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Runoff management during the September 2008 floods in the Belford catchment, Northumberland

M.E. Wilkinson[1], P.F. Quinn[1] and P. Welton[2]

1 School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, UK
2 Environment Agency, Newcastle upon Tyne, UK

Correspondence
M.E. Wilkinson, School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK. Email: m.e.wilkinson@ncl.ac.uk

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Abstract

On 5–6th September 2008, prolonged rainfall in the north east of England resulted in flooding in many towns. Belford lies within this region and has a history of flooding, but on this occasion, flooding was minimal. Numerous houses and businesses are at a risk of flooding but traditional flood defence measures are not considered to be cost effective. In the year before the storm, a series of runoff attenuation features had been developed in the Belford catchment ($\sim 6\,km^2$) as part of Farm Integrated Runoff Management plans. Water-level data from the stream and pilot feature indicated the effectiveness of the feature in storing and slowing runoff during the September 2008 storm. These data indicated that the pilot feature held runoff for approximately 8 h. The effect that this had on the travel time of the peak was significant: it increased from 20 to 35 min.

Introduction

The potential loss of life and damage to property and infrastructure ensures that the risk of flooding remains an area of concern for the public. Within the United Kingdom, recent floods have been exceptionally severe, notably, the widespread floods of 2000, the 2004 flood in Boscastle, the 2005 Carlisle flood, the summer floods of 2007 (Jackson *et al.*, 2008), the north east England floods in September 2008 and flooding in Cumbria in November 2009.

Over the past 50 years, significant changes in UK land use and management practices have occurred, driven by UK and EU agricultural policies (O'Connell *et al.*, 2007). There is substantial evidence that modern land-use management practices have enhanced surface runoff generation at the local scale, frequently creating impacts through 'muddy floods' (O'Connell *et al.*, 2007). Climate model integrations suggest increases in both the frequency and the intensity of heavy rainfall in high latitudes of the northern hemisphere under enhanced greenhouse conditions (McGuffie *et al.*, 1999; Jones and Reid, 2001; Palmer and Räisänen, 2002; Ekström *et al.*, 2005).

These changes in the flood hydrograph will cause an increase in flooding to homes and businesses. Increasing demand for homes and businesses means that developers will build not only on new land outside the city but also on hazard zones such as floodplains and reclaimed land on coasts and estuaries. According to the Environment Agency, 10% of the UK population lives on natural floodplains. It is estimated that 1.8 million homes, 130 000 commercial properties and 14 000 km^2 of agricultural land (12% of the total) are at risk of flooding (Environment Agency, 2007). For example, the floods that occurred in the summer (June–July) 2007 caused flooding to over 55 000 homes and businesses (across the United Kingdom). The human impact is difficult to measure but insured losses are approaching £3 billion (Environment Agency, 2007). These were the most costly floods ever to occur in the United Kingdom.

A common way to protect urban areas from flooding is to build flood defences at the area of concern. This technique has been applied to many urban areas and is a costly process. In some cases, it is impractical to do as there is no room to improve defences because of a shortage of land. In Making Space for Water (a cross UK government programme taking forward the developing strategy for flood and coastal erosion risk management in England), the government recognised that the physical and institutional complexities of urban drainage systems make it difficult to plan and deliver systems with reduced flood risk (Defra, 2008b). Alongside the urban component, Making Space for Water also had a rural component. This allowed flood risk studies to be discussed in both contexts. Therefore, it is important that different flood storage strategies are considered.

There is a strong desire, based on field-scale science, for using land-use management to deliver flood and coastal erosion risk management (Parrott *et al.*, 2009). Making

Space for Water (Defra, 2005), the Water Framework Directive (2000/60/EC), Defra's Water Strategy (Defra, 2008a) and climate change all drive us to deliver sustainable solutions for flood and coastal erosion risk management (Parrott *et al.*, 2009). The European Floods Directive (Directive 2007/60/EC) also states that 'Flood risk management plans shall address all aspects of flood risk management focusing on prevention, protection, preparedness, including flood forecasts and early warning systems and taking into account the characteristics of the particular river basin or sub-basin. Flood risk management plans may also include 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'.

Currently, there is support within the Environment Agency for sustainable flood management solutions (see Environment Agency, 2008a, b). One such flood risk management strategy is presented here with its current application to a small rural catchment. Farm Integrated Runoff Management (FIRM) plans (Quinn *et al.*, 2007a, b, 2009) are based on the concept of the storage, slowing, filtering and infiltration of runoff on farms at source. This is believed to be a practical and achievable strategic investment of agri-environment and flood mitigation funding. There are huge advantages in controlling runoff at source, within hours of the runoff generation. These spatial and temporal windows of opportunity are not being fully exploited in environmental management. The most common way to control runoff within FIRM plans is to construct Runoff Attenuation Features (RAFs). RAFs include bunds, drain barriers, runoff storage features (both online and offline), woody debris dams, buffer strip management and willow barriers. If a typical farm or small catchment can sacrifice 2–10% of the landscape to runoff storage and mitigation features, then the properties of the runoff regime can be altered radically (Quinn *et al.*, 2007a). However, after a few years, these features can fill with sediment, reducing their water retention capacity (Verstraeten and Poesen, 1999). Therefore, the management of these features is an important issue.

