Slowing the floods in the U.K. Pennine uplands…a case of Waiting for Godot?

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Abstract

The possibility that management of the rural landscape might provide a means of reducing downstream flood risk remains the topic of both extensive research and debate. Here, I identify some of the difficulties associated with establishing such a link. Using the c. 120 year instrumented flood record of the City of York I show that land management changes in the upstream catchments of the Swale, Ure and Nidd are plausible reasons as to why there is a pattern of increasing magnitude and frequency of flooding at York. However, I also show that these flood patterns correlate with other drivers of flood risk, such as the changing frequency of dominant flood-producing weather types. I use this evidence as the basis of a wider discussion of the difficulties of using data to identify possible rural land management impacts upon flood risk and to consider the very severe difficulties that catchment-scale flood risk modelling presents. Much of this relates to the complex interaction of a number of controls that almost certainly means that whether or not rural land management impacts upon flood risk depends upon the rainfall event, the catchment and the scale of analysis. It follows that the search for a general conclusion as to rural land management impacts is not a meaningful scientific quest and a clear answer is unlikely ever to emerge.

Key words

Flood risk management, rural land management, York, drainage, uplands, flooding

Introduction

Measures for flood risk reduction associated with the management of rural landscapes can be grouped into three broad sets of measures (Lane *et al.*, 2007): (1) changing the *partitioning* of precipitation between overland (fast) and subsurface (slow) flow, under the hypothesis that land management that reduces the generation of fast flow will lead to less downstream flood risk; (2) increasing the *storage* of runoff within the catchment, under the hypothesis that retention of water will lead to reduced downstream flood risk; and (3) reducing the *speed of conveyance* of runoff within the drainage and channel network, under the hypothesis that slower conveyance will lead to greater flow attenuation and hence reduced downstream flood risk. Such groupings are somewhat artificial: the use of a rural floodplain to slow conveyance, for instance, may involve allowing fields to flood, which may result in both storage and reductions in conveyance. A recent review of the potential role of rural land management in reducing flood risk (Lane *et al.*, 2007) noted that storage measures are already routinely considered as part of flood risk reduction strategies, primarily through the designation of floodplains as washlands, but also in other ways such as through using small dams and bunds in upland catchments (e.g. White Cart Water, Glasgow). Such strategies, particularly floodplain storage schemes, can be readily assessed through existing flood risk assessment methodologies (e.g. addition of storage zones to one-dimensional hydraulic models). What remains a much more elusive goal is providing demonstrable scientific evidence that changing rainfall partitioning or reducing conveyance speed has an impact. Whilst there are both historical and current experiments at the scale of individual fields and sub-catchments (e.g. the 18 km^2 Pontbren catchment, currently the focus of the U.K.'s Flood Risk Management Research Consortium), extrapolating their results to very large catchments of 100s or 1000s of km^2 is necessary in order to assess the extent to which field and sub-catchment scale impacts scale up to impact upon downstream communities. There are two primary upscaling approaches that can be adopted: (a) the analysis of historical flood events and their interpretation with respect to possible drivers; and (b) catchment-scale hydrological modeling. In this paper, I use evidence from research into flood history in the City of York: (1) to show the difficulties in using historical records to resolve land management impacts upon changing flood risk; (2) to discuss the extent to which modeling might provide a suitable alternative; and (3) to provide a broader perspective that questions the extent to which the hypothesis that rural land management activities might impact upon flood risk is a meaningful one to pose. I conclude by arguing that even if the scientific debate can be resolved, rural land management measures are fundamentally different in nature to other flood reduction measures (such as flood defences) and that they should be treated as complimentary measures rather than compared as alternatives.

The changing magnitude and frequency of extreme flood events: the City 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 1). 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 in the centre and 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, including the Yorskhire Ouse. 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. Indeed, there is commonly a delay of anything up to a few days between the timing of peak rainfall in the sub-catchments and the timing of peak flows in the Ouse at York. This emphasises that understanding the York flood record requires an emphasis upon the upstream contributing sub-catchments, rather than the more local urban and lowland arable and pasture environments in the vicinity of York, although the latter do provide a potential flood storage function.

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).

The reason for focusing on the Yorkshire Ouse is that it has a long duration of hydrological records in the City of York itself. Of most importance is the ‘Viking’ record of water level in the centre of the city which provides a daily record of maximum water level from 1878 to present. As a record of water level, it is a true record of the occurrence of flooding (i.e. flooding occurs when water levels exceed a critical defence threshold) and it is also of very long duration. However, it has two problems. First, 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, a record of water level will be a record of both changing precipitation, upstream land management etc. as well as local conveyance, as controlled by the shape of the channel, local river defence activities and the resistance to flow associated with the roughness of the channel boundary and the level of vegetation in the channel. 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. Second, water level changes are not a linear function of flow changes. The rate of change of water level depends upon the rate of change of flow, but also section shape, water surface slope, bed roughness etc. Once flooding starts, the rate of water level increase will commonly fall, as more of the increase in flow is accommodated by increases in wetted width. Thus, the water level record is affected by strong non-linearity, which means that its magnitude must be interpreted with caution. Thus, whilst the Viking record is long, it may be contaminated by effects that are not connected with upstream land management or climate change.

The main alternative to using a water level record is to use a discharge record. A digital record of discharge is available for Skelton, just upstream of York, from 1969 to present. However, this record presents problems. First, it is of shorter duration. In searching for trend in a flood record, as the record length is reduced, so trend may be artificially introduced where the record starts in an exceptionally dry period or artificially hidden where it starts in an exceptionally wet period. Second, up until 1992, it was based upon a stage-discharge relationship. A continuous record of water level is transformed into a continuous record of discharge using a relationship based upon point measurements of discharge for known water level. Thus, up until 1992, the record is essentially a record of water level, expressed as a discharge, and the same conveyance effects described above may apply. However, a greater problem exists. In 1992, a continuously recording ultrasonic gauge was installed. This provides a more reliable measure of discharge and has demonstrated that the peak flows estimated using stage-discharge curve are over-estimated. Thus, the flow record contains a break point in 1992, making its use for the period 1969 to present problematic.

