Physics and Chemistry of the Earth 36 (2011) 630–637

Contents lists available at ScienceDirect

Physics and Chemistry of the Earth

journal homepage: www.elsevier.com/locate/pce

Sensitivity maps for impacts of land management on an extreme flood in the Hodder catchment, UK

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ARTICLE INFO

Article history:
Available online 22 June 2011

Keywords:
Flooding
Adjoint modelling
Catchment modelling
Land use management

ABSTRACT

It is increasingly recognised that the management of land and the management of water are strongly interdependent, and that integrated management approaches are needed. There is evidence that modern land management practices have an effect on runoff generation in rural upland areas, so there is the potential to use land management control as a tool in flood risk mitigation programmes. Flooding from historical extreme rainfall events must be considered when designing mitigation programmes, especially if the designs have to take into account the possibility that such events will become more frequent in the future.

The largest 90 min rainfall ever recorded in the UK was 117 mm, recorded in 1967 in the Dunsop tributary (25 km^2) of the Hodder catchment, northwest England. Extensive land management changes have recently been made in the catchment, including peat restoration, tree planting and reductions in sheep stocking density, and the analysis of the flooding in 1967 has been undertaken as part of a wider study on the potential impact of the recent changes.

A method is demonstrated in which maps of sensitivity are plotted which show how peak flows for extreme events are affected by spatial patterns of changes in runoff generation. This method uses a gridded model for runoff generation containing an embedded hydraulic model of the river network which can calculate sensitivities efficiently and accurately using reverse algorithmic differentiation. The modelling examines the sensitivity of the hydrograph peak at the catchment outlet to changes in flashy runoff generation, which can be affected by land management practices including the blocking of open drainage channels in peat moorland. It is concluded that, as a result of hydraulic and geomorphologic dispersion in the network, changes in land management that affect the flashiness of runoff generation at small scales would probably have had only a relatively minor effect on the flow peaks at the outlet from the catchment during the 1967 extreme event.

1. Introduction

There is evidence that modern farming practices can cause flashy runoff (O'Connell et al., 2007). For example, increases in stocking densities and keeping stock on the land over winter, when soils are susceptible to compaction, have contributed to soil degradation and flashy runoff in the UK uplands (Holman et al., 1999; Marshall et al., 2009). On-farm impacts can be mitigated through good land use management practices that delay or attenuate runoff (O'Connell et al., 2004). The use of land management control as a tool in flood risk mitigation programmes has been advocated in the UK by the Department of the Environment and Rural Affairs (Defra) 'Making Space for Water' initiative (Defra, 2004), and the Pitt review of the summer 2007 floods in the UK (Pitt, 2008). These policy initiatives have wider objectives, including to improve the ecological status of water bodies as required by the Water Framework Directive (Parrott et al., 2009). However, the evidence base regarding the effectiveness of mitigation programmes to alleviate flooding at the catchment scale is very limited; experimentation and monitoring has primarily focused on the small plot and field scale and small headwater catchments. The major gap in knowledge being addressed here is the need to understand the role of the drainage network in propagating impacts from the small scale downstream to sites of major floods.

In the UK, summer is the dominant season for extreme events, albeit at the catchment and local scale rather than regional scale (Hand et al., 2004; Newson, 1975). Extreme events are of interest because they are accompanied by other hazards, including landslides, mud flows, and loss of infrastructure and life (Collier, 2007), and there is the possibility that extreme events may become more common in the future (e.g. Dale, 2005; Frei et al., 2006). In the UK, flash floods having a time to peak of less than 3 h within catchments of 5–10 km^2 (Collier, 2007) are the main source of

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doi:10.1016/j.pce.2011.06.005

danger to human life. Recent extreme floods have brought into focus the vulnerability of communities in upland areas. In 2004, during a localised convective event in north Devon, 200 mm of rainfall was recorded in 4 h (Golding et al., 2005), and 60 properties were flooded in the village of Boscastle (some were destroyed), with the insurance losses estimated at £50 m (Gledhill, 2007). There was speculation that the severity of the flood may have been exacerbated by changes in land management, including increased field sizes and the removal of hedgerows. A report commissioned by the Environment Agency concluded that the effects of land management are difficult to quantify reliably but speculated that they probably had little impact (HR Wallingford, 2005).

Large scale changes in land management are currently being undertaken in the rural upland Hodder catchment, northwest England. The catchment has been instrumented to record the impacts that these changes have on downstream flooding (Ewen et al., 2010). There is a particular interest in possible impacts during extreme floods, but such floods are rarely observed during short monitoring periods. In August 1967, 117 mm of rainfall was recorded in 90 min in the Dunsop headwater tributary, which is the highest point rainfall over this duration ever recorded in the UK. This extreme event has been studied retrospectively to investigate the potential for using land management for the mitigation of large floods. The analysis uses a modelling approach which provides a link between local scale runoff generation and downstream flooding. A novel aspect of the modelling is that the output is in the form of maps which show sensitivities, such as the sensitivity of the downstream hydrograph to changes in runoff generation. These allow conclusions to be drawn about the potential for using land management control in flood risk mitigation programmes for extreme events.

