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Annex 9: Flood mitigation

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1 Introduction

The Welsh Government (WG) brief for this review is to:

- *"identify management interventions which have a quantifiable positive impact on flood alleviation; and to*
- *review the evidence base to assess the ability to spatially target management interventions to deliver tangible flood mitigation and risk reduction outcomes."*

Natural Flood Mitigation (NFM) aims to restore, conserve and enhance natural processes that mitigate flood flows. The diversity of potential measures, the many contexts of application and the lack, or inconsistency, of evidence mean that this is a challenging area to review. Our review is largely based on the Environment Agency's Working with Natural Processes Evidence Directory; thus, it does not represent a comprehensive independent assessment of the scientific literature. However, it does provide a useful synthesis of the most comprehensive evidence review available to underpin WG consultation on their new Sustainable Farming Scheme (SFS).

It is important to point out that in many cases the potential reductions in flood risk are not quantified, and that much of the evidence of effectiveness is based on modelling of the impact of interventions of flood risk, because of the scarcity of empirical data of the observed effects during real flood events.

2 Outcomes

Reduced flood and coastal risk through natural management of floodplains, farmland, woodland and associated small water bodies.

3 Policy Relevance and Policy Outcomes

Closely aligned to two Natural Resources Policy (NRP)[1] priorities:

- Maintaining, enhancing and restoring floodplains and hydrological systems to reduce flood risk and improve water quality and supply; (including catchment management approaches, natural flood management, soil management).

- Restoration of our uplands and managing them for biodiversity, carbon, water, flood risk and recreational benefits.

[1] https://gov.wales/natural-resources-policy

4 Introduction to the Interventions

The main sources used for this review were the following key review reports, supplemented by other relevant literature:

- the 2018 *Working with Natural Processes (WWNP) – Evidence Directory* by the Environment Agency (Burgess-Gamble et al., 2018) and the related literature review[2] *Working with Natural Processes* to reduce flood and coastal erosion risk (Ngai et al., 2017).
- the CEH systematic literature review addressing the question *Do trees in UK-relevant river catchments influence fluvial flood peaks?* This was based on a search of peer-reviewed literature, identifying studies with similar climatic characteristics as UK catchments, but discounting those that did not specifically report the impact of decreasing or increasing tree cover on river floods (Stratford et al., 2017).

The interventions reviewed here are based around the WWNP classification, with a focus on flood mitigation measures of relevance to the SFS (but excluding estuary and coastal management). They are divided into the following three broad groups, each of which covers several interventions related to farmland or woodland management in different parts of the river system:

River and floodplain management

Woodland management and creation for the purpose of flood alleviation

Management of run-off from land in the catchment

4.1 Intervention – river and floodplain management

The main aim of this group of interventions is to slow down and store floodwaters as they pass through the floodplain. The interventions relevant to the SFS[3] are:

- Restoration of floodplain functions and creation or restoration of floodplain wetlands for the purpose of storing flood water;
- Leaky barriers, which are pieces of wood in river channels and on river banks and floodplains (occurring naturally or constructed by man) to help slow flows and store water;
- Offline storage areas are small to medium sized floodplain areas manipulated to store and attenuate floodwater in a managed way.

4.1.1 Restoration of floodplain functions and wetlands

Restoring floodplain functions and wetlands provides a means of transferring some of the floodwater to temporary storage areas beyond the normal river channel, and to slow down the passage of floodwaters by making the floodplain hydrologically rougher. Nearly all of the research investigating the flood risk management (FRM) benefits of floodplain restoration is model-based.

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[2] A traditional literature review, not a systematic review.

[3] We not consider river restoration, or large online engineered interventions, which are considered to be beyond the scope of the SFS.

4.1.1.1 Floodplain function

Restoring the functionality of a floodplain requires or improving the connection between river and floodplain. This can involve removing flood embankments, lowering floodplains and/or raising river beds. Empirical studies that assess such benefits are rare, and modelling has been used in some way in most research papers, although there are some examples where models use empirical evidence. Because the benefits for FRM of restoring floodplain function are site-specific, these are difficult to predict without hydraulic modelling of the specific floodplain, and assessment of possible effects on flood peak synchronisation (Ngai et al., 2017).

