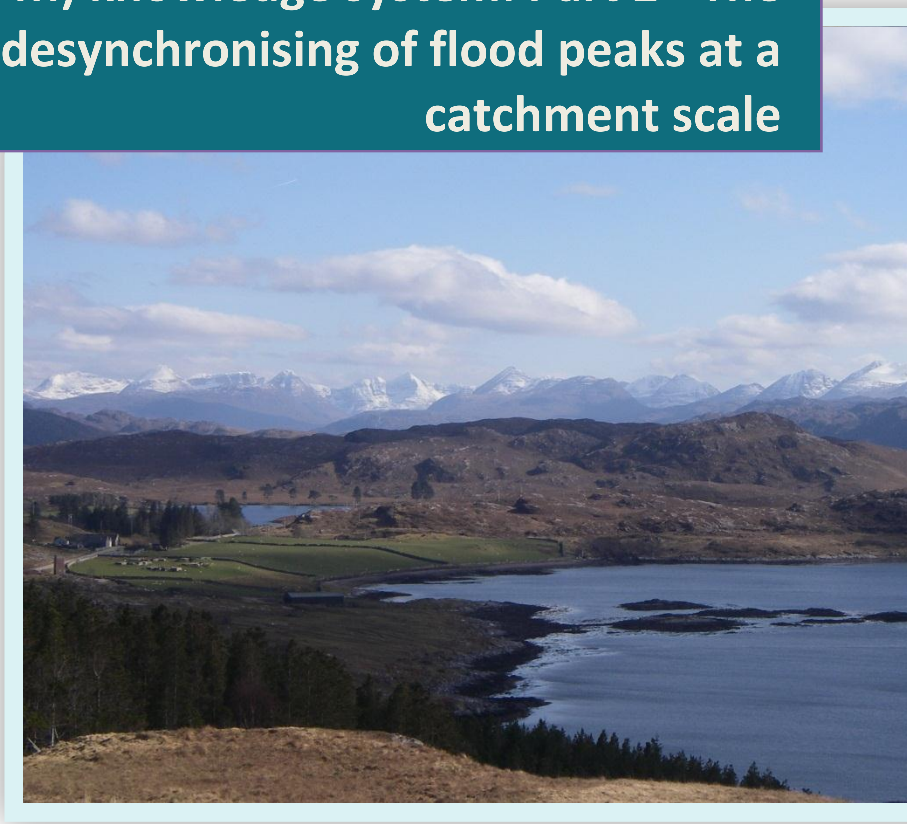
Natural flood management (NFM) knowledge system: Part 2 - The effect of NFM features on the desynchronising of flood peaks at a catchment scale



Final Report

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Contents

Executive Summary

Project reference: Natural Flood Management (NFM) Knowledge System (June, 2012)

Project contractors: School of the Built Environment, Heriot-Watt University

Background to research

Natural flood management (NFM) is currently being promoted as a cost-effective catchment scale approach to managing flood risk and The Flood Risk Management (Scotland) Act 2009 places an emphasis on all statutory bodies to consider the use of NFM approaches where possible. Whilst this emphasis has already led to a number of initiatives aimed at assessing and promoting the more widespread implementation of NFM techniques within Scotland, there remains significant uncertainty regarding the effectiveness of NFM measures at the catchment scale. There is therefore a clear need to improve the evidence base of NFM performance, design and implementation.

Objectives of research

This report is one of three produced for CREW to verify the current state of knowledge on NFM. It focuses on establishing the effectiveness of NFM features at a catchment scale, particularly in relation to how they may be used to desynchronise flood peaks and therefore reduce downstream flood risk.