2. Catchment description

The River Hodder, northwest England, drains an area of 261 km^2 to the Environment Agency (EA) river gauge at Hodder Place (Fig. 1). Relief varies between 40 m AOD at Hodder Place to 544 m AOD in the north, and average annual rainfall is 1600 mm. Northern upland areas are characterised by summit plateaus, covered with rough moorland and almost permanently saturated blanket peat mire, and deeply incised valleys (Chiverrell et al., 2009). Historically, burning has been performed to maintain areas of moorland for grouse shooting (Mackay and Tallis, 1996). In the more fertile valley floors, the land has been improved for dairy and livestock farming. Soils in these areas comprise the Wilcocks and Brickfield associations, which have slowly permeable subsurface horizons and peaty or humose topsoils (Jarvis et al., 1984). Under the United Utilities Sustainable Catchment Management Plan (SCaMP), large scale changes in land management are taking place in the northern headwater tributaries, which are designated a Site of Special Scientific Interest (SSSI). These changes include tree planting, the blocking of man-made open drainage ditches (grips) in peatland and reductions in stocking densities. The main aim of these restoration works is to improve the colour of the water abstracted for public supply and improve the ecological habitat of the SSSI (McGrath and Smith, 2006; Worrall et al., 2007). Field and modelling studies are being undertaken to assess the effect these changes are having on the downstream flood response (Ewen et al., 2010; O'Donnell et al., 2008).

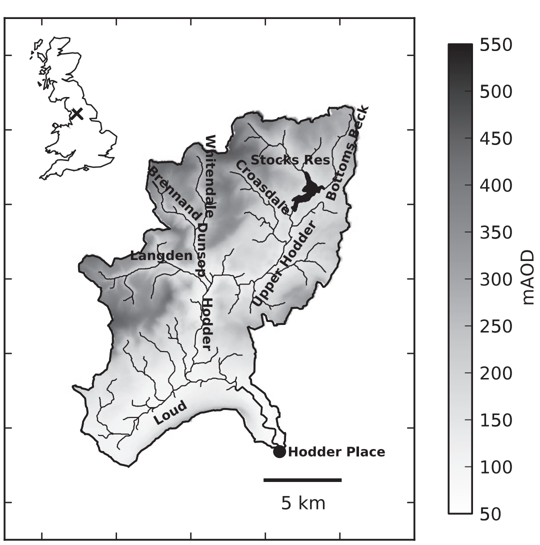

Fig. 1. Hodder catchment (inset upper left: UK location map).

The most extensive land management changes are occurring in the headwaters of the Brennand and Whitendale tributaries of the Dunsop catchment and the Croasdale catchment, which coincide with the storm centre of the 1967 event. Deep, wet, organic blanket peat, with a typical depth of 1–3 m occur on the low gradient plateaux. The hydrological response of peatland catchments is characterised by rapid and efficient transfer of water from hillslopes, resulting in flashy catchment hydrographs and large runoff percentages (Holden and Burt, 2003). The watertable is typically close to the surface throughout the year resulting in significant overland flow which can account for up to 80% of water movement in temperate peatland hillslopes (Holden et al., 2008). Usually there is no significant delayed flow or groundwater contribution to baseflow. Grips, which consist of open drains of typically 1 m depth, were constructed in the Dunsop and Croasdale catchments in the 1960s and 1970s with the aim of draining peat to improve habitat for sheep and grouse. Recently 38 km of grips have been blocked (2008–2009) to improve the condition of the peatland vegetation by raising the water table and also to reduce flow velocities and erosion. There is significant debate on the hydrological impacts of implementing peat drainage, with evidence of both an increase and a decrease in flood peaks at the small scale, which has been attributed to site specific characteristics, including the type of vegetation and the drainage pattern of the grips (Holden et al., 2004). Using nested flow gauges, analyses to detect short-term impacts on hydrographs have been performed in the Dunsop (Ewen et al., 2010). The grip blocking was not found to have a marked effect on discharge in the river channel, but the monitoring period was short and did not cover the full range of hydrological variability.

To regenerate the moorland vegetation and restore vegetation on eroding peat, stocking densities are being reduced in the upland catchments in the Hodder. Sheep tracks that form in intensively grazed upland areas can extend the ephemeral drainage network, resulting in the rapid delivery of water into the drainage network (Meyles et al., 2006). It has also been speculated that reduced vegetation coverage caused by over-grazing in upland areas may also result in rapid runoff (Holden et al., 2008; Orr and Carling, 2006) and the formation of gully systems (Bragg and Tallis, 2001).

In the literature, a wide variety of model structures have been used when predicting the potential impact of land use management practices on catchment scale flooding (e.g. see Breuer et al., 2009; O'Connell et al., 2007). Typically, the modelling approach taken to predict impact involves first running a pre-change simulation in which the model is parameterised using fine-scale experimental data. Then a post-change simulation is run in which the parameters are altered directly (Ballard et al., 2010; Liu et al., 2006; Uhlenbrook et al., 2004) or altered on the basis of some prescribed changes in the dominant runoff processes (Naef et al., 2002; Schmocker-Fackel et al., 2007). In recent work for the Hodder catchment (Ewen et al., 2010) a 'top down' approach was