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The link between land use management and flood risk: a chaotic conception?

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Abstract

There is much policy interest in the possible linkages that might exist between land use and downstream fluvial flood risk. On the one hand, this position is sustained by observations from plot and field-scale studies that suggest land management does affect runoff. On the other, upscaling these effects to show that land management activities impact upon flood risk at larger catchment scales has proved to be elusive. This review considers the reasons for why this upscaling is problematic. We argue that rather than it reflecting methodological challenges associated with the difficulties of modelling hydrological processes over very large areas and during extreme runoff events, it reflects the fact that any linkage between land management and flood risk cannot be generalised and taken out of its specific spatial (catchment) and temporal (flood event) context. We use Sayer's (1992) notion of a "chaotic conception" to describe the belief that there is a simple and general association between land management and downstream flood risk rather than the impacts of land management being spatially and temporally contingent in relation to the particular geographical location, time period and scale being considered. Our argument has important practical consequences because it implies that land management activities to reduce downstream flood risk will be different to traditional flood reduction interventions such as levées. The purpose of demonstration projects then needs careful consideration such that conclusions made for one project are not transferred uncritically to other scales of analysis or geographical locations.

Key words flood risk management; land use; river flow; discharge; peak flow; hydrological extremes

Introduction

It is widely accepted, both in public and academic domains, that the magnitude and frequency of river flooding is currently increasing (Robson, 2002; Hannaford and Marsh, 2007). For instance, in the U.K., recent widespread flood events have been cited as evidence to support this perception. These include the Central England floods of Easter 1998 (Horner and Walsh, 2000), the Sussex and Yorkshire floods of Autumn 2000 (Marsh and Dale, 2002; Kelman, 2001), the flash flood in Boscastle 2004 (Golding *et al.*, 2005; Roseveare and Trapmore, 2008), the Carlisle flood in January 2005 (Environment Agency, 2006), the widespread Summer 2007 floods (Marsh and Hannaford, 2007; Marsh, 2008) and the floods in Cumbria in November 2009.

Figure 1 Hypothesised impact of land use and climate change on hydrological response as a function of spatial scale. (Bloschl *et al.*, 2007).

There are two broad hypotheses for these changing patterns: (1) changes in climate, and notably the sequencing of extreme wet and dry periods, leading to a greater magnitude and/or frequency of hydrological extremes (Arnell, 2003; Huntington, 2006); and (2) the effects of land management upon the relationship between extreme climate events and hydrological extremes (O'Connell *et al.*, 2004; Lane *et al.*, 2007). This review concentrates on the latter of these hypotheses, and specifically whether or not there are situations where land management might be influencing flood risk at scales larger than the plot or field scale.

Bloschl *et al.*, (2007), considered the effects of climate change on both high and low river flows (Figure 1). Climate change occurs at quite large spatial scales. With the exception of very large catchments (e.g. the Amazon basin), it is likely to impact an entire catchment in a similar way, such as the increased probability of an extreme rainfall event occurring. However, land use changes are more localised in nature and the impact of change is thought to decrease with increasing catchment size. It is

then possible to conceptualise a crossover point (Figure 1), one that is catchment specific, and which depends on the sensitivity of the catchment to change as well as the magnitude of the land use changes themselves. Thus it is highly likely that the scale of consideration determines whether or not a land use signal might be detected. It is also probable that land management practices should not be relied upon as an alternative to more robust and proven flood mitigation measures (Beven et al., 2008). Yet a number of organisations have picked up the view that rural land management might be a means of reducing downstream flood risk, and these views are commonly generalised in functional or process-based terms.

Methodologically, demonstrating that land use change might impact upon flood risk is challenging because the impacts to be assessed are small magnitude and diffuse, gaining their effectiveness from upscaling to the catchment scale. Establishing this link is difficult because of the need to disentangle hydrological response due to land use changes from that due to natural and possible human-induced rainfall changes. In the U.K., a series of 'demonstration projects' are seeking to show how land management change can help to manage local flood risk at the same time as contributing to wider environmental objectives. Whilst the methodological difficulty of demonstrating a link between land use and catchment scale flooding does not mean that there is no link and should not imply a policy of not using land management as a flood reducing option (Beven et al., 2008; Parrott et al., 2009), this paper seeks to move beyond these methodological questions to raise a broader set of issues that relate to the fundamental nature of catchment hydrology and which we believe require a much more thoughtful, certainly geographical, approach to thinking through how rural land management might relate to flood risk.

Our review begins with a more traditional approach to the problem: it considers available evidence for the effects of rural land management practices upon downstream flood risk, adopting largely a process-based classification. This review shows that there is at least some *a priori* basis for linking rural land management to downstream flood risk. However, this review also shows that the exact relationship between land management and flood risk more complex than might be imagined because of geographically and temporally specific controls on the cross-over point identified by Bloschl et al., (2007).. First, it depends upon local catchment characteristics, which control how runoff is generated and transmitted across the

landscape. Second, it depends upon the spatio-temporal sequencing of extreme rainfall events, which determine which parts of a catchment respond hydrologically and when. Third, these spatial and temporal processes are additionally filtered (and either magnified or diminished) by the structure of the river catchment, as a control upon the way in which hillslope and tributary flows combine, such that the impact of a given land management activity upon downstream flood risk can change with distance downstream. We use this to argue that attempts to relate downstream flood risk to upstream land management practices, whether using data-based or mathematical modelling approaches, are based upon a very poor conception of the explanatory linkage between them and can be best described in Sayer's (1992) terms as a 'chaotic conception'.