Key findings and recommendations

The key findings of this research are as follows:

- Identifying the impact of specific NFM measures (independent of other factors) is difficult, but there is evidence to suggest that they can reduce flood risk at the local scale, e.g. Wheater *et al.* (2012) predict that afforestation can reduce peak flows by up to 60%, and Acreman *et al.* (2003) report that river restoration can reduce peak flows by up to 15%. However, the scale and direction of such impacts are necessarily site specific, e.g. Bullock and Acreman (2003) report that nearly half of wetlands studied have the potential to actually increase flood risk.
- Farming practice and antecedent soil conditions can have a significant impact on the effectiveness of NFM at the local level, e.g. Jackson *et al.* (2008) report that strategically placed tree shelter-belts can reduce peak flows by up to 40% and Hümann et al. (2011) state that site and soil characteristics can have a greater influence on runoff generation than forest type. However, the impacts are again very site specific.
- NFM measures need to be above a minimum size to achieve noticeable effects on flood risk at the local scale, e.g. Bathurst *et al.* (2011a) consider that forest cover must change by at least 20-30% to provoke a noticeable change in peak discharge.
- There is currently no conclusive evidence that NFM features can be used to reduce flood risk at the catchment scale, and Mayor *et al.* (2011) note that "...extrapolation of runoff values between scales or between catchments of different sizes is meaningless".
- NFM measures can impact on the time to peak of local flows, but their location within a catchment and the spatio-temporal variations in rainfall and runoff have a significant impact on the ability of NFM measures to assist flood peak desynchronisation, e.g. whilst Thomas and Nisbet (2006) predict that forestation of a catchment can increase time to peak by as much as 77%, Pattison & Lane (2012)

consider that location and spatio-temporal rainfall/runoff characteristics may mean that "...the pursuit of generalisations between different land-management practices and flood risk may be a meaningless and unachievable aim**"**.

- There is currently no conclusive evidence that NFM features can be used to desynchronise flood peaks, and there is concern that simplistic application could result in unforeseen outcomes, e.g. Nisbet & Thomas (2008) caution that "…a possible downside of de-synchronisation, however, is that by extending the flood hydrograph there is a risk of consecutive flood events contributing to higher flood peaks if they coincided with the delayed recession limb of the flood hydrograph"..
- Whilst the current lack of evidence and uncertainties does not imply that NFM measures cannot make a significant contribution towards flood risk reduction, it does highlight the need for continuing research in this area. There are now a number of ongoing and planned UK catchment scale 'demonstration projects' that have the potential fill this current knowledge gap.

Key words
Natural Flood Management; Local; Catchment; Peak Desynchronisation

1.0 INTRODUCTION

The first Scottish National Flood Risk Assessment, produced by the Scottish Environmental Protection Agency (SEPA, 2011), reports that approximately one in 22 of all residential properties and one in 13 of all non-residential properties in Scotland are at risk from flooding and notes that the average annual damage to homes, businesses and agriculture from all sources of flooding is estimated to be between £720 million and £850 million. In addition, climate change trends suggest that Scotland will experience more frequent extreme weather events, including intense summer rainfall (SEPA, 2012). Given these predictions, there is a clear need to ensure appropriate flood management processes are in place. Over time, the approach to flood management has changed; an initial focus on land drainage and flood defence throughout the 1950s, 60s and 70s moved towards a flood control and then a flood management approach in the 1980s and 90s. Whilst, these approaches had a strong focus on engineering measures, a more integrated and sustainable flood management (SFM) approach has now been adopted. For example, in Scotland, SFM was established in legislation as part of the Water Environment and Water Services (Scotland) Act in 2003.

Natural flood management (NFM) is "*A set of flood management techniques that aim to work with natural processes (or nature) to manage flood risk*" (SEPA, 2012), and is one aspect of SFM currently being promoted as a cost-effective catchment scale approach to managing flood risk. The Scottish Government has made it clear that NFM measures are an important part of their sustainable flood management policy as evidenced by The Flood Risk Management (Scotland) Act 2009 which transposes the European Floods Directive (2007/60/EC) into Scots law. The Act places an emphasis on all statutory bodies to consider the use of NFM approaches where possible. Already this emphasis has led to a number of initiatives aimed at assessing and promoting the more widespread implementation of NFM techniques, including the formation of a NFM group under the Scottish Advisory and Implementation Forum for Flooding (SAIFF), NFM stakeholder workshops and Government support for demonstration projects. The review of the 2007 summer floods in the UK (Pitt, 2008) also highlighted the potential of NFM by recommending "greater working with natural processes". However, as recent reports have highlighted (ICE, 2011), there is a clear need to improve the evidence base of NFM performance, design and implementation.