Given the above, the focus of this analysis is the Viking record of water levels, based upon peak over threshold and annual maximum flood analyses. The threshold was set at 8.058 m, commonly taken as the threshold at which flooding begins in York. Lane (2003) checked the extent to which this is a reliable surrogate for changes in flow by relating water levels at York to discharges at Skelton, for all flow peaks above the 8.058 m threshold. This restricted analysis to the pre-1992 flows based upon the stage-discharge record. Results suggested a possible decrease in water levels associated with a given flow since 1969, implying that the water level record will be weakly biased towards reduced flood frequency and magnitude through time.

Evidence of change

Figure 2 shows the number of floods per decade (defined as a peak over a threshold series) and an annual maximum flood series, for the York water level recorder (‘Viking’). The results are quite dramatic, suggesting a progressive increase in both the frequency and the magnitude of flood events as a function of time, notably from the 1940s. However, they also reveal: (1) significant between year variability in the magnitude of the annual maximum flood (Figure 2a);

(2) organisation into runs of years with higher annual maximum flood magnitudes (e.g. the 1960s) and lower annual flood magnitudes (e.g. the early 1970s) (Figure 2a); and (3) evidence that floods as large as those in recent living memory (1982 and 2000) can be found historically (1888 and 1947). The first point that emerges from this record is the sensitivity of interpretations to the duration of the record inspected. Robson (2002) shows how what appears (visually and quantitatively) to be trend in series like the annual maximum flood depends upon the duration over which the assessment is made. Records that start in the 1960s and 1970s tend to show trend because of a relatively dry period at the start of this period (Robson, 2002). This reflects wider realisation that the timescales required for detecting change in hydrological record may be significantly longer than the timescales over which the drivers of those changes have been responding (e.g. Wilby, 2006). This is particularly the case for runoff records (Robson, 2002), not least because many river catchments are heavily regulated, making identification of atmospherically-driven runoff signatures particularly difficult (Hannaford and Marsh, 2006). This emphasises the value of long records like 'Viking', especially when what matters for flood risk is water level, which may not be only a function of river discharge. The second point is somewhat in contrast to the findings of Robson (2002) which was that there were no significant trends in key flow characteristics for the River Ouse at York. This may be because of the short duration of the Skelton record, but it may also be because of the extreme uncertainty associated with the magnitude of the largest flood events. If peak flows pre-1992 are over-estimated using the stage-discharge, then this will reduce the identifiability of trend in the complete series since 1969. It emphasises the need to inform analyses of flow records with carefully synthesised historical and contextual information on the reliability of those records.

The rural land management hypotheses

In the simplest of terms, and upon first inspection, rural land management in the Yorkshire Dales could be a plausible hypothesis for the trends shown in Figure 2. There are land management changes that could have contributed to all three of the runoff altering measures identified in the introduction, and three are of particular importance. First, since the 1940s, much of the Swale, Ure and Nidd sub-catchments has been drained, using open drains or grips, which are 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 such that the density varies greatly, as does their spatial arrangement within the landscape (Lane, 2003). Generally, gripping was introduced to drain peaty soils to improve grazing quality and for grouse shooting (Robinson, 1990). More than 50% of parts of the Nidd and the Swale were subject to gripping between 1940 and 1965 (Robinson, 1990), with very high rates (affecting more than 7 km^2 per year) in the 1940s and 1950s. Rates dropped off in the 1960s, but then rose again in the 1970s before declining in the 1980s.

The functional process that ties gripping to flood risk generation is more complex than might at first be thought, not least because evidence as to the effects of gripping upon downstream flood risk is contradictory. 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 larger 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 drying 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.

Thus, grips could both reduce flood risk by hindering the generation of rapid runoff through enhancing soil storage (i.e. a change in partitioning) but also increase flood risk by allowing for the more rapid connection of rainfall to the river network (i.e. a change in connectivity). 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 drainage is located such that it delivers water from late responding parts of the catchment more quickly, then this may actually contribute to increase the catchment flood peak; similarly, if the drainage is located such that it delivers water from parts of the catchment that normally respond early, causing them to respond even earlier, then this may reduce the catchment flood peak. Lane (2003) has shown that the relative timing of flood peaks from the Swale, Ure and Nidd basins is a second order explanatory variable (after flow magnitudes) of the size of flood flows at York, and if grips have caused a systematic change in flood peak timing, then this could lead to higher flood flows for a given rainfall event.

A second plausible hypothesis for the increases 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. Up until the early 2000s, these have subsidised farmers on a per capita basis with the result that stocks have risen, in some cases very sharply. 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 reported a positive relationship between soil bulk density and stocking density and 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 statisitically 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 some restricted *a priori* support for the idea that rising stocking densities in the 1970s and 1980s in the Yorkshire Dales may be contributing 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. More recent studies (e.g. Owens et al., 1997; Greenwood et al., 1998) have demonstrated that reducing stocking densities leads to the long term recovery of infiltration rates. However, changes in standard percentage runoff do not necessarily translate into changes in flood peaks at the catchment-scale, notably if the catchment is already well-saturated or if intervening attenuation effects are important.

The third major group of changes are associated with the management of the Ouse floodplain upstream of the City of York. From the 1940s onwards, farmland upstream of York was progressively defended using low impact levée systems, commonly set back from the river by a small distance, and also accompanied by an expansion in agricultural underdrainage (Longfield and Macklin, 1999). In landscape terms, prior to the development of these defences, the water level (and hence the river flow) required for the onset of flooding would be much lower than today. With greater transfer of water to the floodplain, the riparian corridor should have led to significant flood wave attenuation, although there are no studies that have as yet addressed the extent of this impact. With loss of attenuation, the magnitude of flood flows at York could be much larger.