The aim of this study was to demonstrate the potential for runoff management to reduce flood risk, and protect properties at risk of flooding in small rural catchments. It can also help to provide the evidence for runoff management to be part of flood risk management for larger catchments. Also, the focus of this paper is not to prove that these four features have lowered the flood risk by a fixed amount. It is more focused on the longer term role of RAFs on flood management in the future. The design, functioning and performance of the features during an event of the magnitude of the September 2008 storm will be presented.

Study area

The Belford Burn catchment, North Northumberland (Figure 1), is a small, predominantly rural catchment that flows through the village of Belford (55°35′56.59″N, 1°49′45.77″W). Belford Burn rises in the Bowden Crags (185 mAOD) and flows for approximately 4.5 km before entering the village of Belford (Figure 1). The channel is constricted by garden boundaries and walls as it flows through the village. The catchment area above the village of Belford is 5.7 km^2. After Belford, Belford Burn flows under

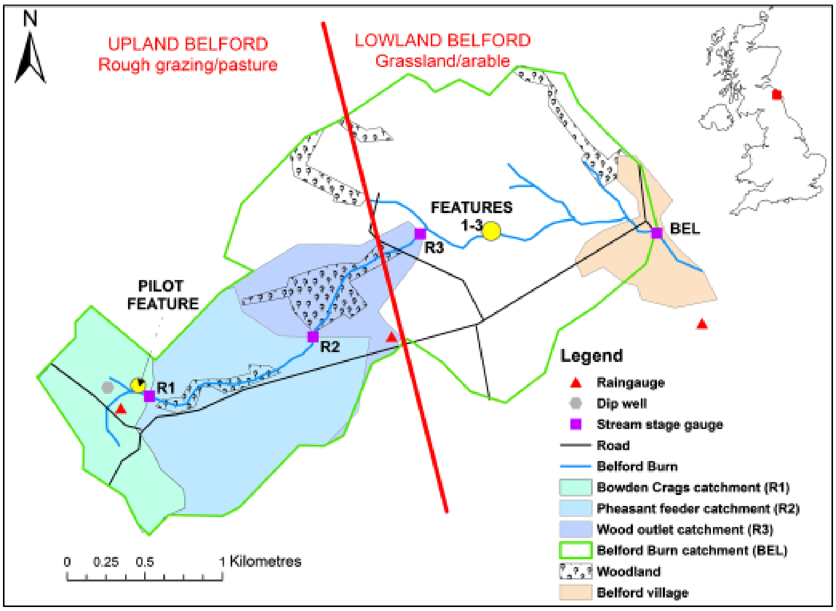

Figure 1 The upper Belford burn catchment (5.7 km^2) and instrumentation.

the A1 trunk road and the East Coast Railway Mainline. These are two of the most important north–south transport routes in the United Kingdom. The stream discharges into the North Sea at Budle Bay and the total catchment area is 28.7 km^2. Budle Bay is an important habitat for wading birds.

At the start of this project, there was no hydrometry present within the catchment. In April 2008, in response to previous flooding issues, the Environment Agency installed a telemetered gauging station for flood warning purposes in the village of Belford. This station is defined in this study as the catchment outlet (Figure 1). The Environment Agency also installed a telemetered tipping bucket raingauge at a nearby farm to help further with flood warning predictions. As part of this study, another raingauge, three gauging stations within the channel, a level recorder in the pilot feature and a water-level recorder in a dipwell (measuring the water table height in the soil) have been installed. At gauging stations, stage height is recorded at 5-min intervals. Data from these subcatchments will help to understand the impact that the features are having on the flood peak hydrograph. The Bowden Crags (R1), pheasant wood (R2) and wood outlet (R3) catchments are 0.5, 1.46 and 2.58 km^2, respectively, in area (Figure 1).

Land use within the Bowden Crags catchment is pasture with a small area of ungrazed moorland. The pheasant wood catchment has similar land use. The wood outlet catchment is also pasture, but includes a large area of woodland. The area downstream of this station to Belford is predominantly hay meadows and intense arable cropping. Three farmers manage most of the agricultural land within the upper Belford Burn catchment. The yearly average rainfall for Belford is 695 mm [calculated using the Flood Estimation Handbook (FEH)]. The geology of the catchment is somewhat complex. The top of the catchment is characterised by Fell Sandstone, and the mid and lower parts of the catchment are dominated by Tyne Limestone and Alston formations. An intrusion of Oxford Limestone occurs through the middle of the catchment (between the pheasant wood and wood outlet catchments). A small band of Great Whin Sill can be located to the north of the village at the outlet of the catchment. The Dunkeswick soil series (typically stagnogley soils with a fine loamy topsoil and clayey subsurface horizons) (Soil Survey of England and Wales, 1984) covers the catchment study area. This type of soil is prone to waterlogging in winter and local farmers have commented on runoff occurring during heavy rainfall events.

