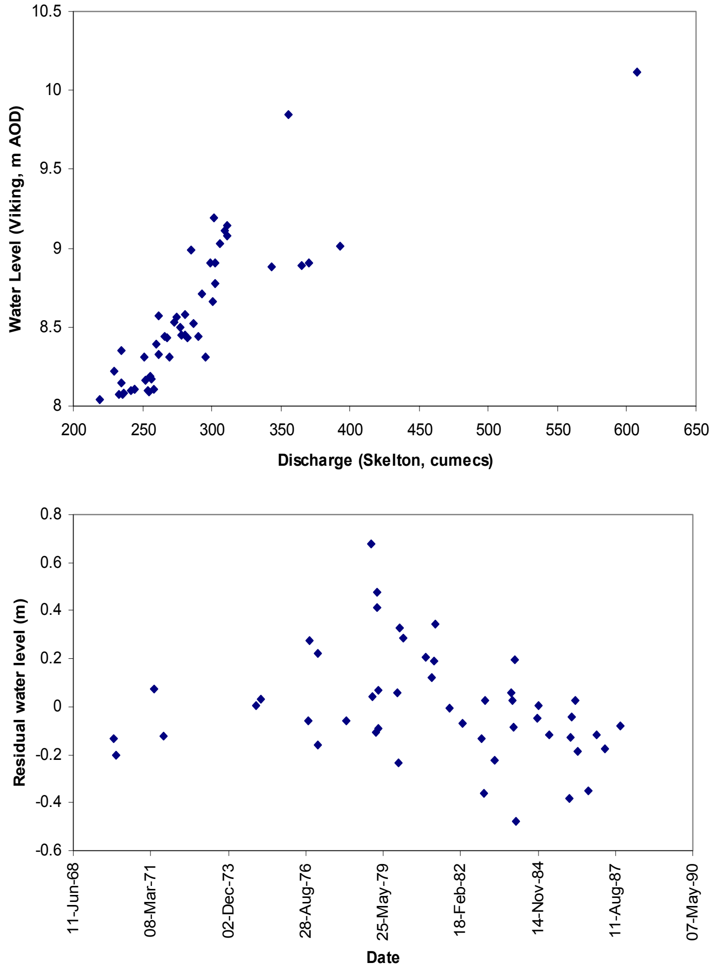

Figure 2. A scatter plot of water level measured at Viking in York against discharge estimated for Skelton upstream of York (2a) and the residuals from the linear trend relationship plotted through time (2b).

The residuals are plotted through time in Figure 2b. A positive water level suggests higher water levels than the trend predicts for a given discharge and a negative residual suggests lower water levels than the trend predicts for a given discharge. The results on this curve do not suggest that residuals have become more positive through time, which would suggest higher water levels associated with a given discharge. If anything, after 1979, the residuals have generally become negative, suggesting lower water levels associated with a given discharge. This does not suggest that there has been any reduction in conveyance through the city that might have resulted in higher water levels being associated with the same discharge, and leading to the increased incidence of high water levels suggested in Figure 1a. It is clear that we have to look elsewhere especially given the increase in flood frequency observed over this period (Figure 1).

Upstream contributing areas and the York flood record

If the factors that explain the York flood record are not local, it is clear that we need to look at climate change and land use change as the two possible hypotheses that might explain the patterns shown in Figure 1. However, the discharge record at Skelton gives us some useful information on which sub-catchments control the amount of water delivered to the Ouse system. This is explored here using the more reliable ultrasonic discharge gauging that began in the early 1990s using the 30 largest flood records identified in the gauge record to September 2001. For the methods used here, it is important to use the ultrasonic record for the estimation of peak discharges, which is the focus of this section, rather than the longer duration stage estimates of peak discharge. Each flood record was traced back to find the associated peak discharge recorded in the Swale, the Ure and the Nidd and the associated timing with respect to the peak flow at Skelton.

Table 2. Correlation matrix for the relationship between peak flow magnitudes and timings in the Ouse-Swale-Ure-Nidd system. These correlations (non-italicised values) should be interpreted with caution as not all variables are normally distributed, and this violates the statistical sampling theory that underpins correlation analysis. The italics indicate the probability value. Significance is accepted at the 95% level (i.e. $p<0.05$) and significant correlations are shown in bold.

	Ouse Flow	Ure Flow	Swale Flow	Nidd Flow	Timing Ouse-Ure	Timing Ouse-Swale	Timing Ouse-Nidd	Timing Ure-Swale	Timing Ure-Nidd
Ure flow	**0.820**	-	-	-	-	-	-	-	-
	0.000								
Swale flow	**0.900**	**0.812**	-	-	-	-	-	-	-
	0.000	*0.000*							
Nidd flow	**0.847**	**0.634**	**0.761**	-	-	-	-	-	-
	0.000	*0.000*	*0.000*						
Timing	-0.044	-0.028	-0.064	-0.107	-	-	-	-	-
Ouse-Ure	*0.827*	*0.891*	*0.750*	*0.594*	-	-	-	-	-
Timing	0.126	0.076	0.009	0.019	**0.768**	-	-	-	-
Ouse-Swale	*0.530*	*0.707*	*0.966*	*0.926*	*0.000*	-	-	-	-
Timing	-0.132	-0.059	-0.016	-0.137	0.263	0.074	-	-	-
Ouse-Nidd	*0.512*	*0.769*	*0.937*	*0.495*	*0.186*	*0.712*	-	-	-
Timing	0.247	0.150	0.109	0.188	**-0.402**	0.278	-0.287	-	-
Ure-Swale	*0.215*	*0.456*	*0.588*	*0.348*	*0.038*	*0.160*	*0.416*	-	-
Timing	-0.065	-0.022	0.043	-0.015	**-0.658**	**-0.604**	**0.554**	0.122	-
Ure-Nidd	*0.748*	*0.911*	*0.831*	*0.943*	*0.000*	*0.001*	*0.003*	*0.543*	-
Timing	-0.190	-0.099	-0.018	-0.112	**-0.391**	**-0.700**	**0.660**	**-0.415**	**0.852**
Swale-Nidd	*0.344*	*0.621*	*0.929*	*0.577*	*0.044*	*0.000*	*0.000*	*0.031*	*0.000*

Table 2 shows signficant correlations in bold, and some quite complex variable interactions. The flow results are not surprising: there is a correlation between the size of peak flows on the three contributing sub-catchments and the size of the flow on the Ouse. However, the timing patterns start to show that there are some interesting and complex interactions between sub-catchment response. For example, there is a strong positive correlation between the time between peaks on the Ouse and peaks on the Swale, and peaks on the Ouse and peaks on the Ure. The same is true for the Swale/Ure with respect to the Nidd. In essence, when the Ure peaks early with respect to the Ouse/Nidd, so does the Swale, suggesting that the two sub-catchments tend to respond in a similar way. There is some sense in which we can talk about the Ure-Swale system, and this is reflected in the fact that both catchments extend west into the Pennines to be affected by similar rain bearing systems (Longfield and Macklin, 1999).

The main problem with interpreting this matrix is the level of inter-correlation within the dataset that makes disentangling causal patterns difficult. Table 3 deals with this using a multivariate technique called principal components analysis. This identifies a set of uncorrelated components that represent decreasing proportions of the original dataset. In this case, the analysis produces 4 new components which together account for 94.3% of the variance in the original dataset. We can then look at the correlation (or loading) of the original data onto these four components. Given that not all of the variables are normally-distributed, these loadings need to be interpreted with caution. However, this problem does not violate the use of principal components analysis. Each of the new components is simply a new variable, pairwise uncorrelated with other new variables: it is the interpretation of the loadings that must be undertaken with caution.