Rural land management and the problem of serial correlation

The above discussion identified three hypotheses that might have contributed to the evidence of changing flood magnitude and frequency shown in Figure 2. Indeed, the three changes described have timings that match well with the flood records. But, this is where the problems begin. Unfortunately, a range of other flood drivers are also correlated with the changing flood record, including records from point rain gauges. For instance, Fowler and Kilsby (2003) note a two-fold increase in the magnitude of extreme rainfall for parts of the U.K. Longfield and Macklin (1999) note that 79.7% of documented flood events (before 2000) in the City of York are associated with just four of the Lamb (1972) weather types: westerly, cyclonic, cyclonic-westerly and south-westerly. Figure 3 shows the cumulative deviation from the average number of days per year with these types of weather. There is a remarkable level of agreement with the overall patterns shown in Figure 2b, with fewer floods per decade in period when there is fewer of these weather types than average. Associated with the positive 20th century trend in the magnitude and frequency of flooding at York is also a trend towards weather types that are more dominant contributors to flood risk. The fact that there is such a strong correlation with weather types which are themselves autocorrelated (albeit spuriously) with changes in land management means that simplistic inspections of runoff records for land management impacts, or any other kind of signal, including climate change, must be treated with some caution.

Complexity in the flood system and the problem of data availability

In identifying serial correlation amongst a number of possible flood drivers, I have begun to unpack the complex nature of the flooding system. Figure 4 expands upon this complexity by identifying a number of factors that cause us to think very carefully about the potential role of rural land management in flood risk reduction. On the left hand side of the diagram is the simple assumption behind empirical testing of the three hypotheses regarding land management impacts, identified in the introduction. The discussion of floodplain management introduced the idea that conveyance might impact upon observed flood magnitude and frequency. The discussion of serial correlation noted changing rainfall characteristics and weather types. To these, the diagram adds two other broad areas that will determine how land management changes might impact upon flood risk management. The first recognises that our conceptualisations of the nature of land management are often much more simplistic than is likely to be the case in practice. For instance, gross data on changing stocking densities, hide much more complex within-year and between-farm variability in how those stock are managed, such as in relation to over-wintering, field rotation and within land holding variability in how land is used and treated (e.g. improved). The second introduces the importance of the catchment as conditioning the effects of land management, including soil type, but also more complex processes associated with the arrangement of a catchment in response to the typical tracks of storms across a drainage basin and hence the sequencing of where it rains when. Taken with atmospheric variability and the importance of conveyance impacts, it becomes clear that attempts to use data to identify land management impacts may be confounded by the multivariate controls upon the flood generation process (Figure 4). Two different interpretations follow: (1) interaction between these variables make identification of a land management signal that is distinct from the noise introduced by other processes especially difficult, but in theory, proper design of data collection systems might allow such a signal to be identified; and (2) the hypothesis that rural land management might impact upon flood risk is one that is beyond scientific investigation because it is meaningless without reference to the particular catchment being considered at a particular point in time.

There is no doubt that at least some elements of assessing the land management hypotheses are impacted upon by issues associated with data availability. In a conventional experiment, each of the factors in Figure 4 would be perturbed, whilst others are held constant, and the associated impact upon flood magnitude and frequency determined. In a more sophisticated experiment, there might be some form of joint factor perturbation. By assembleing enough instances of the phenomenon (in this case, the incidence of flooding at York) and then quantifying each of the relevant factors, then multivariate analysis may be used to distill the core drivers of the system. With so many potentially controlling variables, the number of flood incidents required is likely to run to at least two orders of magnitude. The problem may be broken down somewhat, allowing some progress: for instance, Lane (2003) reported on principal components analysis on the 30 largest flood events at York, which when combined with additional flow data from the Swale, Ure and Nidd, was used to show that the relative time of basin response explained some of the variability in flow magnitude at Skelton.

The Lane (2003) work was based upon records for gauges towards the downstream end of each of the relevant sub-catchments. The logical next step would be to explore the extent to which the relative timing of these sub-catchments could be traced back to catchment-scale land management changes. What is ultimately a reductionist approach to the question ought to become easier, as the shift for a search for explanation moves upstream, to smaller and generally more homogeneous sub-catchments in more upland environments. However, when we get into upland environments, there tends to be severe data availability issues: we simply do not collect the kind of data necessary to do this more upstream analysis. The structure of rainfall recording has not been designed with any sort of scientific experiment in mind. The majority of records are linked to either: (a) water resource management, and notably potable water supply (e.g. they are found at reservoir impoundments); or (b) where they can provide sufficient warning to downstream communities, through telemetry, of an impending flood event. There are even fewer instances of long-term maintenance of water level or flow recorders in upland environments. Such data collection is expensive and requires a long-term commitment to maintain data collection. However, such data collection is commonly exposed to changes in scientific priorities. Figure 5 shows the time between chart change for an upland stage recorder in the Yorkshire Dales. Up until the growth of digital data logging in the 1990s, chart recording was the major way in which long term water level records were obtained. The barrel in each recorder commonly would rotate such that one week would be completed within one rotation. Replacement of the chart, refreshment of the ink and recalibration, is normally required every two weeks in order to maintain the record. Up until late 1983, the Buckden recorder was well-maintained. Responsibility for this rested with the Yorkshire Water Authority until the late 1980s, when the National Rivers Authority took over responsibility. As the public utilities were progressively squeezed under the spending restrictions of the early and mid-1980s, so the frequency of 'sampling' (i.e. chart changing) was reduced to make the record almost valueless by the mid-1980s. The creation of the National Rivers Authority resulted in a progressive improvement in management of the resource until, with creation of the Environment Agency, the quality of management deteriorated. Management of this resource appears to have much more to do with political and economic processes as they impact upon institutions than it has to do with elements of research design or good scientific practice. With the development of digital data logging, the need to visit gauges repeatedly is reduced, but this does not eliminate these sorts of problems. Data storage is finite, and if downloading doesn't occur sufficiently frequently, the data gets over-written. During the foot and mouth crisis of 2001, the Environment Agency placed a blanket order on non-essential field visits, such that many upland data recorders were not visited and data gaps appeared. This was applied regardless of whether or not a gauge was within a restricted area. It is understandable from the perspective of the Environment Agency, which has to maintain a good relationship with land managers. Any form of apparently unnecessary access in relation to such a sensitive issue could have left the Environment Agency with difficult publicity problems, regardless of any actual risk. It is much less understandable from the perspective of generating long-term high quality data from which to test hypotheses regarding the affects of upstream land use upon flood risk. The length of record required to test the land management hypothesis, as with the climate change hypothesis (Wilby, 2006), is likely to be many decades requiring long records for analysis. If the impacts of rural land management measures upon flood risk vary between catchments, then we will need such long records in every candidate catchment.