4.1.1.2 Floodplain wetlands

These are semi-natural areas connected to the river channel with a natural capacity to store floodwater for varying periods. There is evidence from studies cited by Burgess-Gamble et al. (2018) that restoring floodplain wetlands has FRM benefits in terms of reduced frequency and increased time lag of flood events, although there is also a potential risk (shared by most WWNP interventions) of peak synchronisation leading to flooding downstream. Their effectiveness is influenced by site-specific factors, especially how well they are connected to the river, and also their location, landscape topography, soil characteristics and type of management (Burgess-Gamble et al., 2018).

4.1.2 Leaky barriers

These are naturally occurring or constructed rough woody barriers across river channels or along the banks, often created by a build-up fallen trees, branches and other woody debris, which help to slow down the water flow. They also occur (or can be created) on floodplains. As with other interventions in this group, the effects are site-specific, but Burgess-Gamble et al. (2018) report evidence that leaky barriers often improve the connection between the river and its floodplain. They can also *'reduce flood risk locally for small events, increase hydraulic roughness, reduce flow velocities, increase the travel time of the flood wave, create temporary storage and attenuate flood flow'* (Burgess-Gamble et al., 2018), but the authors note that much of the evidence for this is modelled, not observed. Notably, empirical evidence for the effect of leaky barriers on flood flows in the New Forest is discussed by Dixon et al. (2016), but these authors warn that leaky barriers may not be a predictable flood mitigation measure. They suggest detailed hydrological modelling should be undertaken to assess site-specific issues. Synchronicity of catchment scale flood flows is critical. Furthermore, where floodplain vegetation is not woody leaky barriers are likely to have less effect in slowing down overbank flows.

4.1.3 Offline storage areas

Offline storage areas within the floodplain are usually created by constructing a containment bund so that more water can be stored temporarily on a floodplain. The summary here covers only small to medium scale offline storage areas, which may be created on farmland, because creating large volume storage areas may be subject to conditions of the Reservoirs Act and therefore unlikely to be suitable for consideration for the SFS.

There is evidence that they can reduce local risks from small flood events, but because their effectiveness is linked to their size, the bigger the catchment the more offline storage capacity is required (Burgess-Gamble et al., 2018). The review notes that further research is needed to assess the performance of offline storage areas within larger catchments, including fully addressing their potential impacts on peak synchronisation (depending on their location within the large catchment scale).

4.1.4 Co-benefits and trade-offs

4.1.4.1 Water quality

Restored floodplains and wetlands were found by Burgess-Gamble et al. (2018) to have co-benefits in terms of removing sediment and nutrients (N and P), but there is also a risk that nutrients may be released during future flood events. They also note that reed beds are effective in reducing sewage pollution (Burgess-Gamble et al., 2018).

4.1.4.2 Ecosystem resilience

Floodplains and wetlands can provide a wide range of habitats (including priority habitats such fens, reed beds and lowland raised bog) and benefits for species that use these as feeding, breeding and resting areas. Benefitting species and taxa include waders, wildfowl, fish, mammals, amphibians and invertebrates. Three quarters of restored wetlands are used by migrating birds (O'Neal et al., 2008 in Burgess Gamble et al., 2018). Depending on their design and level of maintenance, leaky barriers can benefit fish, other aquatic organisms, reptiles and birds (but if allowed to become blocked could limit fish movement) (Burgess-Gamble et al., 2018).

4.1.5 Magnitude

NFM interventions are likely to have largest effect in small catchments (<100 km^2) for small flood events (5-20 year return period). NFM interventions are unlikely to have a major effect on the most extreme events and small-scale benefits have not been shown at large catchment scales (Dadson et al., 2017). NFM interventions may not be effective in mitigating double peaked events, as storage capacity may be overloaded (e.g. Metcalfe et al., 2017).

4.1.6 Timescale and longevity

Restored floodplains and their wetlands do not have a finite lifespan if properly restored and managed (e.g. by preventing natural vegetation succession on wetlands). Leaky barriers are effective immediately but there is little information on their longevity; they are likely to require some maintenance. Offline storage areas also take effect immediately but they are engineered structures with a finite life and the level of maintenance required is related to their design, size and frequency of flooding (Burgess-Gamble et al., 2018).