The functional approach: hydrological processes, rural land management and the generation of rapid runoff

Hydrology is traditionally replete with notions of the 'process cascade' where water (and materials transported by water) can be found in a series of stores, connected by a series of transfers. Hydrological response is thought to result from the aggregate response of these stores and transfers, allowing us to build up hydrological explanation from a series of sufficient and connected process conceptualisations coupled to necessary boundary condition data (Lane, 2008). This functional approach has been used to consider the ways in which rural land management might influence flood generation (e.g. Lane *et al.*, 2007), thought to be a consequence of: (1) the effects of rural land management upon the partitioning of rainfall between rapid surface and slower subsurface flow; (2) the effects of rural land management upon within-catchment storage of water during storm events; (3) the effects of rural land management upon the ease with which water is delivered from hillslopes to the river network, thought to be a function of hydrological connectivity; and (4) the effects of rural land management upon the conveyance of water within the riparian zone, including both channels and floodplains. We use this structure to review the effects of rural land management upon hydrological processes in relation to the possible effects on downstream flood risk.

The partitioning of rainfall between surface overland flows and subsurface pathways is a potentially significant driver of flood risk, as it determines the speed at which

water is transferred from hillslope to the river channel. Overland flows are thought to be faster routes than subsurface flows, and therefore the proportion of rainfall which takes either route determines the timings of water input into the river. Immediately, this assumption can be questioned, because well-structured or well-drained soils may have rapid throughflow, such as in the presence of soil pipes (Holden and Burt, 2002; Holden, 2005). The processes involved in conditioning the differentiation of flows are infiltration and percolation. These depend on the soil structure and type, topography and antecedent conditions. Specifically, infiltration is the movement of water through the soil via macropores. Therefore the number, size and connectivity of these pores determine the rate of infiltration. If infiltration is limited by any of these factors then overland flow results. Both Hortonian (infiltration-excess; Horton, 1933) and saturation-excess overland flow have been associated with generating rapid runoff during flood events. For instance, Boardman *et al.*, (2003) describe how short-duration high-intensity storm events can lead to rapid runoff generation. They found that particular kinds of land management practices (notably autumn sowing of winter wheat) could make it easier to generate Hortonian overland flow and result in muddy floods for certain soil-geology complexes. Similarly, long duration, less intense rainfall events have been shown to result in catchment-wide saturation and an increased effectiveness for rapid runoff to be generated by heavy rainfall (Bronstert *et al.*, 2002). This highlights the importance of the sequencing of precipitation events, and how the same land management practice could lead to different flood impacts. It is possible that during extreme floods, the effect of land management may be reduced as the catchment is saturated and all further precipitation is partitioned into rapid overland flow.

Water storage within the catchment during a storm event may cause a flood peak to be delayed and attenuated, meaning it is lower, but longer in duration. Examples of surface water stores include wetlands (Mitsch and Gosselink, 2000; Zedler, 2003), washlands, ponds, impoundments and flood expansion areas (Pivot *et al.*, 2002). The exact location of these stores within the catchment is important, as well as their total volume. The mitigation of flood risk by water storage is an established concept and has fewer uncertainties associated with it. Engineered storage in the form of reservoirs is known to reduce flood risk downstream (De Roo *et al.*, 2003). However, diffuse storage management schemes, where there is a large number of small

storage systems which rely on general attenuation, are less well understood than large volume storage systems. An advantage of these types of land management practices, is that they may have multiple benefits including; biodiversity, pollution control, along with floods.

Hydrological connectivity may be associated with flood generating processes for two broad reasons. First, it will control the amount of water that enters the river network during an extreme flow event, and which will generally increase where there is better lateral connectivity. Second the ease of connectivity may influence the speed with which water enters the channel and is transported downstream. Furthermore, the ease of connection may be influenced by the surfaces over which water flows and rougher land surfaces may slow overland flow, increasing the chances of hydrological disconnection. Bracken and Cloke (2007) formulated a conceptual model of hydrological connectivity, which consists of five components; climate, hillslope runoff potential, landscape position, delivery pathway and lateral connectivity. Climate is important as it controls the amount of water in the system and hence the degree to which system components are connected. For catchment-scale hydrological connectivity to occur, prolonged, high intensity precipitation may be needed, although more localised hillslope connectivity can occur quite quickly in smaller storms. Runoff potential depends on the catchment characteristics, such as soil, antecedent conditions and vegetation, making the hydrological response location specific. Ambroise (2004) defined active areas as areas where surface runoff occurs, and contributing areas as active areas which actually connect to the river network. This has also been referred to as “effective hillslope length” (Aryal *et al.*, 2003) and “dynamic contributing areas” (Beven, 1997). Therefore, landscape position is important as areas of the landscape closer to the river channel are more likely to connect. The delivery pathway, such as incisional rills, concentrated overland flow and sub-surface flows are important in controlling connectivity. Finally lateral buffering describes the physical connection between the hillslopes and the channel.