Modelling as an alternative to the analysis of historical data

The alternative to relying upon data is to develop models that are capable of testing land management impacts. In theory, models allow the kind of experimentation that is simply not possible with extant, or even specially-designed, datasets: it is possible to simulate the effects of different drivers in isolation and in combination upon flood risk. Indeed, decisions over current flood risk management are heavily reliant upon models, both hydrological (such as the Flood Estimation Handbook, Institute of Hydrology, 1999) and hydraulic (and notably flood routing and inundation models). There is much innovation in the modelling of rural land management impacts. For instance, O'Connell *et al.* (2007) trace 'packets' of water across landscapes and into predicted hydrographs to see which runoff source locations have contributed to the hydrograph peak. In turn, the geographical locations of the sources that contribute the runoff peak can become the focus of testing possible land management impacts with the aim of attenuating downstream hydrograph response. Two important questions then need to be asked: (1) do models sustain the argument that rural land management impacts upon downstream flood risk?; and (2) can those models be used to develop strategies for rural land management in particular basins?. The first is essentially a question of science. The second is a necessary response to an affirmative answer to the first.

There is now a long history (> 40 years) and also a well-developed critique (e.g. Oreskes and Belitz, 2001) of the use of modelling in hydrology. Central to the critique is the severe dependence of hydrological models upon a system that is never perfectly specified by available knowledge: the problem is seriously under-determined. Here, knowledge includes: (1) the perceptual understanding of what we think matters to the flood system; (2) the conceptual understanding, or physics, necessary to translate our perceptions into mathematical models; (3) the data necessary to provide boundary conditions to those models; and (4) the parameters and processes that are introduced into the model through the chosen physics or necessitated by simplifications to that physics. There are five broad areas of critique of hydrological modelling: (a) the unresolvability of different model configurations (Beck's (1987) non-identifiability or Beven's (1993) equifinality), often bound up with severe uncertainty in model predictions; (b) the failure of models to 'travel' beyond the specific places or time periods for which they have been developed and parameterised (e.g. Konikow and Bredehoeft, 1992); (c) the lack of agreement over what constitutes a reasonable set of model predictions (Oreskes and Belitz, 2001), often cast as a lack of standards in modelling (e.g. Lane and Richards, 2001; O'Connell *et al.*, 2007); (d) the inadequacy of the measurements available to resolve different model formulations; and (e) the problem of applying of modelling processes with a scale range of c. 10^7 m^2 (from an upland drain less than 1 m wide to a catchment with a drainage area of 1000s of km^2). The scale issue represents a particular problem because the evidence of land use management impacts upon rapid run off generation is more clear cut at the plot scale (O'Connell *et al.*, 2007). However, as a result of the processes like attenuation and sub-catchment interaction, these plot scale effects may not necessarily still be detected at the catchment-scale.

Despite the lack of a clear academic consensus as to the most appropriate approach to modelling rural land management impacts, consultants are being called upon to develop land management strategies for particular river catchments and this is proving to be the cause of some controversy. Take the following evidence from an internal report of the Environment Agency's *Delivering Space for Water* project (Environment Agency, 2007). The report compares two contrasting sets of results for the role of rural land management in reducing downstream flood risk. The first comes from the Ripon Multi-Objective project, based on the Skell and Laver catchments that drain into the River Ure. This project used a Probability Distributed Moisture (PDM) Model that transforms input rainfall and potential evapotranspiration into an outlet discharge, conceptualising the hydrological cycle as a series of stores and transfers. The modeling showed that the worst case land degradation scenario led to increased peak flows in Ripon (20% for 1 in 10 year floods, 10% for 1 in 100 year floods) and that the best case scenario for improving land management would reduced peak flood magnitudes by *c.* 8%. The second used a two-dimensional (i.e. spatially explicit) physically-based hydrological model to explore rural land management impacts upon the River Parrett and concludes that land management was having no impact upon flood risk.

The interesting aspect of these two studies is not the studies themselves, but the ways in which they are reviewed in Environment Agency (2007) and then presented in very different ways. In relation to the PDM work on the Ripon Multi-Objective project, it notes (p9, my emphasis in bold): "*The Ripon Land Management Project used scenarios to represent plausible changes to the land management or land use in all or parts of the Ripon catchment, targeting the three main rural land uses in the catchment, moorland, improved grassland and arable. The impact of the proposed land management changes were represented in* ***simple*** *1-D rainfall-runoff models by altering parameters affecting the rate of runoff, soil moisture storage and hydrograph timing.*" The PDM approach is noted to have important weaknesses (p10): (1) *Scale issues - Land use change modelling is undertaken at a sub-catchment scale and does not take account of more localised changes*; (2) *Underlying science issues - Land use changes are simulated by making changes to parameters within the Flood Estimation Handbook (FEH) method, which provides only crude assessment of surface runoff impacts*; and (3) *Limitations in model input data quality* *and setup (e.g. inadequate rainfall data, limited numerical information about field drainage systems, poor knowledge of the underlying geology, limited information on the hydraulic structures and soil characteristics)*. In contrast (p10, my emphasis in bold), the physically-based approach is described as have an underlying science that '*is generally considered to be* ***more robust*** *for this approach (in comparison to the 1-D approach at Ripon) because surface, subsurface and groundwater processes are better represented throughout the catchment using an array of grid cells*.' There is no comparable critique of the River Parrett modeling in the report, even though two-dimensional physically-based models have similar underlying science issues (e.g. how do you simulate a land use change in a meaningful way in the model?) and certainly the same data availability issues. Even if the physics provides a better theoretical representation, the actual representation is only as good as the data available to drive the physical processes. Acquiring spatially distributed information on the kinds of parameters that will drive model response (e.g. soil depth, saturated hydraulic conductivity and its variation with depth) is still almost impossible for anything more than the plot-scale. Understanding the uncertainty in these models is especially difficult because of the large number of model parameters, coupled to their computationally intensive nature. Multiple model runs really need the kind of high performance computing resources still only really found in universities. I am not arguing that these are worse than approaches like the PDM approach: rather that similar critiques of physically-based models can also and should also be made.