In summary, the principal components analysis produces: component 1, which represents the timing of the Ure/Swale with respect to the Ouse/Nidd; component 2, which represents the magnitude of the flows in each of the Swale, Ure and Nidd; component 3, which represents the timing of the Ure/Nidd with respect to the Ouse and the

Swale with respect to the Ure; and component 4, which picks up upon timings already identified in components 1 and 3. As these components are uncorrelated, they can be used to assess the extent to which they explain the variability in the size of the flow in the Ouse: optimising stepwise regression was used to identify those components that contributed significantly to variability in the size of flow in the Ouse. It should be emphasised that this is a test that is sensitive to assumptions made about the data. In particular, the residuals from the analysis should be normally distributed (but, as Johnston (1978) notes, it is not necessary that the dependent variable is normally distributed as well). This can be a problem with extreme flood analysis. In this case, the residuals could not be distinguished statistically from a normal distribution, meaning that the results are reliable.

Table 3. Results of a principal components analysis upon the flow and timing data. Significant principal components are shown in bold and defined by Eigen Values greater than 1.00, following Johnston (1978). Original variables that are significantly correlated (at $p<0.05$) with each principal component are highlighted in bold.

Component statistics	**C1**	**C2**	**C3**	**C4**	C5	C6
Eigen Value	3.14	2.58	1.72	1.05	0.36	0.15
Percentage of variance explained	34.9	28.6	19.1	11.7	4.0	1.7
Cumulative percentage of variance explained	34.9	63.5	82.6	94.3	98.3	100
Correlation of component i with data:						
Ure flow	0.119	**0.516**	0.218	0.038	-0.641	0.51
Swale flow	0.077	**0.549**	0.247	0.072	-0.082	-0.787
Nidd flow	0.108	**0.523**	0.122	0.078	0.759	0.342
Timing: Ouse-Ure	0.353	-0.257	**0.505**	0.007	0.040	0.011
Timing: Ouse-Swale	**0.458**	-0.113	0.216	**-0.465**	0.031	-0.012
Timing: Ouse-Nidd	-0.265	-0.108	**0.563**	**-0.439**	0.053	0.03
Timing: Ure-Swale	0.125	0.223	**-0.447**	**-0.675**	-0.015	-0.033
Timing: Ure-Nidd	**-0.512**	0.137	0.004	-0.349	0.007	0.014
Timing: Swale-Nidd	-0.535	0.008	0.24	0.036	0.015	0.03

Table 4. Results of an optimising stepwise regression to identify which of the four significant components identified in Table 3 contributed significantly to variability in the Ouse peak flow. It should be emphasised that the residuals from this analysis could not be distinguished from a normal distribution.

The regression equation is: Ouse (Skelton) = 336 + 11.2 C1 + 38.7 C2 + 11.4 C3. R-Sq(adj) = 89.1%

	Coefficient	Standard Error	Individual Contribution (%)	t	*p*
Constant	335.863	4.459		75.33	*0.000*
C1	11.225	2.562	8.9	4.38	*0.000*
C2	38.668	2.832	77.9	13.65	*0.000*
C3	11.432	3.467	4.5	3.30	*0.003*

Table 4 shows that 89.1% of the variability in peak flow magnitude at Skelton can be explained by variability in the first three components identified in Table 3. Component 4 did not significantly increase explanation and so was not included. The most important component by far is C2, the flow component, which explains about 77.9% of the variability in peak flow magnitude at Skelton. However, two of the timing components have also emerged, and this confirms that the timing of the flows is also a crucial control upon the size of flow at Skelton. This is commonly observed, but it has not been shown in quantitative terms before. If we look in more detail at Component 1, it contributes positively to the regression relationship, such that high values of component 1 lead to high values of flow. The individual variables that correlate significantly with this component are: Ouse-Swale timing (positive) and Ure-Nidd and Swale-Nidd (negative). Thus, when the time between the Swale peak and the Skelton peak is large, but the timings between the Ure and the Nidd peaks and the Swale and the Nidd peaks are small, the peak flows at Skelton are higher. Thus suggests that component 1 is representing situations where the Nidd peaks late. In terms of component 3, it also contributes positively to the regression relationship. It correlates negatively with three time differences; between the Ouse and the Ure; the Ouse and the Nidd; and the Ure and the Swale. Thus, in all three cases, when the time difference is small, the flood peak at Skelton is large. Thus, component 3 is showing that if the Ure or the Nidd flood early, or the Ure and the Swale peak close together, flood peaks at Skelton tend to be higher.

In summary, this section has demonstrated a crucial property of the Ouse system sub-catchments. How they respond to each other, in relation to the timing of their flood peaks, does have an effect upon the size of flows experienced by the City of York. Thus, one of the possible explanations of the York flood record shown in Figure 1 is that there has been a progressive change in sub-catchment response that means that a given rainfall results in a very different flow and hence water level. This will be a product of two related factors. First, the size of the flows in the contributing sub-catchments matters, and hence the ways in which the catchment attenuates rainfall will also matter. Second, the relative times to peak in each of the sub-catchments matter. Both of these may be explained by changing rainfall patterns (i.e. changes in the way in which rainfall is delivered to the catchment due, for example, to a change in the direction of rain-bearing weather systems) and changing land use (i.e. land use management activities that result in runoff more readily and more rapidly reaching the drainage network). There is an extensive set of undigitised chart records for the Swale-Ure-Nidd system, many of these extending back over 50 years, and these could provide a useful method for assessing whether or not there has been any change in relative timing that matches the patterns shown in Figure 1. The final point to make in this section is to observe that the findings in Tables 3 and 4 emphasise that how we determine the size of a flood with a given return period in large catchments needs very careful thought: the sequencing of sub-catchment response is of importance as well as the relative magnitude of individual sub-catchment response.

Climate change and the York flood record

Following from the above, one hypothesis for the patterns shown in Figure 1 is that there has been some sort of secular change in climate, that has led to an increase in river flows and hence water levels in York. As implied in the previous section, the nature of the climate change that might lead to an exacerbation of flood risk could be quite subtle. For instance, changes in the direction of movement of rain bearing weather systems will affect the space-time patterns of precipitation, and hence affect the relative timings of sub-catchment response. The above section demonstrated the strong sensitivity of flood magnitude to relative timing effects. These complexities aside, this section seeks to explore the extent to which precipitation records can be used to explain the increase in flood magnitude and frequency shown in Figure 1.

The analysis of historical precipitation data

To do this, rainfall data are taken from three stations, one in each of the contributing catchments: at Keld in the Swale (NGR 3892 E, 5011 N, 320 m AOD, annual rainfall 1355 mm per annum); Burtersett in the Ure (NGR 3891 E, 4893 N, 291 m AOD, annual rainfall 1430 mm per annum); and Harlow Hill in the Nidd (NGR 4290 E, 4542 N, 167 m AOD, annual rainfall 789 mm per annum). Although Harlow Hill has a lower annual rainfall than both Burtersett and Keld, it also has one of the longest digitised records and, as is shown below, long duration records are required for this kind of analysis. Daily data were used from the 1960s onwards, although those for Keld were only available monthly from April 1981. All three locations had periods of instrumental malfunctioning when no data were available. Data were supplied by the Environment Agency (Dales Area, North-East Region) and the British Atmospheric Data Centre. All datasets were subject to careful quality control and data points that could not be relied upon were declared as missing. Analyses were done by hydrological year (starting 1st October in each year). This is necessary when calculations are done on an annual basis due to possible serial autocorrelation in weather systems and catchment response. This is weakest at the autumn equinox when soil water recharge commonly begins. Five key descriptors are presented here: (1) annual precipitation by hydrological year; (2) October to March rainfall by hydrological year, reflecting what is commonly known as the 'flood season'; (3) the percentage of rainfall in this flood season, labelled the percentage winter rainfall; (4) a measure of rainfall intensity, the intensity index (I)[1], determined for each hydrological year; and (5) the percentage of rainy days on which rainfall exceeds 20 mm, again determined for each hydrological year.

