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Runoff attenuation features: a sustainable flood mitigation strategy in the Belford catchment, UK

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There is evidence to suggest that modern rural land-use management practices have led to increased runoff production at the farm scale. There are concerns that this may have contributed to downstream flooding of towns/villages, especially during intense local storm events. This paper presents an investigation into the potential attenuation of rural runoff through the application of soft-engineered structures upstream of flood-prone settlements, through a demonstration of ongoing initiatives in the Belford catchment, Northumberland (5.7 km^2). The soft-engineered features that have been considered in the study include storage ponds, barriers, bunds, and the planting of vegetation and the positioning of woody debris in the riparian zone. The Belford study has been active since November 2007 and is yielding an abundance of good-quality data, including several significant flood events, on how runoff propagates through the small rural catchment and causes flooding of the village, and how flood propagation can be attenuated using Runoff Attenuation Features (RAFs).

Key words: *flooding, land use management, runoff, sustainable mitigation, catchments, hydrological data*

Introduction

There are concerns that land-use change and management in rural areas and agricultural developments have contributed to recent flood events, though there is little evidence at the larger catchment scale (>10 km^2) (O'Connell *et al*. 2005). Modern tillage practices, including the removal of hedgerows to enlarge the size of fields, constructing under-drainage and ditching works, increased stocking densities and intense cultivation, alter the storage potential and connectivity of the landscape (O'Connell *et al*. 2007). Research investigating stream water quality in a study catchment in Devon, UK, found clear evidence of increased erosion rates since 1950 (Heathwaite and Burt 1991). The changes were thought to reflect post-1945 intensification of agriculture, which include the modern tillage practices. Heathwaite and Burt (1991) also suggested that reductions in water quality could be attributed to an increase in stocking density from less than four livestock per hectare between 1905 and 1950 to over fifteen livestock per hectare in 1965 (in their study catchments). Intensification of livestock production may increase the level of farm effluents, pesticides such as sheep-dipping chemicals as well as bacteria and protozoan contaminants, which in combination with increased overland flow due to soil compaction may increase the risk of water-quality degradation (Hooda *et al*. 2000). Investigations in the Netherlands have revealed areas of grassland have been increasingly replaced by row crops (such as maize and sugar beet), which are 15 to 20 times more susceptible to erosion than cereals (Van der Helm 1987). A particular issue is associated with changing the timing of tillage operations leading to 'muddy' floods (Boardman 1995), which are more damaging to properties and drainage systems due to the large volumes of particulate matter being deposited by the floodwater. These changes in land use reduce natural attenuation of water within the catchment (Boardman *et al*. 1994).

A study in central Belgium utilised retention ponds into which stream flow was diverted during flood events (Verstraeten and Poesen 1999). The study identified that sedimentation, occurring in the ponds, significantly reduced the storage capacity after only a few years. This highlights the need for management and maintenance of such features. In this region 'muddy' floods are extremely problematic to home owners. The storage of sediment had the benefits of reducing economic damage to flooded

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properties and reducing siltation in the drainage system. There is, thus, the need to target flood flow and associated water-quality elements, such as sediment and associated farm pollutants (see Barber and Quinn this issue).

A series of experimental investigations on Nafferton Farm, UK (294 ha) made some interesting conclusions on the extent of intervention required in a catchment to control flow and pollution. If a typical farm or small catchment can sacrifice 2–10 per cent of the landscape to runoff storage and mitigation features, then the properties of the runoff regime can be dramatically altered (Quinn *et al*. 2007). The mitigation features are typically placed in the corners of fields (to capture runoff and sediment) or connected to the stream network to filter stream flow and improve water quality.

There is the potential to regulate runoff through the temporary storage of flood water, disconnection and lengthening of flow pathways, and roughening the floodplain during flood events, using Runoff Attenuation Features (RAFs). RAFs are soft-engineered interventions designed increase the storage capacity of the catchment where, for example, modern tillage practices have removed the natural attenuation of water within the landscape. RAFs have the potential to be more desirable than traditional engineering solutions, such as a levee or floodwall, due to their low cost and the cumulative benefits to all downstream flood sites. A RAF near a stream, such as a storage pond, slows or stores a fixed volume of water flowing further downstream, whereas a levee defends areas within its reach. A network of RAFs can be introduced to defend a town or village from a flood of a certain return period and, if flood frequency and severity increases, additional RAFs can be added to the system to increase the amount of protection they provide.