There are two important observations that follow from what is described above. First, even if a scientific case can be established for incorporating rural land management in flood risk reduction, we are some way off from having suitable models that can be used by consultants to factor rural land management processes into decision-making. If there is no general relationship between land use management and flood risk, models will need to be applied on a catchment-by-catchment basis. Thus, models suitable for use outside of an academic context will be required. Second, and potentially more seriously, there is an element of hubris in the way in which the PDM and physically-based models are evaluated in the above report. This may not be intentional and simply reflect an inadequate understanding of the limits of physically-based modeling. A less benign interpretation might be that the findings of the Parrett study fitted more with broader opinion in circulation regarding the role of rural land management in flood risk reduction. It is perhaps ironic that in almost all flood risk assessments currently undertaken by U.K.-based consultants, the Flood Estimation Handbook method that is part of the critique of the PDM model remains the primary methodology used for hydrological elements of the analysis, one that has proved remarkably robust for about 35 years. The question that emerges, and which urgently needs research, is the extent to which opinions on rural land management have become encoded to the point that the link to flood risk management is being socially-excluded.

More data, better models or a chaotic conception?

If we put the arguments above to one side, and accept that either more data or better models might actually be forthcoming, I think we are still left with a more fundamental problem in relation to rural land management impacts upon flood risk: it is what social scientists have called a ‘chaotic conception’ (Sayer, 1992). Sayer (1992, 138) defines chaotic conceptions as ‘bad abstractions’ in which the indivisible is arbitrarily divided to create new lumpings of processes and properties that are unrelated and, in the words of critical realism, ‘inessential’. Following Sayer’s argument, the *association* of land use management with flood risk is perfectly legitimate in descriptive terms. However, it is not legitimate to assign *explanation* to such an association, as, quite simply, the same land use management activity cannot always be taken as having the same flood impact. As an example, consider the issue of gripping. Whilst the study of a grip may allow a general conclusion to be reached about the local impacts of that grip upon water balance and the timing of delivery of water from that grip to the drainage network, two important steps need to be taken to move from the general observation of local runoff impacts to a general observation of flood risk impacts. First, the impact of that grip will depend upon where it is within a sub-catchment. Gripping that is closer to the headwaters of a sub-catchment may indeed deliver water more quickly to the drainage network, and be a cause of flood risk. Gripping closer to a sub-catchment outlet, however, may actually enhance attenuation effects, and reduce flood risk. Hence, as the spatial scale of enquiry is changed, so any possible generalisation will need to change: conclusions reached for a single grip may not apply to a whole grip network, let alone an entire sub-catchment. As the spatial scale of enquiry is increased, so the role of other factors will become more important. Similarly, there is a greater probability that the effects of grips will become either counter-acting or synergistic, so making the conclusions difficult to generalise from individual grip studies as well as from catchment-scale empirical generalisation. Second, the effect of a grip may vary in time, such as in relation to the direction that rain-bearing systems follow when moving across a sub-catchment, which controls when rain enters the grip, and hence whether the enhanced connectivity it causes either increases or reduces downstream flood risk. The kind of generalisation that comes from the descriptive association of land management with flood risk has no explanatory power as the impacts of gripping cannot be separated from the nature of the flood event being considered. If the association between rural land management and flood risk is indeed a chaotic conception, not only will it take some time for us to have sufficient data necessary to reach a definitive conclusion, but a definitive conclusion, as with Godot, may never come.

Conclusion: moving flood risk management upstream

The immediate conclusions from this paper are three fold. First, the hypothesis that rural land management impacts upon flood risk is not one that is well-resolved by available data. Second, we do not have a consensus, in academic let alone delivery terms, upon the kinds of models needed to test the hypothesis. Third, the hypothesis itself may never be resolved in a general sense as a result of the sensitive dependence in space in time upon the findings that arise. It is not actually a meaningful hypothesis to investigate.

My final point is the need to think carefully about what a rural land management based flood mitigation strategy might involve, even if these issues could be resolved. Most traditional flood defence schemes have two important characteristics (Lane *et al.*, 2007): (1) responsibility for their effective functioning rests with a single competent authority (e.g. long-term maintenance of a flood defence levée); and/or (2) responsibility for action rests with direct flood victims (e.g. installation of boards or sand bags to prevent flood water entering in a house). As an alternative, rural land management would require many individuals to act, most of whom have no direct responsibility for preventing downstream flooding (e.g. farmers, at least under conventional flood risk policy regimes), let alone the kind of incentive to act that comes from being the potential victims of flooding. For a downstream flood victim, there is no comparison between a conventional flood embankment, maintained by the Environment Agency, and the diffuse, uncertain land management responses of a series of land owners. Recommending the latter instead of the former will inevitably lead to controversy and is likely to remain socially uncertain however scientifically certain the evidence to sustain it might become.

