Appendix A Natural Flood Management Literature Review

A.1 Introduction

A.1.1 Scope of Report

Following the major flooding of York in December 2015, work continues to identify what more can be done to reduce the risk of flooding in the future. In a press release from the Environment Agency (2016a) Floods Minister Rory Stewart said, "Work on future flood protection for Yorkshire is well underway, looking at placing multi-million pound engineering solutions down-stream, alongside natural flood management measures up stream." This report forms part of the work that the Environment Agency is carrying out to identify opportunities for the implementation of Natural Flood Management (NFM) measures in the catchments that impact York.

The report outlines the current evidence and understanding in relation to NFM, including the limitations of our knowledge of the impacts on flood risk. The barriers to the implementation of NFM measures are discussed followed by the potential for the implementation of NFM to manage flood risk through the City of York. This Literature Review has been provided as supporting documentation to the Foss Natural Flood Management Study and has informed the relevant sections of the York Long Term Plan.

A.1.2 Natural Flood Management

Climate change projections over the next century suggest that the frequency and severity of flooding is likely to increase over the next century (IPCC, 2014). York has one of the longest flood records in the UK in the form of the Viking record of water levels on the River Ouse which began in 1878. Analysis of this record suggests that flood magnitude and frequency through York City Centre have increased over the past 137 years (Lane, 2003). This, coupled with population growth, puts increasing pressure on flood management in order to maintain current standards of flood protection in the city.

Review of the Viking flood record on the Ouse suggests three possible explanations for this increase in magnitude and intensity of rainfall events; changes in rainfall characteristics (amount and intensity), changes in river channel conveyance, and changes in land use management (Lane, 2003). Continued focus on traditional flood engineering methods, such as increasing the height of flood walls, is not sustainable and therefore an alternative approach to flood risk management is needed. An integrated catchment management approach is required that manages both land and water through the system, recognising that activities in one part of the catchment can influence flooding elsewhere (SEPA, 2015).

Natural Flood Management (NFM) is a catchment wide approach that involves working with natural processes to manage sources and pathways of flooding. It involves balancing and integrating the restoration of natural processes with existing land uses including the restoration, enhancement and alteration of natural features and characteristics. As no strategy can completely eliminate flood risk, NFM measures are focussed on managing flooding within the catchment. A key component of this is allowing identified areas to flood in order to decrease flood risk elsewhere (Wentworth, 2014).

NFM can deliver multiple benefits across the catchment including habitat creation, water quality improvements, carbon storage, amenity, recreation, and access.

A.2 Literature Review

The following section provides an outline of NFM and presents the current evidence and understanding through the use of key case studies. The limitations of NFM – both practical application and our understanding – and the applicability of NFM as an approach to flood risk management within the York catchment are discussed.

A.2.1 Natural Flood Management Measures

As discussed above, traditional hard engineering approaches to flood risk management are increasingly under pressure from climate change and population growth, and there is a general acceptance that future management requires a more integrated, catchment wide approach. However, whilst grey engineering approaches show tangible and easily quantifiable benefits in terms of flood protection, the benefits of NFM are less easily quantified.

Installation of NFM measures within a catchment (Table A5) aim to reduce the amount of runoff entering watercourses and/or restore/improve the ability of watercourses and their floodplains to manage flood flows. This can be achieved by storing more water on land and slowing the flow of water overland or instream (SEPA, 2015). The desired effect of the implementation of NFM measures is to reduce the downstream flood peak (maximum height of a flood) and/or delay and elongate the flood peak downstream. NFM measures can decrease the quickflow volume of water entering the watercourse, reducing the scale and therefore impact of the flood and can increase the amount of time to prepare for a flood event (Wentworth, 2011).

Measure Group	Measure Type	Main Action
Woodland Creation	Catchment woodlands	Runoff reduction
	Floodplain woodlands	Runoff reduction/ Floodplain storage
	Riparian woodlands	Runoff reduction/ Floodplain storage
Land Management	Land and soil management practices	Runoff reduction
	Agricultural and upland drain modifications (e.g. grip blocking)	Runoff reduction
	Non-floodplain wetlands	Runoff reduction
	Overland sediment traps	Runoff reduction/ Floodplain storage
River and Floodplain Management	River bank restoration	Sediment management
	River morphology and floodplain restoration (e.g. re-meandering, floodplain reconnection)	Floodplain storage/ sediment management
	Instream structures (e.g. woody debris)	Floodplain storage
	Washlands and offline storage ponds (e.g. leaky dams)	Floodplain storage

Table A5: River and catchment based NFM measures *(adapted from Natural Flood Management Handbook, SEPA, 2015)*

Catchment measures are associated with varying levels of uncertainty dependant on where in the catchment they are implemented. Measures installed at the source or spread over the catchment are associated with greater uncertainty than those targeted to a specific area and/or installed further downstream and thereby closer to the receptors. Figure A1 shows the classification of the measures in Table 1 by the location of implementation within the catchment.

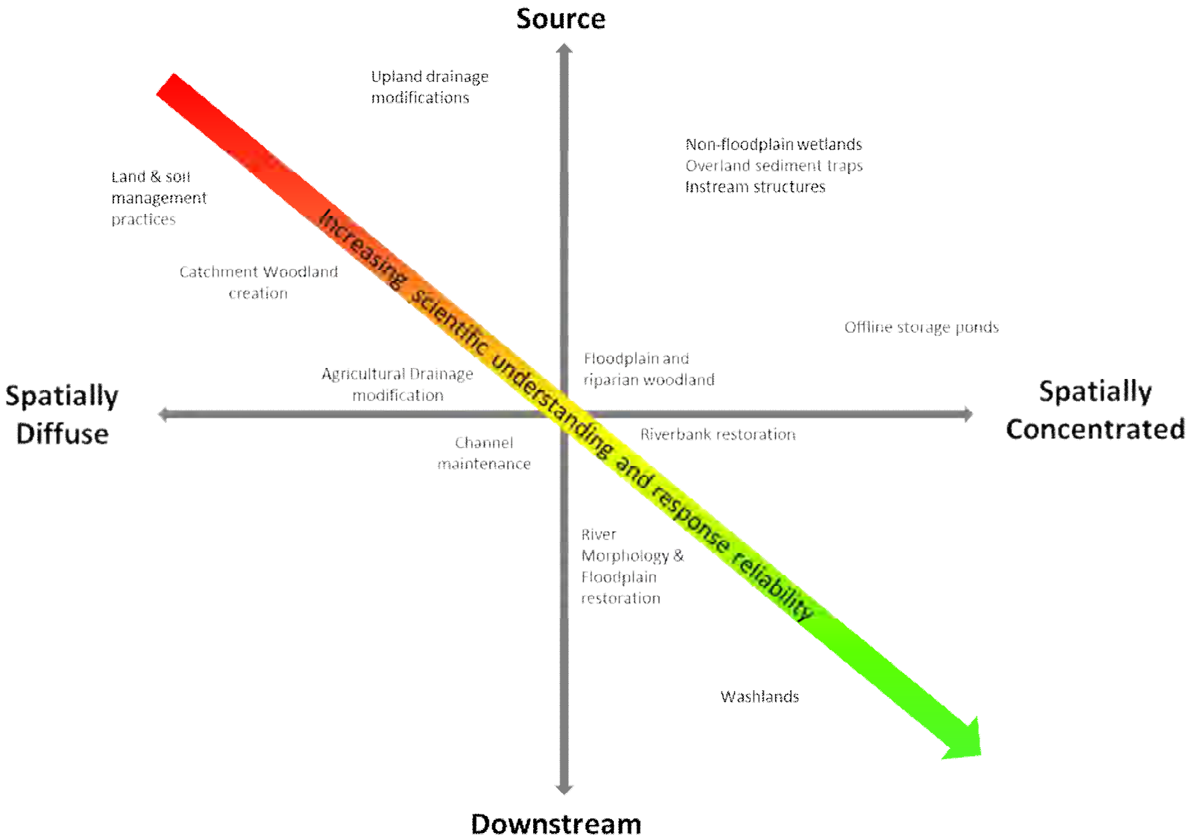

Figure A3: Catchment scale classification of NFM measures, coloured arrow indicates increasing understanding and reliability *(adapted from Thorne et al., 2007)*

A.2.2 Key Case Studies

There are a number of key case studies throughout the UK that can be used as demonstration catchments for this approach. Full details of each project are included in Section A6: Appendix A:

- Case Study 1: Pickering: Slowing the Flow
- Case Study 2: The Belford Project
- Case Study 3: The Pontbren Initiative
- Case Study 4: Holnicote: Source to Sea'
- Case Study 5: Peak District: Making Space for Water

A.2.3 Evidence for Natural Flood Management

A.2.3.1 Woodland Creation

A.2.3.1.1 Rate of runoff

Woodland creation refers to the planting and management of woodland throughout the catchment, from the headwaters to lowland floodplains. Woodland can contribute to flood management through greater water use than open grassland, by increasing the rate of soil infiltration and by increasing the hydraulic roughness of floodplain and riparian woodland (Nisbet & Thomas, 2006). Through these mechanisms the planting of woodland in the catchment, on floodplains and in the riparian zone, has the potential to reduce the volume of runoff entering the channel, and slow the rate of runoff to the watercourse.