Current government policy relating to flood risk management in rural areas recognises the potential of land use solutions such as the creation of wetlands and managed realignment of rivers (Defra 2005). Defra (2005) proposed that priority research should take place to establish the role rural land management techniques may play in managing flood risk at the catchment level. The European Floods Directive's (2007/60/EC) 'Flood Risk Management Plans' focus on 'the promotion of sustainable land use practices, improvement of water retention as well as the controlled flooding of certain areas in the case of a flood event'. The recent Flood and Water Management Act 2010 (UK) encourages maintaining or restoring natural processes wherever possible as a method of reducing flood risk, and permits the designation of natural features that can control this risk (Parliamentary Offices of Science and Technology 2011). These policies in combination with concerns about future climate change highlight the need for the delivery of sustainable solutions for flood management (Parrott *et al*. 2009).

This paper provides a review and evaluation of ongoing initiatives to utilise soft-engineering features to manage flood hazard in the Belford catchment, UK. The approach taken involves hydrological pathway management as part of a broader Catchment Systems Engineering (CSE) approach (Quinn *et al*. 2010). CSE is based on the principle that any catchment and its inhabitants should be empowered to sustainably control its own sources of hydrological connectivity, sedimentation and diffuse pollution in order to improve the overall water quantity and quality at its outlet. CSE relies on close stakeholder involvement, understanding regulations/policy and pursuing active uptake of the proposed catchment change plan (Wilkinson and Quinn 2010).

Study area

The Belford Burn catchment (5.7 km^2), Northumberland in North-East England (Figure 1), is predominantly rural with grazing in the western uplands and arable land in the east. The source of the Belford Burn is Bowden Crags (185 m AOD) from which it flows approximately 4.5 km before reaching the village of Belford. The river channel is greatly constricted by gardens, walls and residential structures within Belford village and the flashy flood response gives rise to properties and businesses being inundated (Wilkinson *et al*. 2010b).

The mean annual rainfall for Belford is 695 mm (Wilkinson *et al*. 2010b). The soil conditions throughout the catchment greatly influence the flashiness of the runoff regime. The Dunkeswick soil series, which are typically stagnogley soils with fine loamy topsoil and clayey subsurface horizons (Soil Survey of England and Wales 1984), cover the catchment study area and are prone to waterlogging.

The village of Belford has been inundated seven times in 7 years, which gives rise to the perception that flooding has increased. There have been alterations to the land management practices in the catchment and there have also been several unusual prolonged and intense rainfall events. It is however difficult to disentangle the role of land use, natural climatic variability and the potential impacts of climate change (Beven *et al*. 2008).

Flooding in Belford presents a risk to 31 properties, a caravan park and two major north–south transport links. The East Coast mainline railway was temporarily shut down owing to a flood event in July 1997. Other notable events in October 2002, January 2005 and July 2007 have caused flooding of properties, infrastructure and local businesses. Traditional flood defences were not applied to Belford owing to the high cost, lack of space for flood walls/embankments and failing to meet the criteria for Grant-in-Aid funding because of the small number of properties at risk (Wilkinson *et al*. 2010b). A

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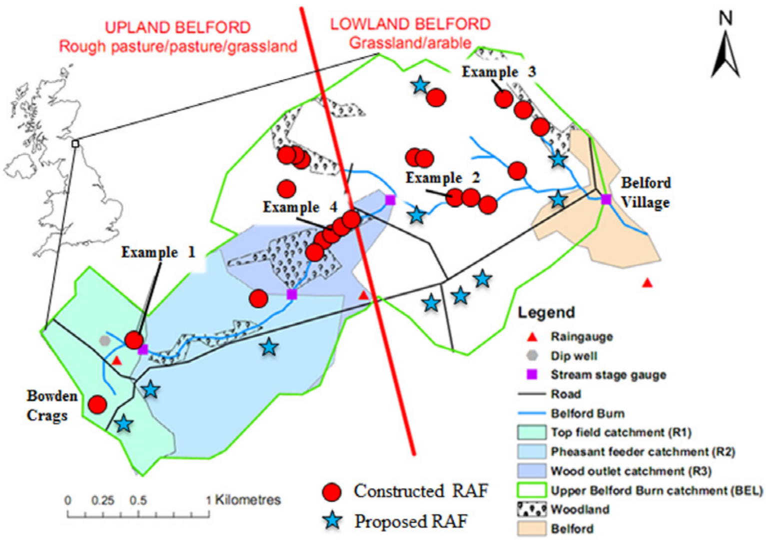

Figure 1 Map of Upper Belford Burn catchment showing locations of RAFs – constructed (circles) and proposed (stars) (as of June 2011, modified from Wilkinson *et al.* 2011)

