

Potential Use of Runoff Attenuation Features in Small Rural Catchments for Flood Mitigation



BY

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Executive Summary

Following a number of recent severe flood events across the North East of England, the Environment Agency (EA) have been working with Newcastle University (NU) to develop a number of small scale, low cost soft engineered flood reduction schemes. These schemes are designed to store/attenuate rapid runoff in small rural catchments (<10km²) during flood events.

Newcastle worked in partnership with the EA to deliver a catchment based flood solution for the village of Belford. This has involved the design and implementation of a network of soft engineered Runoff Attenuation Features (RAFs) upstream of Belford, intensive field monitoring and detailed hydrological analyses.

Royal Haskoning (RH) were independently commissioned by the EA to perform hydraulic modelling studies of Powburn and Hepscott to establish whether sites at risk of flooding have benefitted from recent works. Newcastle also instrumented these catchments for 2 years, but unfortunately no significant events were recorded at these sites during this study period.

Together Newcastle and Royal Haskoning have assessed the impact of the Belford approach to managing flood hazard in small rapidly responding catchments. To summarize:-

- Over the last 4 years Newcastle and the EA have developed a novel method for flood mitigation at Belford.
- A network of 30 RAFs has been implemented, with a total construction cost of £70-100K.
- Newcastle used innovative data analyses and models to create the evidence base to underpin this and future work.
- It has been demonstrated that reductions in peak flows can be achieved through storage/attenuation management.
- For a hypothetical pond network providing 19,250 m³ of storage, the peak flow reduction is estimated to be between 15-30% for both observed events and FEH design storm events.
- As a result of the Belford study, we are confident that it is possible to implement a catchment based solution for reducing flood hazard using a network of soft engineered features.
- The approach may also prove to be an effective way to manage catchments to achieve multiple environmental objectives.

Acknowledgements

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Annex

1 Introduction

“Sandbags and sympathy are not enough”

“Belford finds itself under water and not for the first time”.

The above quotes from residents of Belford were reported in the local newspaper, the Northumbrian Gazette, in 2007. In response to the local community’s demand for action, Newcastle University and the EA implemented a catchment scale flood management scheme using a Natural Flood Management (NFM) approach. The response of the local community to this project has been positive.

“Pioneering ponds save Belford from flooding” 2008 Berwick Advertiser

Phil Welton (Regional Flood Defence Manager for the EA) stated in an official EA video (<http://research.ncl.ac.uk/proactive/belford/videos/>):

“For communities such as Belford that cannot receive traditional defences, this sort of approach gives real solutions, real benefits and at a fraction of the cost”

Whilst this perception is welcomed, empirical evidence is needed to demonstrate that these statements are valid.

During the life of the Belford project the uptake of the NFM approach in Northumberland has been quite rapid.

“Successful Belford 'leaky ponds' scheme extended to Powburn” 2010 Berwick advertiser

An NFM approach has been used in the catchments upstream of the flood prone villages of Powburn and Hepscott, which are assessed in this study. Similar approaches have also been implemented in Great Ayton, Netherton, Dyke Head and the Bowmont Glen.

The purpose of this report is to evaluate the performance of the interventions deployed in Belford, to quantify how well the scheme has worked and provide guidance regarding the circumstances in which a similar approach could be used. Given that many organisations are advocating a NFM approach, and schemes are currently being rolled-out, this report is timely in providing support to policy makers, catchment planners and practitioners.

1.1 Background

Following a number of recent severe flood events across the North East of England, the Environment Agency (EA) have been working with the School of Civil Engineering and Geosciences, Newcastle University (NU), to develop a number of small scale, low cost soft engineered flood mitigation schemes. These schemes are designed to attenuate/store runoff within small rural catchments (<10km²) during flood events. Rural settlements typically fail to receive grant-in-aid funding for structural flood defences due to the low benefit-cost ratios resulting from the low number of properties at risk. For example, Halcrow Group Consultants (Halcrow, 2007) recommended the construction of a flood storage reservoir to capture a 1:50 year flood event in Belford at an estimated cost of £2.59 million, providing protection to approximately 35 properties.

The EA are exploring potentially more cost effective catchment based approaches to solve rural flooding issues, including the use of the Natural Flood Management (NFM) approach.

NFM is being widely promoted as a viable alternative to traditional flood management. In a recent Parliamentary Review (POST, 2011), a range of NFM approaches were classified based on the location of likely deployment and how the strategy may be distributed on the ground (Figure 1-1). In this classification the RAF approach lies in the top left quadrant, being a **spatially diffuse** approach that works close to the **source** of the runoff generation.

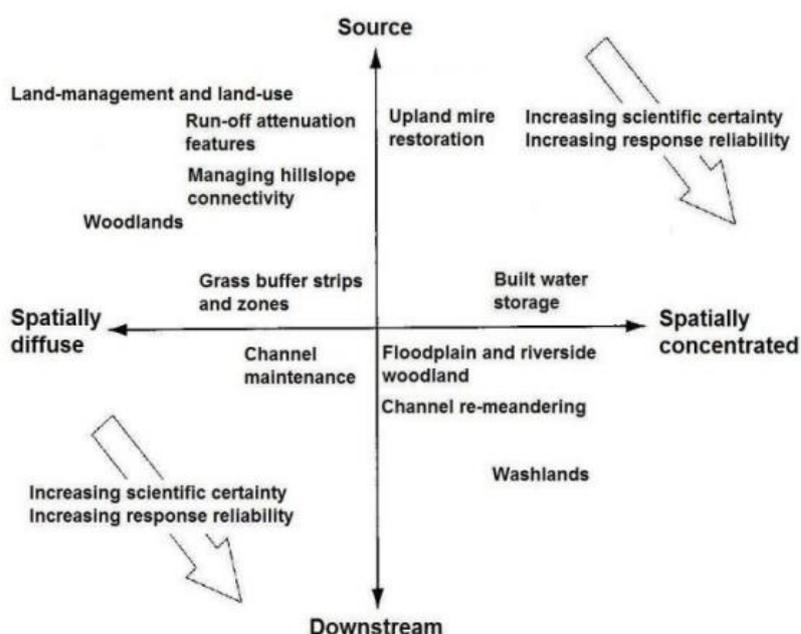


Figure 1-1 A Catchment-scale Classification of NFM Strategies (POST 2012)

To evaluate the potential of RAF schemes in small rural catchments, Newcastle University have collected 5 years of rainfall and stage data from the Belford catchment, and 2 years of data from both the Powburn and Hepscoth catchments. Newcastle was commissioned to construct a network of Runoff Attenuation Features (RAFs) in Belford and perform hydrological analyses of the impacts of the schemes on flood hazard. (Additional information on Belford is available at: <http://research.ncl.ac.uk/proactive/belford/>).

Royal Haskoning (RH) were independently commissioned by the Environment Agency to perform hydraulic modelling studies of Powburn and Hepscoth to establish whether sites at risk of flooding have benefitted from recent works. This builds on similar previous work performed for Northumbria County Council. Newcastle provided discharge data for use in these analyses.

1.2 Report Objectives

This report encapsulates the current understanding of the impacts of the soft engineered solutions on flood hazard in downstream settlements within the study catchments (Belford, Powburn and Hepscoth), based on analyses of observed data and hydrologic/hydraulic modelling. The specific objectives of this report are;

1. To provide guidance on the construction of soft engineered features;

2. To provide an assessment of the local functioning of the installed features during recent flood events;
3. To upscale findings using hydrologic and hydraulic modelling for the assessment of the downstream impacts of interventions in the three study catchments.

The approach taken to aid understanding of how features impact on downstream flood hazard has been to combine hydrologic analyses of the functioning of individual features and hydrologic/hydraulic modelling studies. The hydrologic analyses are classified as local scale interpretations, as they aim to establish how a given feature functioned with regard to capturing local river flow and local runoff. Additionally, these analyses are classified as providing direct evidence as they are based on observational records. The outcomes of these assessments contribute to objectives (1) and (2).

To contribute to objective (3), two modelling approaches have been taken to upscale the data and local scale interpretations for the assessment of catchment scale impacts. Firstly, hydrologic models have been created to both reproduce the observed responses of the features and then to extrapolate the findings to assess impacts of hypothetical networks of features. These analyses provide some guidance on the amount of storage/attenuation that is required to reduce flood risk, using data from a number of recent storms and design storms. This work has focused on the Belford catchment as several flood level events were observed. Secondly, hydraulic modelling has been used to assess the impact of the recent flood mitigation networks that have been installed in the Powburn and the Hepscoth catchments.

The analyses detailed in this report reflect the evolution of the projects. Belford has a more intensive and longer running instrumentation programme and hence many of the hydrologic analyses were performed for this catchment. Based on preliminary findings and interpretations at Belford and other Natural Flood Management schemes, features were installed in the Powburn and Hepscoth catchments by the EA. Hydraulic studies were commissioned to assess impacts at these sites.

1.3 Scope and Limitations

Interesting findings have been produced in the course of this project. However, it is necessary to state the limitations of the study.

1. Detection: It would be expected that the interventions would alter the observed downstream hydrograph shape. As the pre- and post-change records are short, it is not appropriate to use statistical analyses for the detection of changes in stream response. Also, the problem of detection is confounded by strong natural variability in climate (O'Connell et al., 2005).
2. Change in flood hazard: This issue is related to (1). Communities often wish to know the level of protection that a flood alleviation scheme provides. Ideally, this information would be derived from the change to the flood frequency curve (FFC). Despite the number of flood events that have occurred within the monitoring period (specifically at Belford), it is not possible to quantify the impacts of features on the FFC.
3. Extreme events: No major flood events were recorded at Hepscoth and Powburn during the study period. A lack of observational evidence of how the hydrological-hydraulic system,

including the installed features, operates in extreme conditions limits the conclusions that can be drawn for these two catchments.