Studies based on two experimental catchments were set up by the Institute of Hydrology in Plynlimon, Central Wales in the 1960s. One of these catchments was forested (10.55km^2) and the other grassland (8.7km^2). Studies concluded that a completely forested catchment would lose 15% of runoff linked to interception and infiltration compared with the grassland catchment. Whilst no significant statistical difference was found in flood peaks between the catchments (Kirby et al., 1991), and no apparent difference was found between the two catchments for large flow events (Robinson and Newson, 1986), research by Archer (2007) indicated that the forested catchment rises more slowly and less frequently than the grassed catchment suggesting that woodland has an impact on the rate of runoff during smaller storm events.

A.2.3.1.2 Infiltration rates

Increases in infiltration associated with woodland planting have been demonstrated through studies of test catchments. Studies of infiltration rates in the Pontbren catchment (See Case Study 3) found that soil infiltration rates were up to 60 times higher where young native cross slope woodlands were planted when compared to adjacent heavily grazed pasture (Carroll *et* al., 2004). Research carried out by Marshall *et al.,* (2014) in the same catchment demonstrated that median soil infiltration rates were up to 67 times greater in plots planted with trees compared to grazed pasture. In addition to this, surface water runoff volumes were reduced by up to 78% under trees when compared with the grassland plots.

Alongside the evidence gathered from these test catchments, modelling examining the impact of woodland on slowing and storing runoff has shown that there are flood risk benefits but that these are related to the size of the flood and the distribution of the planting. Nisbet and Thomas (2006) suggest that the planting of a small catchment (~10km^2) could reduce flood peaks by 50%-30% for small and large floods respectively.

The impacts of trees on the hydrological process such as interception are well documented; however their impact on flood risk is less well understood (Carroll *et al*., 2004). This is due in part to the short timescales of data records available and the difficulty in isolating and quantifying the effects of a single land use change on catchment scale processes. Whilst the empirical evidence, particularly for larger catchments, is as yet inconclusive, modelling suggests that woodlands may have an impact on local flooding and smaller, more frequent flood events.

A.2.3.2 Land Management

Land management refers to the implementation of management techniques within the catchment that aim to decrease the volume and speed of runoff reaching the watercourse. Land management includes land and soil management practices, agricultural and upland drain modifications (e.g. grip blocking), non-floodplain wetlands and overland sediment traps.

A.2.3.2.1 Land Management Practices

The ability of a catchment to slow and store water is affected by how the land is managed. Land management practices which reduce vegetation cover or increase its uniformity and lower its roughness, and increase soil compaction have a negative impact on the soils ability to infiltrate water and runoff is able to flow faster over un-vegetated soils. Farm practices such as high livestock densities (resulting in intensive grazing), the use of heavy machinery (resulting in soil compaction) and leaving soils un-vegetated over winter can have significant effects on the infiltration rate of the soil and the rate at which runoff enters the watercourse. Techniques including soil aeration and using machinery that minimises compaction, alongside a programme of checking and relieving compaction when required can help increase the infiltration rate of the soil. Reducing stocking densities and using cover crops during winter increase the vegetative cover and roughness thereby slowing the rate of runoff. The use of runoff control features such as cross slope buffer strips and hedges can intercept runoff. Research by the Flood Risk Management Research Consortium (FRMRC) (2008) suggests that suitably placed strips of trees can improve water infiltration into soils and increase interception. Measured overland flow suggests that strategically placed shelter belts protected from grazing can reduce surface water runoff at the hillslope scale, which has shown to be an important component of total catchment runoff in intensively managed improved pasture systems. As part of the attempt to quantify these impacts (research is ongoing to obtain measured results (FRMRC, 2008)), FRMRC carried out modelling of the Pontbren catchment, using the data collected to inform development and calibration of models. This modelling indicates that peak flow reductions of around 40% may be achievable through the optimal placement of tree shelter belts or hedgerows at the field and small catchment scale (~12km^2).

There is considerable evidence to suggest that land management practices can have an impact on the generation of overland runoff, however the impact on downstream flooding is less clear. Large scale research carried out by Defra (FD2114 & FD2120, 2008) using long term datasets on flooding and land use change was unable to isolate the impact of land use change from that of climate change variability. Whilst catchment scale effects are uncertain, changing land management practices has been shown to increase infiltration and decrease runoff rates. This type of management is particularly effective in reducing flood risk for farms or small communities for which structural defences are not feasible or cost beneficial (Quinn *et al.,* 2013). Examples of this include the villages that have been protected as part of Defra's 'Multi-objective Flood Management Demonstration Projects' (see Case Studies 1, 4, and 5). In the villages affected by flooding in these locations the cost-benefit of implementing a capital flood risk scheme was below the national threshold. In these pilot catchments tangible benefits have been observed following changes to land management within the catchment (EA, 2015). Similarly in Belford, the initial recommendation for flood management was to construct a flood storage reservoir to capture a 1 in 50 year flood event at an estimated cost of £2.69 million. As the scheme only offered protection to 35 properties the scheme was not considered eligible for Grant-in-Aid funding. The catchment scale NFM approach taken at Belford has provided measurable flood risk benefits (Case Study 2) for around £100k where improvements were considered to be otherwise non-cost effective (Quinn *et al.,* 2013).

A.2.3.2.2 Upland drains (grips)

Traditionally created to drain upland areas and convey flows to watercourses more quickly, upland grips have resulted in catchments with more flashy flow regimes as well as causing substantial degradation of peat bogs impacting the additional benefits that they provide. Agricultural and upland drain modification refers to the modification of drainage systems including blocking of moorland drains or grips (grip blocking) and modifications to field drainage systems. Research carried out by Wilson *et al.,* (2011) on upland peat in Wales and found that restoration through grip blocking leads to higher, more stable water tables and therefore more stable discharge from the system. Instead of reducing the available capacity for storing rainfall, the increase in overland flow and pooling within blocked grips has led to a less flashy system. Peak flows in both drains and upland streams were shown to be less severe, with more rainfall being retained in the bog suggesting that restoration leads to a more buffered system with more moderate responses to extreme events. Targeting restoration at steeper, smoother grips is likely to have the greatest impact on downstream peak flow reduction (Ballard *et al.,* 2011).

A.2.3.2.3 Agricultural drains and Non-floodplain wetlands

Blocking of agricultural drains, wetland restoration and the creation of non-floodplain wetlands (Constructed Farm Wetlands (CFW)) can also reduce the volume of water entering a river by storing it on the floodplain. CFWs are designed to manage rainfall events by providing runoff attenuation during storm events. They act as buffer zones and can contribute to the reduction of flood flows downstream by reducing the volume of runoff (see also discussion of leaky dams in Section 3.1.3.3) (Carty *et al.,* 2008). Quinn *et al.,* (2007) suggest that targeted measures across 2-10% of a farm or small rural catchment can alter the local runoff regime and reduce local flood risk.

A.2.3.3 River and Floodplain Management

Whilst NFM measures associated with land management and woodland planting in the wider catchment generally deal with reducing or delaying surface water runoff, NFM measures within the river channel and floodplain are more focussed on improving the ability of the watercourse to slow flood waters. Often achieved through implementation of a range of measures, the predominant aim is to restore or enhance the natural hydraulic response to flooding that may have been altered through anthropogenic intervention in the system.