This report is one of three produced for CREW to verify the current state of knowledge on NFM. It focuses on establishing the effectiveness of NFM features at a catchment scale, particularly in relation to how they may be used to desynchronise flood peaks and therefore reduce downstream flood risk. To provide some context for later discussion of the complex interactions that can occur between NFM measures and the wider catchment, this report also includes an overview of a range of relevant studies, with an emphasis on recent work. It should be noted however that this report does not attempt to replicate the many, and more discursive, NFM reviews that have recently been published, e.g. O'Connell *et al.,* (2004); EA, (2007); Beven *et al.,* (2008); EA, (2009); Parrott *et al,.* (2009); FRMRC, (2011); Jacobs Engineering (2011). Rather it presents a brief overview of a range of relevant studies, a summary NFM database (Appendix 1) and a synthesis of the state of the art.

2.0 Local scale impacts on flood risk

Summary: Identifying the impact of NFM measures on runoff and flood risk at the local scale (independent of other factors) is difficult

There have been a significant number of studies undertaken to investigate the impact of NFM measures at the local scale. These studies have involved a variety of different approaches, including observation and analysis of small scale experimental plots (e.g. Hümann *et al.,* 2011; Wheater *et al.*, 2012), analysis of historical data (e.g. Grayson *et al.*, 2010; O'Donnell *et al.*, 2011; Sriwongsitanon & Taesombat, 2011; Fox *et al.*, 2012) and computer simulations (e.g. Krause, 2002; Acreman *et al.*, 2003; Thomas & Nisbet, 2006; Hess *et al.*, 2010; Colin *et al.*, 2012; Levavasseur *et al.*, 2012). Some studies have based their findings on paired-catchments, where different measures are implemented on catchments with comparable morphology and climate (e.g. García-Ruiz *et al.*, 2008; Bathurst *et al.,* 2011a; Dung *et al.*, 2012; Webb & Kathuria, 2012), others have considered single catchment experiments, in which the land cover either changes during the observed study period or is apparent from historical records (e.g. Grayson *et al.*, 2010; Zhao *et al.*, 2010, Ballard *et al.*, 2011; Komatsu *et al.,* 2011), whilst others draw comparisons between the hydrological responses of neighbouring catchments with different land covers (e.g. Lara-Renault *et al.*, 2011). The number of uncontrollable variables in all of these studies makes it difficult to identify conclusive evidence of the impact of NFM techniques independent of other factors.

Specific NFM measures

Summary: NFM measures can have a significant beneficial impact on runoff and flood risk at the local scale

Forest and Woodland. Andréassian (2004) notes that deforestation can increase both flood volume and flood peaks, which is supported by Wheater et al (2012) who predict that full afforestation of a 4km^2 sub-catchment at Pontbren (Wales) could reduce peak flows by up to 60%. Similarly, Reinhardt *et al.* (2011) report that floodplain woodland can reduce both flood volume and flood peaks, and Odoni *et al.* (2010 predict that riparian woodland could help reduce peak flows within the Pickering Beck by 8-10%. Whilst these findings are supported by a number of other studies and reviews (Calder & Aylward, 2006; Calder *et al.*, 2009; EA, 2007; Blumenfeld *et al.,* 2009; Bulygina *et al.*, 2009; FRMRC, 2011; Dung *et al.*, 2012), most researchers report that mitigating effects tend to be restricted to small local events with little impact on extreme floods. Forest and woodland can also indirectly contribute to flood reduction by increasing woody debris load in watercourses, as recent research suggests large woody debris jams act to delay flood peaks and may be a viable soft engineering technique that can be used for downstream flood risk mitigation (Thomas & Nisbet, 2012).

Wetlands. Bullock and Acreman (2003) state that it is widely accepted that wetlands have a significant influence on hydrological cycles. Importantly however, they note that while there are many examples of wetlands reducing flood risk, there are nearly as many examples where they increase flood risk. The potential for wetlands to reduce flood volume was also reported by Blumenfeld *et al.* (2009), who reported that wetlands along the Mississippi River previously had the capacity to store ~60 days of river discharge, but their removal to create canals and levees has decreased this flood storage capacity to only ~12 days.

