LAND MANAGEMENT, FLOODING AND ENVIRONMENTAL RISK: NEW APPROACHES TO A VERY OLD QUESTION

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ABSTRACT

This paper is concerned with the role of hydrological connectivity in upland land management. The management of hydrological connectivity is a crucial component of land management activities, notably through the use of buffer zones to protect water courses from diffuse pollution but also through the flood pulse concept which recognises the ecological and water quality benefits that can accrue from maintaining connectivity between the river and floodplain. However, there are currently few tools for exploring hydrological connectivity, and its impacts that: (a) represent the processes that hydrological connectivity controls with sufficient spatial detail; (b) integrate predictions through to entire catchments; and (c) consider the full range of land management issues in relation to flood risk, water balance and water quality. In this paper, we describe and apply a new tool (SCIMAP) that addresses the above three needs. We illustrate its role in enhanced land management through application to two issues: (1) the role of upland shallow surface drains (grips) in relation to flood generation; and (2) the issue of linkage between river and floodplain in relation to flood risk. There has been considerable debate as to whether or not grips, along with observed changes in rainfall patterns, may be responsible for increased magnitude and frequency of flooding. Some studies have suggested grips increase peak flows whereas others suggest they decrease them. The model demonstrates the crucial role played by the location of grips in relation to hillslope drainage. Grips can capture large areas of upslope drainage and route them to the catchment outlet through the grip network. In the latter, flow velocities may be up to two orders of magnitude greater than flow over the hillslope surface. This will increase flood generation. Downstream of grips, there is a general reduction in surface wetness due to reduced delivery of flow from upslope. This will provide greater potential for storage of rainfall and hence reduce flood generation. Thus, the effects of an individual grip depends upon its location within the landscape. The effects of grips at the catchment scale can only be appreciated through an explicit representation of grip distribution at the catchment scale. The model's representation of river-floodplain connectivity also demonstrates how hydrological connectivity can be managed as part of a land management strategy. It predicts patterns of flood inundation for a 1:10 year flood. This identifies localised sources of overbank flow which diffuse across the floodplain. There is a clear spatial variation in inundation depth that is strongly related to extant land use. The model provides the opportunity for more cost effective and strategic design of flood defence through the spatially explicit treatment of the inundation process. In conclusion, the paper argues that the real power of tools like SCIMAP rests in their ability to address an overly sectoral approach to land management. A sectoral approach involves exploring all dimensions of a problem (e.g. flooding) in relation to possible causes (e.g. land management, climate change). In so doing, it fails to address the linkages between problems that emerge within particular catchments and where any one solution to a problem (e.g. grip blocking) may have positive (enhanced biodiversity) and negative (water colour increases) impacts upon other parts of the environment. Thus, tools like SCIMAP are required if we are to develop truly integrated approaches to catchment management that escape the problems of current sectoral concerns.

KEYWORDS

Hydrological connectivity, LiDAR, flood generation, flood risk, land management, grip blocking

INTRODUCTION

The last twenty years have witnessed fundamental changes in the purpose of and approach to the management of river corridors. First, the purpose of management has shifted from simple anthropocentric, utilitarian needs associated with river channel engineering for flood and erosion/sedimentation control towards the incorporation of a range of goals traditionally optional, but now required (e.g. ecological concerns). As this purpose has changed, so the number of interest groups associated with the management process has increased. Second, there has been the recognition that effective river channel management must be holistic at the catchment-scale (e.g. Newson, 1997), with river management integrated with catchment and corridor management. For instance, the Environment Agency, in no longer granting time-unlimited abstraction licences and in introducing Catchment Abstraction Management Strategies, has explicitly recognised that the river has multiple users and that the needs of all of these users must be integrated to identify an optimal solution for river management. Effective catchment planning which recognises the needs and aspirations of all users will be greatly promoted by the European Water Framework Directive (WFD) requirement to produce river basin management plans for all major rivers in all member and candidate countries nine years after the Directive comes into force. Within this policy change has been the specific recognition that one of the clearly defined 'user groups' is now the river's fauna and flora, introducing a strongly environmental 'requirement'. This is also increasingly legislated (e.g. under the requirement of the U.K.'s Habitat Regulations (1994) to protect sites of nature conservation interest).

The net result of these sorts of changes is that we need to look more carefully at the purpose and nature of flood management in particular and catchment management more generally. The challenge is two-fold. First, many approaches to catchment management remain strongly sectoral in terms of operational management (e.g. focused upon water quality, or flood risk, or low flows, or river habitat quality) rather than recognising the necessary linkages between them. This matters: if traditional tools such as cost-benefit analysis are used to judge the merits or disadvantages of a particular project, the full range of potential costs and benefits may not be identified. Second, despite long-established claims for catchment-scale management activities, much management remains aimed at the local, giving it a somewhat piecemeal feel. In this paper, we argue that the way forward here is to return to a long-established but much less well-articulated theme: that we need to develop hydrological connectivity as the fundamental basis for catchment-scale management. This paper illustrates the importance of hydrological connectivity as a conceptual framework for land management and then introduces a specific tool (SCIMAP), based upon the fundamentals of hydrological connectivity as a catchment scale land management tool.

HYDROLOGICAL CONNECTIVITY AS A CONCEPTUAL FRAMEWORK FOR LAND MANAGEMENT

Hydrological connectivity within the landscape may take one or more of four types (Amoros and Bornette, 2002): latitudinal; longitudinal; vertical; and temporal. Connectivity is important because it will determine the extent to which water and matter that moves across the catchments can be stored within or exported out of the catchment. In this sense, the nature of the connectivity is a crucial part of the process: latitudinal and longitudinal surface connectivity will lead to the rapid delivery of water to the drainage network and the possible entrainment of particulate matter (e.g. soil) from the land surface. If a zone of surface connectivity is separated from the drainage network by a zone where infiltration can occur, then the effects of vertical connectivity and lateral and longitudinal subsurface connectivity within the soil surface will be more important. These processes may be more subtle: water may be lost to storage; transport through certain soil types may remove certain nutrients (e.g. vegetation uptake), may allow certain transformation processes to occur (e.g. denitrification) or may trap particulate matter. Thus, hydrological connectivity in general, and the nature of the connectivity in particular, matters as it controls: (1) the entrainment of both particulate and soluble material; (2) the transformations that the material may undergo during transport to the drainage network; (3) the rate at which water and material reaches the drainage network; and (4) loss to storage before the water and material reaches the drainage network. Whether catchment management is viewed in terms of problems with the river (e.g. flood risk; river erosion and sedimentation), ground water (e.g. rising levels of nutrient concentration) or the wider catchment (e.g. loss of habitat due to certain types of drainage activity), it is clear that a proper understanding of how catchment hydrology connects together is a crucial first step in mitigating existing problems and enhancing the environment more generally.