Flooding in Belford

There has been a long history of flooding in Belford. In the past 15 years, there have been numerous flood events affecting the village, the A1 and railway infrastructure nearby. In Belford, there are 31 properties at risk of flooding in the one in 200 year return period floodplain plus a caravan park and several businesses, with the threshold of flooding for the most vulnerable properties being only 2 years. On 1st July 1997, the East Coast Railway Mainline was temporarily shut down because of flooding. In October 2002, West Street and the Bluebell Farm caravan park were flooded. Flood events have also occurred in the same areas in January 2005 and July 2007. This last flood was reported widely in regional press. The Northumberland Gazette used the headline 'Sick of sandbags and sympathy' on the 12th July 2007 to highlight the villagers' angry reaction to the flood.

There have been a number of factors contributing to flooding in Belford, which are outlined here. The steep topography of the catchment upstream of Belford results in very little attenuation of flood flows and a flashy flood hydrograph. The backing up of water behind West Street Bridge, Belford, results in the flooding of properties upstream of Bluebell Farm, Belford village. The lack of any consistent walls along the banks of the burn results in flood flows spilling into Belford. The nature of the channel as it flows through Belford also contributes to flooding. The channel is confined to a narrow corridor with a significant number of bridge and culvert crossings. This combination means that water levels rise quickly through the town during a storm event (Halcrow, 2007). There are shallow soils in the majority of the catchment. Finally, there is intense livestock and arable farming, resulting in soil compaction and degradation. In extreme cases, soil capping occurs on arable fields.

Traditional flood defences and improvements to current defences are not suitable for Belford owing to the high cost, lack of space for flood walls/banks and not meeting the criteria for Grant-in Aid funding because of the small number of properties at risk. Some minor works will take place in the village. These include a small flood wall and widening the channel at two points in the village. However, this is not enough. It was desired by the local Flood Levy Team and the Northumbria Regional Flood Defence Committee at the Environment Agency to deliver an alternative catchment-based solution to the problem. In 2007, the Flood Defence Committee allocated flood levy money to Belford, to be used to implement FIRM plans in the upper part of the catchment and to carry out channel work in the village. The Environment Agency and Newcastle University are working in partnership to implement FIRM plans in the catchment, and some initial results of this work are reported here.

FIRM plans in the Belford burn catchment

The first installation of the three stream-level gauges, a piezometer, a pilot feature water-level recorder and a

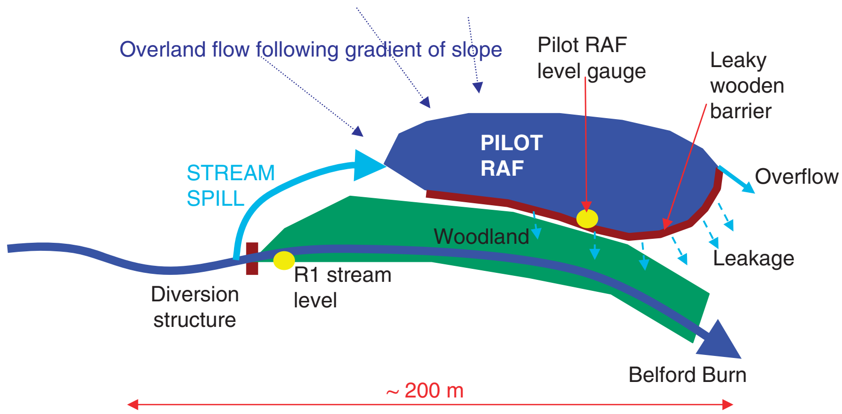

Figure 2 A schematic of the pilot Runoff Attenuation Feature (RAF).

raingauge (Figure 1) was completed in autumn 2007. This provided background data for at least 1 year before anything was built. After the installation of the hydrometry, a demonstration pilot RAF was built at the top of the catchment in a field near Bowden Crags to show the concept of FIRM plans to local farmers, villagers and any other interested stakeholders.

The Bowden Crags field near Bowden Crags offered the opportunity to show that any natural hollow/swale in the landscape could be used to hold flood water. Flow into the RAF arises from within the field (overland flow) and excess flow from the stream channel (Figure 2). As the feature was near the channel, it was important to take advantage of being able to store peak flow from it, therefore reducing the flood peak and increasing the lag time. Extra flow was forced from the nearby channel by a small diversion structure (Figure 2). The site was already very wet and the area was heavily poached by farm animals seeking shelter from the weather. This poaching caused the soil to become degraded and it may have been contributing some sediment and nutrient pollution to the burn. In this way, the FIRM plan was aiming to address water quality issues at the same time by trapping mobilised sediment during a storm in the feature. The main retaining structure for runoff was a vertical timber barrier constructed from green oak. The use of treated wood as the best material was based on several considerations: (i) the material was a sustainably sourced material; (ii) a trapezoidal soil bund, if constructed to a height of 1 m, would occupy up to 6 m of the feature area and would lose a significant amount of the storage capacity; (iii) the farmer was against scraping any soil from this field as the soil was shallow and the permanent pasture had been established for many years; (iv) our willingness to consider design options other than soils bunds, especially if the main issue was flood mitigation; and (v) soil bunds would need to be fenced off, as animals would erode the top surface. To the farmer, the implications of constructing this feature were minimal. The field is pasture and is never cultivated; therefore, ploughing will never be an issue. The feature has no implications on the soil management of the field.