River restoration. Acreman et al (2003) used hydrological and hydraulic models to assess the implications of changes to the channel of the River Cherwell in England, and reported that a number of different river modification strategies (channel rehabilitation and narrowing, bed raising) reduced peak flow at Somerton Bridge by around 10–15%. In contrast, embanking the river, and thus preventing water spreading onto the floodplain at high flows, was found to increase the peak flow by 50–150%.

Farming practice

Summary: Farming practice can have a significant beneficial impact on the effectiveness of NFM measures to modify runoff and flood risk at the local scale, although the effects are complex

In terms of farming practice, Marshall *et al.* (2009) report that, compared to grazed grassland, there is significantly less overland flow within tree planted areas where livestock are excluded. The same authors also suggest that tree shelterbelts, strategically positioned on a hillslope, could act as possible flood peak mitigation features. Similar findings were reported by Carroll *et al.* (2004), who found that strategically positioned planting of trees, even at a small scale, could improve the infiltration capacity of extensive areas of grazed permanent pasture. In model simulations based on this data, Jackson *et al.* (2008) report that the reduction in peaks between the most intensely farmed scenario and shelter belt scenarios could be up 40%. However they questioned the extent to which this would be applicable at larger scales. McIntyre & Marshall (2010) and FRMRC (2011) also report that the exclusion of sheep significantly reduces surface runoff at the plot scale, although the earlier study notes that the evidence is neither conclusive nor necessarily applicable to other catchment types. In addition to the direct impacts resulting from grazing, a recent study by Posthumus *et al.* (2011) reports that agricultural intensification, cultivation of specific crops (e.g. potato and maize) and soil management practices (e.g. exposing soil surface over winter or working land while wet) can exacerbate problems related to increased surface runoff due to soil compaction.

Clay *et al.* (2009) investigated the effect burning has on various hydrological parameters of an upland blanket bog, and identified significant links between burning regime and depth of water table (below ground level), i.e. the shallowest water tables were found on those sites burnt every 20 years and grazed by sheep, whilst the deepest were found on sites that had never been burnt. As the depth of water table is proportional to infiltration capacity, runoff was found to be higher on recently burnt plots

To emphasise how sensitive land is to farming practice, a study by Colin *et al.* (2012) reported that changing weeding practices within 50% of a vineyard catchment, from chemical weeding which results in a soil crust to mechanical tilling that disturbs the upper soil layers, was predicted to result in a 40% reduction in peak discharge.

Soil conditions

Summary: Soil conditions can have a significant beneficial impact on the effectiveness of NFM measures to modify runoff and flood risk at the local scale, although the effects are complex

Bathurst *et al.* (2011a) suggest antecedent soil conditions have a major role in determining runoff from forest cover, which is supported by the results of Hümann *et al.* (2011) who report that site and soil characteristics have a greater influence on runoff generation than forest type. Similar findings were reported by Mueller *et al.* (2009), who found that the effects of agricultural intensification were more pronounced in wet years. The impact of soil conditions is also noted by García-Ruiz *et al.* (2008), who reported different hydrological responses from three different land covers. The response of a densely forested catchment was found to be generally unrelated to the volume or intensity of rainfall; instead, the key influencing factor was considered to be the depth of the water table, which in turn was related to antecedent rainfall. The effect of water table depth on the response of a shrubland and open forest catchment was evident but more limited, while a Badlands catchment responded to storm events year round due to the catchments very limited capacity to store water.

Extent of NFM measures

Summary: NFM measures need to be above a minimum size to achieve noticeable effects on runoff and flood risk at the local scale

In a study of catchments in South America, Bathurst *et al.* (2011a, 2011b) report that the impact of forest cover diminishes as the total rainfall produced during a storm event increases, and that forest cover must change by at least 20-30% to provoke a noticeable change in peak discharge. Similarly, a review by Calder *et al.* (2009) states that no significant effect on peak flows could be expected with less than 20% woodland planting. If such relatively high threshold levels, before the impact of land cover changes can be readily discerned, are applicable to other catchments, then reported cases of afforestation having no noticeable impact may have actually been due to the small scale of the changes implemented; for example, Fox *et al.*, (2012) report that land cover changes of less than 2% had no significant impact on runoff.