BUFFER ZONES TO REDUCE HYDROLOGICAL CONNECTIVITY

The idea of hydrological connectivity is well-established in the development of 'buffer zone' policies for land management over the last 20 years. These have been particularly well-developed in relation to nitrogen and phosphorous. Buffer zones have been shown as important in terms of nitrate uptake by vegetation and microbial denitrification (e.g. Haycock *et al.*, 1993; Vought *et al.*, 1995). For example, Kuusemets and Mander (2001) identified buffer zones as an most effective mitigation method in relation to N loading, estimating that a buffer zone of 460 m length would remove 2,200 to 2,640 kg of N. Buffer zones were found to be more successful than wetlands. Kuusemets and Mander (1999) noted for southern Estonia that a 31 m wide buffer zone of wet meadow and grey alder forest removed 50% nitrogen and that this rose to 87 % nitrogen with a 51 m buffer zone. These local-scale studies scaled up to the catchment scale: well buffered catchments had much lower N export coefficients. Spruill (2000) used statistical evaluation to look at the effects of riparian buffers upon groundwater, both directly, and indirectly through controls on other parameters that might in turn influence denitrification. First, buffer zones may act as a source of dilution (i.e. surface water) for ground water discharges that can improve their environmental quality. Second, they can act as zones where denitirification occurs and, again, if ground water can be connected to a buffer zone before it reaches the stream course, this may also strip nitrate. These two processes in combination were significant: in Spruill's study catchment, nitrate was 95% lower in buffer areas compared with nonbuffer areas, with a 30 to 35% reduction estimated to be due to dilution and 65 to 70% due to reduction and/or denitrification. Haycock and Burt (1993) also found that aquifer-draining water had significantly reduced nitrate loading if it passed through a buffer zone. Third, buffer zones don't simply act as a sink for nutrients and other compounds stripped from water that enters the zones, whatever the nature of the connection (Spruill, 1990). Some of these nutrients/compounds may eventually reconnect with the stream (e.g. as discharge of 'old' groundwater). It was found that pH, specific conductance, alkalinity, dissolved organic carbon (DOC), silica, ammonium, phosphorus, iron, and manganese at 28 sites in the Contentnea Creek Basin were significantly higher ($p < 0.10$) in old (>20 yr) discharging ground water draining areas with riparian buffers compared with areas without riparian buffers. Younger (<20 yr) discharging ground water samples indicated significantly higher specific conductance, calcium, chloride, and nitrate nitrogen from areas without buffer zones. This work emphasises that hydrological connectivity is a complex three-dimensional process in which surface, throughflow and ground water flows interact, in relation to the media through which they pass, to determine the quality of water that eventually reaches the stream course.

Similar findings have been reached with respect to phosphorous in general, although there is some need to differentiate between different types of phosphorous: Vought *et al.* (1995) estimate that vegetated buffer zones of 10 m width could minimize phosphorous loading by as much as 95%; Kuusemets and Mander (2001) noted their 460 m buffer strip could reduce phosphorous loading by 12 to 15 kg P a year; and Kuusemets and Mander (1999) noted for their southern Estonian case-study that the 31 m wide buffer zone removed 78% phosphorus, rising to 84 % phosphorous with a 51 m buffer zone. The extent to which this removal occurs depends upon the nature of the phosphorous transfer process (i.e. whether in solution or bound to particulate matter). If it is bound to particulate matter, then connectivity has also been shown to be important, for both organic (e.g. Ward *et al.*, 2001; Aspetsberger *et al.*, 2002; Hein *et al.*, 2003) and inorganic (e.g. McKergow *et al.*, 2003) material. Indeed, connectivity to the floodplain can act as an important sink of particulate matter even if material is within the channel system, and this is explored further below. Hence, hence buffer strips play two related roles: (1) in insulating the river from hillslope delivered particulate matter; and (2) in acting as a sink for particular matter during periods of high flow. This is also supported by research. Rabeni and Smale (1995) discuss how buffer strips may be used to mitigate against the impact of excessive siltation upon fish communities. McKergow *et al.* (2003) describe how the use of buffer zones in a small agricultural catchment in Western Australia saw suspended sediment concentrations fall dramatically following improved buffer zone management, with an order of magnitude fall in maximum concentrations, a fall in median concentrations from 147 to 9.9 mgl^{-1} and an order of magnitude fall in sediment export from the catchment. In this case, the buffer zones were linked to reduced channel erosion, and this was a prime reason for the improvement. Thus, buffer zones matter, not simply because they trap nutrients or particulate matter, but also because they can add to the wider integrity of the riparian corridor. This includes the diversity of flora and fauna (e.g. Vought *et al.*, 1995; Amoros and Bornette, 2002; Ward *et al.*, 2002) and the connectivity of landscape patches, something of particular concern if species migration needs to occur in order for ecological adaptation to global or regional environmental change.

RECONNECTING RIVERS AND FLOODPLAINS

The above section discussed situations where, in the main, the focus of activity was reducing the connectivity between water courses and the wider catchment. However, it is now recognised that there are crucial situations where lateral connectivity between a water course and the catchment should be enhanced, notably in relation to both wetlands and floodplains (Richards, 2001). Much of this stems from the flood pulse concept (Middleton, 1999) which identifies the role of water level (water table and direct surface water) in developing conditions favourable for seedling establishment and growth and which keeps 'wet' species present along with the mix of more traditional 'dry' species (Richards, 2001). The relationship is complex in relation to the relative timing of seedling production, germination, establishment and soil moisture processes (e.g. Hughes *et al.*, 2000) but appears to be a critical component of the diversity of floodplain woodland systems (e.g. Peterken and Hughes, 1995) and meadowlands (e.g. Martin and Chambers, 2002). However, the flood pulse may be associated with a range of other processes. A number of researchers have identified the role of surface water exchange between the main river and floodplain in the transfer of particulate matter and nutrients (e.g. Ward *et al.*, 2001; Aspetsberger *et al.*, 2002; Hein *et al.*, 2003; McKergow *et al.*, 2003) leading to a more effective nutrient and sediment balance (e.g. Tockner *et al.*, 1999; Nilsson and Svedmark, 2002). In addition to the delivery of water, the flood pulse may also be responsible for erosion and sedimentation that lead to new opportunities for colonisation (Richards, 2001) and this can lead to quite complex patterns of sediment deposition which result in different moisture retention capacities and hence a complex mosaic of vegetation (e.g. Marston *et al.*, 1995). Without the flood pulse, long-term reductions in habitat quality have been observed (e.g. Erskine *et al.*, 1995), and there are examples (e.g. Hudson (2001) in Southland, New Zealand) of the active engineering of rivers (e.g. excavation and dredging) in order to maintain lateral exchange between the river and floodplain habitats. The net result of hydrological connectivity between a river and floodplain is more complex gradients in environmental variables that may explain the commonly observed high levels of diversity in connected river-floodplain corridors (e.g. Nilsson and Svedmark, 2002).