Where rural land management measures might interface with conventional flood defence measures will be through statistical generalisations of flood magnitude and frequency. Rural land management measures may eventually be shown to change the shape of flood duration curves in some situations and so change flood return periods. Policy on flood defence (e.g. PPS25, DCLG (2007)) is largely cast in terms of flood zones where the return period of a given flood defines the kind of development that is permissible in a particular place as well as the kind of measures that statutory bodies like the Environment Agency and Flood Defence Committees should consider. Rural land management measures will never provide the level of protection associated with conventional flood defences. The key hypothesis to investigate is whether or not the progressive agricultural deintensification of large areas of river catchments, the social and economic implications of doing so aside, might contribute to reducing the burgeoning cost of flood risk management associated with conventional flood defences through reducing the level of protection necessary for downstream flood exposed communities. Of course, other benefits might accrue such as in relation to water quality or ecosystem function. However, and ironically, given the statutory way in which we define levels of protection in terms of statistically averaged return periods, such a reduced level of protection might actually translate into greater exposure to flooding for downstream communities if rural land management measures have an impact that is contingent in space and time and not always guaranteed or as expected.

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List of Figures (Figures 1, 2 and 3 are currently being redrawn)

Figure 1. The Ouse catchment upstream of the City of York, northern England.

Figure 2. Records of the number of floods per decade (as a peak over threshold) and the annual maximum flood, for the ‘Viking’ record of water level in the City of York.

Figure 3. The analysis of Lamb weather types for the City of York. The four weather types (south-westerly, westerly, cyclonic and cyclonic-westerly) have been identified as responsible for almost 80% of flood events at York (Longfield and Macklin, 1999). Here, the average number of these four types per hydrological years is subtracted from the number recorded for each year and the deviations are cumulated. Rising parts of the curve show more flood generating weather types than average, falling show less.

Figure 4. A conceptualisation of the flood system for comparison with the serial correlation approach.

Figure 5. The number of days between changes of the chart and resupply of the ink for the Buckden recorder of water level on the River Wharfe, Upper Wharfedale, North Yorkshire.

Figure 1.

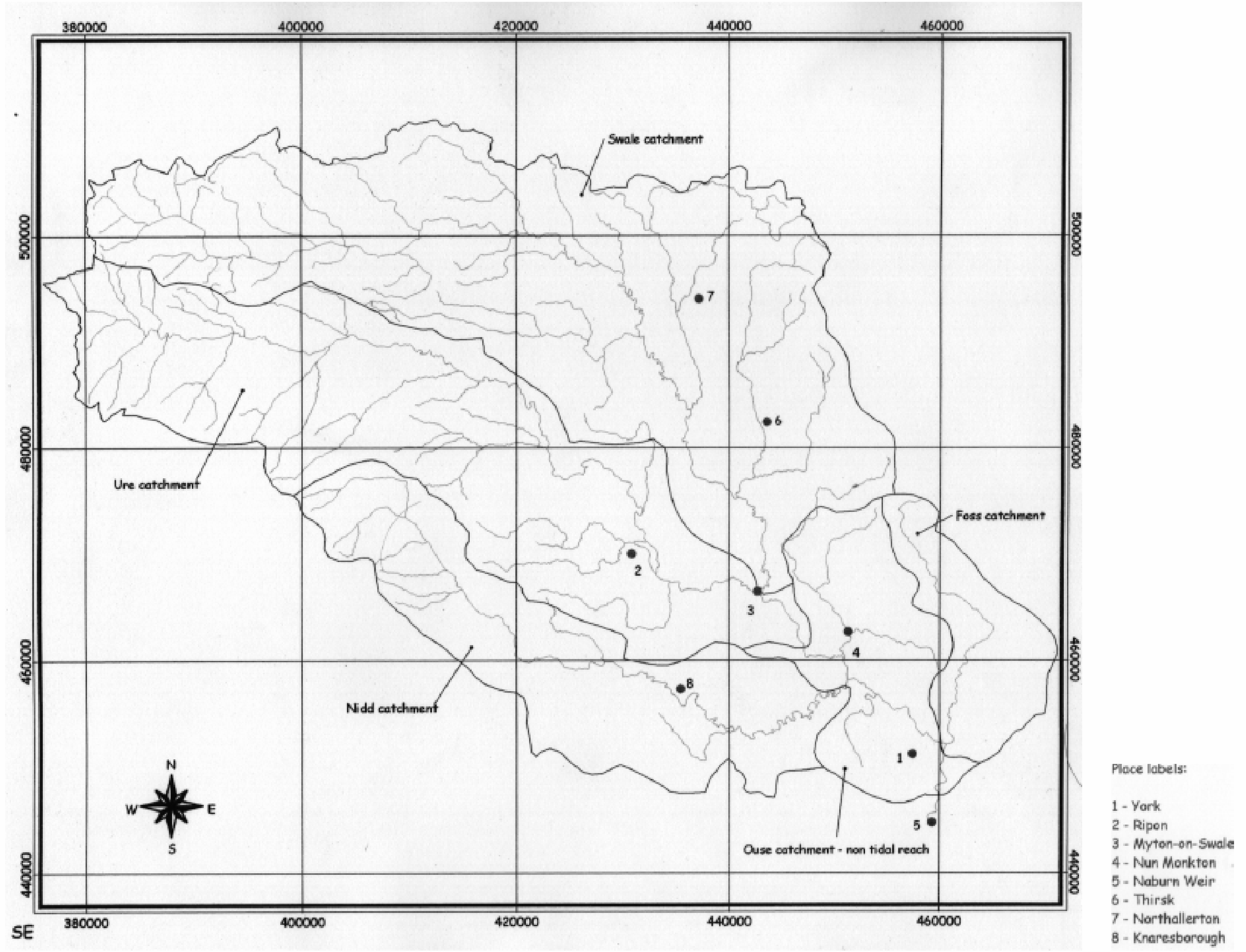

380000
400000
420000
440000
460000
500000
480000
460000
440000
SE
Swale catchment
Ure catchment
Nidd catchment
Foss catchment
Ouse catchment - non tidal reach
N
W
E
S
1
2
3
4
5
6
7
8
Place labels:
1 - York
2 - Ripon
3 - Myton-on-Swale
4 - Nun Monkton
5 - Naburn Weir
6 - Thirsk
7 - Northallerton
8 - Knaresborough

Figure 2.