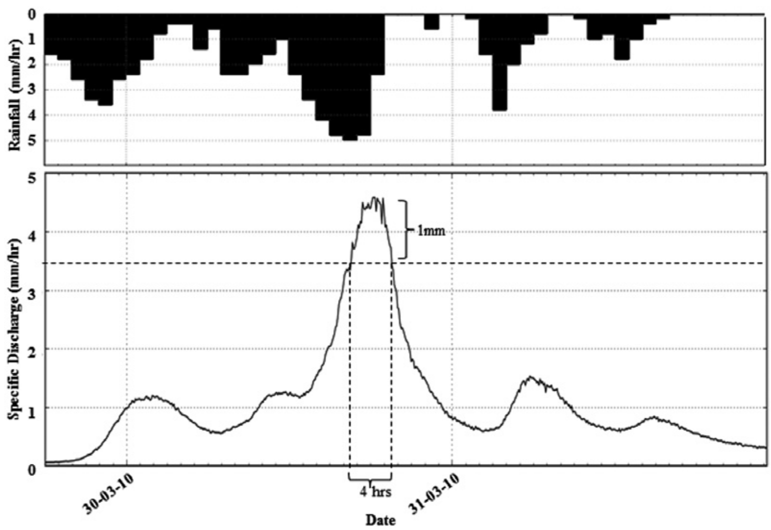

Figure 2 Storm event in March 2010 – showing the need to target key components of the flow

more cost-effective solution was sought through consultations with the Environment Agency, leading to the installation of RAFs within the catchment as part of a holistic catchment runoff management plan. There were, however, a small number of minor flood defence works that took place in the village, such as widening of the channel on a bend and making improvements to the road bridge in the village.

This study uses data recorded during storm events to help identify the possible quantity of storage required within the catchment. Figure 2 shows an example storm hydrograph (the largest on record in the study) measured at Belford village. Assume, for example, the stream begins to flood the village at a magnitude above 3.5 mm/hour, which is based on the smallest magnitude storm event to cause flooding to Belford. For the scenario above, this means 1 mm of rainfall would need storing over a 4-hour period (or 4 mm). This equates to, approximately 20 000 m^3 of storage for a catchment the size of Belford. Importantly, this storage must be effective during the peak flow period. If the storage has been utilised prior to the arrival of the flood peak, the benefits may actually be much reduced. The

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figures relating to potential storage within the Belford catchment are the motivation for this study.

Runoff Attenuation Features (RAFs) in the Belford Burn catchment: progress so far

RAFs, which intercept runoff and increase floodplain/channel interactions during high runoff periods, are ideally positioned in areas of high surface connectivity or areas where the river and floodplain are able to interact. The location of RAFs is generally based on topographic analysis coupled with field surveys to ensure no other factors (e.g. land-drains, ditches or geological conditions) affect the capture of surface runoff. Since the construction began, in August 2008, the project has been steadily expanding and now contains over 20 RAFs, with more proposed and awaiting approval/construction (see Figure 1). Here, a selection of RAFs will be introduced to demonstrate the various design methods used and the outcomes achieved.

Permeable timber barrier

The first RAF (Figure 1; Example 1) constructed was a pilot pond to demonstrate the concept to stakeholders and regulators (Wilkinson *et al*. 2010b). This RAF is located in the headwaters of the catchment and is capable of storing approximately 800 m^3 of floodwater, both from the stream and from surface runoff generated in the small catchment area leading up to the feature (Plate 1, left panel). The RAF diverts peak flow from the stream using a control structure, in the form of a V-notch weir, and stores it during a storm event. During high magnitude storm events the flow diverted into the RAF, from the stream, can be as much as 30 per cent. The pilot pond was constructed by driving timber vertically into the ground, to avoid the necessity to make a pond using the shallow soils of the upland catchment.

Water slowly drains through the timber structure of the RAF (see Plate 1, right panel), allowing it to continue moving through the catchment. One design criteria was that the feature should empty before further extreme rainfall. Analysis of event data indicates that the structure will fill over 8–10 hours (depending on the severity of the storm) and, once the flood wave has passed, it subsequently drains over a 5–6 hour period. This means for the majority of the time the RAF (and others like it) is empty, which is of huge benefit to the landowner as there is no loss of functionality of the area. Capturing data during storm events is critical for presenting the evidence of RAFs to stakeholders and extremely useful for suggesting improvements to their functioning. Wilkinson *et al*. (2010a) analysed data for the pilot pond functioning during a double-peaked storm event in September 2008, which indicated that the drainage rate was insufficent. Modifications were subsquently made by widening selected panels of the timber barrier.