3.0 Catchment scale impacts on flood risk

Summary: There is currently no conclusive evidence that the impact of NFM measures can reduce flood risk at the catchment scale

While the preceding section illustrated that there is significant evidence that NFM measures can reduce local flood risk, there is currently little evidence to suggest that there are benefits in reducing either extreme flood events or events at large catchment scales. Some research indicates that local level impacts cannot reliably be upscaled to the catchment level; for example, recent catchment Source-Pathway-Receptor modelling indicates that differences in the spatial and temporal patterns of rainfall, allied to hydrodynamic dispersion within river networks, can lead to the attenuation of small scale impacts at catchment level (FRMRC, 2011).

Although the importance of catchment scale analysis is widely recognised (e.g. Landell-Mills & Porras, 2002; Andréassian, 2004; Beven *et al.*, 2008; EA, 2009; Gilvear *et al.*, 2012, Newson, 2012; Pattison & Lane, 2012; Wheater *et al.* 2012), there are currently only a few studies published which have assessed the impacts of NFM at these scales. For example, the move towards sustainable flood management and climate change adaptation means the number of river restoration projects in Scotland is growing, but Gilvear *et al.* (2012) note that the number of catchment scale projects remains limited. This lack of evidence may result in difficulties in securing funding for implementing NFM measures unless they can be incorporated into other objectives (Parrott *et al.*, 2009). Furthermore, Landell-Mills & Porras (2002) reported that “The weakest link in persuading downstream communities to pay for upstream forestry is the lack of reliable, site-specific hydrological data illustrating clear forest-water linkages.” However, despite this lack of evidence there is still a drive to incorporate NFM measures into catchment-scale flood risk management (Hess *et al.*, 2010).

Barriers to catchment scale data

Summary: Cost, time and complexity are the main barriers to more comprehensive catchment scale datasets

A number of factors appear to have contributed to the current lack of catchment scale data. Key amongst these are the cost implications of both establishing comprehensive baseline knowledge of a catchment's hydrology and hydrogeology, and monitoring hydrological conditions over the large temporal and spatial scales necessary to assess the impact of NFM measures at the catchment scale.

An additional major issue concerns the uniqueness of each catchment and storm event. On this subject, Pattison & Lane (2012) consider that, as identical land-management practices will have different impacts depending both on where they are implemented and the spatio-temporal characteristics of different rainfall/runoff events, "...the pursuit of generalisations between different land-management practices and flood risk may be a meaningless and unachievable aim**".**

In terms of model simulation, there are significant scaling issues when applied to catchment scale scenarios. Krause (2002) reports that the increasing heterogeneity of a catchment's environmental parameters, in conjunction with decreasing data accuracy and availability on the larger scales, is a major problem which limits the transfer or upscaling of small scale models to large catchments. Blöschl *et al.* (2007) consider that the process is complicated further as, in diverse hydrological situations, impacts "kick-in" at different scales. Mayor *et al.* (2011) note that the redistribution of runoff as it progresses through a catchment is scale and catchment dependent, and will impact on any results, suggesting that "...extrapolation of runoff values between scales or between catchments of different sizes is meaningless".

Catchment scale demonstration sites

Summary: There are a significant number of on-going and planned UK catchment scale demonstration sites

Although the Institute of Hydrology have run three long term demonstration sites focussed on the effects of commercial forest on hydrology (Institute of Hydrology: 1991, 1995, 1998), the barriers outlined herein have historically resulted in few other catchment scale hydrological monitoring studies. However, a number of completed, on-going and planned developments that have potential to provide valuable information are currently now in the early stages of either their development or dissemination, e.g. The Pontbren catchment study[1]; the Eden[2], Hampshire Avon[3] and Wensum[4] demonstration

[1] http://www.floodrisk.org.uk/
[2] http://www.edendtc.org.uk/
[3] http://www.avondtc.org.uk/
[4] http://www.wensumalliance.org.uk/

catchments; the Allan Water project[5]; the Eddleston Water[6], River Enrick[7], Tarland Burn[8] and Bowmont-Glen[9] projects; United Utilities SCaMP project[10].