HYDROLOGICAL CONNECTIVITY AT THE LANDSCAPE SCALE

Despite the examples of buffer zones and river-floodplain connectivity described above, there has been much less emphasis upon consideration of hydrological connectivity at the landscape scale. This is despite evidence that suggests that there can be beneficial landscape-scale impacts (e.g. Kuusemets and Mander 1999; McKergow *et al.*, 2003) and that both buffer zones (Haycock and Muscutt, 1995) and flood pulses may only work when appreciated at the landscape scale. The idea that buffer zones only work at the landscape scale is supported by a number of reasons. First, hydrological connectivity is a complex process that varies between catchments with different geology, soils, hydrology, vegetation and climate (e.g. Muscutt *et al.*, 1993). Establishing the nature of that connectivity at the landscape scale is a crucial first step in determining the role of hydrological connectivity as a land management tool. For instance, Blackwell *et al.* (1999) note that whilst riparian buffer zones are important in reducing processes like stream bank erosion, they can only be effective controls upon diffuse pollution if catchment draining water passes through them: much water leaving catchments will do so through drains and water courses on the surface; or soil pipes and subsurface drains below the surface; that may not connect with a stream side buffer zone. Burt *et al.* (1999) reached similar conclusions for a buffer zone alongside the River Thames in Oxfordshire where much of the agriculturally-draining water bypassed the riparian zone, entering the river directly via springs or through gravel lenses beneath the floodplain soil. Thus, the nature of hydrological connectivity needs to be established in space, and the associated buffer zones need to be placed in the correct location following on from such an appreciation. Buttle (2002) argues that much of the controversy in Canada regarding the potential role of buffer zones is related to an incomplete understanding of catchment hydrology including: (1) a failure to consider how particular types of land use are hydrologically connected to receiving waters; (2) the role of different sources of groundwater (e.g. local, intermediate or regional); and (3) an overly simplistic view that overland flow is the dominant runoff pathway, to the detriment of consideration of channel flow and rapid throughflow, where buffer zones may have little effect. Hence, a fuller appreciation of hydrological connectivity at the landscape scale is required.

Second, it is important to be clear about the process to be mitigated against and the extent to which hydrological, biological and chemical processes will be benefited by that management. For instance, whilst McKergow *et al.* (2003) demonstrated the benefit of riparian management in reducing stream bank erosion, they suggest that in catchments with sandy, low phosphorous sorption soils, there may be limitations on the effectiveness of riparian buffers for reducing phosophorous exports. Similarly, riparian buffer zones that take the form of narrow strips of land between a hillslope and the river are unlikely to provide flood storage through infiltration into the soil zone as these locations will commonly have lower slope and higher upslope contributing areas and so are likely to be saturated anyway. Similarly, wetlands will only have an effect upon flood attenuation if there is the potential for flood storage within them at the start of a flood, and this may require disconnection from the riparian corridor during medium and low flows, with connection only occurring at high flows. Third, buffer zones may provide an inadequate response if other landscape scale processes are more dominant. For instance, Vuori and Joensuu (1996) found that using protective buffer zones was insufficient to moderate against the impact of forest drainage upon instream invertebrates: larger-scale catchment management practices were required.

Similar conclusions relate to the flood pulse concept. Water levels in the channel, and hence groundwater levels within the floodplain and overbank flows onto the floodplain, will be a product of local discharge. The magnitude of this discharge will be a product of catchment water balance, partitioning of flow between different flow paths and the attenuation of the discharge wave within the main river. Flow partitioning will impact upon the nutrient state and particulate matter content of the flow. Thus, the composition and frequency of overbank flows will be controlled in part by wider aspects of landscape hydrology.

The above discussion demonstrates the need for a re-emphasis upon hydrological connectivity as part of integrated, landscape scale, catchment management. This requires both: (1) a clear conceptual appreciation of the nature of the connectivity (i.e. surface versus subsurface; spatial structure; change through time); and (2) the development of management tools that adequately reflect the effects of this connectivity in order to allow improved land management.

A FRAMEWORK FOR UNDERSTANIND HYDROLOGICAL CONNECTIVITY AT THE LANDSCAPE SCALE: SCIMAP

A consortium comprising the University of Leeds, the Environment Agency and the National Trust, with Natural Environment Research Council funding, have embarked upon a long-term project to develop and to test a decision making tool to assist in upland land management: a Sensitive Catchment Integrated Modelling and Analysis Platform (SCIMAP). The prime aims of this tool are: (1) to include an explicit representation of hydrological connectivity in order to improve management of the source area of floods, flood risk, water quality problems and sediment delivery problems, with a particular emphasis upon upland catchments; (2) to adopt a modelling approach that can deliver information at a range of spatial scales (from a 2.0 m x 2.0 m grid square through to an entire catchment), including those (e.g. the field-scale) at which actual management occurs; (3) to make use of the latest generation of readily acquired digital catchment data, and notably topographic data that can be acquired to high resolution using LiDAR; and (4) to integrate together the various model components in order to explore the impacts of catchment management decisions in an holistic way. Indeed, the major theme within the model is the need for an holistic understanding (Newson, 1997) as changes in any one aspect of management practice have may influence a wide range of catchment processes; the effects of these processes need to be evaluated with respect to a wide range of impacts. The knowledge base from which to reach sound decisions has grown, but in a disparate and poorly integrated fashion. Whilst the need for holistic catchment management has been accepted (Newson, 1997) and management systems for putting this into practice (e.g. catchment survey, geomorphological audit, dynamic assessment) are well-established and useful (e.g. Downs and Thorne, 1996; Thorne *et al.*, 1996), predictive tools for establishing the effects of catchment management decisions are less well-developed. The last 30 years has witnessed significant progress in both field-based monitoring of catchment hydrology and hydrodynamics and numerical modelling of the associated processes. However, the issues have typically been investigated in individual projects or in small parts of sub-catchments, and there are very few examples of their holistic investigation, especially with respect to hydrological connectivity. With the exception of the progress made by Coulthard *et al.* (1998, 2000), the UK has fallen behind in this respect: for instance, in the USA (e.g. Montgomery *et al.*, 1995; Dietrich *et al.*, 1995; Montgomery *et al.*, 1997; Dunne, 1998; Benda and Dunne, 1997a,b) and Australia (e.g. Willgoose *et al.*, 1991; Willgoose, 1994; Willgoose and Riley, 1998), there has been extensive investment in tools for holistic analysis of catchment dynamics for management purposes. In the research reported below, we focus upon the representation of catchment hydrology.

TOPOGRAPHY AND HYDROLOGICAL CONNECTIVITY

A major theme in hydrological research is the strong control that topography has upon hydrological processes, including the propensity for parts of the landscape to become saturated (e.g. Anderson and Burt, 1978), the route taken by both surface and subsurface flow over hillslopes (e.g. Wolock *et al.*, 1990) and the magnitude and extent of floodplain inundation (e.g. Marks and Bates, 2000). One of the major developments in recent years is the ease with which topographic data can be acquired at a high resolution and a high precision especially given growing concerns over the use of conventional map-based digital data sources for hydrological research (e.g. Fryer *et al.*, 1995; McCullagh, 1998). Model predictions for hillslope hydrological response have shown a strong sensitivity to the quality and resolution of topographic data that are used to derive them (e.g. Bruneau *et al.*, 1995; Quinn *et al.*, 1991, 1997; Wolock and Price, 1994; Zhang and Montgomery, 1994). There has been a particular focus upon DEM resolution. This affects the distribution of both upslope contributing areas (a) (e.g. Bruneau *et al.*, 1995; Zhang and Montgomery, 1994) and surface slopes ($\tan\beta$) (Bruneau *et al.*, 1995; Zhang and Montgomery, 1994). The propensity to saturation is often assumed to be related to $\ln(a/\tan\beta)$, or the topographic index, and there is growing research that suggests that the topographic index is a useful environmental diagnostic in a much broader sense than just flood risk. For instance, Buttle (2002) report on the use of the topographic index to identify the probability of saturation, where a strong relationship between topographic index and groundwater discharge at a lake margin was found, and which was shown to determine where brook trout are most likely to be able to spawn.