Offline diversion ponds

Offline diversion ponds function by diverting flow from the main channel during peak-flow events. An inlet structure situated on the riverbank, approximately 1-m wide, controls the filling of the pond. RAF-1 (Figure 1; Example 2) has a maximum capacity of 330 m^3. This type of RAF, located adjacent to a river, removes high flow through filling when the water level in the stream reaches a certain height. The RAF therefore has the potential to both reduce

Plate 1 RAF (Example 1) – Full of water following a storm event in September 2008 (left: from Wilkinson *et al*. 2010b; right: demonstrating permeability)

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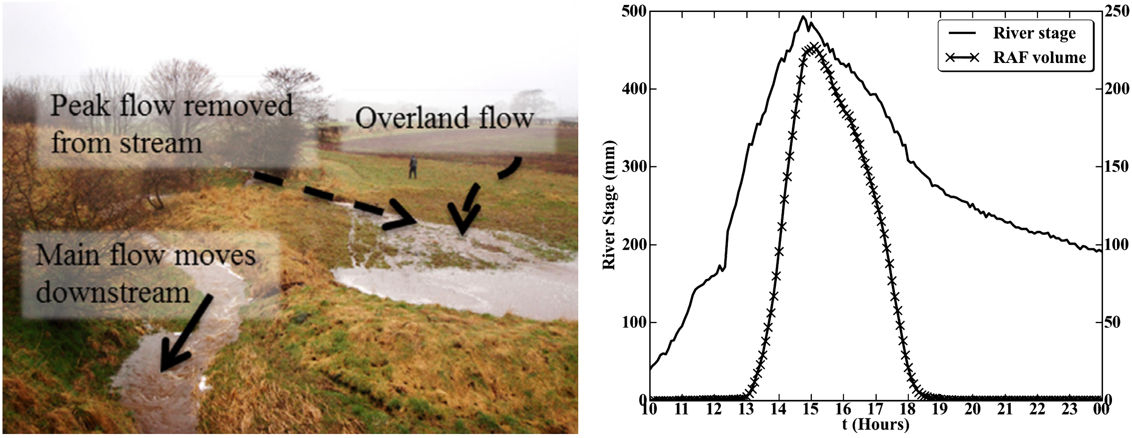

Figure 3 **RAF (Example 2) during storm event. RAF begins to fill when inlet (set at 300 mm) is overtopped (see graph on right)**

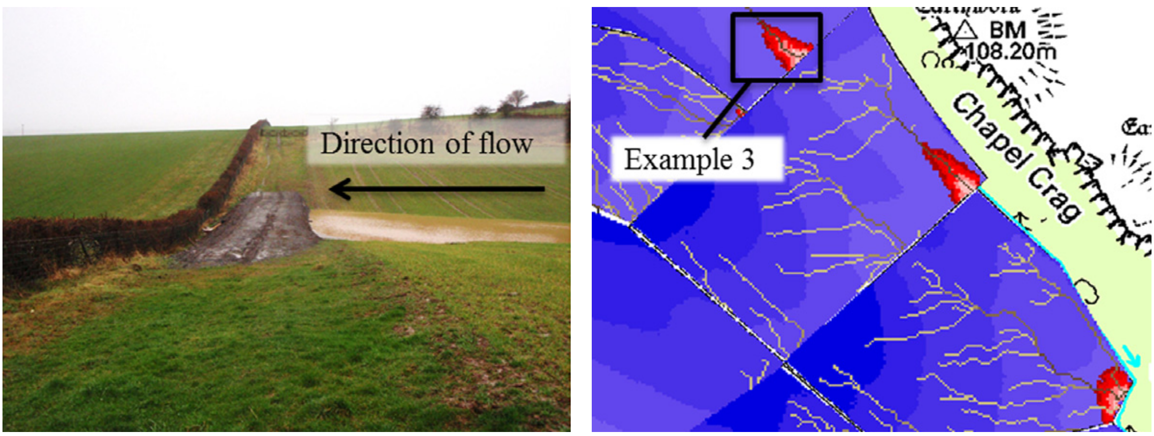

Figure 4 **RAF (Example 3) during a storm event (left). The GIS software identifying the location of the RAF (right: from Wilkinson and Quinn 2010)**

flood peak and increase the lag-time of the flood hydrograph at that point in the river (Wilkinson *et al.* 2010b). This RAF was constructed by scraping the soil from the centre of the pond and using that soil to form a bund around its perimeter.

The functioning of RAF-1 during a storm event shows the relationship between the water level in the stream and the volume of water stored in the RAF (Figure 3, right panel). The graph also indicates the inlet height of the RAF (300 mm). When the water level in the stream rises above 300 mm, the RAF begins to fill. The results presented in the graph indicate that the RAF takes just over 3 hours to completely drain.