During extreme flow events, both river channels and their floodplains will be involved in the conveyance of water. Thus, the way the riparian zone is managed may impact significantly on downstream flood risk. The basic principle here is that when, in an extreme event, water flows on a floodplain, flow depths are generally lower than in

the main river channel. As flow resistance is generally inversely related to water depth (Manning, 1891), floodplain flow velocities are lower and hence conveyance on the floodplain is lower and total flow attenuation higher. In practice, this process is controlled by the ease with which water can enter the floodplain, which is a function of both river and floodplain management. For instance, channel conveyance may be increased through vegetation removal, resulting in higher velocities and hence lower depths for a given river flow, and hence a reduced transfer of water from river to floodplain. This may be both beneficial if the floodplain needs to be defended, but also problematic as it reduces flow attenuation causing flows downstream to be higher than they might otherwise be. Further, because conveyance in the river channel is greater, the timing of the flood peak downstream may be earlier. Whether or not this exacerbates or reduces downstream flood risk then depends upon the timing of the flood peak with respect to other tributaries. Thus, rural land management may impact upon downstream flood risk if river channel conveyance is artificially increased by either channel maintenance or construction of flood defences in rural areas. But, this increase in conveyance may either increase or reduce downstream flood risk according to the relative timing of its effects with respect to downstream tributaries.

The challenges of linking land management to catchment scale flood risk: examples

It is clear from the above review that the same land management activity may impact more than one of the four processes outlined above. For instance, both under and surface drainage may increase the ease by which water may infiltrate into the soil surface, so reducing the propensity to rapid overland flow generation. But, the same measures may provide for a more ready connection of runoff generating areas to the stream channel. Furthermore it is possible that the effect of land use has differing effects at the local field scale and at the catchment scale. This is partly due to channel process such as attenuation, which may counter land management impacts at the field scale, but also the fact that land use changes are typically diffuse within a river catchment. Where specific land management practices are implemented is important in relation to their effect at the catchment scale. This explains one difficulty

in proving the link between land use and flood risk at the catchment scale. Traditionally, certain land management practices have been correlated with changes in flood frequency but, crucially, this correlation does not necessarily imply causality. So, in this section, we use some case examples to reflect upon the difficulties that have been experienced in linking land management activities to downstream flood risk. We consider four examples: (1) arable agriculture; (2) pastoral agriculture; (3) land drainage; and (4) floodplain storage. The first of these examples illustrates the problems of proving causal linkages between changing flood risk and land management. The second shows that one of the reasons for this is that when subject to interrogation, simple process relationships are found to be more complex. The third example then shows how the same land management activity may have multiple process impacts and the final example compounds these three difficulties by showing how land management impacts on downstream flood risk may be sensitively dependent upon catchment location.

Arable Agriculture: the problem of proving causality

The approach to describing the impacts of arable agriculture on downstream flood risk has a number of elements. The first is based upon correlation. The intensification of agriculture over the past 40 to 50 years has been observed to coincide with a rise in flood risk (Kenyon *et al.*, 2008). There is a process-based hypothesis to justify such an association, in which land management influenced reductions in infiltration have been hypothesised as leading to increased runoff. The main cause of this is the thought to be the degradation of soil structure, associated with compaction by heavy machinery (Holman *et al.*, 2003). A commonly observed trend is the increase in the proportion of catchments under arable land use up until the late 1990s. This was initiated by the World War 2 policy of the “plough up campaign” (Crooks and Davies, 2001). If arable land use reduces infiltration rates, then it should increase the ease of rapid runoff generation, regardless of overland flow generating mechanism. Sullivan *et al.* (2004) describe this effect for the River Camel, Cornwall (Sullivan *et al.*, 2004). Cultivation increased from 1969 to 1997 from 14.9 km² to 25.3 km² (8% of catchment area), although it has decreased slightly since then. Five out of the six largest flood events (64-150 cumecs) occurred in the 1990s, which coincides with the most intense level of arable land cover within the catchment. Whilst there is no reason to challenge such correlation, there is a need to

question whether or not it is actually causal, especially as changing rainfall patterns or other land management practices could explain the change.

It is not just the general level of arable activity that has changed, but also crop types, and correlations between changing crop types and changing flood generation have been described. A good example of flooding that has most likely been caused by bare ground in agricultural fields is in the South Downs (Boardman *et al.*, 1994; Boardman, 1995; Boardman *et al.*, 2003). Land use in the period 1900-1950 was grassland for sheep and cattle grazing. Pasture to arable conversion occurred during the second world war due to the “plough up campaign” and then spring crops were replaced by winter crops, such as wheat in the 1970s. These crops were high yielding and had a guaranteed sale price, making them the most economically viable type of agriculture. Prior to the 1970s there was practically no flooding in this area (Boardman, 1995). However, in the period 1976-2000 there have been 138 separate, so called “muddy floods”. This terminology arises from the content of the flood water, which originates from farmers fields. The area under winter crop production has increased over time, from 15% in 1975 to 35% in 1981 to 60% in 1988 and 1991 (Boardman *et al.*, 2003). It has been found that soil erosion is most intense where the land cover is less than 30% (Evans, 1990). Rates of erosion in this area have reached $200 \text{ m}^3\text{ha}^{-1}$ in individual fields, where rills and gullies have formed which transport water much faster than overland flow. Furthermore, field boundaries in critical locations have been removed, increasing hydrological connectivity. In the Autumn of 2000, 2.5 to 3 times the normal amount of rainfall occurred in the South Downs, with a return period of 1:100 years (Marsh, 2001). However, the flooding which resulted from this rainfall was less extreme than the floods of 1987, when there was less rainfall. This has been explained by a decline in winter cereal cropping since the early 1990s, which has been initiated by set-aside schemes and an Environmentally Sensitive Area (ESA) scheme (Boardman *et al.*, 2003).