Given the sensitivity of parameters like slope to topographic error, it is not surprising that the distribution of the topographic index (Bruneau *et al.*, 1995; Quinn *et al.*, 1997; Wolock and Price, 1994; Zhang and Montgomery, 1994), patterns of saturation (Zhang and Montgomery, 1994) and drainage patterns (Wolock and Price, 1994) are also strongly affected by topographic data quality and resolution. It has also been shown that: (1) the optimal method for routing flow over the land surface depends upon topographic resolution (e.g. Quinn *et al.*, 1997); (2) the importance of elevation corrections in relation to data artefacts to drainage is related to grid size (Bruneau *et al.*, 1995); and (3) there is a strong association between hydrological response, model parameterisation and data resolution (e.g. Zhang and Montgomery, 1994; Bruneau *et al.*, 1995). Concurrently, the ease with which we can acquire high quality topographic data is increasing significantly (Lane and Chandler, 2003) and it has proven possible to obtain 1.0 m resolution digital elevation models of catchments with an elevation precision of 0.17 m using 1:3000 scale digital photogrammetry (Lane *et al.*, 2000). The recent expansion of airborne altimetry (e.g. the U.K.'s light detection and ranging or LIDAR system) as a means of acquiring high density topographic data is opening up even greater possibilities as digital elevation models, including both digital ground models and vegetation maps (e.g. Cobby *et al.*, 2001), can be obtained if both the first and the last signal returns are recorded. Indeed, LIDAR is now routinely used for flood inundation modelling (e.g. Marks and Bates, 2000; Horritt and Bates, 2001a; 2001b; 2000), although it has yet to be applied to hillslope hydrological modelling.

Figure 1 shows a relief shaded model of LiDAR data obtained for the headwaters of a stream that drains into the River Wharfe in the Yorkshire Dales, U.K. This is an area of 13.8 km^2 ranging in elevation from 353 m above Ordnance Datum (OD) at the sub-catchment outlet to 640 m on the divide to the north. This reveals a significant amount of topographic detail. A map of the topographic index (Figure 2) demonstrates the potential importance of this topographic detail in hydrological terms especially in relation to the high spatial variability in the index. High values of the index represent a propensity to the formation of saturated conditions and hence generate overland flow. Low values of the index represent areas that will be well-drained and are more likely to be associated with infiltration, except when the average saturation deficit for the catchment falls during a rain storm and the catchment wets up. Even without introducing a dynamic element to the model (see below), this allows a first approximation of hydrological risk: areas that are prone to be wetter will be more sensitive to livestock grazing; will have reduced infiltration rates and generate more overland flow; they will be more likely to suffer from erosion; and, as water that moves over the land surface is more likely to acquire bacteria and parasites linked to animal husbanrdy, these are the locations where the source of microbiological risk will be greatest.

HILLSLOPE HYDROLOGICAL PROCESSES

The topographic index provides a first representation of the hydrology of the upland catchment shown in Figure 1. However, it does not represent hydrological connectivity to any significant degree: areas that are more prone to saturation will be of greater risk if they connect directly to the drainage network through surface drainage rather than their water (and associated sediment, bacteria, parasites etc.) travelling across the hillslope and then re-entering the soil horizon. Re-entry to the soil will slow down the movement of water and may lead to deposition of material in transport. Connectivity is a dynamic process: the most poorly drained areas will be saturated at the start of a rainfall event; the catchment will then progressively wet, the saturated areas will expand, and eventually they may start to connect. Once connection occurs, rain falling on saturated areas will reach the drainage network more quickly and will allow relatively uninhibited transport of particulate matter.

To represent this process, SCIMAP takes the classic hydrological formulation of TOPMODEL (Beven and Kirkby, 1979). However, we allow the connectivity of areas that are saturated to develop during rainfall and then to contract as the rainfall slows. This uses a network index treatment that is based upon a saturated pixel only connecting to the drainage network if the sub-catchment within which it falls has an average saturation deficit sufficient for the pixel to connect. This is described in full in Lane *et al.* (in press). Figure 3 shows an example prediction of unsaturated, unconnected saturated areas and connected saturated areas for a storm event in June 2003. The time slice chosen is the maximum level of connected catchment saturation found for this event. It shows that large amounts of the catchment remain unsaturated, even in the middle of a major flood event. The implications of this are explored below in relation to upland land drainage.

CHANNEL ROUTING AND RIVER-FLOODPLAIN CONNECTIVITY

Once the water enters the drainage network it is routed using a Variable Parameter Muskingum-Cunge method (VPMC) (e.g. Tang *et al.*, 2001). This seeks to get the timing and magnitude of the downstream propagation of the flood wave correct. VPMC is adequate in the absence of significant floodplain storage and where it is not necessary to determine water levels. However, as water generated upstream reaches downstream zones, it is necessary to switch to more sophisticated hydrodynamic models that: (1) include determination of water levels in order to allow proper representation of the connectivity between river and floodplain; and (2) represent the transfer of water from the river to the floodplain, flow of water across the floodplain, and the return of flow back to the river channel. We achieve this using the one-dimensional St. Venant equations to represent the transfer of water within the river system and a two-dimensional treatment of flow on the floodplain. Horritt and Bates (2001a; 2001b, 2002) demonstrate the potential of this approach for representation of flood inundation. In this application, we use the JFLOW approach of Bradbrook *et al.* (in review) but have developed a method that includes a full channel treatment and the proper representation of floodplain structural features (e.g. walls, building) using readily acquired digital data (landlines). The model is applied to LiDAR data, as with the hillslope model. Example results are shown in Figure 4, in the case of inundation of the upland floodplain in the Upper Wharfe, about 15 km downstream from the headwater area shown in Figure 1. This shows how water leaves and re-enters the river in certain well-defined locations where the local elevations of the river bank and river bank levées installed in the mid-1980s are low. Water flows down (and up) the floodplain accordingly. Both of these emphasise the complexity of floodplain flows. As the river dries, a speckled effect remains and these are areas where water ponds (i.e. topographic lows). The areas that will be most prone to development of wetland conditions are clear from areas of predicted deep water and there is a strong correlation between the patterns of inundation and current distributions of land use (hay meadow, improved pasture, rough pasture, wetland). The model is currently being developed to allow a basic representation of infiltration into the floodplain.

CURRENT MODEL DEVELOPMENT

We are currently extending the model to include: (1) the transfer of coarse sediment; (2) aspects related to microbiological risk (and notably coliforms); and (3) water colour associated with dissolved organic carbon. These are all processes where hydrological connectivity is a crucial component of either the recruitment of material, the transformation of that material whilst in transport, or the deposition of that material. In the next two sections, we illustrate how SCIMAP may be used as a tool to enhance upland land management.