Figure 3a shows no trend in annual rainfall for the period 1960 to present in any of the three catchments and this is confirmed by statistical analysis (Table 5). When compared with Figure 1, this was a period when there was a substantial increase in the number of floods per decade, and some increase in the average size of those floods. However, Figure 3b shows that whilst annual rainfall totals are not rising significantly, for Keld in the Swale and Burtersett in the Ure, the amount of rainfall falling in the October to March period is rising by statistically significant amounts. This could represent a flood-relevant signal, but it is not found in the records for Harlow Hill in the Nidd. There were no significant trends in the intensity index or in the percentage of rainy days when rainfall exceeded 20 mm (Figures 3d and 3e), except for a statistically significant decline in the percentage of wet days on which rainfall exceeded 20 mm. Thus, the evidence for the period 1960 to present is not especially convincing; there does not appear to be an especially strong trend in any of the flood relevant precipitation measures (and notably the intensity index and extreme rainfall event statistic) with the exception of the amount of winter precipitation in the Swale and Ure catchments.

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[1] $I = \dfrac{A}{365 - n}$, where *A* is the annual rainfall (by hydrological year) and *n* is the number of rain less days in the hydrological year.

Figure 3. The rainfall records for Harlow Hill (the Nidd), Burtersett (the Ure) and Keld (the Swale) for the period 1960 to present.

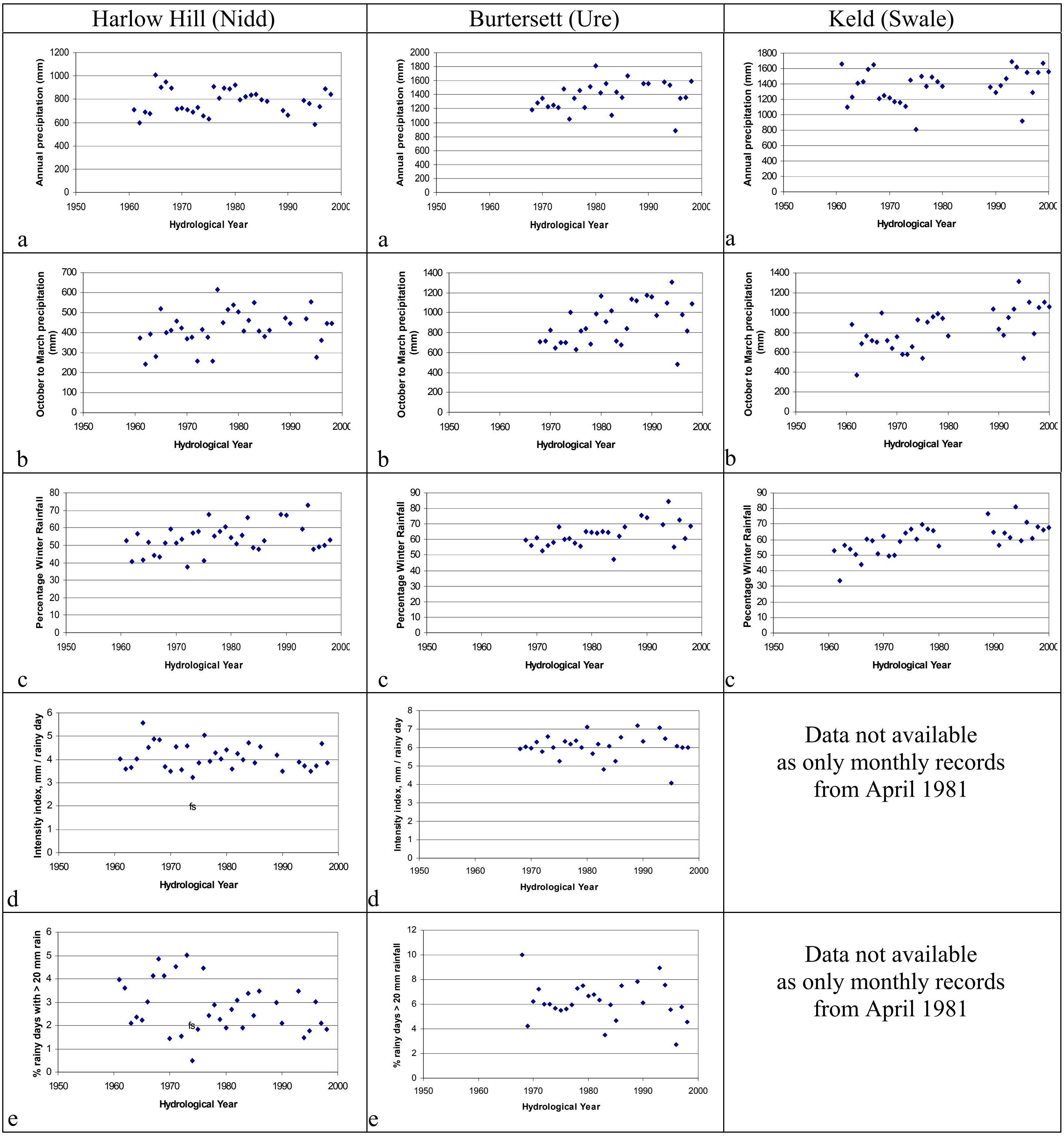
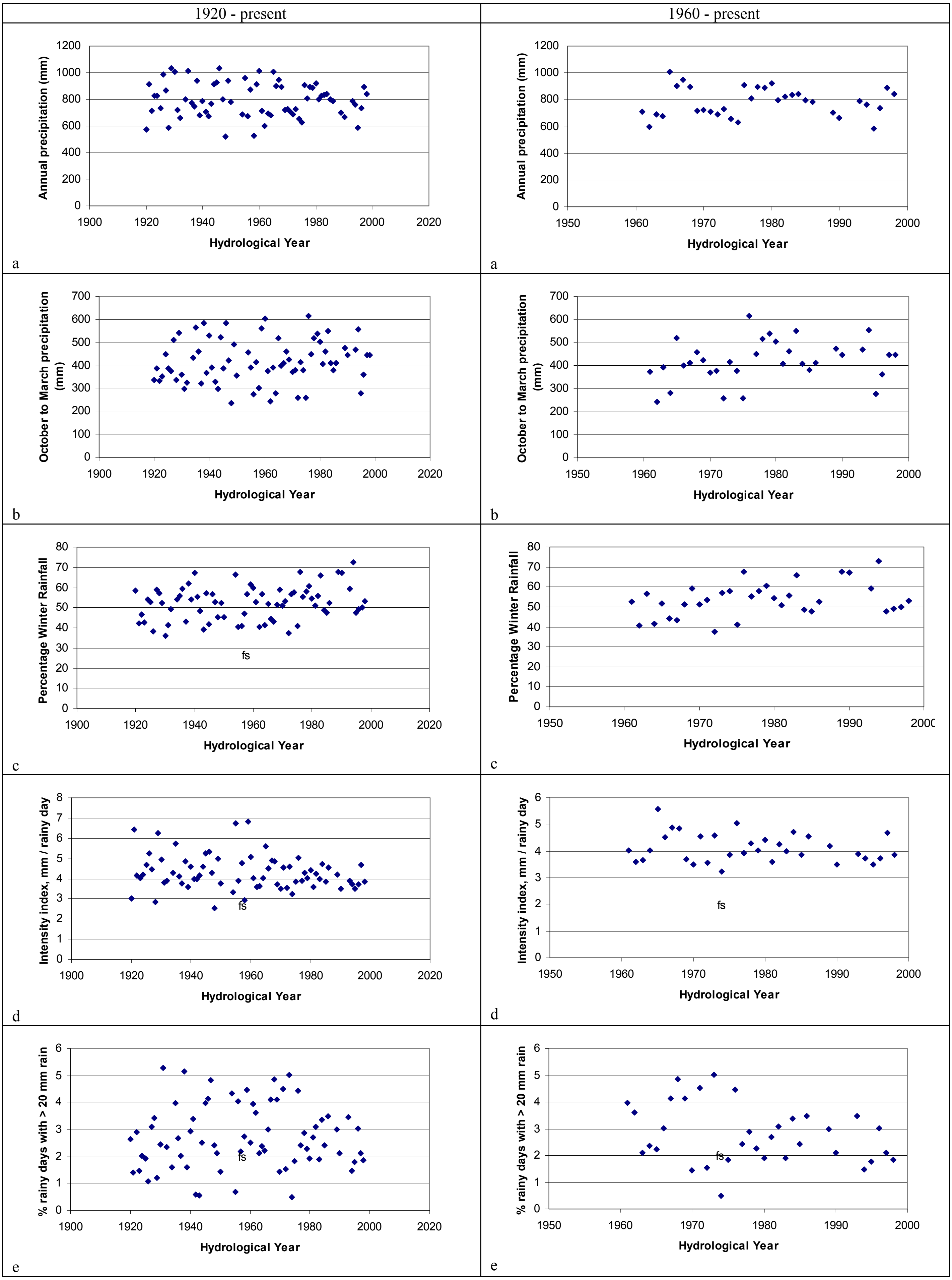