4. Spatial scale: The findings presented herein cannot be extrapolated to the large catchment scale (approx. >10 km²). This is because the role of the river network, including expansive floodplain storage, in propagating impacts downstream has not been considered in detail.

Such shortcomings are not unique to this project; engineering assessments typically experience such difficulties.

2 Rationale for the Runoff Attenuation Feature Approach

“Why does Belford flood?”

Before commencing to describe the catchments and programmes of interventions in detail, it is informative to provide a rationale for the approach taken. In Figure 2-1 the hydrograph and rainfall for a large winter event is shown for Belford. The discharge is expressed as flow per unit area to allow a direct comparison against the rainfall. The signature of the rainfall is clearly present in the hydrograph shape, indicating a rapid response. During the early part of the storm the rainfall intensity approaches 4mm/hr, with the discharge 1mm/hr, indicating significant catchment storage. This contrasts with the response at the time of the main peak when discharge (4.5mm/hr) is marginally lower than rainfall (5mm/hr), indicating that storage has been depleted and overland flow is generated (which has been verified from walkover surveys during large events, Figure 2-2).

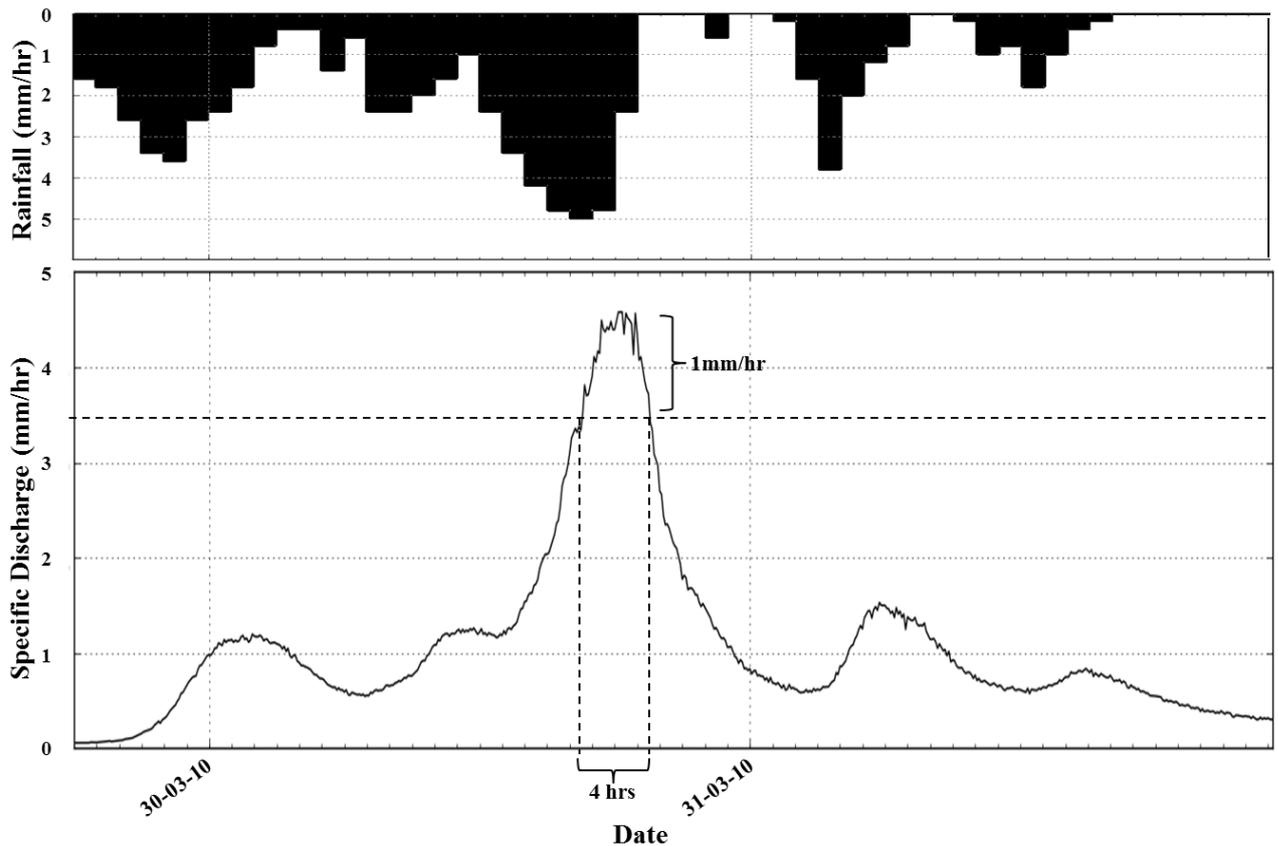


Figure 2-1 Observed storm hydrograph at Belford, March 2010

The horizontal dashed line in Figure 2-1 corresponds to the rate of discharge at which historic flooding has occurred in Belford. The volume of runoff above this line is 20,000 m³ over the duration of 4 hours. This simple analysis has been performed to provide a rough estimate to the volume of flow that would need to be managed to reduce flood hazard in the downstream settlement of Belford for this event. In interpreting such an analysis, a number of cautionary notes are required,

- The amount of flood management required will depend on the magnitude of the flood peak and the duration above the desired level of protection.
- The flood management interventions need to be active (storing and attenuating) at the time of the arrival of the flood peak.
- Attenuation effects (e.g. due to large woody debris) need to be carefully considered; attenuation and storage processes work together.

To return to the simple hydrologic analysis; during extreme events the drainage network expands with ephemeral flow pathways generated by overland flow linking fields and hillslopes to the ditch and stream network. The RAF approach advocates targeting this expanded drainage network, through the installation of features that attenuate and store runoff.



Figure 2-2 Overland flow generated during an intense storm (photograph taken at 12:30pm, March 2010)

Box 2

- Belford and similar rapid response catchments are susceptible to flooding from short duration intense periods of rainfall during multiday events.

3 Runoff Attenuation Features

“What is a Runoff Attenuation Feature?”

3.1 Runoff Attenuation Features: Definition and design philosophy

A Runoff Attenuation Feature is defined as a *man-made landscape intervention that intercepts and attenuates a hydrological flow pathway to provide multiple benefits, including flood management and improving water quality*. Simply, the design philosophy is to create features that ‘slow, store and filter’ runoff in the rural landscape. Key design attributes of RAFs are:

- they are easily accommodated in the landscape;
- they do not significantly impact on farming;
- they are typically small in size or located within a ditch or small stream channel;
- they are designed to be an extension of the farming and land drainage scheme drainage regime (i.e. they must not be viewed solely as flood engineering projects);

The RAF approach advocates the use of many features located throughout the landscape, with the benefits accrued by the network of features rather than one large scale / dominant intervention. Also, the approach does not seek to replace more traditional flood management options, but rather to add to the number of potential options available to flood managers.

3.2 Runoff Attenuation Features: Types of Interventions

“How do you build a RAF?”

Annex A provides summary details of the types of features that may be considered in delivering a RAF-based flood mitigation scheme, including advice on construction, maintenance and impact potential at the local scale. This information is summarised here.

The RAFs installed in Belford can be broadly classified in five types:

1. **Overland flow interception:** Involves creation of a bund (soil, wood or stone barrier) across a flow path to create storage (Figure 3-1). These features are designed to drain slowly; the barrier may be ‘leaky’, have an outlet drainage pipe installed, or often incorporate both of these options.
2. **Online ditch barriers:** Barriers constructed from natural materials are located in drainage ditches and streams to cause backwater effects (Figure 3-2). Often widening drainage ditches is inexpensive and additionally creates an effective sediment trap and new ecological habitats.
3. **Large wood debris:** Logs and branches are situated across the stream, or interlaced in ditches, to increase hydraulic roughness (Figure 3-3).
4. **Offline ponds:** Water is diverted from the stream network into a pond structure creating temporary storage (Figure 3-4). The pond is typically drained by an outflow structure in the form of a plastic pipe which is constructed to allow the feature to drain in 4-24 hours.
5. **Other features (e.g. riparian zone management):** Rather than strictly adhering to the design criterion specified for each type of feature, a more opportunistic and ambitious structure may be proposed based on local knowledge.

The above features are further classified as 'online' if they are located in the drainage network or intercept overflow (types 1, 2 and 3), else 'offline' (type 4). An online feature should not be used where the upstream contributing area to the feature exceeds $\sim 1 \text{ km}^2$; at larger scales stream energy may result in scour and failure. Processes below this scale are broadly classified as the hillslope scale with drainage ditches classified as non-main river. However, consultation for land drainage consent should always be advised when working in channels.

In terms of performance, no one feature type has been demonstrated to dominate and hence a mixture of types should be incorporated into a RAF-based flood mitigation solution. Often a combination of RAFs works well together, for example, an online structure can backup flow and divert peak flow to an offline feature.