A.2.3.3.1 River restoration – river morphology restoration and bank stabilisation

Historic land management for agriculture and infrastructure has realigned and constrained rivers as well as disconnecting the watercourse from its floodplain. This disconnection often leads to the flood risk being passed onto critical areas downstream – for example high flows that cause flooding in a town may be exacerbated by the presence of embankments protecting former floodplain upstream (protected for agriculture purposes for example). Re-meandering straightened watercourses increases the length and decreases the gradient of the river thus slowing the rate of flow and increasing the length of time that it takes water to travel downstream (Wharton and Gilvear, 2007).

Excessive deposition of material in watercourses can restrict the capacity of the river causing increased levels of flooding. Whilst this can be considered positive in terms of reducing the volume of water downstream through increased storage on the floodplain (similar to the intended effect of woody material), there can be conflicts where this flooding impacts vulnerable areas, particularly if these areas did not previously flood. Studies carried out by Natural England (2012) suggest that agriculture accounts for up to 76% of sediment in UK rivers. Runoff capture through changes to land management practices and floodplain storage, coupled with bank stabilisation techniques can help reduce the amount of agriculturally derived sediment entering the watercourse and thereby increase the capacity of these rivers. Stock fencing and cattle drinks can prevent poaching (livestock trampling of the bank) and the inclusion of riparian buffer strips and re-vegetating banks can capture sediment and slow runoff to the watercourse (Natural England, 2011).

A.2.3.3.2 In-stream structures – Large Woody Debris

In the context of NFM, instream structures refers to the use of woody material or (less commonly) boulders placed in the watercourse to increase hydraulic roughness and encouraging out of bank flow thus slowing the flow and reducing the volume of water in the river respectively (SEPA, 2015). Modelling of the potential impact of restoring five woody debris dams was carried out on a small tributary in Wales and indicated that the dams could significantly raise water levels during flood flows to enable reconnection of the watercourse with the floodplain. Model results predicted that flow velocities could be reduced by as much as 2.1 metres per second (m/s) behind the dams and could slow the flood peak by up to 15minutes over a 0.5km reach for a 1 in 100 year flood event. In larger catchments a series of woody dams will be required across the upper and mid catchment to have an impact on flood retention (Thomas and Nisbet, 2007).

A.2.3.3.3 Offline storage – Floodplain reconnection, washlands and storage ponds

Offline storage refers to the storage of water on the floodplain at times of high flows. This could be in the form of areas set aside as washlands or in more formal floodplain storage features such as leaky dams or bunds. Work carried out on the Belford Burn catchment, Northumbria (see Case Study 2) indicated that a network of attenuation features (35 RAFs in a 5.7km^2 catchment) has the potential to significantly reduce peak flows by as much as 30% for a 1 in 15 year rainfall return period event (Nicholson, 2014). In addition to this the use of floodplain storage within the catchment was shown to increase travel time along the catchment by 75% (Wilkinson *et al.,* 2010).

All three methods of river and floodplain restoration outlined above have some form of floodplain reconnection associated with them. When a watercourse is disconnected from its floodplain the river loses its ability to temporarily store water during high flows and thus the flood peaks downstream are higher. By reconnecting the river to its floodplain through raising the bed or allowing sediment to accumulate, lowering banks, removing/ breaching/ setting back embankments, installation of instream structures or diversion from the main watercourse, water can once again be stored on the floodplain in high flows.

A.2.4 Limitations of Natural Flood Management

NFM has been proven a viable technique for reducing runoff in small catchments for some floods, slowing the flow and restoring floodplain connectivity, and thus reducing flood risk downstream. It is, on the whole, a low cost, un-engineered solution that provides an opportunity to deliver multiple benefits. However, despite the success of pilot schemes (see Section A6:Appendix A) NFM has yet to be widely implemented throughout the UK and there is still a high degree of uncertainty surrounding the technique. Added to the gaps in our knowledge of NFM impacts on flood risk, there are barriers to implementation of measures on the ground.

A.2.4.1 Scale

The effects of NFM measures at a large catchment scale are difficult to determine as they are the result of the accumulation of many local-scale impacts that are themselves difficult to quantify. This lack of understanding does not necessarily mean that there are no effects at the catchment scale, just that the nature of the effect differs between catchments and is hard to determine (SEPA, 2012).

Archer et al., (2016) caution against extrapolating conclusions from one scale to another stating that relationships inferred at one scale of catchment or flood magnitude will not necessarily apply at a different scale. In addition much of the current evidence (as demonstrated throughout Section 3.1) is based on numerical modelling and often relies on projecting the impact of NFM measures to the catchment scale. This results in high levels of uncertainty in the robustness of the predicted reductions in flood risk as a result of NFM.

Whilst individual measures are supported by varying levels of evidence, these are generally at the local scale, in small catchments (<10km2), and during smaller, more frequent flood events. There is a lack of empirical evidence that proves that NFM provides a reduction of flood risk at the catchment scale (Wentworth, 2014). There is a general lack of observed evidence of how these systems operate during extreme conditions which limits the conclusions that can be drawn however, studies suggest that during larger flood events, NFM measures are less effective. For example, in the Belford catchment, Nicholson (2014) found that runoff attenuation features in the floodplain have minor impacts on downstream discharge during high magnitude, large duration events.

A.2.4.2 Quantification of impacts

Although it is expected that the interventions associated with NFM will result in alterations to the downstream hydrograph shape, the timescales over which monitoring has been undertaken to date are too short to carry out statistical analyses and thus determine the impact of NFM measures on flood reduction. As seen in Section 3.1, due to the lack of empirical evidence much of the current evidence for NFM is based on numerical modelling. Whilst modelling can provide a realistic representation of real-life conditions, models can be manipulated to demonstrate desired outcomes and can never fully represent all the natural variations present on the ground.

It is recognised that the problem of detection is further confounded by strong natural variability in climate and the difficulty in attributing changes to one particular measure (Nisbet et al., 2011b). The inability to conclusively state the level of protection or reduction in flood hazard that NFM measures will provide can cause significant barriers when it comes to securing funding and stakeholder buy-in to schemes.

A.2.4.3 Potential negative impacts

As with any flood risk management techniques there is the risk of increasing flood risk through the installation of NFM measures if not implemented correctly. Slowing the flow could lead to synchronisation of the flood peak downstream, increasing rather than decreasing the flood peak in these locations.

There are also possible negative measure specific impacts. For example;

- Woody debris has the potential to become dislodged and block structures (bridges, culverts, weirs) downstream causing flows to back up and flood areas not previously at risk from inundation
- Reconnection of the floodplain can change the water table level and re-wet the floodplain meaning that the land is may no longer be suitable for farming in certain ways e.g. rush growth in the uplands is unpalatable to sheep having a negative impact on grazing
- There is also the potential for floodplain attenuation features to become silted up if not properly maintained thus increasing flood risk elsewhere in the catchment and ceasing to function correctly as a NFM measure.

A2.2.1 Barriers to implementation

Alongside the limitations of our understanding of NFM as a flood management tool, there are significant boundaries associated with the implementation of NFM schemes on the ground. Table A6 outlines common challenges associated of NFM measures on the ground.

Barrier to Implementation	Details
Funding	Funding is required for the installation of measures, compensation for land take and maintenance of measures. - Who/ what is responsible for paying for this? - Do current farm subsidy/funding mechanisms /policies impede the implementation of NFM?
Evidence Gap	There is a lack of empirical, measured evidence to support the impact of NFM on reducing downstream evidence. Modelling has been carried out which suggests that NFM measures can positively impact flood risk but there are limitations to the extent to which this can be relied upon (models can be manipulated). The lack of proven, on the ground evidence can be a significant barrier to getting buy-in from key stakeholders *(see 3.2.2)*
Land take	Many of NRM measures require substantial land take for storage areas or woodlands. The incentives for landowners and farmers are often not enough to secure engagement with these schemes *(links to funding and landownership)*.
Land ownership	There are often many riparian owners within a single catchment. For NFM to work best, a suite of measures implemented over the whole catchment is required. This requires buy-in from a lot of different landowners, all with different perceptions and ideas.
Public perception	Benefits are not tangible in the same way that traditional, hard engineered FRM methods are and there is a significant evidence gap at present. This can lead to difficulties getting buy-in from various stakeholders and interested parties. On the other hand there is also need to manage expectations – NFM is not a silver bullet.
Maintenance	Many NFM measures are, by their very nature, self-regulating however; with more engineered measures (storage areas) some maintenance is also required. - Who is responsible for maintenance? Landowner, EA, other groups? - How is this maintenance funded?
Environmental Constraints	Throughout the UK there are areas that are designated for different species of flora or fauna and these designations often dictate how the land is managed. Some NFM measures can require land management practices that are in direct contrast which can cause conflict and a barrier to implementation.