HYDROLOGICAL CONNECTIVITY, LAND MANAGEMENT AND FLOOD GENERATION

One of the major debates at present is whether or not land use management is contributing to current evidence of an increase in flood frequency and magnitude. Whilst there is evidence that precipitation trends are a contributing factor, notably increasing amounts of winter precipitation, in certain situations the increase in flood frequency and magnitude occurs before the increase in rainfall (Lane, in press). In an upland environment, there are two processes that matter in this respect: land use management practices that change (1) properties of the soil surface, and so lead to an increase in the storage of precipitation within the soil; or (2) the speed with which water is delivered from the hillslope to the river network. A reduction in storage or an increase in rate of runoff will reduce the time to discharge peak, reduce flow attenuation, and hence be linked to larger peak flows. However, the nature of land use effects will be complicated by: (1) the nature of the rainfall; and (2) the sequencing of rainfall events. Runoff rates are generally higher under more intense rainfall. The capacity of the soil to store water also declines after wetter periods, as the soil store is progressively filled. It is commonly thought that high levels of catchment saturation are required to produce large floods, and this may be the case, but in upland areas with steep slopes, large parts of the catchment may drain rapidly to be unsaturated even after a period of prolonged rainfall. Research from a range of environments is suggesting that land use management that impacts upon hydrological connectivity may also impact upon flood characteristics. For instance, in a peatland study in the Experimental Lakes Area of Ontario, Canada, Branfireun and Roulet (1998) found that the nature of hydrological connectivity exerted a crucial control on the magnitude and timing of peak runoff. Puigdefabregas *et al.* (1998), for a semi-arid environment, found that the potential conditions for producing overland flow were spatially discontinuous and extremely short-lived. Fitzjohn *et al.* (1998), also for a semi-arid environment, found that surface runoff from sources areas was frequently re-absorbed by surrounding areas which acted as overland flow sinks. Saturation mattered in that it increased spatial connectivity in hydrological pathways, so reducing opportunities for reinfiltration. Heiler *et al.* (1995) noted that changing hydrological connectivity linked to flood processes was crucial in controlling the dynamics of flood pulses. Thus, it appears that how saturated areas connect to the drainage network, and how land management changes this connectivity, may impact upon flood generation.

In the U.K., one of the most important types of upland land management involves open drainage or gripping, using channels up to 0.45 m deep, and ranging from 0.50 to 0.75 m wide at the surface to 0.15 to 0.25 m wide at the base (Robinson, 1990). Drain spacing and arrangement varies widely, but the density of drains and extent of drainage can be substantial (e.g. Robinson (1990) found that more than 50% of some parts of the Nidd and the Swale catchments in North Yorkshire were subject to gripping). Longfield and Macklin (1999) report a strong correlation between increases in the magnitude and frequency of flooding in York and the onset of gripping in the 1940s. However, despite this correlation, the results of studies that have invested grip impacts to date are contradictory. Further, there have been few catchment (or sub-catchment scale) investigations of the effects of gripping upon downstream flood risk.

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

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

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

We are currently using SCIMAP not only to explore these processes but also to assess the best ways in which to reverse the impacts of upland drainage. Figures 5 and 6 illustrate the counteracting effects of grip removal. Figure 5 shows the change in propensity to saturation associated with grip blocking, which increases substantially. This has the potential to increase the overland flow generating potential of the catchment considerably by encouraging the maintenance of high antecedent surface wetness. This should increase flood risk but may have beneficial ecological effects in relation to encouraging the long-term development of peat. Figure 6a shows the travel time estimate, under the assumption of overland flow velocities, for each point in the catchment to the outlet. It also shows the location of grips. Figure 6b shows the estimated change in travel time when the grips are blocked, showing highly significant increases in travels times that will lead to less ready connection of overland flow to the surface drainage network and hence the catchment outlet. It should be emphasised that these differences are indicative and not real as the model requires further paramaterisation prior to acceptance of the results. However, Figure 6b suggests that blocking grips reduces travel times to the catchment outlet which will result in rainfall being delivered more slowly to the catchment outlet which should reduce flood risk. Thus, grip blocking will have contradictory impacts upon flood risk and this mirrors the conclusion of Newson and Robinson (1983). It also means that the only possible means of establishing the catchment-scale impact of gripping in relation to wetness and runoff is through a catchment-scale modelling technique that retains the spatial arrangement of grips, represents their connectivity to the drainage network and does so at a spatial scale that is commensurate with the scale of the grips themselves (i.e. < 5 m).

However, of more interest is the interpretation of Figures 5 and 6 in relation to hydrological connectivity and land management more generally. Both figures emphasise that the prime effect of removing grips in the catchment was to change the way in which rainfall connects to the drainage network. In Figure 5, grip removal resulted in an increased propensity to saturation as it increased the upslope contributing areas downslope from grips. With a grip upslope, hillslope hydrological connecitivity is broken and water is essentially siphoned off into the drainage network, causing lower upslope contributing areas and hence surface wetness. In Figure 6, water that is siphoned off into the drainage network then travels at up to two orders of magnitude faster than it would otherwise do as overland flow on the hillslope (on the basis of field measurements), such that the water is delivered much more efficiently to the catchment outlet. Blocking grips reduces this effect but is an expensive process. Thus, decisions over grip blocking should focus upon those grips that have reduced upslope contributing areas most and which have most effect upon travel times to the catchment outlet. Blocking all grips may not be necessary and spatial optimisation of blocking activities may save significant amounts of time and money. It is also necessary to identify the ways in which grip blocking might have other unintended impacts, both beneficial and otherwise. Does grip blocking reduce or increase water colour? Does it increase the total size of the carbon sink? This is where the integration of different environmental processes is crucial.

HYDROLOGICAL CONNECTIVITY, FLOOD RISK AND LAND USE

The above section illustrated the way in which SCIMAP can be used to rationalise the debate over the effects of upland drainage upon floods, to simulate flood response, and to optimise the process of reversing the effects of grip blockage. Any attempt to block grips may impact upon water balance as well as the timing and delivery of water during a flood. This may have downstream impacts, especially if downstream ecosystems are adjusted to frequent flood pulses as part of natural floodplain dynamics. This is the sense in which it is important to consider the range of upstream and downstream impacts as part of integrated catchment management. One of the major characteristics of floodplains is longitudinal variation in dominant land use. In the case of the Upper Wharfe, the mix of land uses includes intensively managed pasture, less intensively managed floodplain hay meadows and abandoned wetland environments. If flood inundation frequency is going to change (e.g. due to river bed aggradation, land use management linked to grip blocking or forest management, or climate change), it is important to be able to manage patterns of inundation if an existing distribution of floodplain uses is to be maintained. For instance, wetlands and hay meadows may both be dependent upon a flood pulse that occurs with a particular magnitude and frequency. Similarly, if a change in land use is planned, this may allow or even require a change in the magnitude and frequency of inundation. Thus, exploring the changing hydrological connectivity between the river and its floodplain is a crucial issue.

In Figure 7, we provide an example of how SCIMAP can be used to do this. Currently, the true right bank of the river in the upper part of the picture comprises a heavily managed environment involving improved pasture, but which is managed along traditional terms to provide a floristically-diverse hay meadow at some points of the year. Climate change (notably winter precipitation) is expected to result in an increase in the magnitude and frequency of flood inundation.