Figure 3-1 Overland flow interception

Overland flow interception	Target: Temporary overland flow
Positioning	Gullies and ephemeral watercourses, including tracks and pathways, and low points in larger fields. Potential sites can be identified using GIS based terrain analysis e.g. FARM PLOT (Wilkinson and Quinn, 2010).
Construction	Usually soil is used to form a bund, preferably sourced on-farm to avoid importing soil. However, wood and stones can also be used. A controlled spillway must be designed into the feature, with non-erosive material used as armouring to reduce the risk of scour. A bund also requires an outlet pipe. A diameter of approx. 30cm is suggested for a pond capacity of around 500m ³ , but this should be checked with the construction contractor.
Typical storage capacity	~200-2000m ³ (Note that the Reservoirs Act, amended by the Flood and Water Management Act 2010, covers man-made water bodies in excess of 10,000m ³ .)
Maintenance	May be prone to siltation, particularly in arable areas where sediment removal may be required on an annual basis. However, sedimentation may have positive impacts on water quality and can be considered a benefit.
Cost per feature	Wood barriers can be expensive (depending on wood source and labour costs/skills), e.g. 150m for ~£5000, while soil bunds are inexpensive around £750 for a ~50m long bund, 1 metre high (if soil is sourced on site).
Side effects	Care should be taken to prevent seasonal waterlogging on productive land, this requires that the feature should be designed to drain down quickly (typically 4-24 hours).
Comments	Left panel: feature optimised with the removal one plank to increase speed of outflow, thus reducing water logging. Right panel: the feature was constructed using soil and stone to create an access track.
Lifespan	The soil and stone features should last many years if properly maintained, but will need to be replaced at some stage. Visual inspection is needed particularly after large events. Hardwood wood barriers should last many years whilst those constructed of locally sourced pine may only last a few years. Frequent inspection is required.
Design guidelines	Do not be too ambitious with height. A maximum height of 1m is suggested to prevent the need for high levels of engineering.



Figure 3-2 Online ditch barriers

Online ditch barriers	Target: Peak flow in small ditches and channels
Positioning	Any incised ditch or small channel, where the banks afford good support for a barrier.
Construction	Left panel: wood beams. Right panel: living willow barrier planted into the banks.
Typical storage capacity	10-1000m ³ , if used in series.
Maintenance	Left panel: Flow goes under the feature and therefore it may be prone to scour. Right panel: The barrier is designed to be leaky, but accumulation of trash during storms may result in sedimentation; this design feature may be deliberate to deliver water quality benefits.
Cost per feature	Wood can cost up to £1K per feature, willow is inexpensive but requires management.
Side effects	Scouring or deposition is possible.
Comments	Always check with EA/SEPA regarding land drainage consent.
Lifespan	The feature should last many years but will need to be replaced at some stage, regular post-flood inspection needed. Willow barriers require coppicing every 2 years.
Design guidelines	It is important that the features are securely keyed into the bank and can withstand being overtopped. Flow should stay in the ditch and should not flood the surrounding area.



Figure 3-3 Large woody debris features

Large Woody Debris	Target: Peak flow in small ditches and channels
Positioning	Large tree trunks spanning the width of the ditch, 30-40 cm above the typical pre-storm flow depth. Choose location where there is potential for out of bank storage.
Construction	Tree trunks are usually securely pinned in position on the bank and are orientated to cross over each other to aid stability. Roughen the riparian zone/ floodplain with trees and spare brush. See Wilkinson (2010a) for more details on woody debris management.
Storage capacity	Difficult to quantify owing to leaky design. Features attenuate rather than store and are often constructed in series.
Maintenance	Some small scour is allowed after construction resulting in settlement of the trunks. Small amount of movement expected in flood conditions, must downstream movement must be prevented. Inspection is recommended after large events.
Cost per feature	Felling and positioning costs are £100-1000 per feature.
Side effects	Scouring is possible but should be localised. Can be blocked by trash, however it may be preferable to leave the feature as a 'beaver dam' for ecological reasons as it still works as a RAF.
Comments	Right panel: brush from felling is placed on the floodplain. Also trees (holly and hazel) are planted on the floodplain to increase roughness.
Lifespan	Limited lifespan of a few years to 10 years, however. However, frequent inspection and vegetation management may be needed.
Design guidelines	It is important that the features are securely held in position and can withstand being overtopped. Permission to fell trees (sycamore in this case) must be granted, with the trees replaced with indigenous species (e.g. oak). Low growing species are preferable to increase riparian zone roughness (e.g. holly and hazel).



Figure 3-4 Offline pond

Offline ponds	Target: Peak flow in small channels, plus local overland flow pathways
Positioning	Riparian zones, in a buffer strip or sited in the corner of fields
Construction	Draw off channel (left panel) with an inlet armoured with coarse material to prevent scour, soil bund at front of feature (right panel) with a suitable drainage pipe. Wood can also be used (see overland flow interception).
Storage capacity	300-800m ³ . Some opportunistic sites may allow for more storage (200-4000m ³ , but the volume should not exceed the 10000m ³ capacity limit covered by the Reservoir Act)
Maintenance	Left panel: check for scouring of inlet feature. The soil barrier may erode but should stabilise after grass has established. Sediment may accumulate to the level of the pipe and may need removal.
Cost per feature	£5K each but cost can be greatly reduced if several are constructed in close proximity.
Side effects	May be some local water logging and loss of crop production
Comments	It is recommended that the maximum bund height should not exceed 1m and that grass cover is established as quickly as possible. There are additional habitat benefits associated with the feature.
Lifespan	Lifespan is estimated at 10-20 years, but inspection is needed. Grass/weeds should be cut at least once a year.
Design guidelines	Choose an optimum location with the farmer. Permission for draw off channel construction is needed. A skilled digger driver will compact the bund and thus it should not erode. Drainage pipe is usual quite large (roughly 30 cm for a 500m ³ pond) to allow the feature to empty in 8-10 hours. Make sure to design a spillway, this can be engineered with rocks or may use the natural field landscape towards the edge of the bund.

As previously stated, there may be an element of opportunistic choice in the location, the design and the materials used for construction of a RAF. Figure 3-5 shows a ditch within a large flat field that was prone to inundation and located in close proximity to the main stream. A soil bund was installed, providing 3000m³ of storage. Given the size of the pond, a sluice gate was constructed to control drainage and to release flow after a storm event. On occasion it is worth constructing a larger RAF and using a more traditional engineering approach if the potential benefits clearly allow such a feature to be built. However, care must be taken with larger features, particularly with consideration to future management and maintenance.



Figure 3-5 RAF construction: opportunistic locations, a large scale offline pond with sluice gate.

Figure 3-6 shows an online barrier in the Hepscott catchment that is set in a channel which is prone to a high flow and energy regime (upstream catchment area 2.1 km²). The barrier is quite high with ~3m of head being generated during extreme events. This driving head caused serious scour under the feature resulting in eventual failure. The material used is also unnatural in appearance and it is proposed that less aesthetic features be avoided in future.



Figure 3-6 An online plastic barrier in Hepscott that failed during a recent flood event

The EA Development and Control team prefers channels not to be blocked as this may result in detrimental impacts on habitat. Where a 2 km² upstream catchment area threshold is crossed, it is recommended that a draw off channel and swale is constructed upstream of any offline mitigation feature. In a recent project a stone armoured draw off feature was constructed at Dyke Head on the Upper River Wansbeck, Figure 3-7.



Figure 3-7 Armoured draw off channel at Dyke Head on the River Wansbeck.

3.3 Design of a RAF Network

“Where should a RAF be located?”

There is no fixed design for locating a RAF other than identifying fast flow pathways and choosing an appropriate site to target the peak flow of a storm. Farmers often possess this knowledge, which can be augmented with topographic digital data and simple flow accumulation rules to identify suitable locations (Heathwaite et al., 2005; Wilkinson and Quinn, 2010). Walk over surveys are also beneficial; often evidence of overland flow can be observed in swales and valley bottoms. The schematic shown in Figure 3-8 illustrates an idealised network, and also provides design rules regarding the appropriate scale at which features should be installed.

It is appropriate to raise a number of salient points that should be considered in the planning stages. It is imperative that the construction of a RAF network involves a partnership between regulatory bodies, farmers and land owners, the local community and other relevant stakeholders. Experience has shown that a transparent and inclusive process avoids later complications and quickens the regulatory process. Keeping as many people informed as possible, for example through Town Hall meetings, often encourages additional uptake of the approach by farmers, land owners and land managers. The approach taken at Belford has evolved to fit within the current regulatory framework and has been readily accepted by the local community.

There may be a need to refine individual features to improve their functioning during flood events; often visual observation during an extreme event can be used to determine whether an inlet feature or drainage rate needs modification. Any indication of feature scouring or collapsing can also be reported. It is beneficial to engage those in close proximity to the sites, including farmers or local farming advisors, to conduct visual surveys.

There is anecdotal evidence that land owners and those living within the catchment prefer the use of natural materials in the construction of RAFS, purely from an aesthetic standpoint. Many different materials were used in Belford, which can be broadly grouped into 4 categories:

1. In a more upland area with livestock and thin soils, a farmer preferred the use wood or stone as soil bunds require more space and use up valuable soil. Some cattle farmers are concerned that exposed bare soil increases the risk of diseases that can kill cattle, hence wood is preferred.
2. In a lowland area with arable crops the use of bunds was preferred by the farmer as the soil was deeper and readily available. In the case of one farm, the farmer had spare soil on farm owing to the creation of new hard standings that would reduce poaching from his tractor around the farm steadings.
3. Online ponds can use treated wood or willow spilings (only use native species of willow). Experience of using recycled plastic has proven to be less desirable for aesthetic reasons (Letts, 2012). The widening of ditches yields material that can be used to construct bunds either within the ditch or to raise the ditch bank height.
4. Clearly large wood debris requires tree trucks. Experience, has shown that the EA team would prefer the removal of non-native species (sycamore in Belford) with replacement with native species (such as oak, if outside the riparian zone). The brash created by the tree felling can be used to roughen the local floodplain. Brash must be secured in a 'natural fence' type feature. On the riparian zones of woodlands it is recommended to plant low growing species of tree such as hazel and holly as these provide more roughness to complement the brash on the floodplain.