The main problem with correlating changes in flooding magnitudes and frequency with a specific land management change is that it is rare for all other possible factors that might influence flood generation to be constant during the period of correlation. Indeed, many of the land use changes described above are themselves correlated (if not causally) with changes in rainfall patterns (Lane 2008). Thus, the second broad approach to assessing arable land use impacts is based upon more controlled

experimental investigation and two examples are provided here. First, set-aside and fallow periods have been recommended as “best practices” as they have aimed to reduce the intensity by which land is managed. Set-aside areas are fields or parts of fields planted with cover crops and are thought to increase the infiltration capacity of the soil and reduce overland runoff (Auserwald, 1998). Bormann *et al.* (1999) studied the effects of fallow periods on flood risk by instrumenting three types of land use: bare fallow, intermittent fallow and reduced cultivation. Bare ground fallow was found to increase the rate of runoff due to surface capping caused by raindrop effects (Niehoff *et al.*, 2002) and reduced roughness of the surface due to no vegetation cover. Intermittent fallow was found to reduce runoff, but was highly dependent on the location within the catchment where this was implemented. The optimum land management was found to be reduced cultivation which consisted of less ploughing and resulted in a reduced peak discharge due to lower runoff rates caused by higher infiltration capacities.

Figure 2 Schematic showing the effects of compaction on soil infiltration (adapted from O’Connell *et al.*, 2004)

The second example is ploughing, which has been thought to increase the rate of surface runoff (Kwaad and Mulligen, 1991; Martyn *et al.*, 2000; Clements and Donaldson, 2002), due to soil compaction and associated reductions in soil infiltration capacity. Heavy machinery is used in this agricultural practice, which leads to wheel tracks being compacted. Figure 2 shows how the infiltration capacity of compacted soils (Figure 2b) are lower than uncompacted soils (Figure 2a). Experiments have shown that the hydraulic conductivity of soil decreases by up to 40% in the wheelings or tracks introduced during ploughing (Coutadeur *et al.*, 2002).

The amount of compaction is dependent upon the characteristics of the load, including weight and the amount of time the soil is under load, and the characteristics of the soil, including its texture, water content and hydraulic conductivity. For instance, it has been found that low pressure tyres reduce the amount of soil compaction (Boguzas and Hakansson, 2001) and that rubber tracks cause compaction of the topsoil but less deep compaction (Febo and Planeta, 2000). The direction, angle and depth of the wheel tracks have been found to be important in determining the runoff rates at the local scale (Duley and Russel, 1939; Schwab *et al.*, 1993). The timing of ploughing has been shown to have a measurable impact on runoff generation. It was found that ploughing in the spring and autumn, and not in winter, leads to a 30 to 100% reduction in runoff (Kwaad and Mulligan, 1991). Taken together, these instrumented studies imply that the way arable land is managed might have an impact upon processes like infiltration that in turn might have an impact upon flood generation. However, they are primarily conducted at the plot and/or field scale and it is not yet clear that their effects can be detected over large spatial scales. It may be argued that these kinds of studies provide the process or functional justification for the observed correlations between changing arable land use and changing flood risk. However, it is possible for these process impacts to exist at the local scale whilst the larger scale time-dependent increases in flood risk still have primarily atmospheric drivers, and the association between changing land use and increasing flood risk remains spurious.

Pastoral Agriculture: the problem of process complexity

Marsh and Dale (2002) highlighted the different effects of upland and lowland land use changes on flood risk. Pastoral fields are commonly found in the uplands of catchments, which are known as “less favoured areas” (Sansom, 1999) and are more susceptible to soil degradation and erosion. The major trend concerning pastoral agriculture is the exponential increase in stocking numbers and densities and, as with arable land uses, this has been correlated with changing flood risk. Sheep numbers in the UK in the 1860s were about eight million. The population of sheep in the UK increased from 19.7 million in 1950 to 40.2 million in 1990 (Fuller and Gough, 1999). Such changes have been correlated with runoff and flow regimes in the River Derwent (Evans, 1996) where sheep numbers doubled between 1944 and 1975, and which coincided with an increased runoff rate of 25%. Orr and Carling

(2006) found no trend in the rainfall data, but increasing flow peaks in the upper catchment of the River Lune, and qualitatively related this to increased stock densities.

As with ploughing, these correlations do not necessarily imply causation. The retort to this argument might be that they are supported by process observations and Figure 3 shows a proposed conceptual model (after Orr and Carling, 2006). Increased sheep densities have been linked to overgrazing of pasture, reducing the biomass, which meant that evapotranspiration losses declined. Jones (1967) found that when sheep are excluded from heathland, there was a 30% increase in heather (biomass by weight) in two years and an 88% increase 15 years later. However when sheep were re-introduced there was a 10% reduction over a 12 year period. Furthermore root depths decreased, which meant a reduction in infiltration rates. Second, it has been found that sheep follow particular pathways, concentrating the hoof pressures on a small area of the fields (Sheath and Carlson, 1998; Gilman, 2002). This causes compaction and a reduction in soil bulk density, meaning the infiltration capacity of the soil declines. Langlands and Bennett (1973) found a positive correlation between soil bulk density and sheep density and a negative relationship between soil pore space and stocking density. Furthermore, compaction of the soil by animals may degrade the ecological status of the soil, reducing the number of earthworms which improve drainage (Guild, 1955; Hills, 1971). These processes could lead to an increased runoff rate, as less water is lost to the atmosphere (evapotranspiration) or partitioned into the slower subsurface throughflow pathway (Owens *et al.*, 1997). Within the Yorkshire Ouse catchment, over 40% of sites investigated after the autumn 2000 floods had high soil degradation, and this was estimated to have caused an increased runoff rate of between 0.8% and 9.4% (Holman *et al.*, 2003). Heathwaite *et al.*, (1989) found that 7% of rainfall was converted to runoff in ungrazed fields, while this increased to 53% in grazed fields. Furthermore, Heathwaite *et al.*, (1990) found that infiltration capacity was reduced by 80% on grazed areas compared to fields with no stock. By converse, a recent study at Pontbren (Carroll *et al.*, 2004; Jackson *et al.*, 2008; Marshall *et al.*, 2009; Wheeler and Evans, 2009; McIntyre and Marshall, 2010) found that small tree strips on hillslopes have the potential to reduce peak flows by 40%, as the land is no longer trampled by livestock. The Pontbren study is a critical and rare