If inundation occurs too frequently, it may be necessary to embark upon flood protection in order to maintain this land management system. However, it is important to minimise the extent to which

If inundation occurs too frequently, it may be necessary to consider whether the retention of the ecologically valuable hay meadow and its concurrent traditional farming practice constitutes a sufficient driver for management to protect this feature. This would require an evaluation of the options in the wider context of other catchment features required, for example the hydrological connectivity of the river with its floodplain and protection and expansion of wetlands. Although contrary to the latter, one option might be to raise the right bank levée alongside the hay meadow to protect it. Thus, Figure 7 shows the effects of raising the right bank levée to protect the hay meadow. This has a relatively small effect on water levels downstream because the volume of water leaving the main channel alongside the hay meadow is small and flow depths in the hay meadow are relatively small as compared with areas downstream. This approach requires economic support for water management change based on ecological and cultural drivers. Again, it can be undertaken in a way that recognises the full spatial impacts of current decision-making processes.

CONCLUSIONS

This paper has demonstrated a new tool that we have developed explicitly to improve the management of upland environments. As compared with other hydrological models, it has the unique distinction of combining: (1) an explicit representation of hydrological connectivity; with (2) model sub components that allow consideration of a range of environmental processes linked to land use; and (3) a computationally efficient treatment that allows catchment-scale application but retains the basic principle that processes operating at quite small spatial scales (less than 10 m) are a crucial component of system response. Of most importance, by using hydrological connectivity as the integrating conceptual framework, it avoids the classical sectoral response associated with land management where a range of possible causes is explored in relation to a single problem. For instance, there is much current debate over whether or not precipitation changes are being exacerbated by land management to make flooding problems more serious. This is a sectoral view of the environmental management where the problem (flooding) is explored in relation to a range of causes. However, it is difficult to allow generic conclusions to be made: whether or not land use management matters depends upon the catchment that is under consideration. Even if land management might have some beneficial flood-reducing impact, a sectoral approach also overlooks other potential environmental benefits (and costs) that might derive from a more enlightened approach to land management (e.g. restoration of blanket peat bog if drains are blocked in an appropriate way). By taking a catchment-scale view, supported by an appropriate decision-making tool, it is possible to escape the limits of sectoral enquiry and produce land management decisions that address environmental risk as a whole rather than one narrowly defined sub-component of that risk.

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ACKNOWLEDGEMENTS

This research is supported by NERC Grant NER/D/S/2000/01269 awarded to SNL, MJK and AMcD and a NERC Postdoctoral Research Fellowship awarded to JH. Additional support has been provided by the Environment Agency, the National Trust and the University of Leeds. Kate Bradbrook (JBA Consulting) commented on an earlier draft of this paper.

FIGURES

Figure 1. A shaded relief model based upon 2.0 m resolution LIDAR data for an upland area. Tests suggest the point elevations are precise to ±0.12 m.

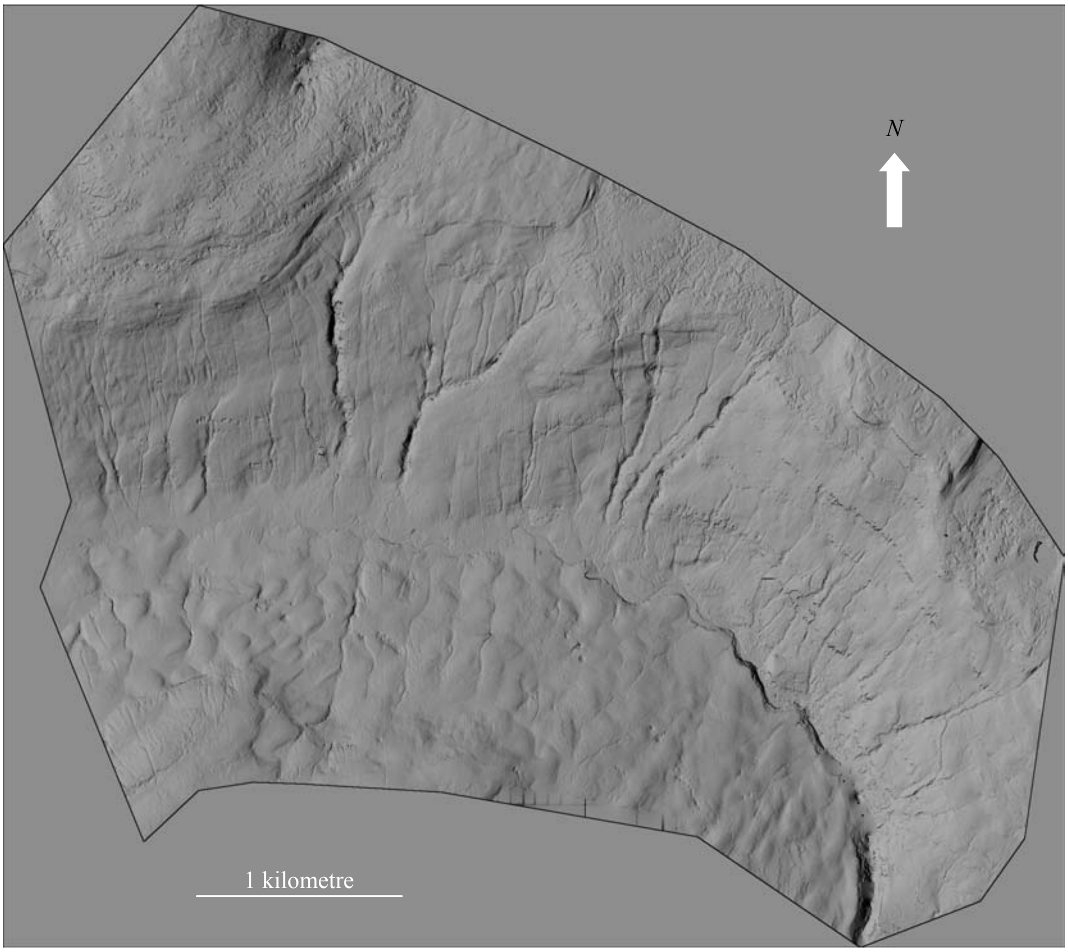

Figure 2. A map of the topographic index for the area shown in Figure 1. Areas of high topographic index will be more prone to saturation.