Table 5. Rank correlation between various precipitation measures and hydrological year. *p* values are shown below the correlation. Those that are significant at the 90% level are highlighted in bold.

	Keld (Swale)	Burtersett (Ure)	Harlow Hill: 1961-present (Nidd)	Harlow Hill: 1920-present (Nidd)
Annual precipitation	0.237	0.264	0.014	-0.080
	0.191	*0.183*	*0.936*	*0.508*
Winter precipitation	**0.565**	**0.451**	0.258	0.134
	0.001	*0.018*	*0.141*	*0.266*
Intensity index	NA	-0.018	-0.181	-0.187
		0.931	*0.307*	*0.119*
Percentage of rainy days with greater than 20 mm rainfall	NA	-0.176	**-0.290**	0.046
		0.379	*0.097*	*0.703*

Figure 4. The rainfall record for Harlow Hill (the Nidd) for the period 1920 to present.



However, these results need to be put into context. The period 1960 to present is a short one, much shorter than the available flood record for York shown in Figure 1. The record at Harlow Hill extends back to 1920 and the results are shown in Figure 4. The first column shows the full record. The second record shows the same plots as in Figure 3 for Harlow Hill. This emphasises an important point. What looks like trend over the shorter period of 1960 to present (e.g. Figures 4b, 4e and 4f, 1960 to present) does not look like trend when viewed over the longer period (1920 to present). Indeed, over the period 1920 to present, which is coincident with the major increase in flood frequency and magnitude shown in Figure 1, there are no statistically significant changes in annual precipitation, October to March precipitation, the intensity index or the percentage of wet days with more than 20 mm of rain. This is especially the case for the marked increase in flood magnitude and frequency observed from the 1940s onwards.

The above analysis needs to be viewed critically for a number of reasons. First, no account has been taken of the type of precipitation and especially of snowfall effects. Some of the largest floods in the Ouse system occur during winter rainfall events, when rain falls on snow. Rapid snowmelt ensues, leading to very high river flows. Second, the above analysis presents data from only three stations with the relevant catchments. They are all located relatively close to the upland environments where rainfall amounts are highest. However, no attempt has been made to assess the extent to which these rainfall records are representative of the catchments within which they fall. For instance, comparison of Harlow Hill with Keld and Burtersett is not straightforward as the annual average rainfall in Harlow Hill is lower. If changing rainfall patterns are experienced most noticeably in the upper Nidd, then the Harlow Hill record may not show this. Third, it is important to assess the rainfall records for individual storm events. Daily rainfall records do not provide reliable data on the intensity of individual rainstorm events and can be misleading if a major rainfall event occurs across two days. This requires hourly (at least) rainfall records, which are not widely available for long periods of time for many gauge locations. Thus, the main conclusion of this section is that whilst there is a weak winter rainfall signal for the period 1961 to present in two of the Ouse sub-catchments, this is not apparent in the longest available record, with increases in the magnitude and frequency of flooding at York observed before any rainfall observed trend.

A Yorkshire perspective on future climate change

Hulme *et al* (2002) provide predictions of climate change under four future scenarios expressed in terms of possible levels of greenhouse gas emissions: low emissions, medium-low emissions, medium-high emissions, high emissions. In national terms, they note that the Central England Temperature record rose by 1° centigrade (C) during the twentieth century and the 1990s decade was the warmest since records began in the 1660s. Days with air frosts have been declining in frequency. Under a high emissions scenario, average annual temperatures in the U.K. are forecast to rise between 2°C and 3.5°C, with an extension of spring temperatures by up to 3 weeks earlier and autumn temperatures by up to 3 weeks later. Concurrent with these temperature changes, winters have been getting wetter, with a larger proportion of rainfall falling in the heaviest downpours. Summers have been getting slightly drier. Under a high emissions scenario, average annual precipitation is forecast to fall slightly, but with wide seasonal and regional differences. Summer precipitation may fall by up to 50% by the 2080s and winter precipitation may rise by up to 30%. Extreme winter precipitation will become more frequent.

What do these mean for the Ouse sub-catchments? Table 6 shows predictions of temperature and precipitation change for these region on the basis of the UKCIP02 predictions in Hulme *et al.* (2002). These data show that under the more extreme emissions scenarios, there will be major changes in both temperature and precipitation. From a flood perspective, the prime driver will be changes in precipitation (Table 5b), and an increase in winter (December, January, February under UKCIP02 definitions) precipitation is forecast for all scenarios for all of the prediction decades (2020s, 2050s, 2080s). Combined with this is an increase in precipitation intensity, with more than a 10% increase in the magnitude of the 2 year return period precipitation for all scenarios (Hulme *et al.,* 2002). This emphasises the serious concerns arising from possible future climate changes. It is interesting to note that the increase in winter precipitation is already detectable in two of the sub-catchments (Swale and the Ure) for the period 1960 to 2000. Trends in spring and autumn are less discernible (Table 6b), but those in the summer suggest quite dramatic reductions in precipitation. The result is a slight decrease in (net) annual precipitation and, again, this seems to match the data that comes from the sub-catchments.