4.0 Desynchronising flood peaks

The impact of NFM measures on downstream flood peaks depends on the relative phasing of various runoff sources within a catchment, which in turn depends on:

a) the time to peak of each runoff source;

b) the relative location of each runoff source; and,

c) the spatio-temporal variation in rainfall runoff processes.

Time to peak

Summary: NFM measures can impact on the time to peak of local flows and may therefore assist flood peak desynchronisation

The majority of the published studies that have investigated the impact of NFM measures on time to peak data have been based on computer modelling activities. Wheater et al (2012) report that a modelling study of a $4km^2$ sub-catchment at Pontbren (Wales) showed that full afforestation increased the time-to-peak by 30 minutes. However, the authors acknowledge the relatively large uncertainties present in this data and that, due to specific catchment characteristics, the results may not be generically applicable. Similarly, Thomas and Nisbet (2006) undertook a more accurate, and computationally demanding, combined 1D/2D modelling study of the River Cary sub-catchment of the River Parret. They reported that complete (133Ha) and partial (50Ha) forestation of the floodplain along a 2.2km reach would extend the flood peak travel time from its baseline 180 minutes to 320 and 210 minutes respectively, as well as increasing floodplain storage by 71% and 15% respectively.

An early modelling study by Gregory *et al.* (1985) reported that a system of debris dams along a 4km reach of a small watercourse within the New Forest delayed the typical flood wave travel time at high discharges (~58 minutes) by 10 minutes. The same study also identified that the delay was inversely proportional to discharge, with the impact of the dams being more significant at lower discharges. A more recent modelling study by Thomas and Nisbet (2012) reported that, for a 1-in-100 year flow, a system of 5 large woody debris dams within a 500m section of the River Fenni (Wales) could delay the typical time to peak within the main watercourse (~10 hours) by up to 15 minutes.

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[5] http://www.cress.stir.ac.uk/allanwater/
[6] http://www.tweedforum.org/projects/current-projects/eddleston
[7] http://www.gulup.org/
[8] http://www.macaulay.ac.uk/tarland/
[9] http://www.tweedforum.org/research/borderlands
[10] http://corporate.unitedutilities.com/scamp-index.aspx

An example of a relevant field based study is the Glendey sub-catchment of Glendevon in Central Scotland, which has been restored to wetland and includes a variety of different NFM measures, such as blocking drains planting trees, and installing large woody deflectors (WWF, 2007). In combination, these measures were found to delay the typical time to peak (~ 440 minutes) by 45 minutes, as well as reducing peak flows by 16%.

Location

Summary: Location of NFM measures within a catchment has a significant impact on their ability to assist peak desynchronisation

It is widely accepted that the location of a NFM measure within a catchment is key to the effectiveness of its performance (Warburton *et al.* 2012). For example, whilst Thomas & Nisbet (2006) report that restoration of floodplain woodlands will locally decrease flood peaks, they also indicate that a detailed analysis of the hydrographs of each tributary would be required to identify where the restoration of floodplain woodlands would exert the greatest benefit in terms of decreasing main flood peaks.