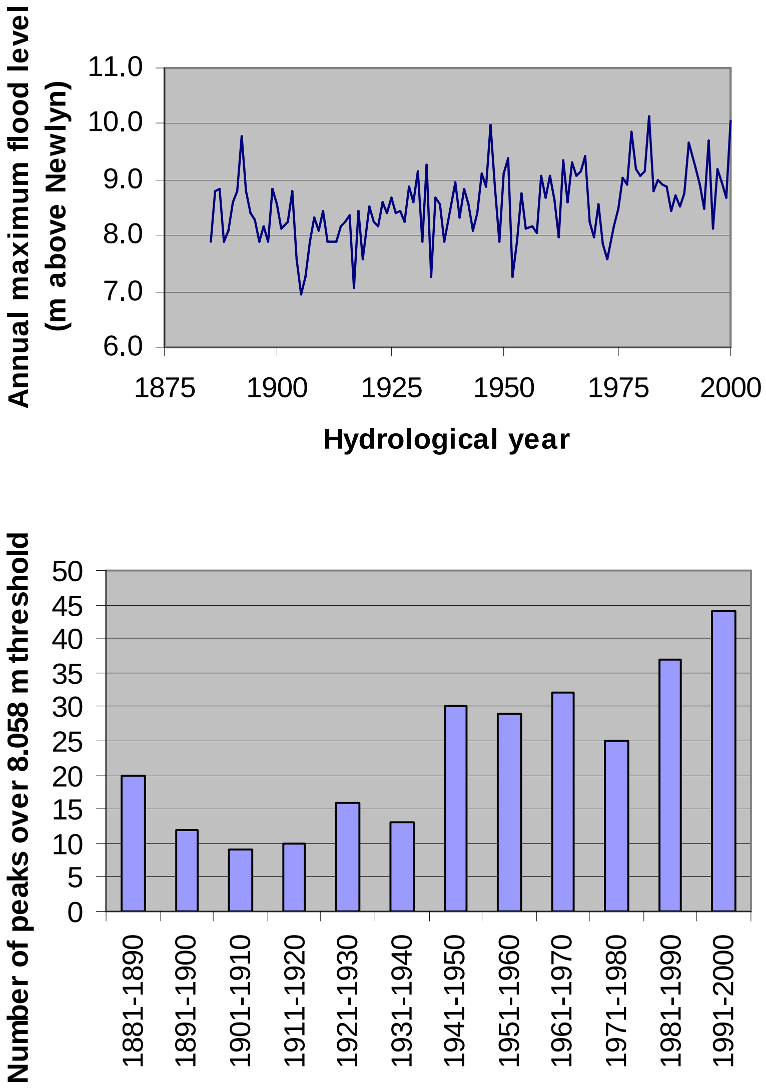
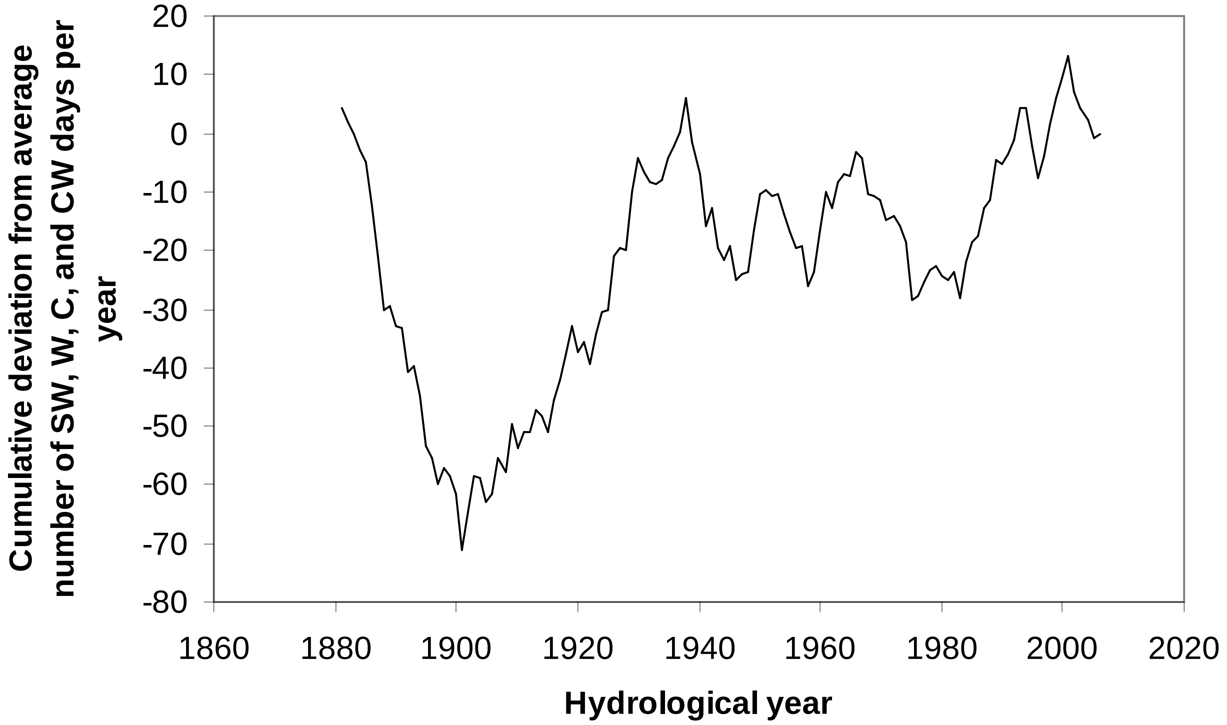

Annual maximum flood level (m above Newlyn)
11.0
10.0
9.0
8.0
7.0
6.0
1875
1900
1925
1950
1975
2000
Hydrological year
Number of peaks over 8.058 m threshold
50
45
40
35
30
25
20
15
10
5
0
1881-1890
1891-1900
1901-1910
1911-1920
1921-1930
1931-1940
1941-1950
1951-1960
1961-1970
1971-1980
1981-1990
1991-2000

Figure 3



Cumulative deviation from average number of SW, W, C, and CW days per year
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
1860
1880
1900
1920
1940
1960
1980
2000
2020
Hydrological year

Figure 4.