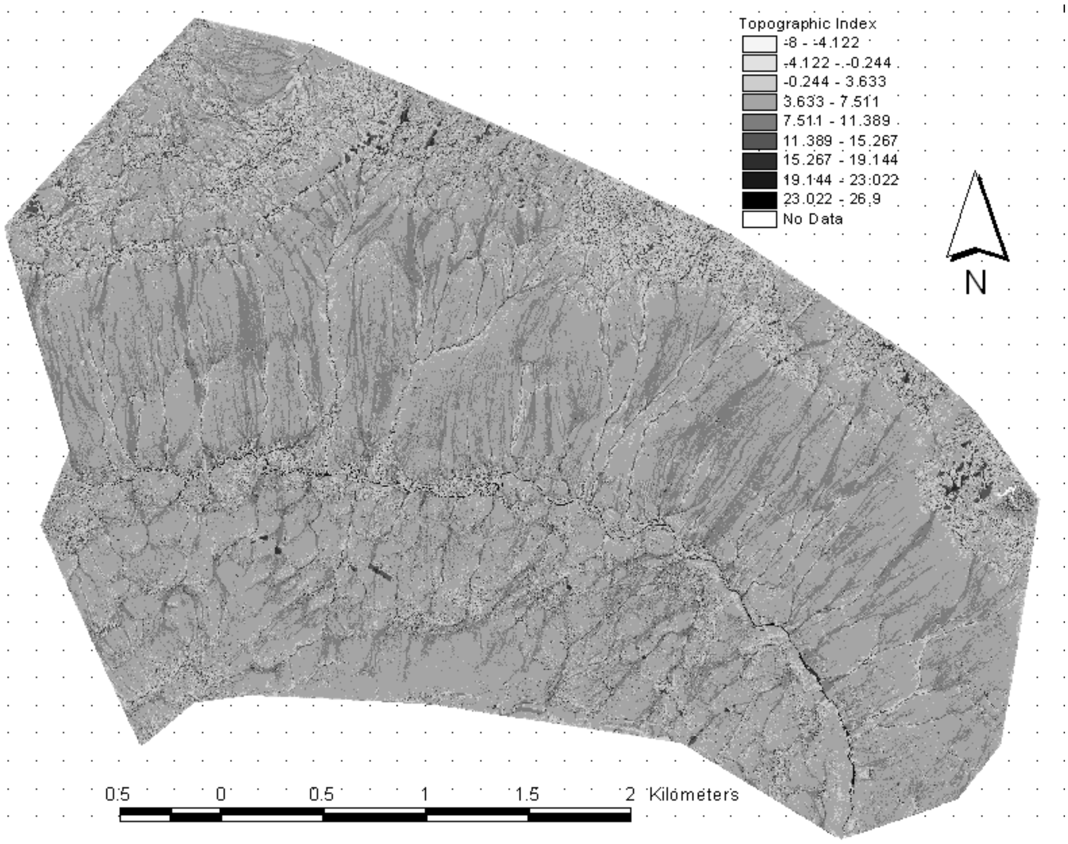

Figure 3. Prediction of unsaturated, unconnected saturated and connected saturated areas for 6 from the onset of rainfall for a storm event in June 2000.

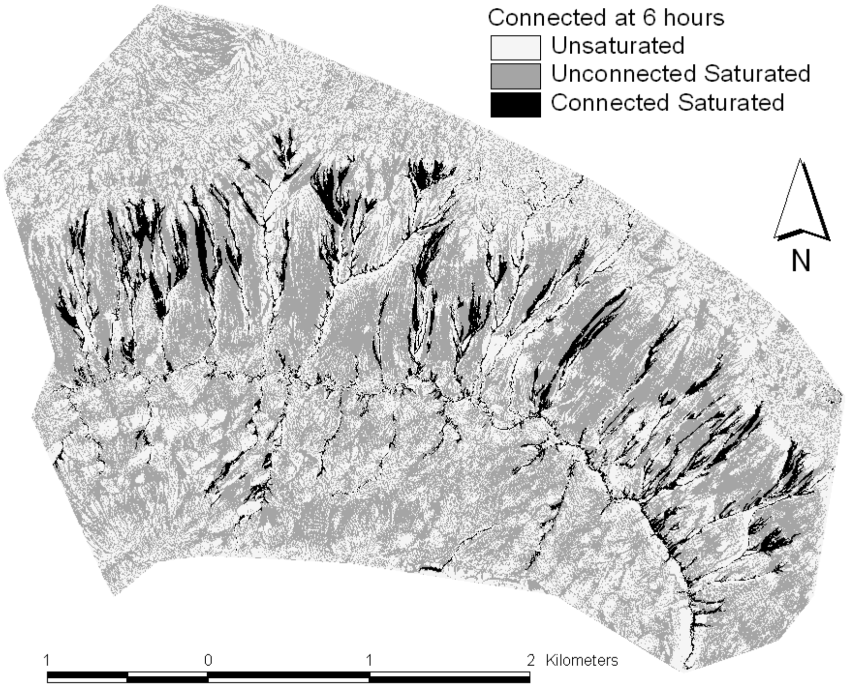

Figure 4. Patterns of inundation in an upland floodplain for the same storm event shown in Figure 3.

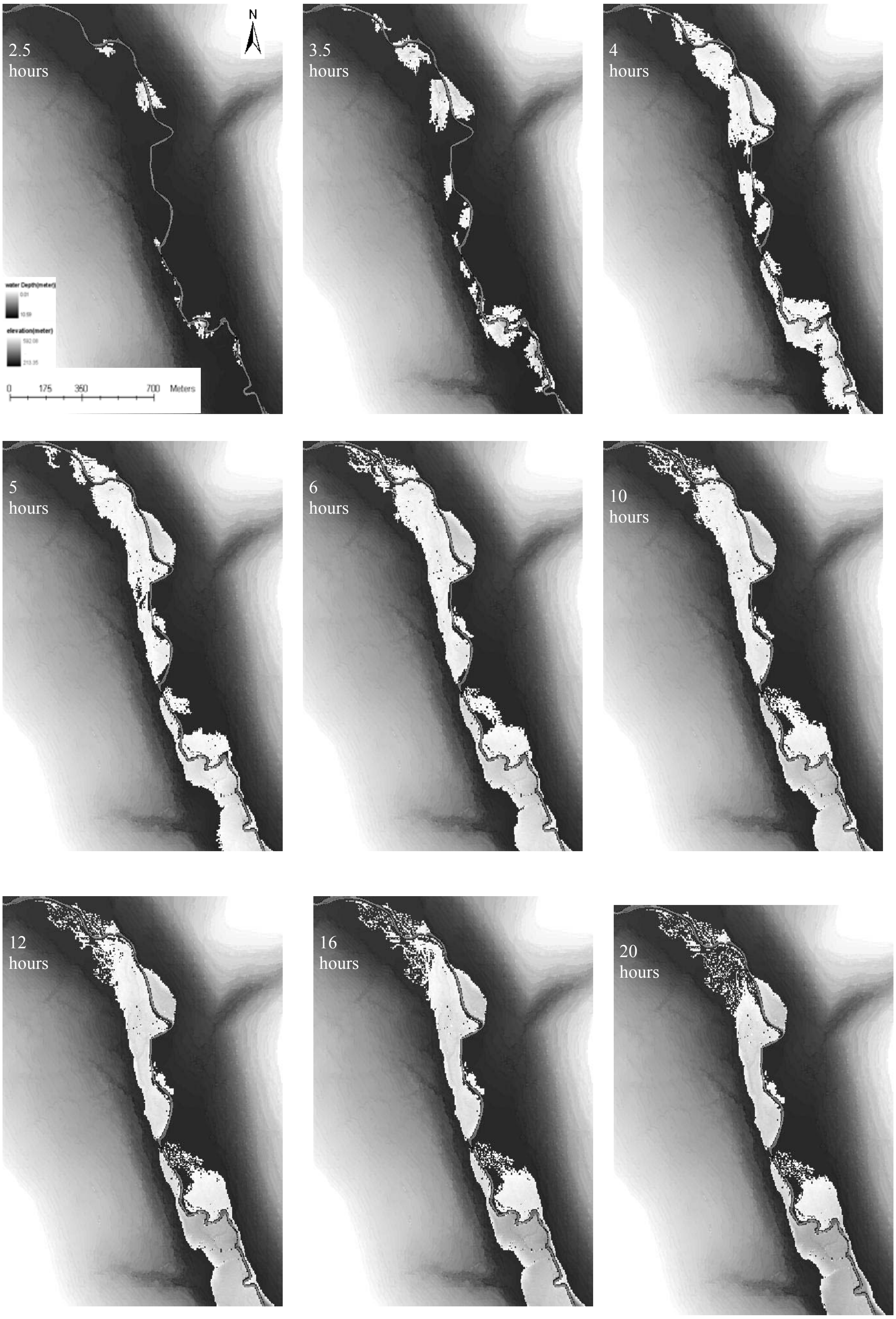

Figure 5. A map of the change in propensity to saturation for part of the area shown in Figure 1 associated with removing grips. The scale is set from no change (white) to an increase in the propensity to saturate (dark grey) when grips are removed.