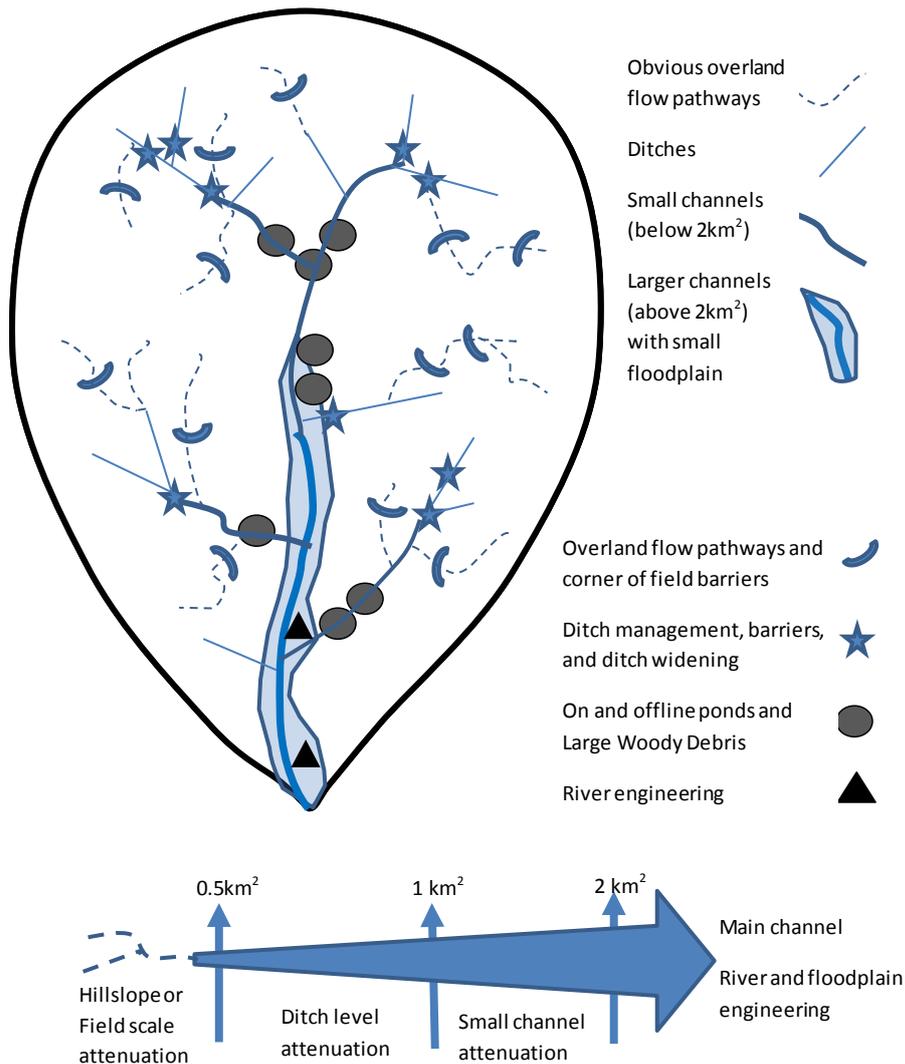


Figure 3-8 Design of a RAF network

Box 3

- A RAF is a man-made landscape intervention that intercepts or modifies a hydrological flow pathway for the purpose of mitigating the impacts of flood and diffuse pollution, whilst improving the ecological environment.
- Key findings on the design and implementation of RAFs are:
 - The types of RAFs considered include online and offline features.
 - A range of materials can be used in construction, with treated wood, soil, stone, woody debris and willow spilings preferred over plastic.
 - Offline RAFs typically occupy $100\text{-}500\text{ m}^2$, with an average cost of £1-5K.
 - Online features are best suited to smaller channels, with an upstream contributing area of $<2\text{ km}^2$.
 - At areas above 2 km^2 offline features should be used, connected to the stream network by an armoured draw off channel.
- There is no simple recipe for siting or constructing a RAF. This will depend on local factors, including land owner/farmer preferences and local terrain.
- It is essential to engage stakeholders, as this may encourage uptake by farmers.
- These findings could be of use in informing works at other similar sites in the UK.

4 The Belford Study

4.1 Catchment Description

The upper Belford Burn catchment (5.7km²), Northumberland, is predominantly rural with grazing in the western uplands and arable land in the east, Figure 4-1 (Nicholson et al., 2012; Wilkinson et al., 2010b). The predominate soil series is Dunkeswick, a stagnogley soil with fine loamy topsoil and clayey subsurface horizons prone to waterlogging (Jarvis, 1994). The source of the Belford Burn is the Bowden Crags in the west of the catchment (185m AOD) from which it flows approximately 4.5 km before reaching the village of Belford. Within Belford the river channel is constricted by gardens, walls and residential structures. There has been a long history of flooding in Belford, with 35 properties identified as at risk in the EA Indicative Floodplain maps.

FEH catchment descriptors for Belford are provided in Table 4-1. The Standard Percentage Runoff (SPRHOST), defined as the percentage of rainfall that causes a short term increase in flow, is 40%, and the Baseflow Index (BFIHOST), the ratio of long term baseflow to total streamflow, is 0.313 (IH, 1999). The time to peak (TP), a measure of the time between the flood-producing rainfall and the resulting flood response, is 2 hours. These attributes are typical of rapid response catchments that are prone to flooding (EA, 2011). Long term mean annual rainfall is 695 mm, but this value can vary significantly from year to year.

Legend

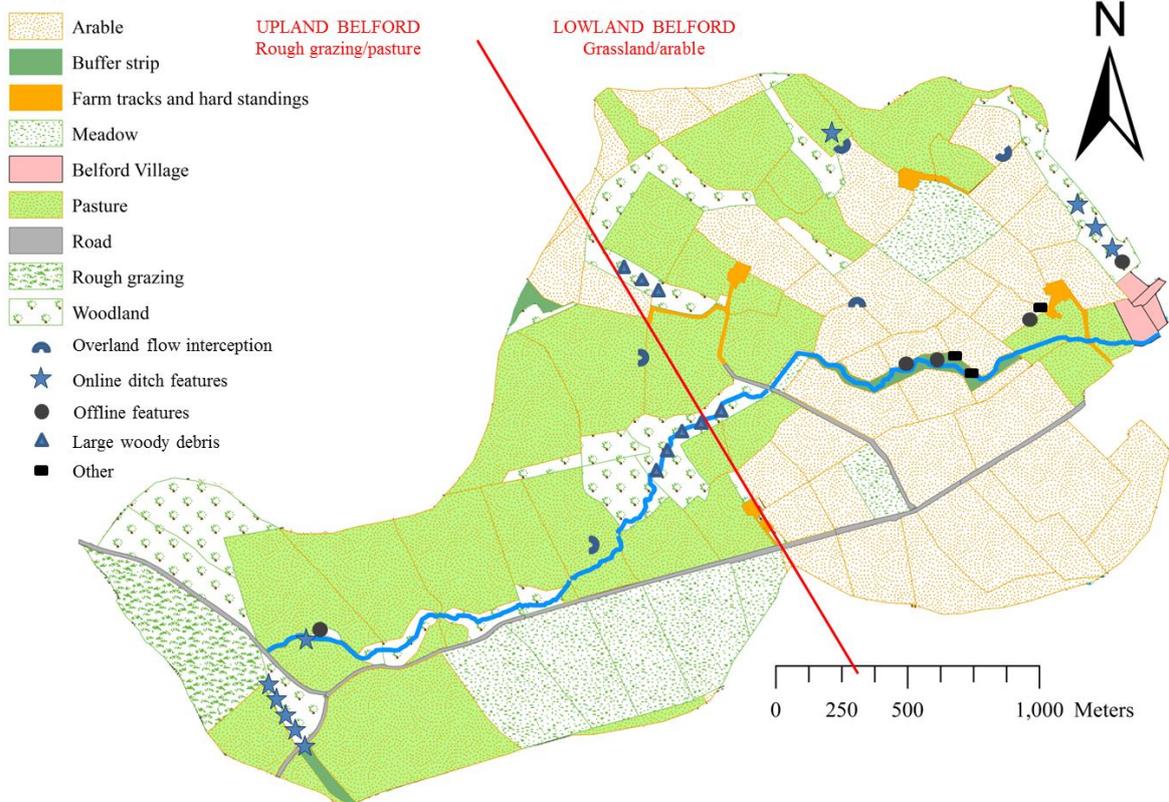


Figure 4-1 Upper Belford Burn catchment with locations of RAFs

Attribute	Value
<i>Physical attributes</i>	
Area, km ²	5.7
Mean catchment altitude, m (*ALTBAR)	118
Mean slope, m/km (*DPSBAR)	62.5
Floodplain extent, fraction 0:1 (*FPEXT)	0.0427
Fraction of urban extent, 0:1 (*URBEXT)	0.0
<i>Hydrological attributes</i>	
Baseflow Index, fraction 0:1 (*BFIHOST)	0.313
Average annual rainfall 1961-90, mm (*SAAR)	695
Standard percentage runoff, % (*SPRHOST)	40.76
Time to peak (*TP(0))	2.03

Table 4-1 Attributes of the Belford Burn Catchment to Belford (* = FEH descriptor; IH, 1999).

4.2 Belford RAF Network

Summary details of the 35 RAF features installed in Belford prior to January 2012 are provided in table 4-2 and their locations are shown in Figure 4-1. It should be noted that the value specified for total storage in Table 4-2 (9-10K m³) is less than the 20K m³ depicted in Figure 2-1. This value does not however include the attenuation effects created by wood debris and within channel barriers, which is more difficult to quantify. (Specifically, the backwater storage and attenuation effects of these features are a function of stage, which is event specific.) In terms of contribution to total storage, the main type of RAF employed in Belford is the offline pond. The hydrological analyses detailed below have therefore primarily focused on this type of intervention. (The wider environmental benefits of the features have not been analysed as this falls outside the scope of this report.) More features have recently been added by Newcastle University and the EA, but as the project has now ended the new features have not been included in this study.