It must be noted that the cost of constructing a timber wall was approximately five to seven times more expensive than scraping soil on site. The height of the barrier was 1 m at maximum and had a total length of 100 m. The storage capacity of the feature was approximately 800–1000 m^3. A water-level recorder was installed in the pilot RAF shortly after construction to measure the water levels during flood events. The barrier was designed to leak (through gaps in the wall), allowing stored water to slowly drain out over a period of 1 day. It was important that the feature was fully drained after a day so that, if another large event were to occur, the feature can store runoff from that event too. It was also important to demonstrate to the farmer that the feature would be empty for most of the year, only storing water during the large storm events. Therefore, the feature would only have a very small impact on land productivity but would provide an important purpose in flood risk reduction in Belford. Similar features (microponds) were considered in the Kamp catchment, Austria, as part of the CRUE project (CRUE, 2008) to effectively manage hillslope runoff. However, the features proposed in this catchment are different from RAFs as they drain slowly into the ground. This process can take a long time depending on the soil type and wetness. It may not be drained in time before the next storm. The pilot RAF has been in place in the catchment since May 2008 and during that period, it has only held a significant amount of water during the September 2008 storm and was empty after 1 day. This stresses the point that the farmer does not lose the productivity of the land within the FIRM plans.

The pilot RAF (Figure 2) is serving as a good demonstration site to the local community. It has helped to show farmers in the catchment how FIRM plans work. Other features have subsequently been constructed. Figure 3 shows

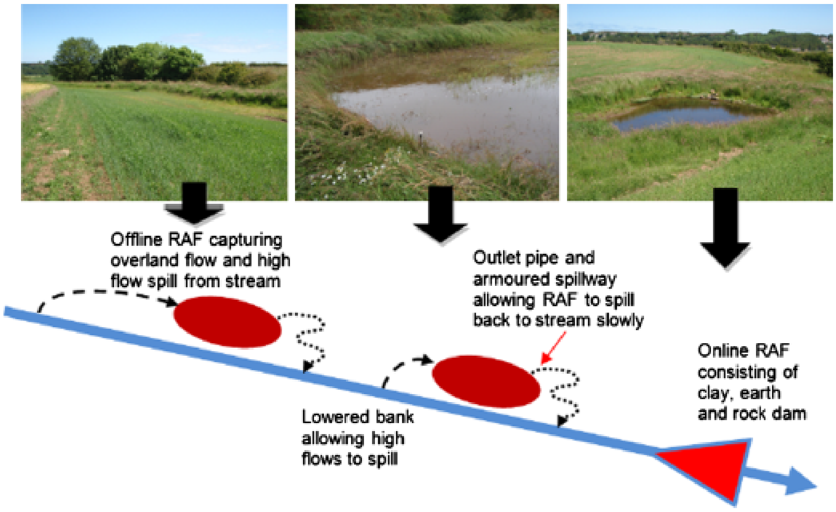

Figure 3 A diagram of features 1–3 constructed in late August/early September 2008 (features 1–3 on Figure 1).

a series of RAFs that were constructed in late August/early September 2008. Two of these RAFs were created by scraping soil on site and dropping the height of the river bank to allow peak flow to spill from the stream into the feature. The other RAF was created by tidying and modifying an old earth dam located in the stream. Willow has been planted on the floodplain to slow overbank flow but has yet to establish any substantial growth and therefore it may be presumed that it did not help in attenuating the September 2008 flood. All the features in Figure 3 fit into the buffer strips (the riparian area) of the fields.

Shortly after the construction of the first four RAFs, the 6th September 2008 storm event occurred in the catchment. The dense hydrometric network installed in the catchment captured the event. This allowed the effectiveness of the pilot RAF, the travel time of the peak discharge and the hydrograph shape to be examined. No instrumentation was present in the RAFs shown in Figure 3 owing to the storm occurring just 3 days after the completion of their construction, and therefore, only a qualitative description of their performance can be provided.

Effectiveness of the pilot feature

The summer of 2008 was an exceptionally wet summer, with monthly rainfall totals during June, July and August significantly higher than the long-term average. During 5th and 6th of September, a deep low-pressure system, centred over England, led to a band of heavy rain feeding in from the North Sea around this system. This resulted in flooding to towns throughout the region, including flooding on the rivers Wansbeck, Aln, Coquet and Ouseburn, which are all to the south of Belford and within 60 km. The heavy rainfall on an already saturated catchment led to widespread flooding in the Wansbeck catchment, and most significantly in Morpeth, where every defence was overwhelmed by the volume of water travelling through the system. Over a thousand properties were inundated as well as numerous businesses and public buildings. The response effort was huge, with all of the respective agencies called into action, leading to the successful evacuation of all of the flooded properties. Although a very extreme and very rapid event, no lives were lost. However, 1 year on, and some residents in Morpeth have yet to return to their homes.