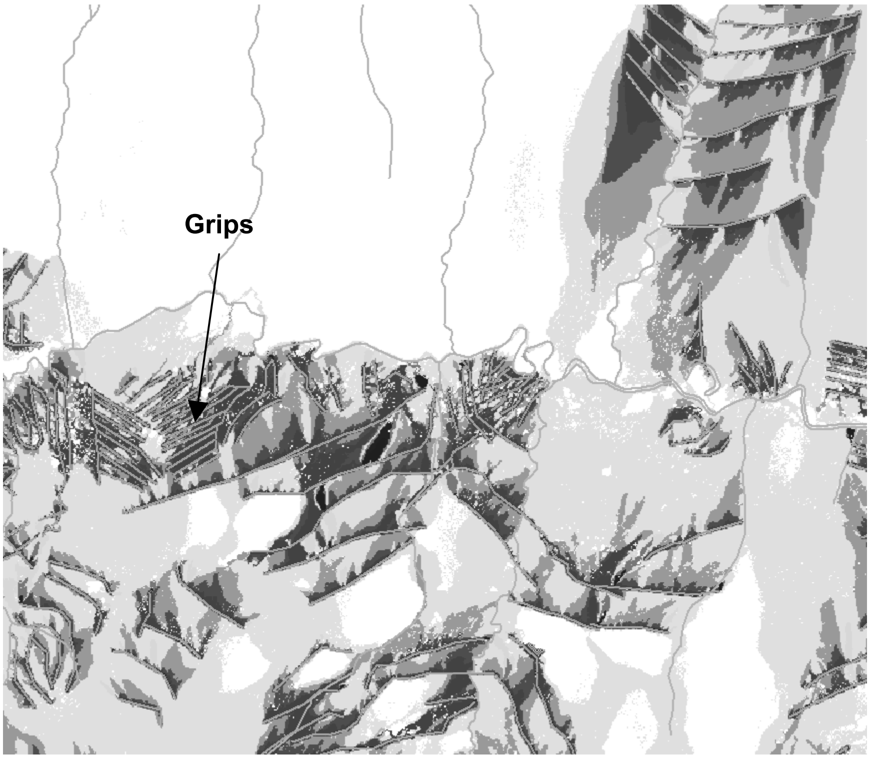

Figure 6. Travel times to the catchment outlet without grips (in hours) (6a) and, for the same area, the reduction in travel time when grips are added (6b). Note that this assumes that all routing over the hillslope surface is at a constant overland flow velocity estimated from field sampling. The grip network is shown overlaying the travel time map.

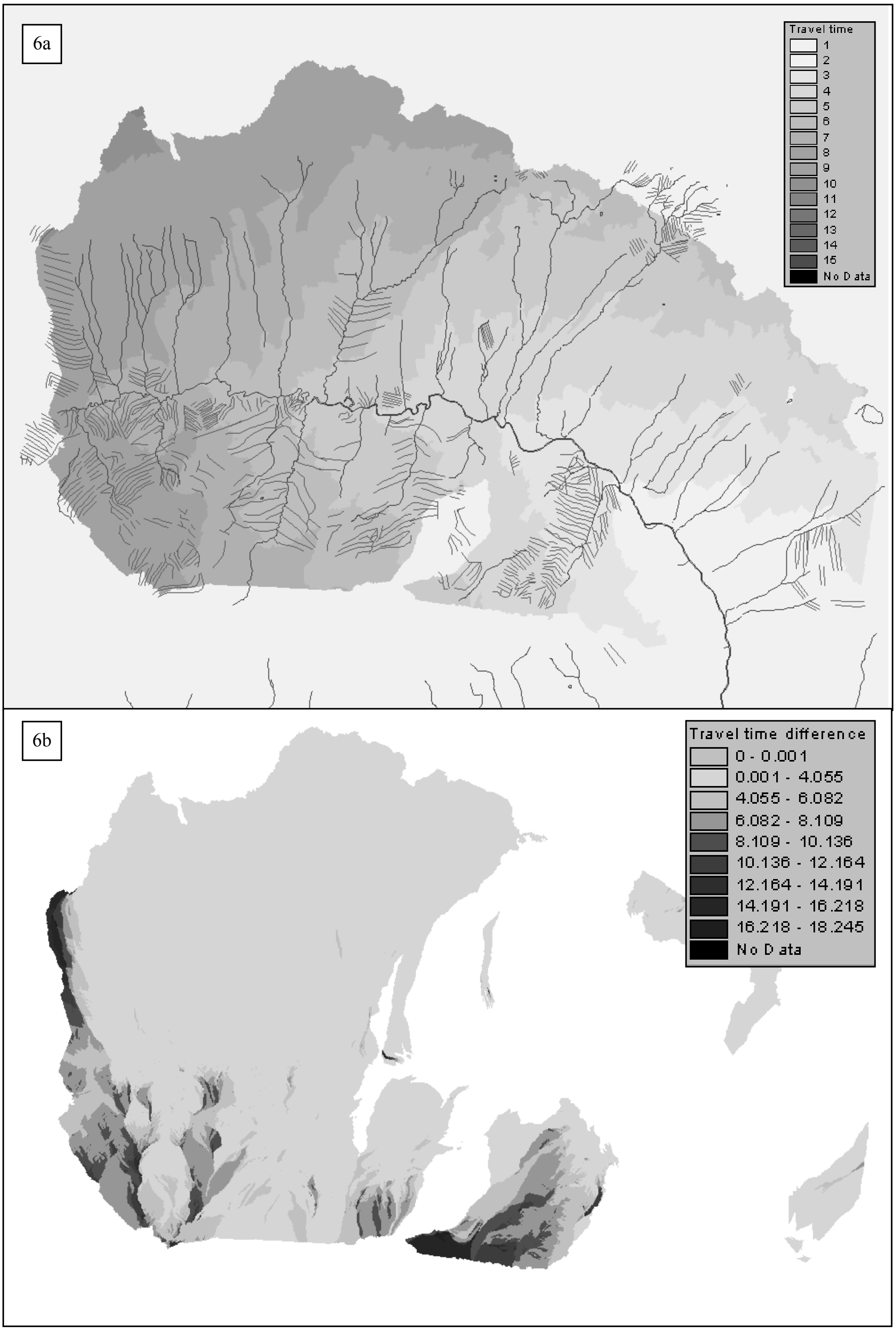

Figure 7. A repeat of the simulation shown in Figure 3, but where the right bank levees are raised to protect hey meadow when there is a risk of increased magnitude and frequency of extreme flood events which may result in too many flood pulses for a sustainable meadow system.