The estimated cost of the features in Belford £70K-100K relates only to construction costs, Table 4-2. (The actual cost of implementing the features in Belford was higher due to the research, management, engagement and scoping expenditure). The range of estimated construction cost values associated with the feature types indicates that a similar amount of storage could have been created at a lower cost. However, actual costs depend on the availability of locations and their site specific characteristics.

Table 4-2 Features built in Belford and estimates of typical capacity and cost. Note, some Large woody debris sites contain more than 1 feature. (Consultancy and research costs are not included).

Feature type	Number built	Typical min, max storage m ³ / feature	Estimated cost
Overland flow interception	5	300-1000	1K-5K
Online ditch features	10	50-150	1K-3K
Offline ponds	5	200-3000	2K-6K
Large woody debris	12	50-150	1K-3K
Opportunistic RAF sites	3	1000-3000	1K-10K
TOTAL	35	Estimate for Belford 9000-10000m³	£70K-100K

4.3 Hydrological Analyses: Storm Selection

Two flood events have been chosen for the hydrological analyses; a summer and a winter event. Both events, which caused flooding in Belford Village to a small degree, are the largest events recorded since the project began in late 2007 (Figure 4-2).

The winter March 2010 event was the result of a two day storm, with 59 mm and 77 mm of rainfall recorded over the 24 and 48 hour periods preceding the flood peak, respectively. Using the FEH Depth Duration Frequency rainfall model, the return period for the 24 and 48 hour totals are estimated at 5 and 12.5 years. The summer July 2009 flood event was also a result of a 2 day event, with rainfall totals of 46 mm and 70 mm in 24 and 48 hour periods, respectively, with return periods of 10 and 17.5 years.

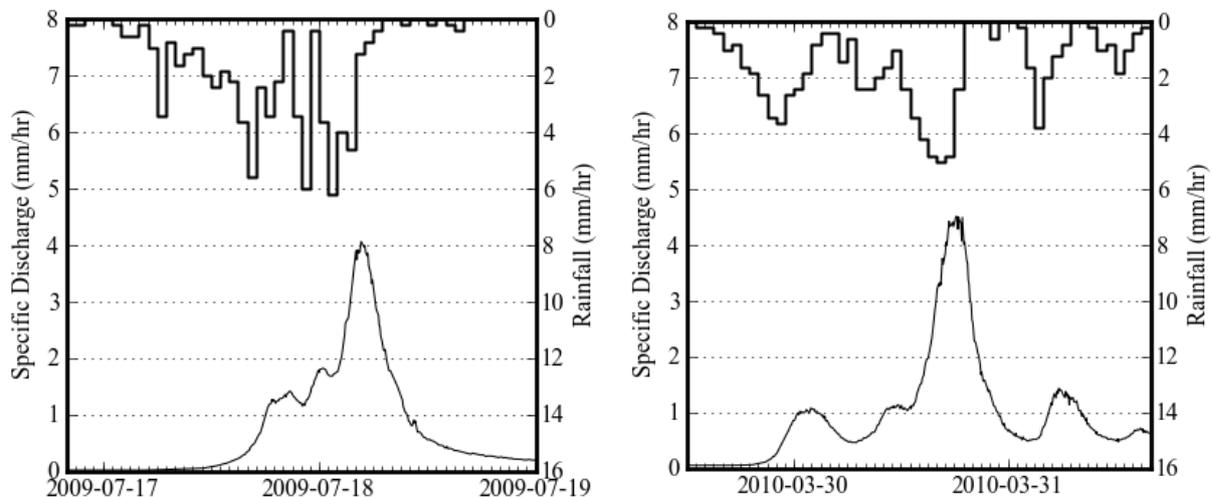


Figure 4-2 Historic events used in analyses (left panel - July, 2009; right panel March 2010)

4.4 FEH Design Storms

In this section, guidance in using the FEH rainfall-runoff methodology for flood analyses is provided through the comparison of design storms against observed storms. In Figure 4-3 the March 2010 storm is compared against the 1 in 100 year event derived using 12 hour and 24 hour FEH design storm events. These design storms were selected as they have a peak flow and a hydrograph width broadly corresponding to the observed hydrograph. It is known that the March 2010 event had a return period of less than 100 years; for example the 24 hour rainfall return period was 12.5 years and several flood events of this magnitude have been recorded in Belford in the last 10 years. (Note, there are insufficient data to reliably estimate the actual return period of the observed storm.) It is concluded that analyses based on design storms may be unreliable in terms of interpretation of return periods.

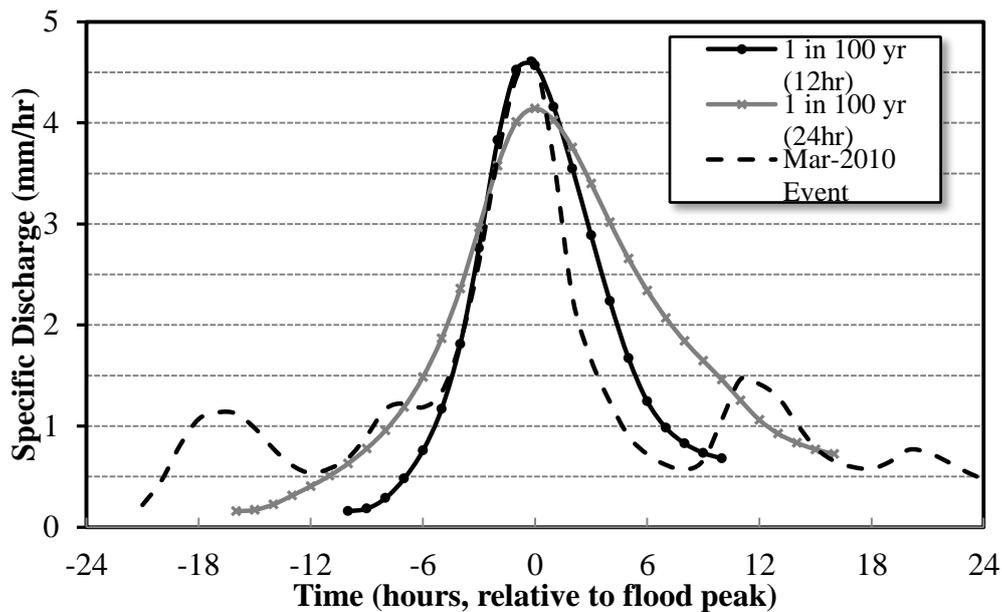


Figure 4-3 Comparison of historic event and FEH design storms

4.5 Functioning of a RAF

In this section, the value of collecting monitoring data is demonstrated through the forensic examination of RAF-3, an offline pond located immediately upstream of Belford (Figure 3-4). To allow this investigation the following data were measured or derived:

1. Stream stage heights immediately upstream of the pond inlet (measured using pressure transducers; ~15min recordings)
2. Current flow measurements, which were used to derive stage/discharge relationship. Applied to (1) to derive a time series of upstream stream flows.
3. Stage heights within the offline pond (pressure transducer/15 mins)
4. Field surveys of the pond to provide the stage/volume relationship. Applied to (3) to derive a time series of pond storage volumes.

Example data sets are provided in Figure 4-4 for the July 2009 storm. The onset of infilling occurs when the stream stage exceeds the spillway height, which is ~0.35 m for RAF-3. Based on these data, some interpretations of the performance of RAF-3 are:

- The pond has a potential storage volume of 370 m³. It is effective at capturing flow, but it reaches 90% capacity ~1 hour before the arrival of the main flood peak. Detailed information of this type can be used to modify features for improved performance. In this case the spillway height was subsequently raised to delay the onset of filling and increase available storage capacity later in the storm.
- The pond empties in ~6 hours. This is deemed appropriate. If the pond outflow pipe is too large the feature will not fill; if it is too small the pond will not sufficiently drain to provide capacity for the next storm event. As a general rule, it is suggested that ponds should drain within 6-10 hours, so that there is storage available in the eventuality of multi-day extreme events.

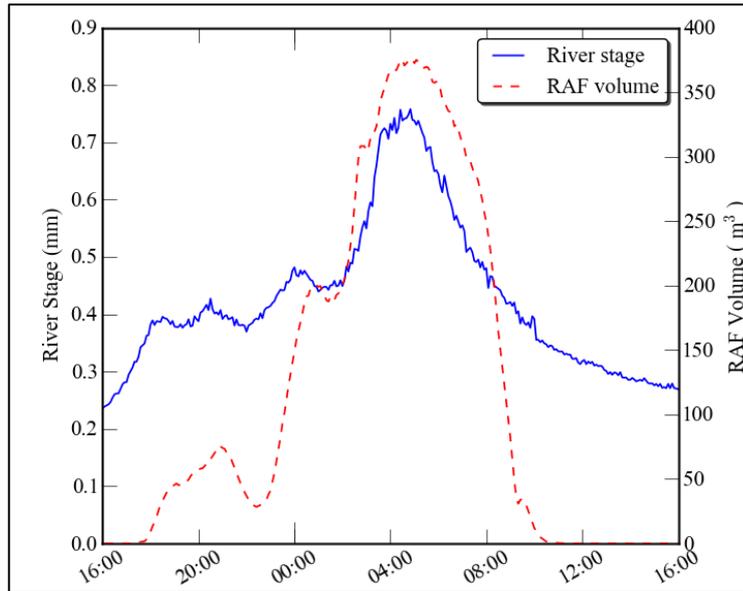


Figure 4-4 Data from RAF-3, 17th July 2009

4.6 Local Scale Impact of Features

“How does a RAF work?”