Table A6: Barriers to implementation of NFM measures

Many of these barriers stem from the lack of empirical evidence and inability to provide proven, quantifiable benefits for the implementation of NFM measures. With the ongoing research being undertaken in this area of flood risk management, and the increasing need for alternative, sustainable solutions to complement more traditional engineered forms of flood management, some of these barriers may be reduced in the future. However, even with a greater evidence base, uncertainty will still remain and innovative monitoring and modelling will be required to inform decision making (Wentworth, 2014).

A.3 Applicability to York

As with any flood management technique there are limitations, and the applicability of NFM measures needs to be considered on a catchment by catchment basis. There are two main watercourses flowing through York - the River Ouse and the River Foss. These have been assessed separately with regard to their applicability for the implementation of NFM measures.

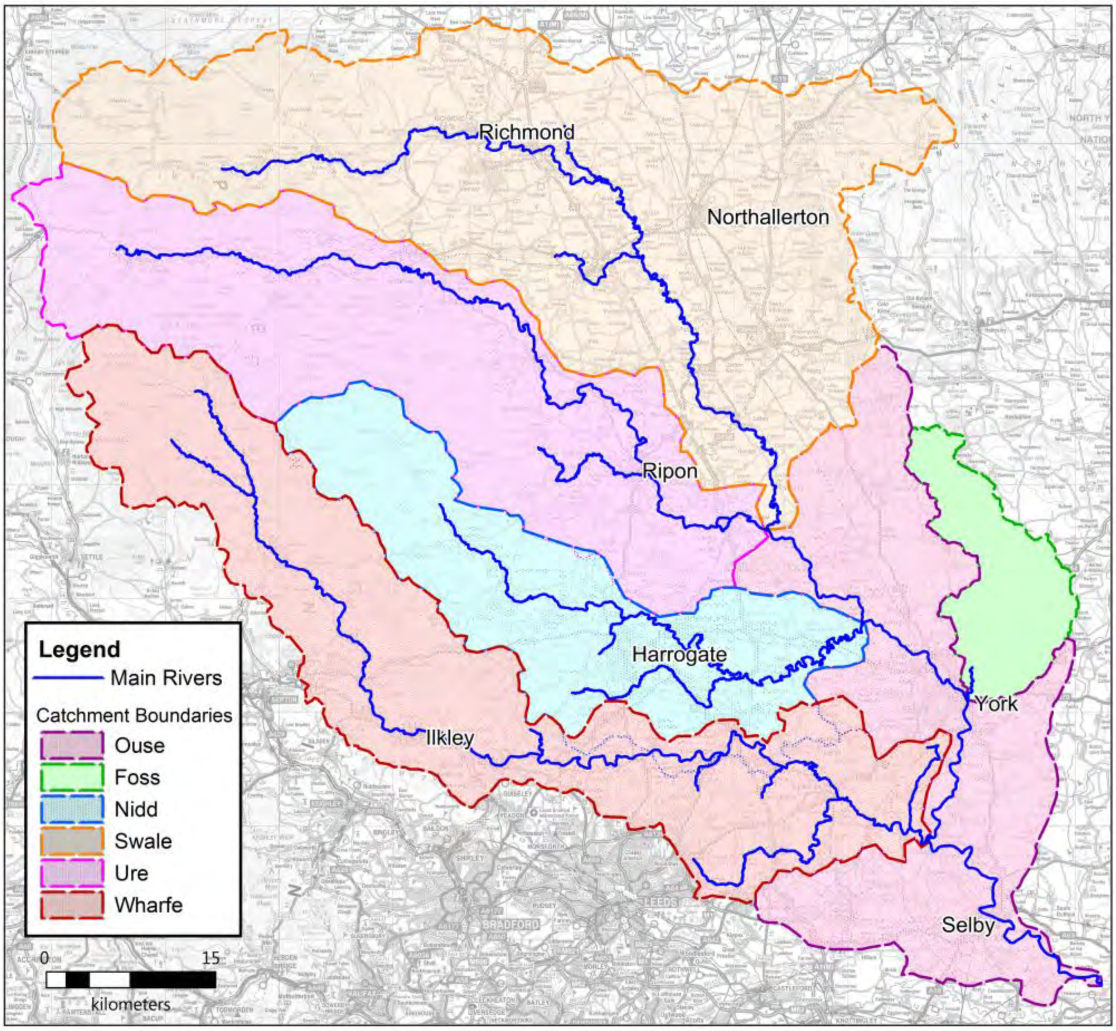

Figure A4: Catchments feeding the River Ouse through York

A.3.1 SUNO Catchment

The River Ouse at York drains a very large catchment with an area of approximately 3,500km^2, including the catchments of the Rivers Swale, Ure and Nidd (collectively referred to as the SUNO catchment). This is a predominantly rural catchment dominated by grassland and agricultural areas. The headwaters, dominated by peat moorland, extend over much of the Yorkshire Dales which is where the greatest proportion of rainfall is concentrated.

The large catchment will present significant opportunities to implement runoff based NFM measures which could be targeted at the upper and mid areas of these catchments. Storage of water in these areas could have the potential to impact flood flows downstream. Changes to catchment management have the potential to reduce runoff and to store water in fields or uplands, and there is potential for increased storage of flow in the headwaters through peat restoration.

However, the size of the SUNO catchment is a potential barrier to the effectiveness of NFM. A flood event in York could result from a high flow event in any of the SUNO catchments therefore NFM measures would need to be implemented across a very large area requiring significant investment. The evidence in favour of NFM is associated with catchments of the order of 10km^2, whereas there is a lack of evidence to suggest that they would be successful in a catchment the size of the SUNO where the maximum annual flood is usually in excess of 300m^3/s and the 1 in 100 year flood of the order of 600m^3/s. In comparison the available evidence is from significantly smaller flood events. Floods in York also tend to be associated with a large volume of water. The storage capacity of NFM measures are likely to get overwhelmed early in a flood event and would consequently have less impact on the peak flow. In addition, events in York tend to result from long duration winter events in which the upper catchment becomes saturated. This would fill up available storage for prolonged periods in winter months and make NFM measures much less effective.

The existing flood defence infrastructure means that in all but the most extreme flood events, York can go about its business as usual. It is the large, extreme flood events where York requires additional protection and it is these events where questions remain as to the effectiveness of NRM. Whilst the SUNO catchment presents great opportunities to implement NFM measures which could bring benefits locally, given the scale of the floods in York they are unlikely to be effective in attenuating extreme events.

A.3.2 River Foss Catchment

The River Foss drains a much smaller catchment than the Ouse. The watercourse rises on Yearsley Moor and flows in a southerly direction through The Vale of York before discharging to the River Ouse downstream of the Foss Barrier. The catchment is relatively low lying draining an area of approximately180km^2 including the Main River tributaries: Tang Hall Beck and Osbaldwick Beck. The upper reaches are predominantly rural (mainly arable and grassland), whilst in its lower reaches the watercourse flows through Huntington into the centre of York.

There is great potential to implement NFM measures throughout the Foss catchment, particularly in the rural areas in the upper and mid reaches and along the tributaries. As with the SUNO catchment, rainfall is greatest in the headwaters of the main River Foss and the tributaries. The annual maximum flood on the River Foss usually falls between 10 and 15m^3/s and therefore is more comparable with those flood events discussed in the literature review, relative to the Ouse flood flows. Therefore the implementation of NFM is considered more likely to be effective in the Foss catchment. Further analysis of the catchment is however needed to identify and quantify the most appropriate opportunities, and target them to areas where they will provide the greatest benefit.

A critical consideration to implementation of NFM measure in the Foss catchment is the Foss Internal Drainage Board (IDB). The Environment Agency Main River designation ends downstream of Westfield Beck and New Earswick, upstream of which the River Foss becomes the responsibility of the IDB. Implementation of any NFM measures would need to be undertaken in partnership with the IDB.

A.3.3 Pickering – Directly comparable?

Following the winter floods many comparisons have been drawn between the events in Pickering and York and the impact that the flooding had on both urban areas. Comparisons between the Pickering and Foss catchments during the Boxing Day floods in 2015 are presented in Table A3. Due to the scale and complexity of the catchments comprising the SUNO catchment this has not been included in this comparison.