Changes in temperature are important in addition to changes in precipitation for two main reasons. First, increases in temperature will lead to direct and indirect (enhanced plant growth) increases in evapotranspiration, which will increase the potential for surface soil moisture storage. Second, the increases in winter temperature (Table 6a) will reduce the extent to which rain falls as snow. Indeed, the data in Hulme *et al.* (2002) suggest reductions in winter snowfall by the 2080s of between 50 to 60% under low emissions scenarios and more than 90% under high emissions scenarios. A major cause of severe flooding in the Ouse is when rain falls as snow, resulting in significant within catchment storage, but which is then melted by a high rainfall event, so delivering much more runoff to the river than from just the rainfall event itself. Indeed, if the ground below the snow is frozen, as the rate of melt of surface soil can be quite slow, infiltration rates into the soil surface may be reduced, so exacerbating the generation of rapid runoff. Clearly, if there is less snow fall, snowmelt-exacerbated flood events ought to become less frequent.

Table 6. Summary of UKCIP02 temperature and precipitation changes with respect to the 1961-1990 average for different emissions scenarios for the Ouse sub-catchments (from Hulme *et al.,* 2002).

a. Temperature change (°C)

Scenario	Decade	Annual	Winter	Spring	Summer	Autumn
	2020s	+0.5-1.0	+0.5-1.0	+0.5-1.0	+0.5-1.0	+0.5-1.0
Low	2050s	+1.0-1.5	+1.0-1.5	+1.0-1.5	+1.5-2.0	+1.5-2.0
	2080s	+1.5-2.0	+1.0-1.5	+1.5-2.0	+2.0-2.5	+2.0-2.5
	2020s	+0.5-1.0	+0.5-1.0	+0.5-1.0	+0.5-1.0	+0.5-1.0
Medium-Low	2050s	+1.5-2.0	+1.5-2.0	+1.5-2.0	+1.5-2.0	+1.5-2.0
	2080s	+2.0-2.5	+1.5-2.0	+1.5-2.0	+2.0-2.5	+2.5-3.0
	2020s	+0.5-1.0	+0.5-1.0	+0.5-1.0	+1.0-1.5	+1.0-1.5
Medium-High	2050s	+1.5-2.0	+1.0-1.5	+1.5-2.0	+2.0-2.5	+2.0-2.5
	2080s	+3.0-3.5	+2.0-2.5	+2.5-3.0	+3.0-3.5	+3.5-4.0
	2020s	+0.5-1.0	+0.5-1.0	+0.5-1.0	+1.0-1.5	+1.0-1.5
High	2050s	+2.0-2.5	+1.5-2.0	+1.5-2.0	+2.0-2.5	+2.5-3.0
	2080s	_3.5-4.0	+2.5-3.0	+3.0-3.5	+4.0-4.5	+4.0-4.5

b. Precipitation change (%), NV 'indicates within natural variability'

Scenario	Decade	Annual	Winter	Spring	Summer	Autumn
	2020s	0→-10	0→+10	NV	-10→-20	NV
Low	2050s	0→-10	+10→+15	NV	-10→-20	0→-10
	2080s	0→-10	+15→+20	0→-10	-20→-30	0→-10
	2020s	0→-10	0→+10	NV	-10→-20	0→-10
Medium Low	2050s	0→-10	+10→+15	NV	-20→-30	0→-10
	2080s	0→-10	+15→+20	0→-10	-30→-40	0→-10
	2020s	0→-10	0→+10	NV	-10→-20	0→-10
Medium-High	2050s	0→-10	+10→+15	0→-10	-20→-30	0→-10
	2080s	0→-10	+20→+25	0→-10	-40→-50	0→-10
	2020s	0→-10	+10→+15	NV	-20→-30	0→-10
High	2050s	0→-10	+15→+20	0→-10	-30→-40	0→-10
	2080s	-10→-20	+25→+30	0→-10	<-50	-10→-20

The above observations demonstrate the complexity of the relationship between temperature, precipitation and flood risk. In practice, it is well-established that the prime control upon flood risk is the nature of weather-bearing systems (e.g. Longfield and Macklin, 1999). The U.K.'s weather bearing systems are driven by the North Atlantic Oscillation (NAO), which is an oscillation in the pressure gradient between the Azores and Iceland. When the NAO is positive, the airflow across the U.K. is more westerly, leading to wetter but milder weather. When it is negative, airflow is more influenced by the European continent, with colder but drier weather. The year-to-year variability in the NAO is high (Hulme *et al.,* 2002). However, model predictions suggest that by the 2050s, under the medium-high emissions scenario, there is a statistically significant increase in the NAO, leading to more westerly weather systems. In terms of understanding climate change, the variability caused by the NAO means that we will continue to have drier and wetter winters, perhaps making it difficult to perceive that the climate is indeed changing. However, as the data suggest for 1961 to 2000, and the models forecast for the 21st century, a key process driver is the shift towards a positive NAO, which will increase the tendency towards milder and wetter weather.

The extent to which this will apply to the three sub-catchments needs some clarification. Longfield and Macklin (1999) found that four circulation types (westerly, cyclonic, cyclonic-westerly, and south-westerly) generated 79.7% of the peak over threshold flood events recorded at Viking to 1996, with 64.3% attributed to westerly and cyclonic air masses alone. Westerly events will affect the Swale-Ure-Nidd catchments heavily, as they lead to a strong west-east precipitation gradient, with high rainfall totals in the Pennines (Longfield and Macklin, 1999). Cyclonic conditions will deliver more uniform rainfall across the Ouse basin. The results presented above demonstrate the importance of the relative timing of sub-catchment response. The type of weather system will influence rainfall totals, but also rainfall timing, and hence the timing of sub-catchment response. Hence, as there are shifts between the dominance of rainfall events associated with different circulation systems (Longfield and

Macklin, 1999), so the relative timing of sub-catchment response may change, making peak flows higher or lower according to the nature of the circulation system that occurs. It would be especially valuable to take the distributed network of rain gauges across the Swale-Ure-Nidd system, and to explore the extent to which different circulation systems can be linked to different spatio-temporal patterns of rainfall delivery and hence different sub-catchment responses.

Land use management

The other major hypothesis for explaining the changing flood record is land use change (Longfield and Macklin, 1999). This is concerned with the partitioning of rainfall between flow within the soil surface and flow directly over the soil surface, or overland flow. There are two processes that matter in this respect: land use management practices that change; (1) properties of the soil surface, and so lead to an increase in the storage of precipitation within the soil; or (2) the speed with which water is delivered from the hillslope to the river network. A reduction in storage or an increase in rate of runoff will reduce the time to discharge peak, reduce flow attenuation, and hence be linked to larger peak flows. However, the nature of land use effects will be complicated by: (1) the nature of the rainfall; and (2) the sequencing of rainfall events. Runoff rates are generally higher under more intense rainfall. The capacity of the soil to store water also declines after wetter periods, as the soil store is progressively filled. It is commonly thought that high levels of catchment saturation are required to produce large floods, and this may be the case, but in upland areas with steep slopes, large parts of the catchment may drain rapidly to be unsaturated even after a period of prolonged rainfall.