In this section an example of the impact of a representative offline pond, RAF-3, on local stream flow is quantified. Further details of this work are provided in Nicholson et al. (2012) and Nicholson (2013). The local impact of a pond is simply the difference between the pre- and post-change flows in the stream channel immediately downstream of the feature. Obviously, the pre-change flows are not available for an historical event and hence impact is indirectly calculated from the net gains and losses from the stream channel to the pond:

$$Impact(t) = [Q_{in}(t) - Q_{out}(t)]$$

where Q_{in} is the inflow from the channel to the pond and Q_{out} is the outflow from the pond. As the pond fills ($Q_{out} < Q_{in}$) there will be a positive impact, with a net loss of streamflow to the pond and reduction in stream stage height. As a pond empties ($Q_{out} > Q_{in}$) after the flood peak there will a negative impact. It should be noted that the storage/attenuation of flow along the travel paths to and from the pond are not quantified in the above equation; it has been assumed that the pond is closely coupled to the channel. This is a reasonable assumption for the majority of ponds. Also the local lateral overland flow inflows and infiltration losses from the pond are assumed small and are neglected.

The flows into and out of the pond cannot be directly quantified as the flow depths are too shallow to allow the accurate measurement of depth and velocity. Instead, the inflows are derived from a weir equation and stream stage, and the outflows from a hydrostatic equation and pond depths. These equations (termed the Pond Model) have been validated by establishing that the simulated pond storage accurately reproduced the observed.

The results for the summer and winter events are shown in Figure 4-5. The pre- and post-change hydrographs are very similar and the impact is small. For both events there is a net storage on the rising hydrograph limb (positive impact) and a net loss on the recession limb of the hydrograph (negative impact). At the time of the arrival of the main flood peak the impact is small because there is little storage available (Figure 4-4).

However it should be stressed that it is the collective network of RAFs, rather than individual features, that aim to provide flood mitigation, as demonstrated below.

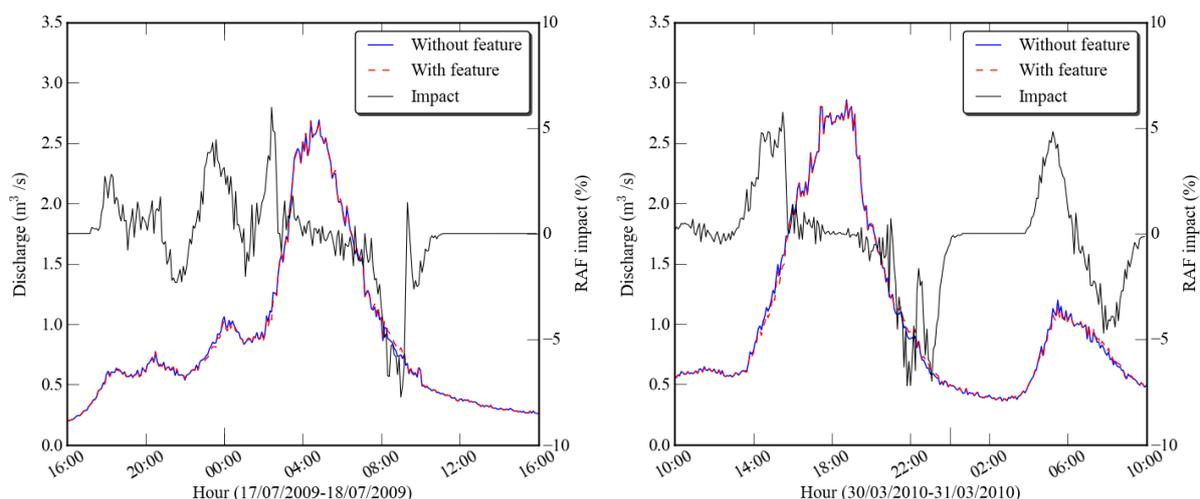


Figure 4-5 Pre- and post-change hydrographs for RAF-3 and impact; left panel July 2009, right panel March 2010

4.7 Catchment Scale Analyses of Network of Features

“How many RAFs do we need?”

Given the above findings, there is a need to establish how much storage is required to significantly reduce flood impact in Belford. The approach taken has been to assume a hypothetical reach of channel (Figure 4-6). Based on experience of the size of interventions that are acceptable to land owners, each pond of is allocated a storage potential of 550 m³.

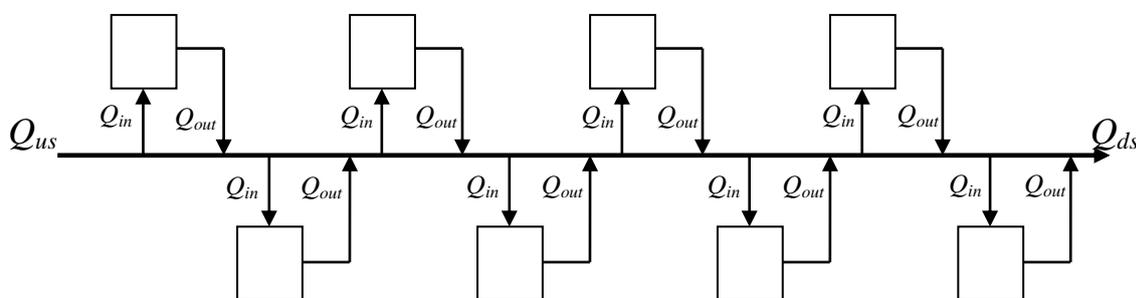


Figure 4-6 Synthetic pond network

Using the Pond Model developed above, simulations have been performed in which increasing numbers of RAFs have been assigned to the channel reach. (A subset of the configurations has also been simulated using a 2D hydraulic model; the general conclusion drawn was the same, hence the

results are not presented here). Simulations were performed for the summer and winter events detailed above, with the upstream channel stage height (Q_{us}) set as in the previous analyses.

In Figure 4-7 each line represents the downstream channel flow (Q_{ds}) with an additional RAF attached to the channel reach. The upper blue line represents a single feature (550 m^3 of storage) and the lower green line 35 features ($19,250 \text{ m}^3$). Increasing the number of features results in the attenuation of the flood peak, with water being stored in the RAF network on the rising hydrograph limb and returned on the recession. As a pond starts to fill, the flood stage immediately downstream is reduced and hence there is a delay in the onset of the filling of the subsequent pond, producing a cascade effect along the reach.

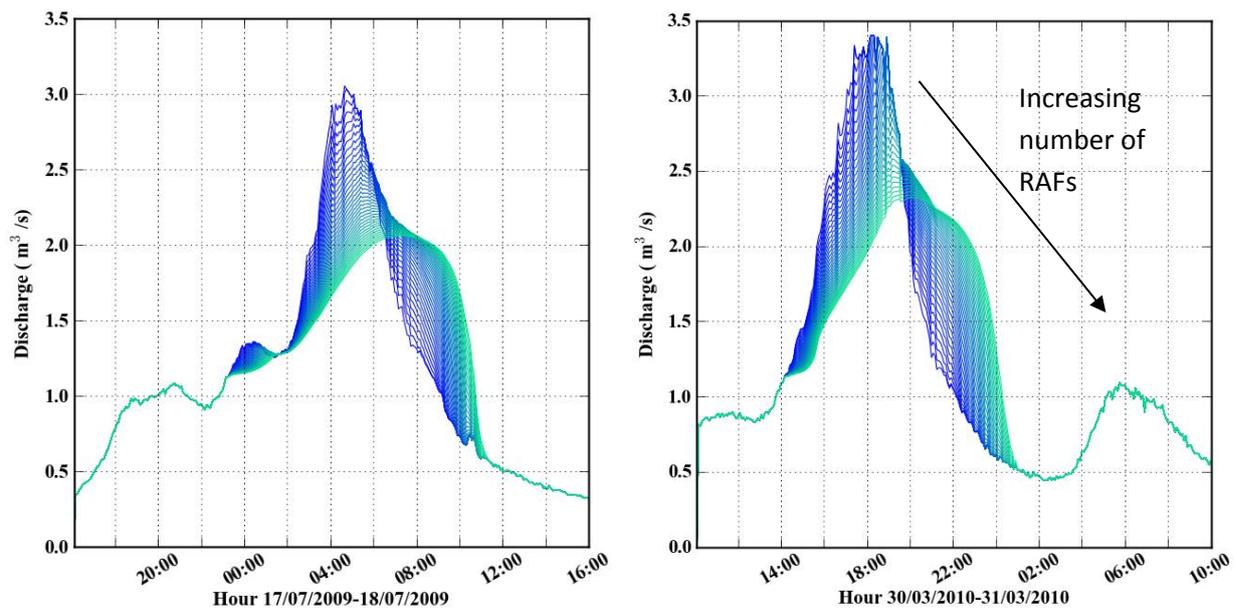


Figure 4-7 Impact of different configuration of ponds along a hypothetical stream reach (left panel July 2009; right panel March 2010)

A similar analysis has been performed for the 100 year (24-hour) return period event derived using the FEH rainfall-runoff methodology, Figure 4-8. In comparison to the historic events, which had similar peak flows but were of shorter duration, the impacts of increasing the numbers of ponds on the flood peak is less. This is because of the shape of the hydrograph. The time effectiveness of a pond network relates to both the flood magnitude and the duration that the stream stage level exceeds the spillway inflow elevation.

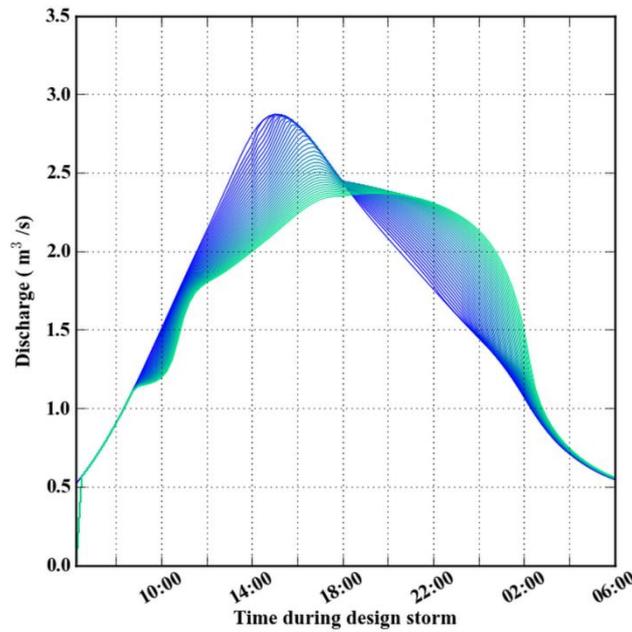


Figure 4-8 Impact of different configuration of ponds along a hypothetical steam reach, 100 year design period event

In Figure 4-9, the impacts of increasing number of ponds are illustrated for the three events detailed above. A storage of 19,250 m³, which is similar to that depicted in Figure 2-1, results in a reduction of the flood peak by approximately 30% for the historic events and 15% for the design storm.