4.1.7 Spatial issues

The benefits of NFM at small scales do not necessarily combine for larger scale catchments (Dadson et al., 2017; Metcalfe et al., 2017; Hankin et al., 2017a). There are many challenges in obtaining observed or modelled evidence for their effectiveness at large scales (Lane, 2017). The spatial configuration of catchments is very important in relation to the synchronisation of flood flows. Subcatchment interventions that slow flood flows may exacerbate flooding at the larger scale through synchronisation (Dixon et al., 2016; Metcalfe et al., 2017). Furthermore, the effectiveness of NFM interventions will depend on the spatial pattern of rainfall driving the flood event under consideration so account should be taken of multiple extreme event scenarios (e.g. Hankin et al., 2017b). To account for the effect of distributed small scale NFM interventions at the larger catchment scale new modelling frameworks have been proposed (e.g. Hankin et al., 2017a and Metcalfe et al., 2017). The approach of Hankin et al. (2017a) opens up the possibility of evaluating the importance of antecedent conditions as well as sub catchment synchronisation effects. However, as evidence is limited on how the processes being represented in such models are affected by NFM it is very important that uncertainty is integral to all assessments (Lane, 2017 and Metcalfe et al., 2017).

4.1.8 Displacement

Where floodplain wetlands and offline storage features are created or extended there will be displacement of agricultural production. In the case of offline storage areas, most of the displacement will occur only when they are flooded, but the frequency of occurrence and extent of this will of course vary.

4.1.9 Climate interactions

NFM interventions may contribute to adaptation to climate change by mitigating enhanced flooding given future flow predictions. The ability of NFM to offset future flows depends on the catchment type and its location (Kay et al., 2019). NFM is most likely to mitigate future flows under low emission scenarios and early time-slices.

Floodplain soils and wetlands can be important in protecting and increasing soil carbon stores, especially on peat soils (but wetlands can also act as source of methane). Floodplain woodlands sequester carbon and the shade they provide can help to regulate local water temperatures (Burgess-Gamble et al. (2018), citing a number of studies).

4.1.10 Social and economic barriers

Depending on the current agricultural use of floodplains, land managers may be reluctant to adopt interventions to restore floodplain functions if flood events are likely to affect improved land at critical times of year and could have an impact on their business well beyond the period of the flood event itself (e.g. loss of a young crop too late in the season to replace it).

4.1.11 Metrics and verification

Verification for payment is similar to existing WG system for capital grants and environmental land management payments.

4.2 Intervention - woodland management and creation for the purpose of flood alleviation

This broad group of interventions covers three types of location-specific woodlands and also the effects of woodland presence in the catchment as a whole:

- Cross-slope woodland, small areas or strips of woodland across hill slopes, aimed at intercepting runoff from agricultural land further up the slope.
- Riparian woodland, with potential to slow down flood flows.

- Floodplain woodland, subject to flooding and managed for the purpose of slowing flood flows.
- Catchment woodland, the total area of woodland within a catchment and its potential to mitigate floods through several mechanisms including water use, infiltration and surface roughness.

4.2.1 Floodplain woodland

Floodplain woodlands are characterised by being subject to flooding, naturally or deliberately. They range from productive woodlands to native wet woodlands and are often broadleaved. The trees, understorey and woody debris have the effect of slowing down flows by making the floodplain hydrologically rougher than any other vegetation type (five times rougher than grassland), and also by helping to divert the flow into channels and pools. Because floodplains are generally wider in the lower and middle reaches of a river these woodlands are expected to be most effective in these areas within larger catchments. However, most of the evidence of effectiveness comes from modelled studies, and Ngai et al. (2017) point out that the effects of floodplain woodland planting shown by these studies might be due to uncertainties in the models or the values of roughness they use. Although roughness is often represented as a surface using Manning's *n* coefficient, this doesn't account for the drag that may occur[4] (Rameshwaran and Shiono, 2007). In the absence of catchment level studies, there is insufficient evidence on the impact on flood peaks. For example, Dixon et al. (2016) showed that forested floodplains (upper and middle catchment) have a general impact of reducing flood flows at the catchment outlet, but when subcatchment flows are slowed the possible synchronisation with downstream flows and increased flood risk should be considered (Dixon et al. 2016). Floodplain woodland is effective only if it is able fully interact with flood flows, which may require the removal of any existing embankments or other barriers (Burgess-Gamble et al., 2018).