Along with the prolonged rainfall, the antecedent conditions in the catchment were close to saturation owing to the previous wet summer. In Belford, over a duration of 36 h, 96 mm of rainfall was recorded. The rainfall return period was calculated using the FEH rainfall frequency software (Institute of Hydrology, 1999) and found to be 48 years, highlighting the severity of rainfall during this event. However, flooding in Belford was minimal, with only two houses affected. The extensive monitoring equipment around the pilot feature at the top of the catchment was able to monitor the event and quantify how well it worked. Firstly, it was possible to investigate antecedent conditions in the catchment using the monitored dipwell located next to the pilot RAF (Figure 2). This data provided information on the soil water table and how rapidly the soil was reaching saturation, and therefore provided an indication of the magnitude and timing of subsurface flow that was occurring. Subsurface flow may also be a significant runoff generation source in rural catchments. There is a common misconception that the bulk of the flow is generated by overland flow. In a large storm event, subsurface stormflow is equally responsible for runoff volumes (Weyman, 1970; Sklash and Farvolden, 1979).

The summer months before this storm had been wet. As in 2007, August 2008 was exceptionally wet and the water

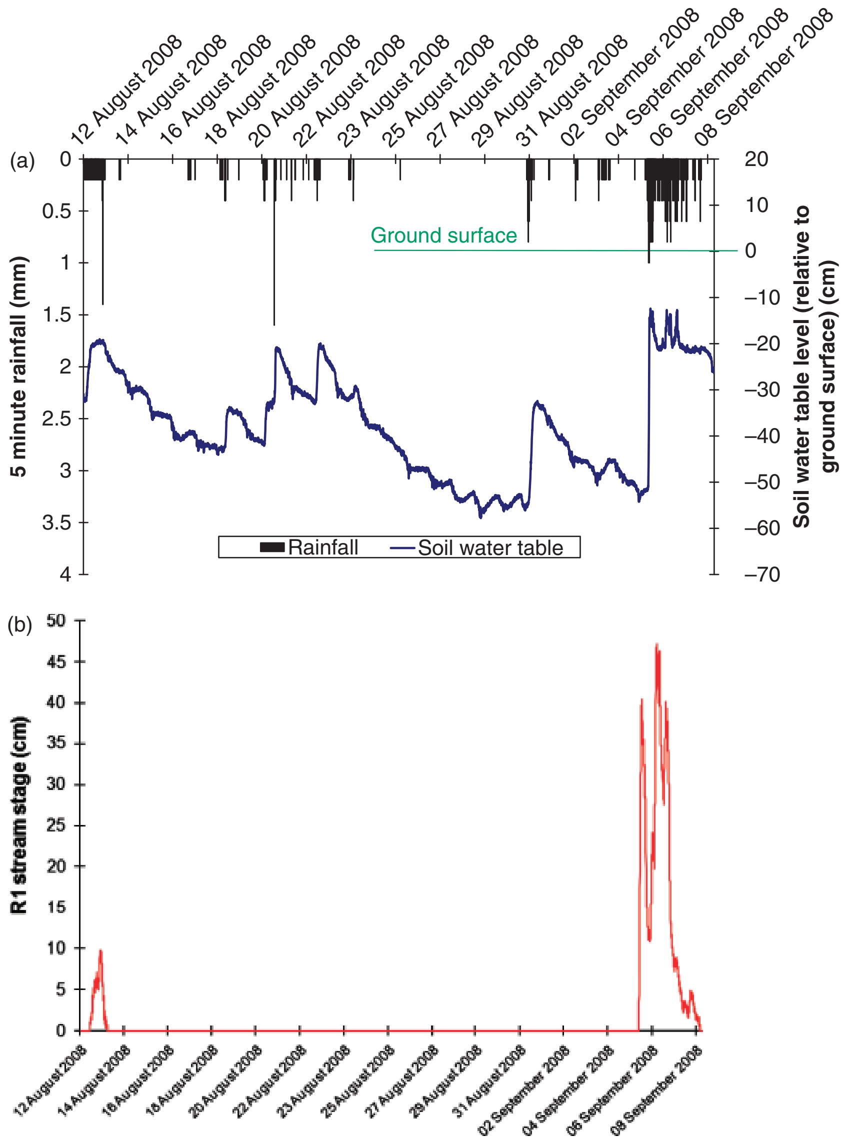

Figure 4 (a) Dipwell data showing the water table levels in the soil before and during the storm event and (b) stage height in the stream at R1 (note: the sensor is located 4 cm above the base of the stream).