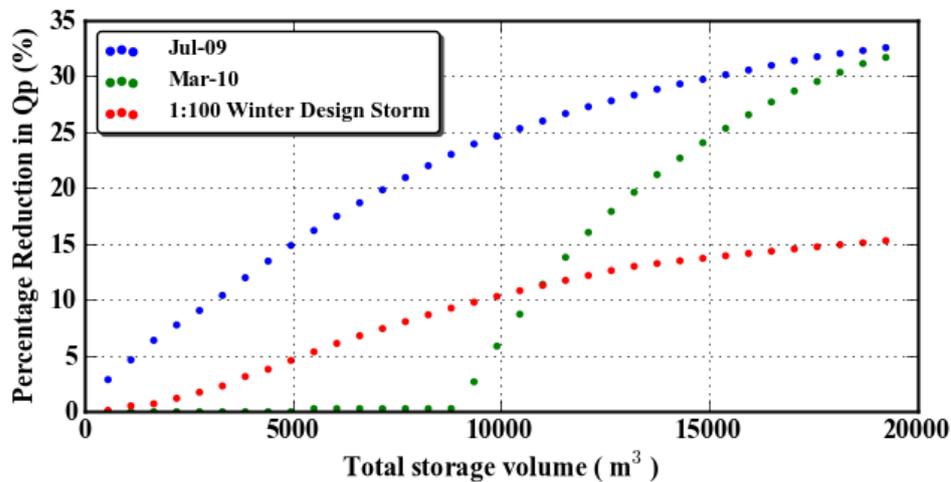


Figure 4-9 Graph showing number of RAFs versus reduction in peak discharge Qp (each RAF has a storage of 550m³)

It is interesting to note that for the March 2010 event, which is the largest, there is no significant reduction in the flood peak until a storage of ~10,000 m³ is added to the network. This is because at lower levels of added storage all of the ponds fill before the arrival of the main flood peak. There is probably a critical number of RAFs that are needed in order to create significant peak flow reduction in catchments similar to Belford.

Box 4

- RAFS are designed to target fast runoff pathways and should fill and empty in a timely fashion (ideally <10 hours).
- The instrumentation or observation of features is recommended to establish how features operate during extreme events and to highlight the need for improvements in design.
- Each RAF performs a small amount of runoff storage/attenuation.
- It is the collective network of RAFs, rather than individual features, that aim to provide downstream flood mitigation.
- Based on results from modelling, a network of Runoff Attenuation Features has been demonstrated to have a positive impact on flood hazard in small catchments.
- The effectiveness of networks of RAFs to attenuate flood depends upon the shape of the hydrograph; RAFs are more effective for flashy short duration flood events.
- The impact of RAF networks on the Flood Frequency Curve has not been assessed.
- The FEH method has proved to be misleading for Belford, specifically in terms of return period interval.
- Therefore conclusions drawn regarding flood magnitude and the required mitigation derived from FEH may be misleading.
- The success of the Belford project has been in gaining knowledge of the cause and effect of runoff processes and the mitigation thereof. This evidence is supported by high quality observed data sets.
- For Belford a shift in the time of peak of 2-3 hours greatly reduces flood hazard.
- The approach of using networks of RAFs in the rural landscape could potentially provide a cost effective means to reduce flood risk in small rapid response catchments.
- For a hypothetical pond network providing 19,250 m³ of storage, the peak flow reduction is estimated to be between 15-30% for both observed events and FEH design storm events.

5 The Powburn and Hescott Studies

“Do the mitigation schemes in Powburn and Hescott work?”

Newcastle University installed a rain gauge and 4 stream flow gauges within the Hescott and the Powburn catchments (see Annex D). However, there were no significant storms recorded during the 2 year instrumentation period. Several of the mitigation features were instrumented with water level recorders, but with the exception of one feature (Crawley Dene), no inflows occurred. The Hescott and Powburn studies are therefore not described in detail, although some results from ISIS hydraulic simulations performed by Royal Haskoning are provided in the supporting Annexes. In Annex B and C the performance of the mitigation schemes for design storms are provided.

In Table 5-1 the catchment characteristics of Powburn and Hescott are compared to those for Belford. The physical and hydrological characteristics of the three catchments are broadly similar. The most significant difference is the time to peak (T_p), a measure of the time between the flood-producing rainfall and the resulting flood response, which is significantly larger at Hescott (3.9 hours). This reflects the shallower topography in this catchment (as defined by DPSBAR). A note of caution is required in the interpretation of T_p ; the values have been calculated using a multilinear regression relationship derived from nationally available datasets rather than site specific information (IH, 1999). (Also note that the urban extent of Hescott is probably significantly larger than that given by the FEH descriptors.)

Table 5-1 FEH catchment descriptors

FEH Descriptor	Description	Belford	Hescott	Powburn
<i>Physical attributes</i>				
AREA	Area, km ²	5.5	8.0	10.7
ALTBAR	Mean catchment altitude, m	118	73	47
DPSBAR	Mean slope, m/km	62.5	23.7	84.4
URBEXT	Fraction of urban extent, 0:1	0.0	0.0159	0.0005
<i>Hydrological attributes</i>				
BFIHOST	Baseflow Index est from soil type, fraction 0:1	0.313	0.317	0.408
PROPWET	Proportion time SMD ≤6mm 1961-90, fraction 0:1	0.45	0.34	0.45
SAAR	Average annual rainfall 1961-90, mm	695	698	761
SPRHOST	Standard percentage runoff est from soil type, %	40.76	40.98	37.14
Tp(0)	Time-to-peak of an instantaneous UH, hours	2.0	3.9	2.3

In comparison to Belford, fewer mitigation features were built in Powburn and Hescott, but generally the features were larger (Annex B and C). Also the schemes were significantly different to the RAFs used in the Belford study and, hence, it is not possible to draw reliable conclusions about their effectiveness based on experiences in Belford. It is recommended that additional monitoring is performed of the individual features within in these catchments.

In the absence of observational evidence for extreme events, hydraulic simulation was used to provide insight into the performance of the Powburn and Hescott schemes. Existing ISIS models

that included a representation of several mitigation features were used. As described in the previous section (4.4, Figure 4-3), the use of design storms may give misleading results, so Belford events were used as a surrogate for extreme events. The results from the ISIS models indicated that the impact of the features on downstream flood levels were negligible for large events. However, it should be noted that it has not been possible to validate the models' performance in simulating the features due to a lack of in situ observations. Additionally, there are questions regarding the suitability of the Belford flows used, which were simply scaled by area to provide flows for the target sites. The simulation results are not shown herein but the experience has highlighted the need for future flood studies in small catchments to take into consideration both the duration and return interval of design storm events.

Box 5

- The mitigation schemes implemented by the EA in Hepscoth and Powburn differ significantly from the RAF network installed in Belford.
- It is therefore not possible to reliably extrapolate findings and interpretations from Belford to these two catchments.
- Hydraulic simulations using observed flow from Belford may have been too large to allow the local mitigation features to be fairly evaluated.
- Due to a lack of data and the simulation results, there is no clear evidence as to whether the Powburn and Hepscoth schemes work. Hence, there is a need for continued observation to derive the necessary datasets to underpin analyses and modelling of impacts on flood hazard. We recommend that individual mitigation features and/or shorter river reaches should be monitored, as in the Belford case study.

6 On-going Research and Future Research Needs

There is not a simple methodology or tool for designing an appropriate network of RAFs to achieve a desired level of reduction in flood hazard for a particular catchment. This challenge is being addressed by Newcastle University as on-going work. The first step has been to produce a model that can estimate the impact of a network of ponds detailed, above.

6.1 A Catchment Scale Model of Runoff Attenuation Feature Impact

As part of this study, catchment scale modelling simulations were performed using a simple lumped conceptual rainfall runoff model (TOPMODEL, Quinn et al., 2008). Calibrated simulations show that the observed flood events at Belford can be reasonably reproduced using time series of rainfall and evaporation as model inputs (Figure 6-1). This model has the potential to simulate runoff dynamics and could provide an alternative to the FEH methodology for impact assessment in rapid response catchments.

The calibrated model was subsequently modified to capture the storage/attenuation effects of the RAF network in Belford using a simple routing function (a Unit Hydrograph), which was calibrated to emulate the output of the Pond Network Model (section 4-3). Figure 6-1 shows the simulation of the mitigated scenario which includes the impacts of adding a network of RAFs.