4.2.2 Catchment woodland

Catchment woodland is of many different types and species, and includes plantations, cross-slope, riparian and floodplain woodland. There is good evidence of the different ways that catchment woodland can affect flood generation processes (see Nisbet et al., 2011).

A systematic review of the impact of catchment woodlands on floods was undertaken by CEH (Stratford et al., 2017). When considering all evidence together, only distinguishing between increasing or decreasing tree cover, they found broad support that trees influence flood peaks. Increasing the amount of tree cover resulted in a decrease in flood peaks and decreasing tree cover resulted in the reverse. However, if a distinction is made between model and observational based studies the conclusion is less clear. Most statements supporting the relationship between increasing and decreasing tree cover and peak flows originated from model based studies. The observational based studies give more mixed results. When further distinguishing evidence on the basis of flood magnitude, they found that peak flows of small events were reduced by increasing tree cover but large events were not influenced. However, the number of studies in all cases was small. A similar systematic review by Carrick et al. (2018) reported, based on a limited number of observed studies (n=7), that increased tree cover reduces channel discharge.

[4] Manning's *n* is a coefficient that represents the roughness or friction of the watercourse.

However, as they found the effect was small and variable and the likelihood of confounding and publication bias was high, the overall strength of evidence is low.

Stratford et al. (2017) also emphasise the importance of effect modifiers, which may explain some of the variability in the relationship between trees and flood flows.

4.2.3 Cross-slope woodland

These are strips or patches of woodland strategically located across the slope of agricultural land with the aim of intercepting the run-off from higher up the slope, especially during heavy rainfall.

There has been only one observational study of the effect of creating cross-slope woodland, on improved grassland in a headwater catchment at Pontbren in mid-Wales. Some studies had linked higher stocking densities to increased surface runoff, and therefore the Pontbren study compared recently planted strips of native broadleaf trees to both grazed and ungrazed pasture. On average, compared to the grazed pasture, runoff volumes were reduced by 48% in ungrazed pasture and by 78% in the woodland, and five years after tree planting soil infiltration rates were 67 times greater in the woodland than in the grazed pasture. Further work is needed to understand the full impact of trees as they reach maturity, and whether the ability of soil below trees to store water could be further improved through tree species selection (Marshall et al., 2014). A modelling study using the observed Pontbren data predicted an average 5% reduction of a severe flood event as a result of creating woodland strips across 7% of this 12km^{2}catchment (McIntyre et al., 2012).

Although these studies show that both sheep-exclusion and cross-slope broadleaf planting will help reduce run-off from improved grassland slopes in many rainfall events, the Pontbren observations did not continue for a sufficient time period to assess the impact of variable (winter) rainfall on soil water deficits (Burgess-Gamble et al., 2018). For example, there might be reduced impact on run-off reduction if a large event followed a period of wetting.

4.2.4 Riparian woodland

Riparian woodland is usually quite narrow, described by Burgess-Gamble et al., (2018) as typically a strip of native broad-leaved woodland <5m wide along the side of a watercourse or standing water, and often unmanaged. Riparian zones are especially important as they influence in-stream processes as well as providing a very diverse habitat for both aquatic and terrestrial organisms. As for a river channel, a healthy riparian zone reflects the dynamic processes to which it is subject to, and, thus, interactions between riparian vegetation and physical processes to provide a complex, dynamic physical habitat mosaic across the river channel and its riparian margins (Gurnell et al. 2016a; Gurnell et al. 2016b). The new CEN standard on river hydromorphology, currently being developed, explicitly acknowledges the important role of riparian vegetation (O'Hare, pers. comm.)