example of the systematic investigation of land use effects on rapid runoff generation, showing how tree shelter buffer strips and stock exclusion has impacted on soil processes and runoff generation at the local scale. Notably, tree planting has been shown to increase the saturated hydraulic conductivity of the soil (the ease at which water flows through the soil) resulting in greater throughflow and less overland flow, so reducing peak runoff (Marshall et al., 2009).

Figure 3 Impacts of overgrazing on runoff and soil erosion (Orr and Carling, 2006).

However, process studies have suggested that simple associations between runoff generation and livestock density can be more complex than might be thought. Betteridge *et al.* (1999) compared the effects of cattle and sheep on soil compaction and found that cattle cause soil disturbance through upward and downward movement, while sheep cause surface compaction. Godwin and Dresser (2003) estimated that 40 kg sheep, with a foot area of 0.0006 m², exert a pressure of 160 kPa when static, 320 kPa when walking and up to 480 kPa under moving more quickly. The dynamics of stock movement become important. Stocking may also result in other flood-related landscape changes but these may be exacerbated by soil type. Stock reduces the vegetation cover, which may lead to soil surface crusting and reduced overland flow resistance (Ferrero, 1991). Thus, in addition to questions over correlation, it is also clear that the type of stock, and the type of land upon

which they graze, as well as the way that they graze may also impact upon runoff generation and, possibly, downstream flood risk.

Upland Open Drains / Grips: the problem of competing process effects

As with the intensification of arable cropping and stocking densities, land drainage also increased markedly in the post-war period peaking in the U.K. in the early 1980s. Open drains in upland environments, known as grips, provide a good example. In terms of correlation, a study in the Upper River Tees catchment in the North Pennines by Conway and Millar (1960) found that peak flows increased by 85% and took a shorter time to peak by 1.6 hours (46% reduction) as a result of gripping. This contrasts with the study of Newson and Robinson (1983) in Plynlimon, Wales which found that after the installation of grips, the peak flow decreased by 40-45%. This study also found that the time to peak increased by 25% (Newson and Robinson, 1983). This shows that the same land management change can result in completely opposite effects on flooding. Reflecting similar observations regarding process complexity and stocking densities, McDonald (1973) highlights the lack of comparability of these studies, especially the different local characteristics. The importance of local factors upon the effect of grips on flooding, such as the peat/soil type (McDonald, 1973), the drainage patterns, depth and density (Robinson, 1980; Stewart and Lance, 1991), and the location of drains within the river network (Heikurinen, 1968; Higgs, 1987), will all challenge the notion that there might be simple linkages between upland drainage and downstream flood risk.

However, in process terms, grips are complex systems where multiple processes operate in combination (Holden et al., 2004) and they actually have two opposing effects on runoff such that whether or not the increase or decrease peak flows depends on the balance of these effects (Robinson, 1990). Firstly, they lower the water table adjacent and downslope of the channel (Holden 2006). This increases the infiltration capacity of the soil and reduces the development of soil saturation. Holden (2006) observed that drained landscapes have deeper throughflow and greater pipeflow contributions to runoff. This is compared to undrained peat environments (Holden and Burt, 2003) with lower peak flow, a longer lag time between peak precipitation and the flood event and an increase in the duration of the peak flow due to multiple sources of runoff arriving at different times. However, this

observation is dependent upon whether or not the subsurface flow is slower than overland flow, and whether processes such as pipeflow mean that it is faster than initially thought. Antecedent conditions (water saturation/deficit) also have an important influence on the partitioning of rainfall between the surface and the subsurface. Furthermore, the extent and exact locations of the drains within the catchment are important considerations, as different areas may have different runoff characteristics such as slope, or upslope contributing areas. Further complexity is caused by the dependence of the impact of drainage upon the soil type, whereby drainage increases the peak flow for permeable soils, but decreases the runoff for clay soils (Gilman, 2002).

The alternative way in which grips affect hydrological processes is by increasing drainage density, such that hillslopes become more efficient in discharging water to the catchment outlet. Water flows faster in channels than as overland flow or as throughflow and the few studies that have quantified overland flow velocities in peatlands imply that the difference may be an order of magnitude (Holden et al., 2008). Therefore, gripping increases the ease of hydrological connection between hillslope and channels. This process is thought to be more important in the uplands than the lowlands, as runoff rates are affected more in the uplands due to the steep slopes, which mean the flood wave is conveyed downstream faster.

Lane *et al.*, (2003) criticises past research on the effect of grips, stating that it has focussed too much on empirical studies of individual drains or small networks, rather than furthering our understanding of hydrological connectivity at the catchment scale. Recently, grips have been blocked, which appears both to decrease connectivity to the channel and increase the height of the water table (Price et al., 2003). However, the effects of this land management measure at the catchment scale remain uncertain. Observed correlation does not necessarily imply causation, process impacts depend upon location within the catchment as well as more general catchment characteristics and in the case of drains, the same drain may result in competing hydrological impacts, greater flow retention due to increased infiltration and more rapid flow conveyance if the drains retain the greater hydraulic efficiency associated with their initial installation. The effects of land drainage on flood risk are contingent, with the impact unable to be generalised without considering their spatial context.