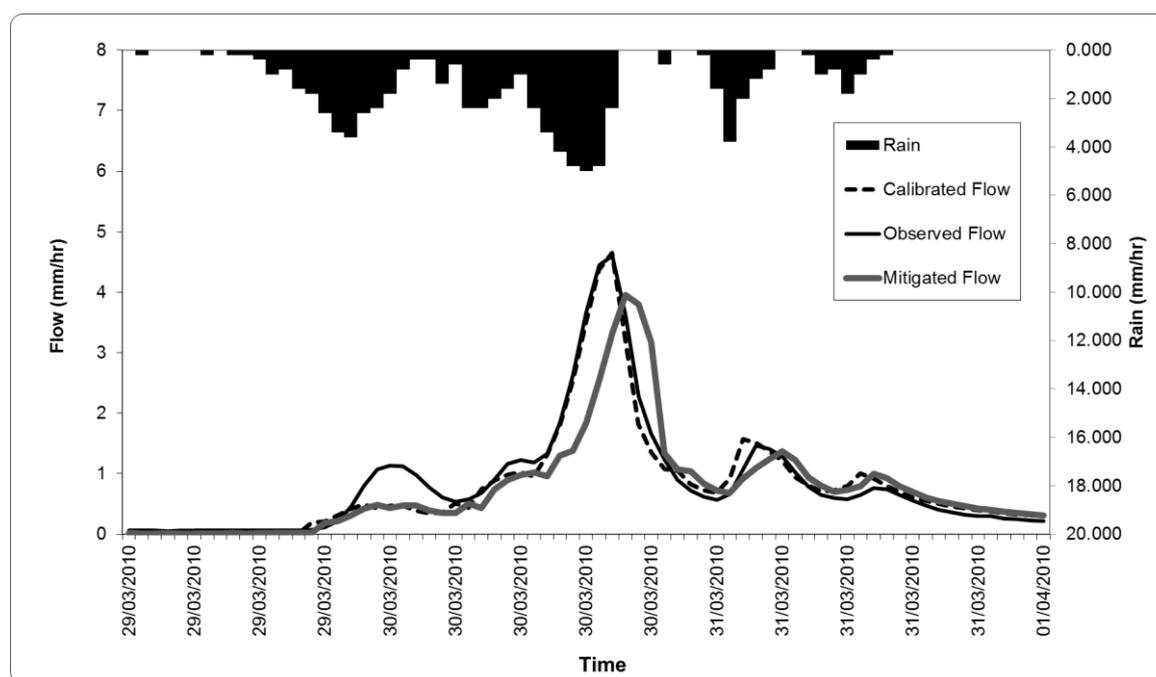


Figure 6-1 Observed data for the March 2010 storm, the calibrated model and the impact of mitigation assuming the simulation is attempting to emulate the output of the full RAF network.

Based on the outcomes of the above simulation, it is concluded that a simple hydrological model has the potential to emulate the impact of a RAF network. Hence, this model could provide the basis for small catchment scale impact studies (<10km²), although it must be recognised that there is uncertainty in predictions. This approach could be used as a simple assessment tool to assess the costs required to achieve specified levels of flood peak reduction.

The model is still under development. In particular, there is a need to understand linkage between the type, location and density of the RAFs and the likely impact on the overall runoff regime. This will

require additional data, which the study catchments are providing. However there is also a need to reconcile detailed hydraulic simulations and hydrological approximations.

6.2 Resources

Additional information on RAFs, including details of multiple benefits, can be found in the following peer reviewed papers:

- Wilkinson ME, Quinn PF, Welton P. Runoff management during the September 2008 floods in the Belford catchment, Northumberland. *Journal of Flood Risk Management* 2010, **3**(4), 285-295.
- Barber, NJ and Quinn P.F. Runoff attenuation features: a sustainable flood mitigation strategy in the Belford catchment, UK. *Area*, 2012, **44**(4), DOI: 10.1111/j.1475-4762.2012.01099.x.
- Nicholson, AR, Wilkinson, ME, O'Donnell, GM, Quinn PF. Runoff attenuation features: a sustainable flood mitigation strategy in the Belford catchment, UK. *Area*, 2012, **44**(4), DOI: 10.1111/j.1475-4762.2012.01099.x

The following are on-going PhD studies related to Belford:

- **Implementation and assessment of the impact of RAFs at Belford**- PhD. Alex Nicholson (due for completion in 2013).
- **Impact of RAFs on water quality (nitrate, phosphorus and sediment)**-PhD. Nick Barber. Due to complete in 2013. RAFs are being assessed at Belford and Netherton and both sites are showing positive impact of RAFs to water quality.
- **Impact of hydrological models on flood flow using RAFS**- PhD. Gareth Owen, studying Great Ayton (30km²), and three 10km² catchments in the River Eden. (First year of study). The model will attempt to map the impact of interventions across more complex river networks.
- **An object orientated hydraulic simulation of RAFs at the catchment scale**- PhD. Luke Smith, using advanced computational fluid dynamics to simulate RAFs by creating individual objects that can be mapped onto real catchments. Belford will be the test site for the model. (First year of study).

7 Conclusions

The key question that this report has addressed is:

“Does the RAF approach work in Belford?”

Ideally, this question would also be posed for Hepscott and Powburn, but due to a lack of observational data it has not been possible to derive reliable findings. However, some general recommendations are provided.

The above key question has been tackled through a series of more focussed questions:

“Why does Belford flood?”

- Belford and similar rapid response catchments are susceptible to flooding from short duration intense periods of rainfall that occur within multiday events.

“What is a Runoff Attenuation Feature?”

- A RAF is a man-made landscape intervention that intercepts or modifies a hydrological flow pathway for the purpose of mitigating the impacts of flood and diffuse pollution.

“How do you build a RAF?” and “Where should a RAF be located?”

- Key findings on the design and implementation of RAFs are:
 - A variety of RAFs can be used, including online and offline features.
 - A range of materials can be used in construction, with treated wood, soil, stone, woody debris and willow spilings preferred over plastic.
 - Offline RAFs typically occupy an area of 500m², with an average cost of £3K.
 - Online features are best suited to smaller channels, with an upstream contributing area of <2km².
 - At areas above 2 km² offline features should be used, connected to the stream network by an armoured draw off channel.
- There is no simple recipe for siting or constructing a RAF. This will depend on local factors, including land owner/farmer preferences and local terrain.
- It is essential to engage stakeholders, as this may encourage uptake by farmers.
- These findings could be of use in informing works at other similar sites in the UK.

“How does a RAF work?” and “How many RAFs do we need?”

- RAFS are designed to target fast runoff pathways and should fill and empty in a timely fashion (ideally <10 hours).
- The instrumentation or observation of features is recommended to establish how features operate during extreme events and to highlight the need for improvements in design and performance.
- Each RAF performs a small amount of runoff storage/attenuation.
- It is the collective network of RAFs, rather than individual features, that aim to provide downstream flood mitigation.
- Based on results from modelling, a network of Runoff Attenuation Features has been demonstrated to have a positive impact on flood hazard in small catchments.

- The effectiveness of networks of RAFs to attenuate flood depends upon the shape of the hydrograph; RAFs are more effective for flashy short duration flood events.
- The impact of RAF networks on the Flood Frequency Curve has not been assessed.
- The FEH method has proved to be misleading for Belford, specifically in terms of return period interval.
- Therefore conclusions drawn regarding flood magnitude and the required level of mitigation derived from analyses of FEH events may be misleading.
- The success of the Belford project has been in gaining knowledge of the cause and effect of runoff processes and the mitigation thereof. This evidence is supported by high quality observed data sets.
- For Belford a shift in the time of peak of 2-3 hours greatly reduces flood hazard.
- The approach of using networks of RAFs in the rural landscape could potentially provide a cost effective means to reduce flood risk in small rapid response catchments.

Returning to the key question ***“Does the RAF approach work in Belford?”*** based on the evidence presented in this report it is concluded:

- At least 30 RAFs providing $\sim 10,000 \text{ m}^3$ of storage and runoff attenuation are required to significantly impact on large flood events in Belford. The estimated construction cost is £70-100K.
- For a hypothetical pond network providing $19,250 \text{ m}^3$ of storage, the peak flow reduction is estimated to be between 15-30% for both observed flood level event and large return interval FEH events (see section 4-7).
- The effectiveness of RAFs, in terms of reduction in peak flow, is related to the event return period.
- It is therefore recommend that additional RAFs should be built, if costs allow, to reduce flood hazard further.
- The RAF approach as implemented at Belford is suited to similar small rapid response catchments.

Finally, some comments relating to Hepscoot and Powburn:

- The mitigation schemes implemented by the EA in Hepscoot and Powburn significantly from the RAF network installed in Belford.
- It is therefore not possible to reliably extrapolate findings and interpretations from Belford to these two catchments.
- Hydraulic simulations using observed events from Belford may have been too large to allow the local mitigation features studied by RH to be fairly evaluated.
- Due to a lack of data, there is no clear evidence as to whether the Powburn and Hepscoot schemes work. Hence, there is a need for continued observation to derive the necessary datasets to underpin analyses and modelling on impacts to flood hazard.

7.1 A strategic future for RAFs at the catchment scale

There is a desire to actively management catchments to provide a host of ecosystem services. This is driven by recent legislation, including the WFD and the Nitrates Directive. The Defra funded Demonstration Test Catchment (DTC; <http://www.demonstratingcatchmentmanagement.net/>)

initiative is exploring ways of reducing diffuse agricultural pollution at the catchment scale, while ensuring the delivery of sustainable food production. The approach taken by DTC has similarities with the philosophy underpinning the use of RAFs for flooding. Hence there is a potential to harmonise and co-fund interventions aimed at reducing flooding and improving water quality, but to date this has not been exploited. Closer cooperation and funding of ecosystems services could encourage the wider uptake of the RAF approach.

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Annex

Supporting information for these projects can be found at

<http://research.ncl.ac.uk/proactive/belford/>

Annex A – Runoff Attenuation Features Handbook, Newcastle University and the Environment Agency 2011

Annex B – Hepscoth Flood risk Study Report, Royal Haskoning, July 2011

Annex C – Powburn Flood Risk Study Report, Royal Haskoning, November 2011

Annex D – Flood Mitigation Features in two Northumberland Catchments Catchment Assessment and Development of Rating Curves, I. Franzen MSc project, 2012.