	Pickering Catchment*	Foss Catchment†
Catchment Size	$69km^2$	$180km^2$
Rainfall total	50mm	>100mm
Duration of event	36hr	36hr
Event type (peaks)	Single Peak	Single Peak
Antecedent Conditions	Wet	Wet

Table A7: Comparison of the Pickering and Foss catchments during the Boxing Day floods (December 2015).

*****Slowing the Flow Partnership (2016) † Environment Agency (2016b)

Table A7 demonstrates that the catchments are not directly comparable with regard to either the catchment characteristics or the magnitude of the event experienced during the December 2015 event. The analysis carried out in Section A2.4 outlines the limitations related to larger scale catchments and higher flow events and highlights the need to evaluate the effectiveness of NFM on a catchment specific basis.

Whilst it may not be possible to directly translate the results of NFM seen in Pickering to the Foss catchment, the work at Pickering was nevertheless shown to be effective at reducing peak flows during the December 2015 event. When compared to similar events in 2008 and 2009 (50mm rain over 24-36hrs) the December peak flows were noticeably lower - $9.9m^3$/sec instead of 12 m^3/sec and $12.1m^3$/sec in 2008 and 2009 respectively – suggesting that the catchment measures reduced peak flows by $2m^3$/sec, or 15-20%. Whilst it is difficult to separate contributions from different aspects of the scheme, based on the extent of inflows to the flood storage area it is estimated that half of the reduction can be attributed to upstream land management measures and the other half to the flood storage area (Slowing the Flow Partnership, 2016). This demonstrates the benefit of using catchment wide NFM measures in conjunction with more traditional, harder engineering solutions.

Ultimately, further analysis of both the SUNO and Foss catchments is required to determine how the opportunities that NFM presents could be applied, and how effective they are likely to be. Whilst it may be necessary to sub-divide the large catchments for the purpose of measure identification and analysis, it is critical that any programme of NFM considers the catchment in its entirety to maximise benefits and avoid synchronising flood peaks. The SUNO and Foss catchments must also be considered in conjunction with one another to avoid increasing flood risk through York.

Management of expectations will be crucial in York. NFM will not 'solve' flooding in the city but can be used to complement existing flood risk management techniques. Stakeholder engagement must be a principal component to the implementation of any NFM scheme in the SUNO and Foss catchments.

A.4 Conclusions

This review has shown that NFM measures have the potential reduce runoff from the catchment and slow the flow of water downstream, reducing the flood peak and giving communities greater time to prepare for flood events. Although local measures may contribute to reducing flood risk on small catchments for low magnitude events, there is no general ‘quick fix’ to alleviating the impacts of extreme rainfall and flooding on medium to large catchments (Archer et al., 2016).

NFM can bring multiple benefits but it is important to appreciate them in context – both spatial and temporal– and to understand the limitations of scale and implementation on the ground. Using a combination of the NFM measures discussed above will enable delivery of a co-ordinated, whole catchment approach to managing flood risk that draws on the individual strengths of different techniques (Nicholson, 2014).

The evidence to date (Sections 3.1 and 3.2) is largely based on modelled evidence in catchments approximately $10km^2$ in size. Whilst measures have been shown to be effective at this scale, there is little empirical evidence available, and there are limitations associated with scaling up the impacts.

In the context of York, there is the potential for NFM to be implemented both the SUNO and Foss catchments. However, based on the evidence available to date, it is likely that measures would be more effective in the smaller Foss catchment. Due to the heavily protected nature of York city centre it is considered that any NFM measures that are implemented would act as an additional benefit to complement existing flood risk infrastructure and provide additional climate change resilience.

There are additional complications in delivering NFM within the SUNO and Foss catchments – for example the extensive IDB network within the Foss catchment and potential conflicts of interest with regard to management of these lowland areas. Further studies are required in both catchments to determine how NFM opportunities could be implemented on the ground and how effective they are likely to be.

Table A7 demonstrates that the catchments of Pickering Beck, the River Foss and the SUNO catchment are very different – with regard to both catchment characteristics and the events of 2015.

Whilst the events in York and Pickering are not directly comparable, the NFM work undertaken in the Pickering Beck catchment has been shown to be effective in reducing flooding in the town of Pickering. In particular the combination of traditional ‘grey’ engineering flood storage mechanisms alongside the implementation of NFM measures is something that should be considered when considering NFM measures in the SUNO and Foss catchments. Based on the current public perceptions of the comparability of the catchments and their responses to the 2015 events, management of the expectations of NFM will be key in York.

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A.1 Appendix A: NFM Case Studies

This appendix contains fact sheets on key pilot catchments around the UK that have shown the benefits of implementing NFM measures within a catchment. Details of the location and background of the sites, as well as the NFM measures implemented and any measured results are presented.

The following case studies have been reviewed:

Case Study 1: Pickering: Slowing the Flow

Case Study 2: The Belford Project

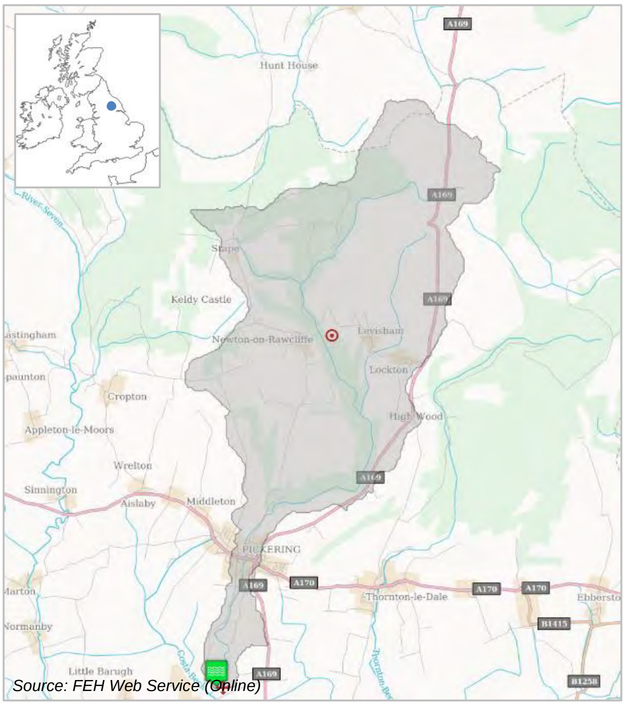
Case Study 3: The Pontbren Initiative

Case Study 4: Holnicote: Source to Sea

Case Study 5: Peak District: Making Space for Water'

Case Study #1

Pickering: Slowing the Flow



Source: FEH Web Service (Online)

Location: Pickering, North Yorkshire

Cost: £3.2M

Catchment size: 69km^2

Project Partners: Defra (lead funder), Forest Research (Project lead), Forestry Commission England, Environment Agency, North York Moors National Park Authority, Durham University, Natural England, Local Authorities.

Representatives of all partner organisations form the Slowing the Flow Partnership Board.

Project Background: 'Slowing the Flow' at Pickering is one of three Defra commissioned pilot schemes initiated in response to the 2007 Pitt Review.

Pickering Beck flows through the town of Pickering in North Yorkshire, fed from the North York Moors to the north. The River Severn catchment is located adjacent tot to the Pickering Beck catchment and flows through the town of Sinnington. Both towns have longstanding problems with flooding with millions of pounds of damage to homes and businesses sustained in Pickering between 1999 and 2007.

Proposals for a capital flood alleviation scheme in the town were shown unaffordable when set against national cost-benefit thresholds. Instead a catchment scale, land management approach was devised to deliver flood protection by 'working with natural processes'. A central part of the approach was to better understand how floods are generated in a catchment and how land use and management affects the speed and volume of flood flows. Most intervention measures were targeted at the Pickering Beck catchment although some measures were implemented on the River Severn, helping to alleviate flooding in Sinnington.

Scheme Outline: At the core of the whole-catchment approach at Pickering is the implementation and evaluation of a number of land management interventions to help slow down and reduce flood flows. By attenuating flow upstream, water flow can pass through Pickering within an identified safe conveyance level, alleviating pressure at major pinch points such as at the Ropery Bridge. The storage solution includes a combination of natural catchment measures and traditional floodplain storage.