table was high. However, in the 2 weeks before the storm, there had been 10 days of dry weather (except from a small event on 31st August) (Figure 4). The water table level before the storm was approximately 50 cm from the ground surface. During the first few hours of the storm on 5th September, the water table rose 40–10 cm below the ground surface. At the location of the dip well, the water table never reached the ground surface (fully saturated soil) and it is assumed that its location on a slope with a slight gradient is the reason for this. However, there was noticeable overland flow occurring (witnessed by eye-witnesses and recorded as part of this study) in many areas of the catchment, because the soils were generally shallow and freely draining. Surface and subsurface runoff therefore occurred rapidly at this site and could therefore result in a flashy flood hydrograph. The purpose of the pilot feature was to disconnect the surface runoff pathway as well as attenuating the high-flow peak from the channel. Subsurface flow bypasses the surface features and goes directly to the stream. Therefore, the most effective way to capture both subsurface and channel runoff was by diverting the peak stream runoff into a pilot feature.

Water-level data from the pilot RAF and from the stage gauge downstream of the pilot RAF diversion structure are presented in Figure 5. The lack of data at this stage of the project has made it impossible to derive a full rating curve and therefore only stream stage data are presented. Figure 5

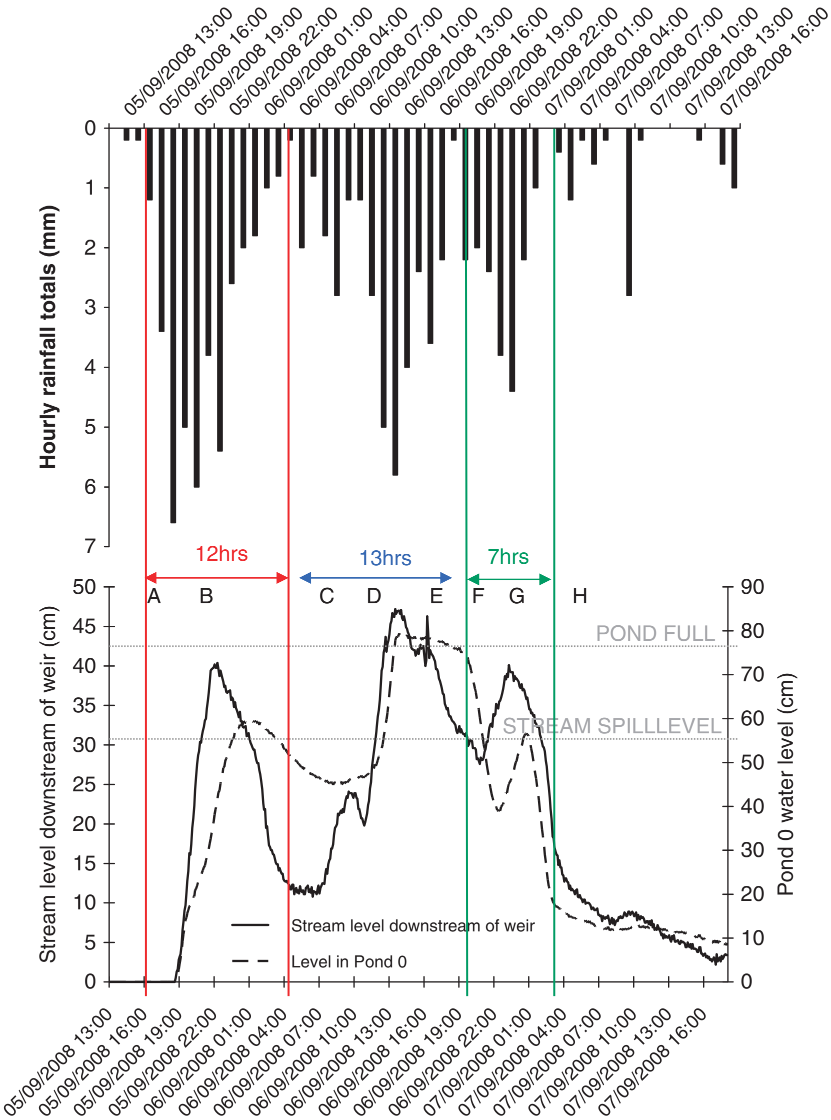

Figure 5 Pilot RAF (Pond 0) and stream (downstream of diversion structure) water level from the 5–7th September 2008 flood event.

shows that there were three phases to the storm with a combined storm duration of 36 h. Figure 5 has been broken down into eight parts, each with their own individual characteristics. These are summarised below.

Part A was before the storm with the stream at base flow conditions (almost dry) and the pilot RAF empty (Figure 6b). Part B was the first phase of rainfall, which was the most intense and resulted in the sharp rise of the water table and the stream-level recorder (Figure 4). The pilot RAF began to fill with surface runoff. When the stream stage gauge reached ~35 cm, the diversion structure became operational and stream runoff flowed over the field into the pilot RAF. Letting the stream spill over the land naturally induced a tortuous course for the spill water and therefore helped in the attenuation process. Over the first band of intensive rainfall, the pilot RAF filled to ~75% of its capacity. In part C as the rainfall became less intense and the stream level began to decline below the spill activation level, the RAF began to drain slowly, slowly enough, so not as to add too much extra flow onto the recession limb of the hydrograph, but quickly enough to allow storage for another band of rainfall. Over a 6-h period (from 02:00 hours on the 5th to 08:00 hours on the 6th), the RAF declined to 60% capacity.