As noted above, there are two major land use changes that have affected the Swale-Ure-Nidd system over the last 60 years that might help to explain the increase in the magnitude and frequency of flooding at York: (1) upland land drainage; and (2) increases in stocking densities. The focus here is these three sub-catchments, and not lowland drainage in the Vale of York itself. This is because of the strong rainfall gradient from the Swale-Ure-Nidd system into the Vale of York and because of observed travel times of peak flows (of the order of days) from the occurrence of rainfall in the contributing catchments through to the onset of flooding at York. Whilst land use management in the Vale of York (and notably agricultural underdrainage) may have increased the speed of runoff delivery to the Ouse system, this is likely to be well before the onset of the major flooding due to the Swale-Ure-Nidd system. The only exception to this will be during extreme flood events associated with multiple peaks, where lowland runoff due to the second rainfall peak is coincident with upland runoff associated with the first peak.

Upland open ditch drainage or gripping

The prime type of surface drainage in moorland environments typical of all three sub-catchments is open drainage or gripping, using channels up to 0.45 m deep, and ranging from 0.50 to 0.75 m wide at the surface to 0.15 to 0.25 m wide at the base (Robinson, 1990). Drain spacing and arrangement varies widely. Figure 5 shows the grips that have been installed in part of the Upper Wharfe (the Wharfe joins the Ouse downstream of York): the density varies greatly, as does their spatial arrangement within the landscape. Generally, it is introduced to drain peaty soils to improve grazing quality and for grouse shooting (Robinson, 1990). Figure 6 (modified from Robinson, 1990) shows the extent to which parts of the Nidd, Swale and Ure systems were gripped in the period 1940 to 1985. This is clearly a major land use change, with more than 50% of parts of the Nidd and the Swale subject to gripping. Robinson (1990) notes that the highest gripping rates (affecting more then 7 km^2 per year) were in the 1940s and 1950s. Rates dropped off in the 1960s, but then rose again in the 1970s before declining in the 1980s. Given: (1) the clear coincidence of more frequent and higher magnitude flooding at York from the 1940s with this land use change; (2) the observed importance of the relative travel times of sub-catchments for flood magnitude at York (and notably earlier peaks on the Swale); and (3) the ambiguous rainfall records considered in the previous section, the obvious question is the extent to which gripping has contributed to flooding at York. Unfortunately, assessing the potential effects of gripping is not straightforward for two main reasons. First, the results of studies that have been completed to date are contradictory. Second, there have been no catchment (or sub-catchment scale) investigations of the effects of gripping upon downstream flood risk. These issues are explored below.

Figure 5. Map of grip locations in the Oughtershaw sub-catchment of the Upper Wharfe, North Yorkshire. This is superimposed to a map of predicted catchment travel times to emphasise that grips don't simply affect the partitioning between overland flow and subsurface flow; they also affect the relative timing of flow delivery.

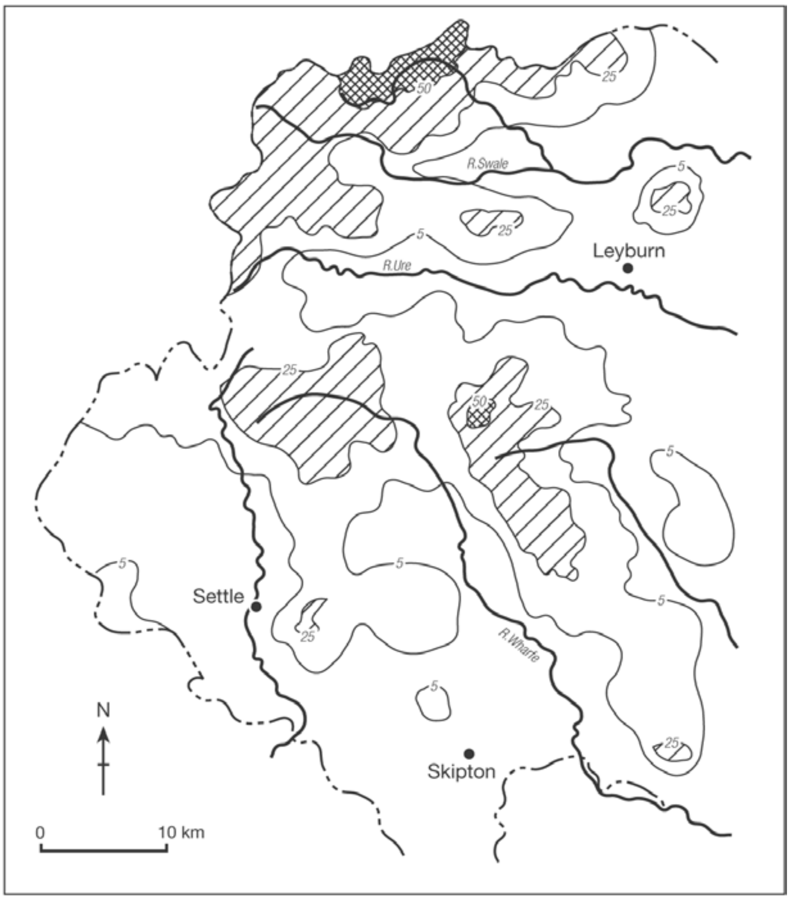


Figure 6. Percentage of land in the western Yorkshire and Pennine region which was gripped between 1940 and 1985 (redrawn from Robinson, 1990).

Traditionally, the debate over grips has centred around the differing effects of grips upon water storage and travel times. Conway and Miller (1960), for a Northern England, peat covered catchment, found that open drainage increased peak runoff. Robinson (1986) studied 0.5 m deep, 4.5 m spacing drains set in peat varying in depth from 0.5 to 3.0 m in Coalburn, Northern England, with turf ridges in between. The drains increased stream network length 60 fold. The study compared two time periods, pre-drainage (1967-73) and post-drainage (1974-78), and found that despite similar annual rainfall totals and seasonal distributions of rainfall that the 90% daily flow excedance was doubled post-drainage. This was attributed to significant increases in the percentage of rapid runoff and a reduction in the time to peak. However, the drains had a restricted lateral effect, as had been observed by Hudson and Roberts (1982) and Robinson and Newson (1986). Further, the effects on peak flows were only significantly different for intermediate flood flows, not for large flood flows including the mean annual flood. Robinson (1990) reached similar conclusions for Blacklaw Moss in southern Scotland, with markedly shorter hydrograph response times post drainage.

These observations contrast with those that suggest that drainage has reduced peak flows because it provides greater opportunity for water storage and hence reduced stormwater production. Burke (1975) found that drains led to the progressive dying of peat, with water tables 0.20 m below surface in winter and 0.45 m below surface in winter. It was argued that this lowering of the water table would increase water storage so reducing flood peaks. Similarly, although for backfilled rather than open drains, Newson and Robinson (1983) found for peaty gley and podzol soils on Rhiwdefeitty Fawr, Plynlimon, Wales that drainage lengthened the duration of storm runoff and reduced peak flows due to lowering of water tables.

The obvious question is which of these two effects dominates, and under what circumstances. Newson and Robinson (1983) note that the effects of grips upon flood flows will depend upon soil type, location of the grip within the drainage system, and the nature of the drain. Indeed, too much grip research has focused upon empirical studies of individual grips or small grip networks. At the catchment-scale, the location of the drainage activity is a crucial variable. The effect of grips will be to change which parts of the catchment deliver storm runoff when: if water table lowering dominates and the drainage is located such that it delays storm peaks from parts of the catchment that normally respond early, then this may actually contribute to increase the catchment flood peak; similarly, if timing effects dominate, and the drainage is located such that it delivers water from parts of the catchment that normally respond early, then this may reduce the catchment flood peak. Hence, the catchment-scale effect of individual grip systems is the complex result of how the grips as a whole change the way in which saturated areas connect to the drainage network. As the scale of investigation is increased, so the effects of gripping will become more subtle and potentially complex, and a grip signature will start to be dampened by other controls upon flood wave conveyance (Robinson, 1990) such as channel shape. At present we have very little research that explores, in a physically-based way, the extent to which grips might cause major changes in the size and timing of flood peaks at the basin scale. Thus, on the basis of the correlation in time between grip installation in the Ouse system and the increase in flooding at York, grips remain a hypothesis for explaining the Observations in Figure 1.