Another example of the importance of appropriate siting is demonstrated in a scoping study investigating the factors that would influence the implementation of NFM measures within the Allan Water catchment (Nutt & Perfect, 2011). This modelling study used a GIS based flow routing model to determine “time to outlet” values for each sub-catchment, hence allowing identification of the sub-catchments which contribute most to the flood hydrograph peak. Analysis of the results indicated that the flows from three specific sub-catchments (headwaters of the Muckle Burn, majority of the River Knaik and the upper Allan Water) have a significant contribution to the peak and trailing limb of the flood hydrograph at the catchment outlet. It was therefore suggested that delaying the progression of floodwater from these areas will assist in desynchronising the contributing sub-catchment flood peaks, with a net effect of reducing flood risk at the catchment outlet. However, the same analysis suggested that slowing of flood waters in the lower tributaries of the Allan Water would be likely to result in an increased coincidence of flood peaks, with a subsequent increase in flow rates downstream (Nutt & Perfect, 2011). The study also noted that planned moorland improvements to the Muckle Burn headwaters, designed to delay runoff from the sub-catchment, may actually serve to partially synchronise it with the hydrograph peak. In contrast, a similar planned moorland improvement to the Danny Burn was shown to help desynchronise the runoff from this sub-catchment with the rest of the Allan Water.

In terms of impact on flood risk, Richert *et al.* (2011) note that there is a particular need for action on sites with fast runoff components such as surface runoff, saturation overland flow and fast interflow. Therefore any proposed measures need to be adapted to the geomorphological and pedological characteristics of the area. For example, they suggest that the effects of forest cover on runoff would be limited in areas of shallow soils on steep slopes. However an increase in storage capacity which leads to a relevant delay and reduction of runoff can be reached when forest grows on deep soils.

Spatio-temporal variations in rainfall and runoff

Summary: The spatio-temporal variations in rainfall and runoff have a significant impact on the ability of NFM measures to assist flood peak desynchronisation

García-Ruiz *et al.* (2008) emphasise the spatial and temporal variations that occur in runoff throughout a catchment. A number of other studies report that, due to this spatio-temporal variation, NFM impacts are very site specific. For example, Ballard *et al.* (2011) and Holden *et al.* (2011) found that the effect of open ditch drainage of peatland appears to be dependent on local conditions, sometimes decreasing and sometimes increasing peak flows.

Pattison & Lane (2012) identify the importance of the location of NFM features with respect to the geography of a catchment, but they also consider that the effectiveness of the measures depend on where the feature is situated relative to the temporal evolution of any individual storm event, stating that "...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." Similar findings were reported by FRMRC (2011), where a marked variation in impact from storm to storm was found to be a result of differences in the spatial and temporal patterns of rainfall.

Specific desynchronisation data

Summary: There is no conclusive evidence that NFM features can be used to desynchronise flood peaks at the catchment scale.

Jacobs Engineering (2011) used model simulations of a 16km reach of the River Enrick river system to assess the effect of various NFM features on the attenuation of peak flows. The results show that when the time to peak for the lower catchment is increased through drain blocking, the tributary flows are slightly delayed. This delay in the tributary flows results in the upper catchment flow synchronising to a greater extent with the peak of flows from the lower catchment, resulting in a slight increase in the main channel flows in comparison with the base case. Similarly, the relative delay in main channel flows, representing the effect of riparian woodland, results in greater synchronisation of the hydrograph peaks, i.e. coincidence with the peak flow originating in the upper catchment. However, they note that a slightly different result may arise in a catchment with different characteristics and the wider applicability of these outcomes may merit further consideration.

Lane (2003) notes that both the flood peak magnitude and timing need to be considered when determining downstream flood risk, and a study by Pattison *et al.* (2008) on the Eden Catchment in Cumbria concluded that, although the primary controls on downstream flood risk are the magnitudes of the peak flows in the upstream contributing sub-catchments, the relative timing of the sub-catchment peak flows is a critical secondary factor. Interestingly, the timing of the sub-catchment peak flows within the Eden catchment seem to have significantly increased in importance in the last 30 years (i.e. 10% of downstream flood risk was attributed solely to sub-catchment timing interactions during the period 1977-1987, while the 1997-2007 analysis indicates a 23% contribution). The researchers have no satisfactory explanation for this increase, which again highlights the complex spatial and temporal hydrological process that can occur, even in seemingly stable natural environments.