<u>Natural Catchment Measures</u>

This aspect of the project was led by the Forestry Commission. Opportunity mapping was carried out by Forest Research and hydraulic/hydraulic modelling by Durham University to identify locations where the watercourse could be reconnected with the floodplain, consequently slowing the flood of water downstream. The range of interventions includes:

•**Construction of large woody debris (LWD) dams** – 129 timber dams were constructed in the upper catchment area of Pickering Beck. The dams consist of a "leaky" framework of logs and branches that straddle the water course, secured in place by wedging and wiring the logs to bankside stumps or posts. At £55-500 each to build, depending on size, they represent a relatively cheap and sustainable option for flood storage. The leaky nature of the dams also means that passage of fish is unaffected.

Large Woody Debris Dams encouraging out of bank flow

•**Construction of timber bunds** – a larger version of the LWD dams. Two were constructed in the River Seven catchment as part of a trial. They are 16.5m wide and

57.5m wide, each with a 1.5m high wall of stacked logs across the full width of the floodplain to form a leaky bund.

•**Blocking moorland drains and controlling erosion** – three moorland drains identified as discharging too much run off were blocked. Nearly 200 small check dams were assembled using heather bales, helping to alleviate run off from other drainage points. Reseeding of other sites and repair of footpaths also helped reduce run off.

•**Establishing no-burn buffer zones** – heather burning can exacerbate surface run off by reducing roughness of soil and increasing its hydrophobicity. Ten-metre zones were established alongside watercourses to protect riparian vegetation and soils.

•**Planting riparian and floodplain woodland** – 19ha of riparian woodland was planted within the Pickering Beck catchment and 10ha in the River Seven. This technique can be effective by increasing channel and floodplain hydraulic roughness, delaying flood flows and raising upstream water levels (i.e. flood storage).

•**Planting farm woodland** – land use for farming, both arable and livestock, can lead to increased run off through compaction of soil, whereas woodland planting increases soil infiltration and water evaporation. 15ha of farm woodland was planted in the River Seven catchment.

19ha of riparian woodland planted in the Pickering catchment

•**Farm scale measures** – examples include installing sediment ponds, swales and check dams, cross drains on tracks and small scale storage. This approach involved close engagement with farmers and advising them of grant support on offer to implement such measures.

Flood Storage

The Environment Agency led the more traditional flood storage approach. 2km upstream of Pickering, a suitable site was found for the construction of a bund (large raised reservoir). The reservoir has a capacity of 120,000m^3 and consists of a 1km embankment split into two sections: a spillway 2m above natural ground level and a lateral embankment protecting the adjacent North York Moors railway. A concrete control structure in the centre of the embankment restricts flow downstream to 14.5m^3/s.

Bund at Newbridge providing flood storage

Benefits/ Results:

•Reduced risk of flooding in the town of Pickering – analysis of the Boxing Day floods of 2015 suggests that the risk of flooding has reduced from a 25% chance in any given year to less than 4%.

•A strong and enthused local partnership in place to take the project forward, by maintaining the implemented measures and seeking opportunities to extend them to further reduce the risk of flooding in Pickering and Sinnington.

•An engaged local community, who have embraced the concept of working with natural processes and believe that this approach makes a positive difference to flood risk management – the scheme having performed successfully already during high rainfall events in 2012 and 2015.

•An exemplar site where natural catchment management approaches have been used alongside more traditional flood storage methods to reduce flood risk downstream.

•A more joined up approach to flood, water and land use management across the catchment driven by strong local and regional partnerships.

•Raised awareness of multiple benefits/ services provided by working with natural processes and has informed better economic evaluation of ecosystem services.

•Greater national awareness and consideration of the benefits of working with natural processes and positive influence on Government policy and support for woodland creation.

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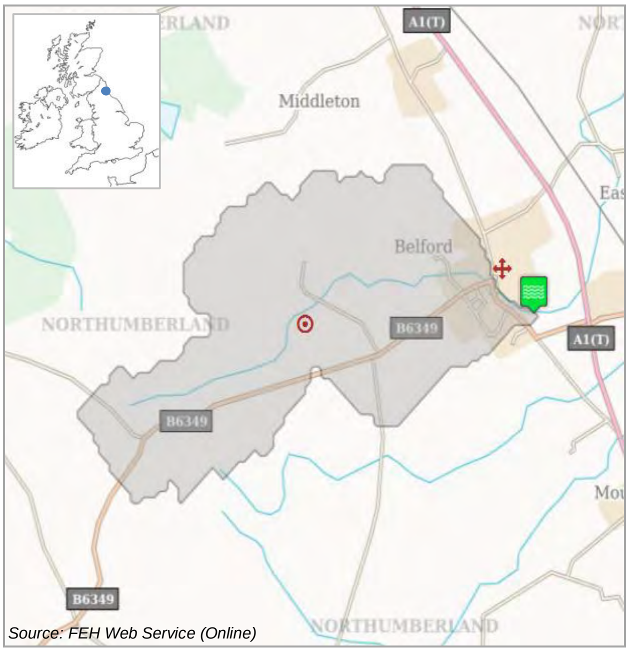
Case Study #2

The Belford Project



Source: FEH Web Service (Online)

Location: Belford, Northumbria

Cost: £300k

Catchment size: 10km^2

Project Partners: Environment Agency (North East Flood Levy team), Newcastle University, Northumbria Regional Flood Defence Committee (Project Funders)

Project Background:

The rural community of Belford, Northumberland, has a population of about one thousand and is at high risk of flash flooding from the Belford Burn which runs through the town. The catchment to Belford ranges from upland pasture to lowland arable farmland. During periods of heavy rainfall, water flows quickly off the land and into the many watercourses before passing through the centre of the town. Flooding in the town resulted in regular inundation of properties.

Funding for a traditional flood defence scheme could not be justified due to high cost, lack of space for flood walls / banks and the low number of properties at risk. The Northumbria Regional Flood Defence Committee allocated funding to implement a catchment management scheme to deliver an effective, sustainable and economically viable approach to reduce flood risk for the town.

A partnership project between the Environment Agency and Newcastle University was established with the aim of working with landowners upstream of the town to reduce flood risk and deliver other improvements in the catchment.

Scheme Outline:
The Belford Project started in 2007 and began with the aim of constructing dozens of flow intervention structures in the catchment upstream of the town. A variety of different techniques have been used to slow and store flood water during time of heavy rainfall.

Techniques that have been used include:

- Online ponds
- Offline ponds
- Measures that intercept overland flow (including bunds and ponds)
- Large Woody Debris
- Features to increase channel and floodplain roughness

Online and offline storage features - involve either a bund across the river channel or a bund adjacent to the river that excess water spills or is diverted in to. The features work by storing water when the river is high, and releasing it slowly back to the river after the peak has passed. Some of these ponds have been designed to hold water all year round to provide additional ecological benefits.

Offline storage area created using leaky timber bund to enable slow release of flow back to the watercourse.

Series of offline ponds that also act as sediment traps.

Intercepting Overland Flow Pathways – to slow overland flow and trap sediment being washed from the fields. Bunds have been constructed across overland flow pathways to intercept flow. Where possible these were constructed using local materials and were built in the lowest and therefore dampest, parts of the fields. In addition to slowing and storing rapid runoff these can be used to reduce sediment runoff from fields.

Dams across agricultural field drains to back water up and slow the flow. These are built raised from the bed to allow low flows to pass under the dam and backing water up in higher flows.

Bunds across known surface water flow paths to retain runoff and sediment. This bund acts as a track, elevated above the saturated ground, enabling access to the rest of the field and providing an additional benefit for the farmer.

Large woody debris - has been installed in woodland to slow the flood peak and divert it on to the floodplain. Planting shrubs and pinning timber to the woodland floor has provided greater roughness. Techniques such as fencing of watercourses and planting bank-side vegetation have complemented the other, more formal, interventions.