Floodplain Storage: the problem of spatial location

Traditionally, channel modifications, including channel straightening and bank/bed changes, and levées and embankments have been central to local attempts to reduce flood risk: channel straightening, for instance, increases conveyance, reducing the water level associated with a given flow; embankments increase the water level required for the onset of inundation. These kinds of solutions represent situations where the objective is to prevent floodplain inundation. But, there may be situations where flood inundation is possible, and the associated storage of water on floodplains during storm events may increase attenuation and so reduce downstream flood risk. In theory, restoring the connection between rivers and floodplains may be a means of reducing downstream flood risk in situations where flood inundation is possible

Acreman *et al.*, (2003) modelled the effects of floodplain restoration on flood risk. This study applied the one-dimensional model iSIS to a five kilometre reach of the River Cherwell. Simulations included assessment of the effects of channel narrowing to pre-engineered dimensions and changing the interaction between the channel and its floodplain through removing embankments. Historical maps were used to extract the pre-engineered topography, while airborne LiDAR was used to obtain floodplain topography for current cross sections. The model was calibrated through adjusting the Manning's n parameter and the effects of these scenarios were assessed for four flood events. It was found that restoring the channel to pre-engineered dimensions, peak flow downstream was reduced by 10-16%. Embanking the channel increased the flood magnitude downstream by 52-153%. However, the local scale effect differed depending on where the changes were made, where both scenarios led to water stage increasing, by 0.30-0.47m for the channel restoration and 0.53-1.59m after introducing embankments. The restored channel delayed the timing of the peak flow by 3 to 17 hours, as the shallower channel reconnected the channel to the floodplain, while building embankments made the peak flow occur earlier by 33 to 47 hours. This showed the important role of the floodplains in attenuating high flows.

Changing the land cover of the floodplain can also change the amount of attenuation as the roughness changes with different vegetation covers. Thomas and Nisbet (2007) studied the effects of floodplain wet woodland in more detail and found major

impacts. They also compared the results from a 1D model (HEC-RAS) and a 2D model (River2D). With reference to a baseline, they considered floodplain changes to a broadleaf cover, both on one bank, and the entire floodplain, for a downstream distance of 500m. Manning's n values were altered to simulate these land cover vegetation effects, with values of 0.04, 0.035 and 0.15 used to represent the channel, pasture and woodland respectively. Results showed that water level was raised by a maximum of 270mm, while floodplain storage was increased by 71%. Water velocity through the altered reach decreased by 60-70%, while peak flow timing downstream was delayed by 140 minutes.

Figure 4 Mechanism by which flood embankments reduce peak flow magnitudes a) without levee; b) with levee

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

By contrast, flood storage is often controlled, by structures which either control the opening/closing of gates or are levees which control the water level which storage starts at (Jaffe and Sanders, 2001). These mean that water is only stored temporarily and can be managed to reduce the rising limb and peak flow and then release water on the falling limb (Forster *et al.*, 2008; Chatterjee *et al.*, 2008). The storage structure should be emptied as soon as possible after the river water levels decrease, so that maximum storage capacity is available for future high flow events (Hall *et al.*, 1993). The Elbe flood in August 2002 was lowered by 40 cm due to a temporary detention

area at the confluence of the Havel and Elbe rivers. Furthermore dike failures in another location led to floodplain storage which reduced the river stage by 11 cm ($220 \text{ m}^3\text{s}^{-1}$) in Wittenberg (Forster *et al.*, 2008).

However, if the storage area is utilised too early then the detained volume is taken from the rising limb and is full by the time the peak flow arrives. If the gates are opened too late then the volume is just taken from the falling limb. Neither of these two scenarios reduces the peak flow considerably (Silva *et al.*, 2004). Figure 4 shows how a flood embankment can be used to increase the effectiveness of water storage on the floodplain. The presence of a levée between the river channel and the floodplain delays the time at which water begins to be stored, meaning that it is the peak of the flood wave that is stored. Without a levee, storage would occur during the rising limb, meaning that by the time the peak flow arrived the floodplain would be at capacity and therefore the peak would just travel downstream without being attenuated.

Thus, specific location of a flood defence is critical in evaluating its effect on a flood peak, with flood defences close to the settlement being beneficial, as they take the top of the peak of the flood. Flood defences further away from the settlement contain the water within the channel, conveying more water downstream, potentially causing a higher peak flow downstream than would otherwise be the case. Therefore, it is beneficial to have no flood defences further upstream, so that water is transferred to the floodplain, reducing the amount of water travelling downstream and attenuating the flood peak, but flood defences that control the use of floodplain storage closer to the settlement.