Part D started at 06:00 hours on 6th September 2008 when a second phase of heavy rainfall occurred over the catchment. Saturated conditions from the first band of rainfall resulted in overland flow being generated more quickly and the stream responding rapidly. The start of part E was at 1200 when the spill level in the stream was reached

Figure 6 Photos of the pilot RAF at full capacity (a) and before the 6th September 2008 storm (b), with complementing pictures from the stream diversion structure during (c) and after (d) the same event.

(Figure 6c) and the RAF filled rapidly as the peak of the flood was being diverted to it. Within a 2-h period, the RAF filled by 30% from stream spill and overland flow. From 1400 to 1900, the RAF remained full (Figure 6a) as the stream level was still above the spill level. During this time, the RAF was attenuating the runoff from the stream and overland flow. At 1900, the stream declined below the spill level and the RAF started to empty (part F).

A third minor phase of rainfall occurred in part G as the RAF was emptying and this resulted in a brief filling period. However, as the RAF is already draining, it had the capacity to cope with this minor rise in the stream. Finally in part H, from 01:00 hours to 03:00 hours on 7th September, the RAF drained from 50% capacity to a near-empty state. The rate at which the RAF drained was a result of there being no stream spill input (Figure 6d) and no overland flow input as the rainfall had stopped completely. On the basis of the data from this storm event, it is estimated that the pilot RAF can drain from full to near empty in approximately 8 h.

As rating curves are still being developed, it has not been possible as yet to validate the runoff values. However, at feature 2 (Figures 1 and 3; a small dam in the channel), it was possible to calculate the peak discharge based on a postevent survey of the trashmark levels, the hydraulic behaviour of the dam crest and the 0.45 m diameter culvert pipe. The estimated peak discharge was $2.1 \pm 0.4\,m^3/s$. The error bounds are 60% confidence intervals. The catchment area of Belford burn at feature 2 is $2.99\,km^2$.

Table 1 Travel time of flood peak before and after the construction of the pilot Runoff Attenuation Feature (RAF)

Date	R1 maximum stage (m)	R1–R2	R2–R3
High level peaks with no pilot feature constructed			
22/11/2007	0.119	45 min	20 min
09/12/2007	0.112	25 min	20 min
04/01/2008	0.18	20 min	10 min
04/01/2008	0.216	20 min	25 min
21/01/2008	0.271	10 min	25 min
11/04/2008	0.187	10 min	15 min
30/04/2008	0.145	20 min	20 min
01/05/2008	0.153	10 min	20 min
Average travel time of peak		**20 min**	**19 min**
High-level peaks with pilot feature constructed and active			
Peak 1 (Figure 5) – 05/09/2008	0.404	30 min	30 min
Peak 2 (Figure 5) – 06/09/2008	0.472	50 min	25 min
Peak 3 (Figure 5) – 06/09/2008	0.401	25 min	10 min
Average travel time of peak		**35 min**	**22 min**
Distance between stations (m)		1350	1050

Movement of the flood peak

Using the level data from the four stage gauges in the catchment, it was possible to follow flood peaks as they moved down the catchment (Table 1). Flood peak times before and after the construction of the pilot RAF were compared with examine whether or not the feature and diversion structure slowed down the flood peak wave.

Eight peaks were recorded before the construction of the pilot RAF. The time of travel of the peaks between R1 (beside the pilot feature) and R2 varied from 10 to 45 min with an average travel time of 20 min. Between R2 and R3, the peak travel time varied from 10 to 25 min, with an average travel time of 19 min. After the construction of the pilot RAF (1st June 2008), three peaks have since been recorded, whereby the diversion structure in the stream has spilled water to the pilot RAF. These peaks are all larger than the preconstruction peaks (Table 1). With the pilot RAF active, the travel time of the peak from the pilot RAF to R2 varied from 25 to 50 min, with an average travel time of 35 min. The travel time of the peak was delayed by an average of 15 min when the pilot RAF spill mechanism was active. However, the average travel time of the peak between R2 and R3 was 22 min, showing no significant change from before the pilot RAF construction.

Although no data were available from the new features (RAFs 1–3) further downstream, the visual evidence was striking. The RAFs were full at the peak of the flood and took approximately 1 day to empty.