Benefits/Results:

The project has demonstrated the multiple benefits that can be achieved through the thoughtful implementation of a variety of features. The benefits include:

- Reduced flood risk downstream
- Reduced levels of diffuse pollution
- Habitat creation
- Increased biodiversity
- Preventing the loss of topsoil and fertiliser from farmland
- Increased farm productivity from re-use of captured sediments
- Additional benefits to farmers, for example bunds may act as tracks across farm land during wet events
- Good engagement with landowners/farmers and the utilisation of local knowledge to help site RAFs in the best locations

References

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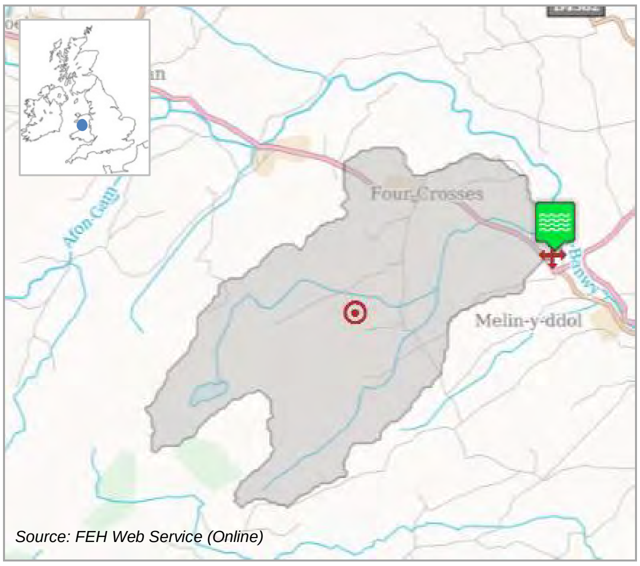
Case Study #3

The Pontbren Initiative



Source: FEH Web Service (Online)

Location: Pontbren Stream Catchment, nr Llanfair Caereinion, North Powys

Cost: Unspecified

Catchment size: Approx.1,000ha (10km^2)

Project Partners: Ten neighbouring farms along with The Pontbren Farmers Group which includes, amongst numerous others, ADAS, CEH, Coed Cymru, Countryside Council for Wales, Welsh Assembly Government, Defra, EA, Forestry Commission, LEADER, Scottish Power, and Enfys.

Project Background:

The Pontbren Initiative consists of ten neighbouring families who farm about a thousand hectares in the catchment of Pontbren Stream near Llanfair Caereinion in North Powys. The Pontbren project is a result of neighbouring farmers coming together to provide an economically viable management plan for their land in the face of increasing costs and unsustainable practices.

Initial woodland planting and hedge restoration projects were paid for by the farm businesses, with additional funding provided by farming and forestry grants from the LEADER scheme. Scottish Power's Rural Care Scheme supported the scaling up of these improvements as more farms joined the project. Funding for hedgerows, ponds and wetlands restoration came from the lottery-funded programme Enfys. Woodland planting projects were supported by funding from the Woodland Trust.

Due to the nature of the project it has received a lot of academic attention and has been used as a pilot site to assess the impact of woodland planting on catchment hydrology for a considerable length of time.

Scheme Outline:

It began in 1997 with a group of three neighbouring farmers planting hedges and trees to provide more shelter for livestock grazing on steep, windswept land. By 2001 ten farmers were managing 1,000 hectares of farmland across the catchment. The Pontbren project is an example of the environmental benefits of farm woodland. Water management is being made more sustainable by restoring and re-establishing the traditional farm ponds and wetlands.

Tree Planting – over 120,000 trees have been planted within the catchment. Research has shown that where trees have been planted the infiltration rate of the soil is greatly increased, thereby reducing the runoff from the steep sided hills into the watercourses at the bottom of the valleys.

Hedgerow and Shelterbelt Planting – Over 26km of hedgerow have been planted throughout the catchment. These provide shelter for livestock, increase diversity and have the added benefit of preventing stock

When planting began only 1.5% of the catchment was woodland, now more than 5% of the Pontbren land is woodland.

Restoration of ponds and wetlands – 12 ponds covering 5.4acres of ground have been established and wetlands have been fenced off to ensure protection. These have great biodiversity benefits and provide some additional runoff attenuation in high rainfall events. These ponds also act as a source of irrigation for surrounding fields.

Sustainability measures – a tree nursery has been established as part of the project and all the trees and hedgerows planted are grown in peat free compost from seed gathered on the farms. Offcuts and windfalls from trees and hedges are recycled to create woodchip bedding for livestock.

Woodchip used for livestock bedding is one of the many sustainable practices in use on the farms in the Pontbren catchment.

Benefits/Results:

An unintended benefit of the Pontbren project that became apparent during the course of the tree planting work was the improvement to soil structure and the subsequent impact upon catchment hydrology. As a result of observations initially made by the farmers' and Coed Cymru staff in 2001 (after initial planting stages), detailed research work was then undertaken by the Flood Risk Management Research Consortium (FRMRC)3, with the project site providing an ideal field-study location for research on a catchment scale. Pontbren has also been a site for Welsh Government funded work on water quality and has been linked to numerous other R&D projects and PhD studentships.

The benefits of the catchment scale work undertaken as part of the Pontbren Initiative include;

- Increase in woodland with no loss in agricultural productivity
- Successful integration of woodland management into upland livestock farming has also 'future-proofed' their farms, by improving the capital value of the land, making it more resilient to the effects of severe weather events as the climate changes
- Improvement in the biodiversity of the catchment including the return of Otters and Water Vole sightings. Three bird species on the UK Red List of species of highest conservation concern and nine on the Amber List are present in the catchment.
- Increase in infiltration rates as a result of woodland planting. Soil infiltration rates were up to 60 times higher where young native cross slope woodlands were planted when compared to adjacent heavily grazed pasture (Carrol *et al.,* 2014). In 2014 median soil infiltration rates were shown to be up to 67 times greater in plots planted with trees compared to grazed pasture. In addition to this, surface water runoff volumes were reduced by up to 78% under trees when compared with the grassland plots (Marshall *et al.*, 2014).

A key factor in the success of Pontbren has been the farmers – collaborating as a group, co-operating with the scientists, but each remaining firmly in control of the management decisions on their own land.

Pontbren landowners who have been integral to the ongoing success of the project.

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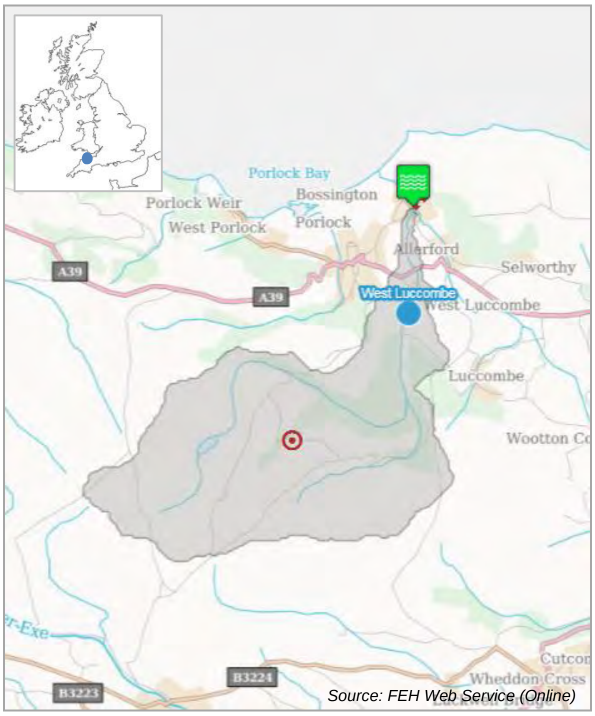
Case Study #4

Holnicote: Source to Sea



Source: FEH Web Service (Online)

Location: Holnicote Estate, Porlock, Somerset

Cost: £722k

Catchment size: 22km^2

Project Partners: Holnicote Estate, The National Trust, Defra, Environment Agency, Penny Anderson Associates, JBA Consulting / JBA Trust

Project Background:

Horner Water drains the hills of Exmoor to the confluence with the River Aller, from where the combined river flows into Porlock Bay seeping through a large shingle ridge. The key flood risk receptors in the catchments are the villages of Allerford, West Lynch and Bossington. 90 properties in these villages are at risk of flooding from the watercourses, which are influenced by a legacy of flow constrictions within the drainage networks, such as narrow historic stone bridges, and the lack of undeveloped channel and floodplain capacity through the built-up areas.

In 2009, in response to one of the recommendations of the Pitt Review of the Summer 2007 Floods, Defra commissioned three new projects as part the Multi-Objective Flood Management Demonstration Scheme. This scheme aims to generate hard evidence to demonstrate how integrated land management change, working with natural processes and partnership working can contribute to reducing local flood risk while producing wider benefits for the environment and communities.

In Holnicote the aim is to demonstrate that by looking at whole catchments and strategically targeting changes in land use management practices, sustainable support to flood management may be achieved. In addition, it is recognised that through rural land management change and intervention comes the opportunity to enhance the provision of a range of other ecosystem services including landscape quality, biodiversity, carbon sequestration, water quality, amenity and recreation.