Increases in upland stocking densities

The second major explanation of the increase in flood magnitude and frequency at York relates to the increases in stocking densities that have been observed since the 1970s, largely associated with European Union agricultural policies. These have subsidised farmers on a per capita basis with the result that stocks have risen, in some cases very sharply. This is a topic that has been widely researched but, as with gripping, its catchment-scale effects have yet to be properly demonstrated.

The basic hypothesis that stocking densities might impact upon flood generation relates to a range of processes. APEM (1998) note that high stocking levels: (a) may lead to biomass loss, which reduces evapotranspiration rates, so maintaining high levels of soil wetness, and also reduces root depth which reduces infiltration into the soil; and (b) leads to increases in surface soil compaction, which also reduces infiltration. Sheep are of particular concern: Betteridge *et al.,* (1999) demonstrated that different types of cattle had different effects upon the soil surface: cattle caused upward and downward soil movement leading to high levels of soil disturbance; sheep caused more surface compaction.

These observations are supported by a wealth of studies from a range of different environments. Much of the early research was conducted in rangeland type of environments (e.g. Rhodes *et al.,* (1964): Rauzi and Hanson, 1966; Gillard, 1969; Langlands and Bennett, 1973). Langlands and Bennett (1973) explored rangelands with different stocking densities and reported a positive relationship between soil bulk density and stocking density and a negative relationship between soil pore space and stocking density, leading to lower infiltration rates. This was attributed to trampling but also the puddling action of raindrops as they hit soil that had a greater probability of being exposed due to over-stocking. Gifford and Hawkins (1978) for rangelands, also found that ungrazed infiltration rates were statistically different from grazed infiltration rates at the 90%level. However, most of this difference was attributed to heavy grazing rates as opposed to moderate/light grazing. Observations that high stocking densities change soil surface properties and hence infiltration rates have been extended to include studies of runoff. Branson and Owen (1970) found a statistically significant relationship between the percentage bare soil and annual runoff on the basis of 17 sites in a semi-arid sub-alpine region. They noted the relationship was strongest in the spring due to greater livestock trampling plus the effects of winter grazing before regrowth began again. Similarly, Owens *et al.* (1997) reported a reduced proportion of rainfall occurring as runoff as a result of reducing stocking densities.

The above studies suggest that increases in stocking density will change the partitioning between overland flow and through flow, and hence have the potential to change the ease with which floods are generated. There is basic *a priori* support for the idea that rising stocking densities in the 1970s and 1980s in the Yorkshire Dales may have contributed to the increasing magnitude and frequency of flood events. Research commissioned following the November 2000 flood events within the Ouse system (Holman *et al.,* 2002) suggested that 4.6% of sampled sites were severely degraded (sufficient to enhance runoff to cause widespread soil erosion that is not confined to wheelings/tramlines) and 36.1% of sites were highly degraded (sufficient to enhance runoff across whole fields where slope allows). These results were used to assess changes in standard percentage runoff at the catchment scale and the authors suggested increases in runoff of between 0.8% and 9.4% for the Ouse system as a result of soil degradation. Although the assumptions behind these data need careful exploration, and the propagation of error associated with their derivation is also required, they indicate the extent to which land management may have a catchment scale effect. The most recent studies (e.g. Owen *et. al.,* 1997: Greenwood *et al.,* 1998) have demonstrated that reducing stocking densities leads to the long term recovery of infiltration rates. In theory, this provides a means by which existing and future flood risk might be managed, either by reviewing existing stocking densities as a whole, or by exploring mechanisms by which stock can be managed to reduce their runoff producing impact. However, such a simple conclusion overlooks a set of much more complex issues that need to be explored before it is possible to justify such a management measure. First, landscape-scale increases in stocking densities mask a much more complex pattern of land management at the sub-landscape scale. Given the importance of hydrological connectivity for runoff generation, whether or not a field-scale increase in stocking density is going to lead to a hydrological impact will depend upon field location within the catchment and in relation to adjacent fields with potentially different types of land management. The hydrological impact of individual field management practices will then need to be scaled up to the catchment-scale. Sheath and Carlson (1998) provide one of the few sub field-scale studies of this phenomenon. They found that for upland topography, soil surface damage associated with cattle was greatest on animal tracks/camps and in areas of lower slope (less than 25°) where cattle access was possible: i.e. patterns of stock movement at the sub field-scale will determine hydrological risk. Second, the same complexity exists in relation to timing. The effect of stock trampling will depend upon the wetness of the soil surface and the degree of protection afforded by extant vegetation cover. Wetter and less well-protected soil will be more prone to trampling effects. As stock get moved round within individual farm units, generalising the effects of increasing stocking densities to hydrological impacts at the landscape scale must be undertaken with caution.

In summary, this section has demonstrated that there is evidence that stocking densities have risen and that a series of research papers have demonstrated that high stocking densities may have a significant hydrological effect. Unfortunately, the correlation between the flood record and the stocking density changes needs much closer investigation in order to assess whether or not it is a possible explanation of an increase in the magnitude and frequency of flood risk. This is especially the case because it is possible that the rainfall signal since the 1960s may have also contributed to changes in flood magnitude and frequency.

Research issues

The above results suggest some form of correlation between increase in flood magnitude and frequency at York and landscape scale changes in land management in the upstream contributing catchments. However, this is purely a correlation. Whilst the above discussion provides *a priori* evidence that supports this conclusion, there are still a number of areas where further research is required before land management can be said to be a crucial issue.

First, this study has only worked with a very small proportion of the available rainfall and flow records available for the catchment. It is vital that the small number of rainfall sites that have been considered is increased to make sure that the trends identified are indeed representative. Techniques for doing this are available (e.g. Fowler and

Kilsby, 2002) and are being applied to these datasets. Of particular importance will be a more event-based approach, similar to that started in Longfield and Macklin (1999) for the York flood record, and used by Fowler and Kilsby (2002) for interpreting the role of the North Atlantic Oscillation in explaining changing precipitation patterns. Similarly, there are records of stage flow that extend back before the 1970s for the Swale, Ure and Nidd. These are largely chart records and require manual digitising. However, they are valuable as they will allow us to build up a picture of sub-catchment response over a much longer time period. These rainfall, stage and flow records also need to be interpreted in relation to large-scale atmospheric data. This was done by Longfield and Macklin (1999) who were able to link characteristic weather types to the magnitude and frequency of flooding. The next stage is to link this research to larger scale atmospheric data (such as in relation to the North Atlantic Oscillation) and also to the sequencing of rainfall events at the sub-event level. These sorts of analyses are important as it is probable that future climate changes won't affect the magnitude of precipitation, but also its spatial pattern.