Notwithstanding the established use of floodplain storage schemes as part of flood risk management, it raises a final question regarding flood risk management through land use management. The storage example showed that to deliver flood risk benefits to a given location, the nature of the land management practice required changes with distance upstream: from encouraging disconnection, except at high flows when the storage is used, immediately upstream of a risk zone; to encouraging reconnection further upstream. In other words, this land management measure requires a decision to be taken as to where the risk is to be managed which has implications for the kind of flooding that is allowed both locally and upstream. Two

problems follow. First, most agricultural landscapes are not empty ones, containing land uses that may sustain local livelihoods, as well as towns and properties. Thus, flood risk reduction through reconnection and disconnection has to be evaluated relative to other flood risk zones. Second, any change in attenuation needs to be evaluated with respect to other tributaries: locally attenuating a flow to benefit one flood risk zone might delay the flow delivered to downstream zones, so changing the likelihood that the delayed flows are coincident with downstream tributary flow peaks. What is beneficial for one flood risk zone may exacerbate flood risk for other zones downstream. In essence, the problem is a relational one. Any decision, whether it is ploughing, stock management, removal of drainage or adopting storage has impacts on the flux of water through river catchments. These impacts will scale up in complex ways that mean that one set of geographically-confined impacts can only be evaluated by considering other locations and there is no way in which a general conclusion might be reached regarding land management impacts on flood risk.

A chaotic conception?

These four examples were each chosen to allow different observations regarding the effects of a particular rural land management activity upon downstream flood risk. The arable case study shows that it is possible to correlate land management activities with changing flood risk. In turn, these may appear to be sustained by research which shows that land use management impacts on runoff generation at the very local scale (plots and fields) even if this research has been less successful in showing that these results can be upscaled in relation to downstream flood risk. The example of stocking densities shows how an apparently simple impact may actually be much more complex than otherwise thought, with impacts dependent upon the precise nature of land management, the local-scale and catchment-scale context of the land management, and interactions between them. The discussion of open drains or grips showed how the same land use practice can have very different hydrological effects, with the likely dominance of runoff enhancing and runoff reducing processes dependent upon the precise location of a drain with respect to the catchment network. Consideration of flood storage not only questioned simple notions that reduced downstream flood risk can result from reconnecting rivers with their floodplains but that whether or not this effect results depends on how far upstream the storage is with respect to the flood peak that is to be reduced.

Figure 5 (adapted from Lane, 2008) tries to draw these observations together. It shows that if there is a relationship between land use management and downstream flood risk it is through the interaction of a range of processes (labelled 1 to 4). Some of these processes are event specific. For instance, if interactions between tributaries drive downstream flood risk, and rural land management measures are seeking to change this, then it must be recognised that the timing of runoff generation and hence tributary interactions are also driven by the way in which a weather pattern moves across a river catchment.

Figure 5 Conceptualisation of the flood system that links land management changes to changes in flood risk. (adapted from Lane 2008)

Figure 6 shows how the hypothetical impact on downstream peak flows of an area of compacted agricultural land is dependent upon where in the catchment the changes occur. When the area of compacted land is downstream (Figure 6a), the rapid runoff caused by the less permeable surface occurs before the main peak arrives, meaning that the main peak is now preceded by a smaller peak, but the main peak flow is

reduced in magnitude. If the compacted land is upstream (Figure 6b), then the rapid localised runoff coincides with the main flood wave, leading to a higher magnitude peak downstream. Along with highlighting the importance of spatial location of change, this example highlights the importance of the timing of runoff and flows from different parts of the whole catchment. Even if a particular land use management activity can be shown to reduce downstream flood risk at one scale, this association may well change for other scales.

Figure 6 *Effect of land management change location upon the downstream flood hydrograph. (Blue area shows area of compacted soils, solid line indicates pre-change hydrograph, and dashed line shows post-change hydrograph). (Based upon O’Connell et al., 2004)*

Our final point is that the search for a relationship between rural land management and catchment scale flood risk is a critical example of a wider policy and practice confusion in hydrological sciences in particular and environmental sciences in general, one that goes to the heart of the kinds of questions we ask and experiments we design to understand difficult environmental issues. Sayer (1992) introduces the notion of the ‘chaotic conception’. This is based upon what he calls (p138) a ‘bad abstraction’. A system is arbitrarily divided into unrelated parts which are then associated either because of convenience (e.g. their ease of measurement; availability of data) or because of an apparent shared pattern that merits simple

description. The division of a system into parts serves to remove critical chains of causality which have important explanatory power. Following Sayer (1992), we can consider a catchment as a system, which cannot be divided into new units without losing explanatory power. It is appropriate to associate these two factors (land use and floods) in descriptive terms, such as statistically, but inappropriate to associate them causally because although land use might be related to changing flood risk, there is no necessity for this association. Changing land use in response to the message that appears to follow from a statistical description is meaningless because the description involves variables with no necessary relationship. Such descriptive relationships become 'chaotic' because they cut across actual chains of causality and do not capture the sensitive dependence of those chains upon the specific catchment, scale and event under consideration. Not only does a particular intervention in a rural landscape to reduce flood risk have to be carefully sited with respect to the geography of the catchment, but whether or not it has beneficial impacts will end up depending upon precisely where it is situated geographically, in relation to the temporal evolution of the event under consideration. This observation unsettles the current overall aim of identifying an universal answer to the question of the link between land use and catchment scale flood risk, even for a specific land use measure.

This discussion has a number of implications for both research practice and policy, much of these relating to precisely what research can demonstrate and how policy might work with the implications of what is demonstrated. Again, Sayer (1992) is useful for identifying these implications. The first observation is a distinction between what Sayer calls the 'empirical' and the 'actual', between what we observe and what actually exists. The distinction is not simply important because of the difficulty of measuring extreme flow events such that most flood observations already contain a mix of measurements and theory (Odoni and Lane, 2010) the latter sometimes highly uncertain (e.g, extrapolation of relationships between water level and river discharge to high flows). Rather it is the existence of apparently simple correlations, such as between land use and flood characteristics, which may be seen to provide a sufficient burden of proof and so hide a deeper analysis of flood generating conditions.