There is little observational evidence of the impact of riparian woodland on flood flows at catchment scale, and modelled data provide the best source of evidence. For example, Dixon et al. (2016) modelled riparian forest restoration in the New Forest and found that de-synchronisation of flood waves resulted in a significant reduction in peak flows at the catchment scale (~100km^2).

Modelling shows that where a riparian woodland is placed in a catchment influences the scale of the peak flow effect by synchronising or desynchronising subcatchment flow responses (Dixon et al., 2016).

4.2.5 Co-benefits and trade-offs

4.2.5.1 Water quality

Woodland cover is generally a very effective means of protecting water quality, and in appropriate locations can reduce the risk of diffuse pollutants from adjacent agricultural land reaching watercourses. However, in a few locations there is a risk of woodland capturing airborne acid and ammonia pollutants, although forest design and management can address this (Burgess-Gamble et al., 2018).

4.2.5.2 Ecosystem resilience

Woodlands provide a wide range of habitats and functions that are enhanced by diversity of structure, tree species and management both at the local and landscape scale. Creation of new woodlands in floodplains and other parts of the catchment, especially where current tree cover is sparse, could bring wider benefits.

4.2.5.3 Farm resilience

Creating new woodlands for flood alleviation might bring additional benefits for the farming system (e.g. shelter, biosecurity).

4.2.6 Magnitude

See 4.1.5.

4.2.7 Timescale

Woodland creation may have some flood alleviation effects soon after establishment, but these may be linked to excluding grazing from former agricultural land (as at Pontbren). Mature woodland takes decades to develop.

4.2.8 Spatial issues

See 4.1.7.

4.2.9 Displacement

Where woodland is created on existing agricultural land there may be displacement of crops and grazing.

4.2.10 Longevity

Woodland creation is a long-term land use change, which can be maintained in perpetuity, and existing woodlands are subject to felling/replanting requirements.

4.2.11 Climate interactions

In addition to their role in flood alleviation woodlands contribute to climate adaptation (see 4.1.9). Woodlands provide significant climate regulation services, through carbon sequestration and storage (in above ground biomass and woodland soils) and they can contribute to climate adaptation of agricultural systems by altering the local microclimate (e.g. shading and shelter).

4.2.12 Social and economic barriers

Where there is a change of land use from agriculture to woodland there may be a range of economic effects in both the short- and long-term, depending on the current land use, the type of woodland, its productive potential. Farmers may not have the skills and knowledge needed for woodland management.

4.2.13 Metrics and verification

Verification for payment is similar to existing WG system for capital grants and environmental land management payments.

4.3 Intervention – management of run-off from land in the catchment

In addition to the use of trees for NFM, other interventions across the rural landscape aim to intercept and slow down run-off before it reaches the river and increase infiltration and soil water storage. Some run-off pathway management measures are more engineered than others and may involve the construction of flow control structures to enable their full operation.

The categories of runoff management intervention used in Burgess-Gamble et al. (2018) are discussed in this section and these include:

- Soil and land management (of arable, grassland and landscape features)
- Headwater drainage management
- Run-off pathway management

4.3.1 Soil and land management

Burgess-Gamble et al. (2018) found limited evidence that changes in arable crop management (e.g. early sowing or using cover crops) help to alleviate flood risk, and the available evidence is conflicting. There is good evidence that soil aeration and sub-soiling improve water infiltration and storage, and some evidence of tillage having similar short-term benefits. Landscape features such as hedges and buffer strips can slow and store water (Burgess-Gamble et al., 2018).

The WWNP evidence directory (Burgess-Gamble et al., 2018) concludes that *'soil and land management practices have a localised flood risk benefit. There are currently no studies that provide qualitative or quantitative evidence that specifically links soil and land management changes to catchment-wide changes in flood risk'*.

4.3.2 Headwater drainage management

There are two main types of intervention in headwater catchments, management of agricultural land and restoration of upland peatland. Both types can disrupt and attenuate overland flow and reduce flood risk – but only locally and for small events (Burgess-Gamble et al., 2018).

4.3.2.1 Agricultural headwater management

Although some agricultural headwater measures can help to slow and store water and to obstruct flows, there is very little quantifiable evidence of their impact on flood risk, especially at catchment level.