Second, Figure 7 shows one of the more problematic challenges associated with undertaking this type of analysis. Up until the late 1990s, most water level recorders were chart-based. Many have now become digital dataloggers. Chart recorders commonly involved cylinders, with a calibrated rotation speed allowing water level to be recorded through time. Periodically, the cylinder paper would need to be reset and the ink would be topped up, commonly once every week or fortnight. Figure 7 shows the period of time between visits to the Buckden stage recorder on the River Wharfe. Unfortunately, the cylinder reset periods have a stronger correlation with the state of the U.K. economy than they do the need to collect scientific data routinely and accurately from a given recorder. This problem is most notable during the mid-1980s: as a progressive squeeze on the public utilities resulted in a general reduction in emphasis upon non-operational monitoring activities. The advent of automated monitoring systems is making long-term monitoring more cost efficient and reliable but even then events can intervene that can cause major gaps in data (e.g. access to upland sites to download data loggers was prohibited during the 2001 foot and mouth crisis resulting in some missing data).

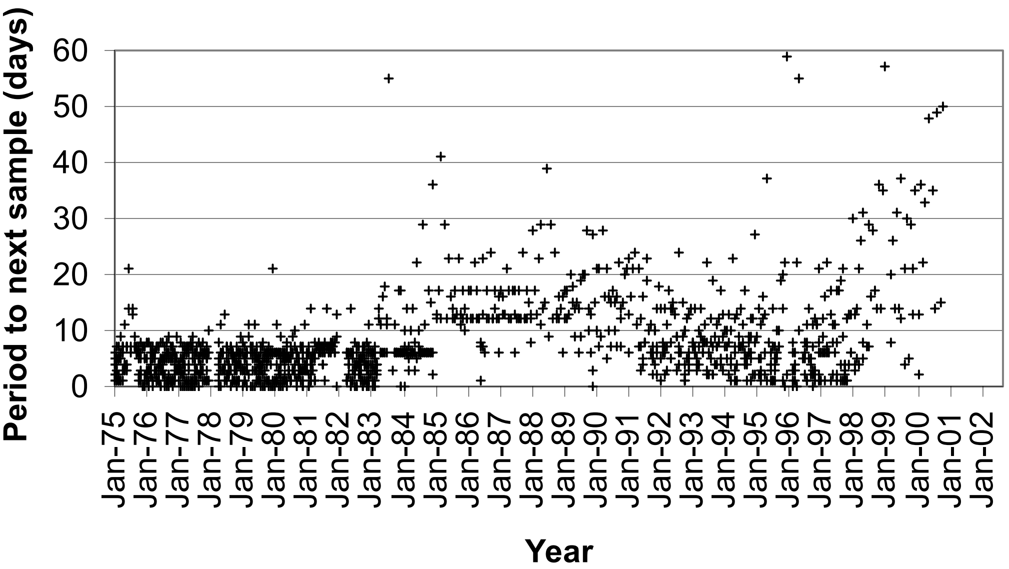


Figure 7. The time in days between visits to the Buckden stage recorder on the River Wharfe, North Yorkshire.

Third, and this is especially the case with respect to stocking issues, description of a progressive increase in stocking densities at the catchment-scale will hide much more complex patterns of stock management at the within-catchment scale. Especially in upland areas, there will be strong spatial variability in the maximum stocking levels that are desirable from the perspective of an individual farmer, as defined by accessibility, land suitability, local climate etc. The result will be strong variability in stocking density even within an individual land holding. At the same time, the hydrological susceptibility of fields to changes in stocking density will depend upon local relief, soil type etc. High stocking densities are likely to have most impact where they lead to local increases in stocking density in hydrologically sensitive parts of the catchment. In these areas, general reductions in surface infiltration due to trampling may increase overland flow. However, and potentially more importantly, they may increase the connectivity of more readily saturated zones to the drainage network. We know very little about this process. It is further complicated by interactions with the stock grazing calendar, which can lead to much higher stocking densities for short periods of time. Finally, the cumulative effects of high stocking densities upon surface infiltration, especially on sensitive soils, may require long term monitoring.

Fourth, whilst there have been many plot and field scale studies of the effects of land management upon runoff generation, there has been much less progress in reconciling the contradictory findings that they suggest. The debate over the effect of grips upon upland drainage is a good example of the need to undertake a proper synthesis of research results in an attempt to understand these contradictory observations. Much of the problem is the reliance upon field experiments, which are sensitive to the locations in which instrumentation is installed, and the time periods used for instrumentation. Thus, different conclusions arise because of the differing response of land units, with different land management practices, local relief, soil type, geology and climate (Robinson, 1990). For instance, preliminary results from a project to develop an integrated forecasting tool for assessing flood and water quality issues in the uplands (Lane *et al.*, in press) demonstrates that the effects of grips upon saturation are sensitively dependent upon local relief. It follows that land management effects need to be generalised in a more sensitive way than has hitherto been the case.

Finally, we are lacking studies that integrate local investigation of land use management effects with processes operating at the scale of large catchments. This is a major issue because as the scale of enquiry is increased, so the relative timing of sub-catchment response becomes more important. This was demonstrated in the analysis of the Swale-Ure-Nidd system above. Figure 6 showed that gripping was strongly associated with the Swale and the Nidd, and less so with the Ure. The general characteristic of these systems is a peak on the Nidd, before the Ure, which is in turn before the Swale. Flooding is more acute if the peaks on these rivers are closer together. If it is assumed that gripping increases the speed of catchment response, producing higher peak flows and lower times to peak, then the Nidd gripping will have increased the probability that the Nidd peaks earlier than present, reducing the probability of coincidence with either the Ure or the Swale, so reducing flood occurrence in York. However, the Swale gripping will increase the probability that the Swale peaks closer to the Ure, so increasing flooding in York. When these processes are combined with the complexity of timing of rainfall events and issues associated with impoundment, the need for scaling up to the catchment-scale becomes clear.

Conclusions

The above prognosis of future climate change in the three sub-catchments emphasises the importance of future changes in precipitation for increasing flood risk. The discussion of precipitation records for the three sub-catchments questioned the extent to which the existing 20th century increase in flood frequency could be attributed to changing precipitation patterns alone: there were major increases in flood magnitude and frequency before there was any marked increase in precipitation in the sub-catchment with the longest rainfall record. This is the sense in which increases in flood frequency need to also be considered in relation to land management. However, as shown above, disentangling a land management signal from the observed hydrological record is not easy, and alternative techniques will be required to assess the extent to which plot-scale studies of land management impacts scale up to the hydrological scale. This is unlikely to be achieved successfully using conventional empirical flood estimation methods (e.g. the rainfall-runoff method) as the boundaries of the model are defined by empirical data, and these data contain flood signals due to a range of influencing factors. This is the sense in which advanced modelling methods are really required.

If the predictions of increased rainfall in Table 6b are correct, then it will be important to consider the full range of flood mitigation options and these will have to include upland land use management. Under the European Union Water Framework Directive, integrated catchment management comes to the fore, and traditional solutions to flood risk management based upon flood defences need to be evaluated with respect to other impacts upon the water environment (e.g. ecological consequences). The ease with which traditional flood management options can be adopted will be increasingly questioned, in an era when Yorkshire's flood risk is likely to continue to increase.

Acknowledgements
This work is supported by NERC Grant NER/D/S/2000/01269 awarded to Professors Stuart Lane, Adrian McDonald and Mike Kirkby of the School of Geography, University of Leeds, and Dr Liz Chalk of the Environment Agency. Data were provided by Mike Stokes and Victoria Townend of the Environment Agency and by the UK Meteorological Office through the NERC British Atmospheric Data Centre. Paul Stelfox extracted the thirty largest flood records used in the principal components analysis. Kate Bradbrook (JBA Consulting) commented on a preliminary draft of this paper. Figure 6 was redrawn by the Graphics Unit, School of Geography, University of Leeds, from Robinson (1990).

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