The second distinction is between the actual and the mechanisms that are responsible for the actual. Sayer (1992) argues that what makes an actual event is the combination of one or more mechanisms in particular places at particular times such that the nature of the flood is a function of that contingency. Hydrologists are well-used to this contingency even if it is often expressed implicitly: the dependence of the size of an extreme flood upon antecedent soil moisture conditions and rainfall intensity, for example, means that the same rainfall depth when averaged over certain time periods can lead to very different peak river flows. Thus, even if a statistical association between a flood record and land management is an 'actual' one, there is no certainty that it will transfer in time, space or scale. It is the mechanisms that hold some if any generality and this is why models are a necessary component of hydrological investigation: observations on their own tend to have too poor a spatial or temporal coverage; numerical simulation is a means of extrapolating observations using models that generally have a physics base.

The third implication is a differentiation within the category of mechanisms that relates to the extent to which the mechanisms retain generality in space and time. For instance, there are many time of flood-generating mechanisms, associated with rainfall-runoff processes, river versus direct rainfall flooding, groundwater effects, tidal flooding and so on. Not all of these mechanisms are relevant to all places, nor even to all time periods, but certain mechanisms may become perceived to be more important than others. Since their development from 1999, the U.K.'s on-line flood maps have presented the risk of inundation from river and coastal flooding and not rainfall and other indirect (i.e. non-river, non-tidal) sources, even though flood events suggest that 40 to 50% of flood losses may be related to indirect mechanisms. Likewise, the U.K.'s Flood and Coastal Foresight project initially overlooked the need to include these indirect effects. The difficulty here is that the characteristics of a particular place condition those flood generating mechanisms that are relevant. Flood events take on importance in this respect because they force us to rethink the mechanisms being used to provide a particular explanation. The 2007 flood events in the U.K. led to a major review of a number of elements of U.K. flood science and policy, one of which included the concern that the dominant focus of flood science had been on river and tidal flooding to the exclusion of other mechanisms of flood generation such as direct rainfall flooding.

Sayer's distinctions are valuable because they cause us to think carefully about the notion of 'demonstration' in flood risk science and policy. If a null hypothesis is set that rural land management does not impact on flood risk, and its rejection is taken as a general confirmation that it does, then the demonstration may over-generalise the evidence by applying it to contexts (e.g. catchment characteristics) where, if applied explicitly, the null hypothesis would be confirmed. In Sayer's terms, demonstration that land management can be used to reduce flood risk does not necessarily imply that upstream land management is a solution to downstream flood risk problems. There will be situations where a land management practice that has been demonstrated to have beneficial effects in one location, for one time period and for one scale may have negative effects in other locations. The transferability has to exist in what might be labelled mechanisms, not general policy recommendations derived from either statistical land use – flood risk associations or 'demonstrated' benefits of land management impacts on downstream flood risk. Decisions to recommend land use change to reduce flood risk should only follow from understanding of how those mechanisms combine together with particular places to reduce downstream flood risk. In some senses, this is no different to a conventional assessment of flood risk reduction measures, or options appraisal (Environment Agency, 2008) in which possible interventions are tried out in at a particular place for a range of possible flood events. However, for rural land management, it may require a fundamental re-evaluation of how practitioners (e.g. consultants), as distinct from researchers, undertake hydrological modelling. Such modelling needs to be explicitly spatially-distributed, to develop means by which the optimal locations for intervention and the form of intervention necessary may be identified, and tested, in terms of the range of scales (local to catchment) that they might have impact. Such models may need a much stronger grounding in the specific catchment to be modelled (e.g. Odoni and Lane, 2010) and the range of measures that might be scientifically, but also socially, economically and politically feasible in the catchment to be modelled.

Conclusion

From this review it is clear that the link between rural land management and flood risk represents a fundamental challenge, which needs to be assessed at multiple

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

The second reason why there are challenges linking land use and catchment scale flood risk is the uniqueness of catchments (Beven, 2000). The effect of the same land management practice will be different when implemented in different catchments and also different parts of the same sub-catchment.

The third important area relates to the issue that the land management effects are not mutually exclusive from the climatic effects in the flood record. This is one of the main reasons why proving the land use link to flooding has proved so difficult as this impact has to be disentangled from the climatic change effect. At present it is thought that land use change effects are of second order importance behind natural climatic variability (O'Connell *et al.*, 2004). It is likely that land use changes are amplifying the effect of climatic variability, and this does not mean that land management policies cannot be used to mitigate the effect that climate variability has on increasing flood risk.

In conclusion, this review has argued that the link between land management and catchment scale flood risk is a "chaotic conception". It has been shown that the effect of any given land management measure is both spatially and temporally dependent. This means that the same land management practice will have different effects depending on where it is implemented, and also when implemented in the same

location may have different impacts on different flood events due to unique spatio-temporal patterns of precipitation and storm tracking. As the spatial scale of enquiry changes the effect of a land management entity e.g. field, grip, may change, as different processes and interactions emerge. An important aspect of this is how the individual location interacts with others within the sub-catchment and the whole catchment. Therefore, the pursuit of generalisations between different land management practices and flood risk may be a meaningless and unachievable aim. Our argument has important implications for both future research and policy makers. Demonstration projects, that seek to show that land management can be used to reduce flood risk, need very careful thought, because what they demonstrate pertains to a restricted geography and restricted time periods. What can be generalised on the basis of demonstration might not be as much as previously assumed and expected.

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