Discussion

The pilot RAF stored and attenuated runoff from over land flow and peak flow diverted from the nearby stream. Figure 5 showed that the storm occurred in three phases; at the end of each phase, the RAF began to drain slowly, before the next phase of rainfall. The leaky nature of the feature allowed the water to slowly drain away after the rainfall had stopped and runoff generation was decreasing. If the feature was full when a second band of rainfall occurred, it would no longer be a useful attenuation feature. The pilot RAF can store 800 m^3 of floodwater in a catchment of 0.5 km^2, which represents a total runoff of 1.6 mm. A further slowing/attenuation of the flow will also be occurring; hence, a 'transient' storage effect will also be in operation. The impact on flood flows through Belford could be more significant than appears from the runoff stored number. This is because all of the rainfall will not create runoff; hence, the percentage of stored water compared with runoff will be much greater. How this rainfall translates to cubic metres of flood flow is a more appropriate way to assess the impact of the storage sites. The current onset of flooding in Belford is from a 1 in 5 year event, and represents a flow of 4.56 m^3/s, estimated using the FEH. The flooding in Belford is flashy owing to the small size and steepness of the catchment. Flood durations are typically < 2 h. The volume of flow, assuming 4.56 m^3/s for 2 h, is 32 832 m^3. The existing four RAFs can store up to 2800 m^3, which represents a reduction in flood flow of 0.4 m^3/s or 8% of the 1 in 5 year event. It is therefore anticipated that some significant changes to the level of flood risk facing Belford can be achieved by continuing the construction of RAFs in this project for the next 2–3 years and all features being maintained after this time. It is not unreasonable to assume that through the minor works in the town, the conveyance through the town can be improved and particular low spots in defences can be filled, yielding an initial Standard of Protection of 1 in 10 years (5.6 m^3/s). It is then also expected that by continuing the catchment management techniques upstream and scaling up the number of features, for example if the total catchment storage was to increase to 10 000 m^3, the flood flow through Belford can be reduced by at least 1.44 m^3/s (based on a 2-h flood peak). This would take the Standard of Protection for Belford to 1 in 25 years, which was the original objective of the project. However, while flooding was lower in Belford (compared with the region), we cannot as yet ascribe the lowering in flooding in Belford to the RAFs. Local storm patterns and other unknowns may have accounted for the perceived lowering in flood impact.

The data in Table 1 indicate that the travel time of flood peaks after the construction of the pilot RAF increased on average from 20 to 35 min over a 1.35 km stretch of stream (R1–R2). Similarly, the speed of the propagation of the flood peak decreased from 1.12 to 0.64 m/s between R1 and R2. It is important to note that the logging interval was 5 min; hence, it is likely that the peak may have occurred a few minutes before or after the time stated. However, it is not feasible to log at a smaller time resolution owing to the logger capacity. The flood peak then travelled at a normal speed down the catchment as no features were present up to the woodland outlet (R2–R3). This demonstrated the importance of allowing the high flow runoff to be diverted into a storage feature. Placing more features like this around the catchment could result in the lag time of the peak in Belford being increased, allowing for better flood warnings.

Conclusions

Normal flood walls cannot be built in Belford owing to the constricted nature of the stream. FIRM plans were developed and RAFs were deployed in the catchment to alleviate a flooding problem in the village of Belford. Initially, a pilot RAF was constructed as a demonstration to show farmers the concept of how RAFs would work in the catchment. Data were collected from the pilot RAF during a large storm event. This showed that it stored runoff both from overland flow and channel flow diverted from the stream. This was successfully attenuated, with the RAF holding the water for approximately 8 h. The pilot RAF also increased the travel time of the peak from 20 to 35 min, compared with the peak flows before construction. The storage capacity of the current features was small but the attenuation effects of these features on the flood hydrograph can be seen.

The main focus of this paper was not to prove that these four features have lowered the flood risk by a fixed amount, but rather to show the performance of the RAFs during a significant flood-level event. Early results indicate that RAFs may work best in low-order channels. Theoretical hydraulic and engineering concepts in the literature have influenced the design of the features. However, in this study, the novel component was to apply these theories appropriately in a rural catchment. Later papers, analysis and future modelling exercises will help resolve the flood impact of each feature, the ranking of the performance of the individual features and their ensemble impact. The September 2008 flood and the implementation of the RAFs create a debate as to the potential for RAFs for the future and how they might be improved and optimised. The data arising from the September 2008 event are compelling but subject to great uncertainty at the moment.

It has been noticed that the features currently active in Belford are collecting some sediment. Collecting excess sediment in the ponds during high-flow events will help to improve water quality. This demonstrates the multipurpose nature of these features. However, as more sediment is collected, the storage volume will decrease. Therefore, it is important to acknowledge the maintenance that is required with these types of features, for example, emptying sediment from features, keeping pipes clear and ensuring that bunds are stable. At the moment, the maintenance is covered in the project costs. However, it is envisaged that in the future, these types of features will be covered in Natural England Entry Level and Higher Level Stewardship (ELS/HLS) farm payments. There is an element of risk, like in any water storage feature, that it may leak or have a failure point. However, if one were to fail, owing to the small capacity of these features and the distribution of these features in the catchment, the risk to Belford is low. Currently, no negative or unintended impacts of the RAFs have been observed. More RAFs are being planned throughout the catchment over the coming years and these will be closely monitored to understand to what extent the RAFs are reducing flood risk in Belford.

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