In a study by Nisbet & Thomas (2008), a model was used to simulate the effect of planting 40 ha of floodplain woodland across a number of sites in the River Laver catchment (78 km^2). They reported that the increased resistance resulting from the presence of trees, undergrowth and woody debris caused a significant reduction in the velocity of flood flows (up to 2.8 m/s), which itself resulted in a significant delay in the timing of the flood peak (15 to 20 minutes between sites). The lag was greatest for the sites with the largest wooded area and, although the effect of the individual sites was not found to be additive, delaying the flood response in the River Laver desynchronised the peak flow from contributions from the River Skell. As a result of the desynchronisation, the arrival of the flood peak at the downstream extent of the Laver catchment (~17 hours) was delayed by 55 minutes, and also resulted in a 1-2% reduction in the design peak flows predicted in Ripon downstream of the confluence of the two rivers. The lag was greatest during the early part of the flood event, a consequence of the effectiveness of the woodland in holding back and spreading flows at shallow flood levels. For simulated floodplain woodland of 8 ha extent the delay to the flood peak reduced to 22 minutes. The authors note that "…a possible downside of de-synchronisation, however, is that by extending the flood hydrograph there is a risk of consecutive flood events contributing to higher flood peaks if they coincided with the delayed recession limb of the flood hydrograph".

Desynchronisation was also predicted in a simulation study by Odoni *et al.* (2010), where the installation of combined riparian woodland and woody debris dams was predicted to reduce the flows in the Pickering Beck, at Pickering, by 8-10%. The predicted reduction was a result of extending the hydrograph duration by slowing the headwater flows, whilst allowing the lower catchment flood waters to flow past the target site at the normal rate.

Desynchronisation is not only relevant to rural environments. Yang *et al.* (2011) found that watersheds with urban locations close to the outlet tend to produce lower peak flows, primarily because the urban-derived peaks occur earlier, hence desynchronising the urban response from the rest of the watershed. Therefore, any changes in runoff and peak flow timings resulting from NFM measures may have unforeseen impacts on urban planning and water management.

5.0 Conclusion

The majority of the NFM studies published to date have concentrated on small scale experimental catchments and measures as there are a number of advantages to the use of such sites. Most notably, they tend to be relatively homogeneous in terms of topography and lithology, and can therefore be considered representative of a certain environment. In addition, installation and maintenance of different types of NFM feature and measurement device is relatively straightforward, quick and cost effective. However, whilst many small scale studies report that NFM measures have an impact on local runoff generation, there is no general agreement regarding the magnitude, direction or consistency of the impact (i.e. the situation is dominated by uncertainty). In addition, although it is widely acknowledged that small scale experimental sites make a substantial contribution to increasing understanding of the impact of NFM measures on hydrological processes, the significance of results generated from these plots in terms of catchment scale processes is still unclear.

The phasing of peak flows from sub-catchments and tributaries with respect to main channel discharge is key to how local scale runoff changes are propagated to the catchment outlet. The effectiveness of NFM features in desynchronising flood peaks is highly location and rainfall event dependent. Specifically, it is influenced both by the runoff properties of the site (e.g. slope, land use, soil conductivity and saturation) and by the spatio-temporal sequencing of storm events which determine both when and where a catchment will respond to the event. These factors may be reduced or magnified by the combining of sub-catchment flows, such that the impact of any NFM feature upon downstream flood risk can change with distance downstream. Although current research, predominantly based on model simulations, indicates the potential for NFM measures to reduce flood risk through the desynchronisation of flood peaks from contributing sub-catchments there is as yet no reported field based evidence to support this. In addition there is a concern that simplistic application of NFM measures, without consideration of the knock on effects or the spatio-temporal nature of rainfall events, could actually lead to the synchronisation of flood peaks. Whilst the current lack of evidence and concerns does not imply that NFM measures cannot make a significant contribution towards flood risk reduction both at a local and catchment scale, it does highlight the need for continuing research in this area.

Given the current uncertainty, in both the local level impact of NFM features and the upscaling of these impacts to greater spatial and temporal scales, it clear that further longer term, catchment scale field studies are required in order to more accurately assess the true benefits of NFM features. Whilst such activities are costly, both in financial (initial and ongoing) and temporal terms, a series of catchment scale ‘demonstration projects’ are currently being developed within the UK to determine whether NFM features can help deliver flood risk management benefits.

CREW Facilitation Team

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