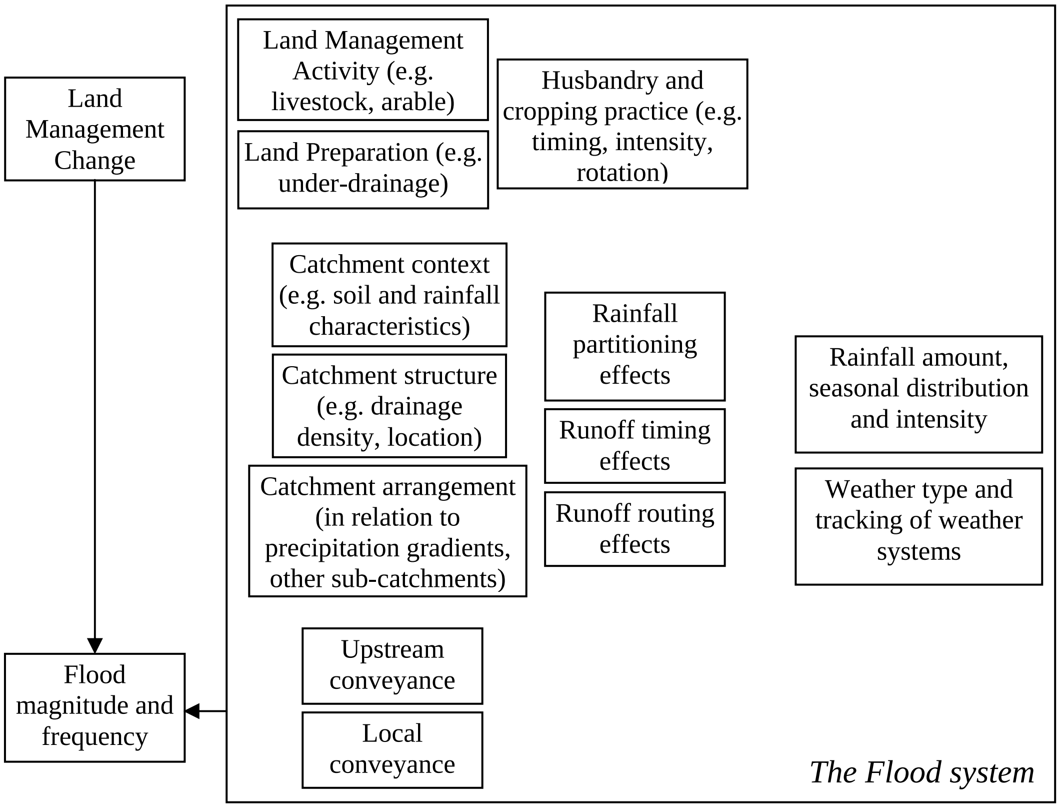
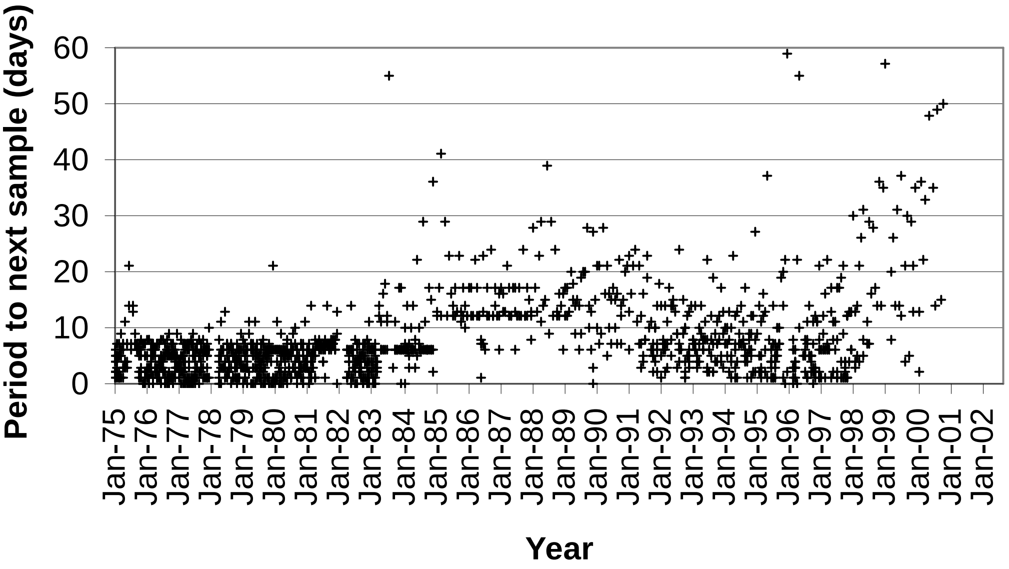

Land Management Change
Flood magnitude and frequency
Land Management Activity (e.g. livestock, arable)
Land Preparation (e.g. under-drainage)
Husbandry and cropping practice (e.g. timing, intensity, rotation)
Catchment context (e.g. soil and rainfall characteristics)
Catchment structure (e.g. drainage density, location)
Catchment arrangement (in relation to precipitation gradients, other sub-catchments)
Rainfall partitioning effects
Runoff timing effects
Runoff routing effects
Rainfall amount, seasonal distribution and intensity
Weather type and tracking of weather systems
Upstream conveyance
Local conveyance
The Flood system

Figure 5.


Period to next sample (days)
60
50
40
30
20
10
0
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Jan-98
Jan-99
Jan-00
Jan-01
Jan-02
Year