The gathering of empirical evidence has been a central project objective and a robust hydrological monitoring programme has been set up across the catchment.

Scheme Outline:

A range of assessment and analysis techniques were employed to explore how hillslope runoff generation and hydrologic connectivity issues could be tackled across the Aller and Horner Water catchments. The team identified where opportunities existed to enhance flood attenuation functions, either in-channel, on hillslopes or on the wider floodplain areas, through targeted interventions and modifications. The placement of these changes has been mindful of how they might affect the hydrological response downstream.

A range of potential catchment change interventions have been explored across the study area, including:

Moorland restoration in the headwaters – including heather restoration, grip blocking, surface drainage management (on tracks, paths and roads). Hundreds of shallow earth bunds have been installed to intercept rapid flow pathways, slowing the flow and redirecting floodwater back onto the moorland surface where there are further opportunities for infiltration and temporary storage.

'Catch pools' on Exmoor created to slow the flow downstream and encourage re-saturation of moorland areas.

Woodland extension – afforestation up onto the edge of Exmoor

In-channel woody debris dams – to slow the flow of water as it travels downstream and to reconnect the floodplain by encouraging out of bank flow. These include artificially created dams using natural materials and the cessation of woody debris removal management and allowing fallen trees to remain in the channel where they fall.

Natural woody debris dams on Horner Water and the River Aller.

Creation of flood meadows – earth banks / bunds have been installed on the middle Aller floodplain upstream of Allerford. These retain water during high flow events and controlled pipe outlets through the bunds allow water to be released back to the watercourse after the flood peak has passed.

Shallow scrapes were excavated on the Aller floodplain to provide additional habitat for wetland birds and other wildlife.

Implementation of best practice - in-bye grassland and associated soil management and arable soil management.

Benefits/Results:

- Demonstration of practical implementation of measures
- Close stakeholder / landowner partnerships established
- Flood meadows have worked effectively to slow down and temporarily store floodwaters on the Aller floodplain. The newly constructed offline bunded flood storage areas helped to deliver a 10% reduction in flood peak during a severe storm in late December 2013 on an already saturated catchment. Fine sediment was also effectively retained on the floodplain.
- Greatest water quality impairment was observed in the most intensively farmed central part of the Aller catchment associated with arable land use, so results suggest that wherever possible arable reversion to grassland especially on steeper slopes should be encouraged, together with riparian woodland.

Flood storage area in use during 2013 flood events. Storage of water on these bunded floodplains helped to prevent water ingress to properties in Allerford. Close engagement with landowners and farmers has been crucial to enable delivery of farm based measures.

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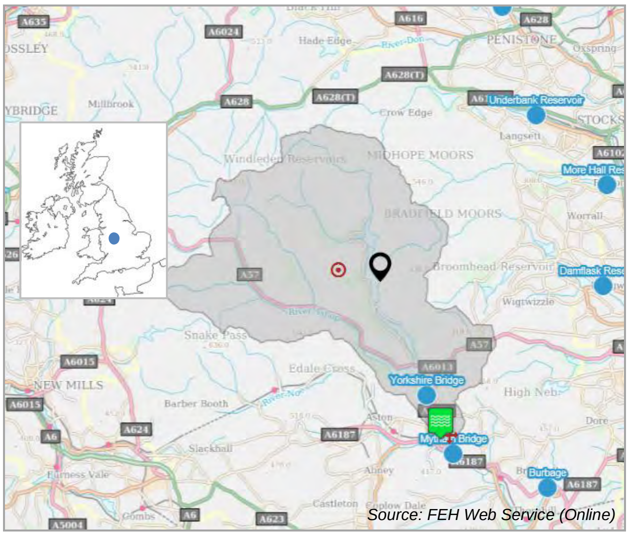
Case Study #5

Peak District: Making Space for Water


Source: FEH Web Service (Online)

Location: Upper Derwent Valley, Peak District National Park

Cost: Unspecified

Catchment size: Approx. 130km^2

Project Partners: Moors for the Future Partnership, Environment Agency

Project Background:

The Upper Derwent catchment, located within the Peak District National Park, is a major source of water for regular flood events affecting the entire length of the River Derwent including the Lower Derwent and City of Derby, downstream into the Trent towards Nottingham and beyond. The upland catchment for these regions in the Peak District is predominantly moorland, giving way to extensive areas of farmland.

The Making Space for Water in Project aims at demonstrating how practical restoration of degraded moorland can add benefit to reducing flood risk at the same time as delivering other benefits. Practical work conducted could reduce the impact of flooding downstream by holding water back and increasing the time it takes for rainwater to reach the river during a storm. The project aims to restore presently heavily eroded moorland by blocking erosion gullies and re-establishing vegetation on bare soils.

Scheme Outline:

A suite of moorland restoration measures were implemented throughout the catchment and the impacts monitored to determine the effects on downstream flood risk and biodiversity.

Revegetation - Moors for the Future have re-seeded 600 hectares (equivalent to 1200 football pitches) to prevent the erosion of peat, which contributes to carbon emissions. The re-seeding used 8 billion grass and heather seeds. 150,000 dwarf shrub plug plants have been planted on the moors, with the assistance of volunteers and 15,000 cottongrass plants were grown from seed by volunteers between 2004 and 2007 and planted.

Planting of moorland plants by volunteers

Grip / Gully Blocking - Gullies are naturally formed channels, whereas grips are cut, primarily for agricultural or shooting reasons. Gully (as opposed to grip) blocking has formed the majority of the work carried out as part of the Making Space for Water Project; however grip blocking is a major issue in some other parts of the country, such as the North Pennines AONB.

Gully blocking involves blocking or ‘damming’ eroding channels within the blanket bog and raise the water table, thus addressing hydrological issues which are fundamental to a healthy moorland habitat. Gullies have been blocked using a variety of materials including wood, plastic, stone, peat and heather.

Creating stone dams across deep gullies in the Peak District National Park

Raising the water table reduces the effects of wind erosion and helps support plants (both new and existing). One of the other benefits is that if the water is slowed down by this process it could reduce the chances of flash flooding further down the catchment (e.g. in towns and cities).

Series of gully 'dams'holding back water and re-wetting moorland

Grazing control – there were an estimated 116,000 sheep grazing the Peak District in 1994, stripping native moorland vegetation and replacing it with less edible grassland species. In April 2003 a 31km fence was erected around a 25.2km^2 area of Bleaklow to prevent young growth being eaten.This was funded by an ESA stock exclusion payment. Managing stocking densities through the use of agri-environment scheme subsidies has significant lowered grazing numbers and reduced the pressure on moorland vegetation.

Benefits / Results:

The following key findings have come out of the Moors for the Future Project with regard to flood risk;

Restoration by re-vegetation and gully blocking has had statistically significant effects on peatland hydrology and storm-flow behaviour, specifically:

- o Reducing depth to water tables (up to 38%);
- o Increasing overland flow production (up to 18%);
- o Increasing storm-flow lag times (up to 267 %);
- o Reducing peak storm discharge (up to 37 %);
- o Attenuating storm hydrograph shape (up to 38 % reduction).

1. Gully blocking has apparent additional benefits for attenuating flow, but these are not statistically significant.

2. The observed changes are consistent with the hypothesis that re-vegetation and gully blocking has an increased surface roughness effect. Surface re-vegetation reduces overland flow velocities, and gully blocks and associated gully floor re-vegetation may also reduce in-channel velocities.

3. Peat restoration by re-vegetation and gully blocking has benefits for downstream flood risk reduction by 'slowing the flow' in peatland headwater catchments, but modelling is required to evaluate the benefits at larger catchment scale.

4. However, there has been no change in percentage runoff within storm events (i.e. the proportion of storm rainfall producing discharge).

There have been numerous additional biodiversity and ecosystem services benefits as a result of this project.

References:

Moors for the Future Partnership (2015) *Restoration of Blanket bogs; flood risk reduction and other ecosystem benefits* Annex 5. Flood Risk. Final report of the Making Space for Water Partnership [Online] Available at: http://www.moorsforthefuture.org.uk/sites/default/files/Annex%205.Flood%20Risk_0.pdf

Moors for the Future Partnership (2017) *Making Space for Water* [Online] Available at: http://www.moorsforthefuture.org.uk/making-space-water