Overland flow disconnection pond

An overland flow disconnection pond is purely for the interception and storage of overland flow. The site of this RAF (Figure 1; Example 3) was found to contain a dominant overland flow-pathway propagating through it. A geographic information system (GIS) tool, using terrain analysis and Light Direction And Ranging (LiDAR) data, was used to identify an appropriate location for this feature (see Figure 4) (Wilkinson and Quinn 2010). The GIS tool has also been used to communicate appropriate site selection to the landowners and provided an accurate estimate of the potential storage, which is 500 m^3. The GIS tool is extremely useful in communicating and gaining support for features from the farmer and local regulators.

The RAF was constructed using locally sourced soil and boulders to form a bund over the natural gulley in the field. The bund itself also provides the land owner with a track to drive vehicles and machinery over the waterlogged zones of the field during wetter periods. Features like Example 3 are ideal for disconnecting fast flow-pathways during the

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Figure 5 Large woody debris installed in Belford Burn

peak of storm runoff, which relieves the river network throughout the catchment during a storm event.

Large woody debris

Large woody debris (LWD) (Figure 1; Example 4) has been installed in the riparian area of the catchment (see Figure 5). The construction of LWD came with an opportunistic decision to have sycamore trees removed and replaced with less intrusive suitable tree species. The LWD and associated floodplain barriers were located at six locations (15 m apart) over the reach of the stream within a wooded riparian zone (Wilkinson *et al*. 2010a). The presence of LWD in riparian zones has multiple benefits for sediment transport, nutrient cycling and other geomorphologic processes and form microenvironments for terrestrial and aquatic organisms during extremes in weather (Dudley *et al*. 1998).

During states of high discharge, LWD forces the water level in proximity to them to rise and spill onto the flood plain, where further woody debris is installed to increase friction (see Figure 5, right panel). This process slows the propagation of the flood peak by creating a far more tortuous route downstream. The hydraulic resistance of LWD varies as a function of flow depth (Gippel 1995). The LWD in the Belford catchment have shown evidence of having a great effect on flow resistance, which can possibly be explained by the size of the debris in comparison to the flow depth. It has been shown by Beven *et al*. (1979) that when debris is greater in size than the flow depth, the roughness coefficient is abnormally high (Manning's $n > 1$). As the flow depth increases and the LWD becomes submerged, its effect on resisting the flow diminishes.

Discussion

Analyses and modelling techniques, employed as part of this study, are revealing how RAFs are altering flood flow within the catchment. The RAFs are currently being monitored and modelled using storm events of varying magnitude and types. The data obtained from the intensive monitoring network within the catchment have yielded a great amount of information as to how RAFs function during storms. The RAF network installed in the upper Belford Burn catchment carries an estimated storage capacity of 10 000 m^3. In terms of total storage, this number is still some way from the target 20 000 m^3; however, the features do not operate on physical storage alone. Transient storage, through altering flow paths and increasing floodplain roughness, creates attenuation effects. The ability to quantify the temporary storage effects and the impact of overland flow interception is still ongoing. The decision about how many RAFs are required, and where and how to build them, is being optimised through the Belford study. Consideration will also be required of the level of protection that can be provided with respect to flood magnitude. For example, if the aim is to alleviate high return period events, the offline diversion ponds should activate at a high river stage to ensure that they have not filled prior to the arrival of the main flood wave.

Conclusions and recommendations

The upper Belford Burn catchment has been inundated by several flood events over recent years. The village of Belford failed to receive Grant-in-Aid funding for traditional flood defences because of the low number of properties at risk. The Environment Agency's local flood levy team funded research into local on-farm storage features (RAFs). More than 20 of these features have been installed throughout the catchment, several of which have been described in this paper. The hypothesis discussed in the Introduction identified that there is a certain quantity of excess flood water that must be

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targeted and mitigated during a storm event. In realistic terms, the magnitude of the flood has a huge impact on the degree of intervention required to alleviate downstream flooding. The desired impact of RAFs should be determined at an early stage in a project, so that it becomes possible to identify what magnitude of storm they are being designed to attenuate. To aid this theory, a toolkit of simple graphical models is being developed to demonstrate the potential impact of RAFs on downstream discharge. Opportunities to fund and construct multiple functional RAFs across a landscape may be more attractive if water quality and ecological factors benefits are also provided. The possibility of increased flood frequency, as a result of climate change, is a driver for the development of future flood management techniques. Flood-proofing a catchment can potentially be achieved by installing a network of RAFs and, if flood frequency and severity increases, more RAFs can be added to the system.

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