Within arable fields the tramlines can collect and speed the flow of run-off but this can be disrupted by breaking up the compacted soil within the tramlines. Farm tracks, roads and livestock paths can concentrate water flow but installing cross-drains, humps or other features that divert the flow laterally into fields or ponds may reduce flood risk. Altering ditches, by widening or flattening them, or making the ditch vegetation 'rougher' (e.g. by planting willow as a living barrier within the ditch) can slow or attenuate the flow of water. (Burgess-Gamble et al., 2018).

4.3.2.2 Headwater peatland restoration

Restoring the natural hydraulic functions of upland peat slows the movement of storm water through the catchment. There are three main types of interventions - vegetation management, grip blocking and gully blocking.

There is significant evidence at a range of scales that replacing bare peat with vegetation can reduce run-off rates by increasing hydraulic roughness. Evidence for the effectiveness of grip blocking is inconsistent – depending on local catchment and drainage characteristics, it can increase or decrease discharge rates at a hill slope scale. However, grip blocking is never as effective as intact peat. There have been insufficient studies of the impact of gully blocking on run-off rates to be confident about its effect on reducing flood risk, although modelling indicates possible long-term flood attenuation after the intervention is mature and settled in (Burgess-Gamble et al., 2018).

4.3.2.3 Run-off pathway management

This group of interventions on agricultural land includes ponds/bunds, swales[5], and sediment traps.

There is evidence that run-off pathway management measures slow, store and filter water, reduce flood risk locally for small events and have positive flood risk management benefits (especially at source) within hours of the flow being generated. Run-off attenuation features work best as clusters of features at landscape scale, rather than one large feature. (Burgess-Gamble et al., 2018).

4.4 Co-benefits and trade-offs

4.4.1.1 Water quality

Drain blocking generally improves water quality by increasing sedimentation of particulate matter.

4.4.1.2 Ecosystem resilience

Intact peatland provides crucially important ecosystem services and rewetting upland peatlands provides habitats for a range of specialised plants, fungi, birds, amphibians and water mammals (Burgess-Gamble et al., 2018).

[5] Also known as grassed waterways, swales are linear, dry, grassy channels with a shallow fall.

4.4.2 Magnitude

See 4.1.5.

4.4.3 Timescale

Agricultural headwater management and run-off pathway management interventions take effect immediately. Peatland interventions take time to settle in and during this process soil properties change and adapt to the restoration measures, which means that their effects on flow (positive and negative) are not static over time.

4.4.4 Spatial issues

See 4.1.5 .

4.4.5 Displacement

Peatland restoration management may displace some extensive livestock production, and pond creation could take land out of production.

4.4.6 Longevity

Soil and land management interventions are temporary and may vary as a result of unrelated decisions about the farm business. Run-off pathway management and agricultural headwater interventions are longer lasting but require maintenance. Headwater peatland restoration management is generally permanent.

4.4.7 Climate interactions

In addition to adaptation, effects of NFM (see 4.1.9 above), peatland restoration could have significant long-term benefits for carbon sequestration and storage.

4.4.8 Social and economic barriers

Not significant, except for headwater peatland restoration management which in some cases will involve long-term management changes on several contiguous land management units.

4.4.9 Metrics and verification

Verification for payment is similar to existing WG system for capital grants and environmental land management payments.

5 Evidence Gaps

Stratford et al. (2017) stated that a priority for further synthesis would be '*to extract the contextual information (e.g. tree type, amount of cover, age, forest management, antecedent conditions, soil properties, pre-afforestation drainage, location of tree cover within the catchment etc.) that can be crucial to explaining the detailed response of different situations*'. They further state that '*future work should focus upon defining clear reporting guidance for contextual information from such studies, in the form of systematic meta-data, to facilitate clear and objective comparison between studies, and further detailed comparative analysis*'. Other knowledge gaps these authors identified include:

i. a clear lack of consistent reporting on hydrological impacts across the available literature and need for more consistent reporting

ii. where possible observed data are used to calibrate and validate models; crucial that uncertainty is considered and reported in both observational and modelled studies, and differences between the results of observational and modelled studies should be investigated further

iii. future work should attempt to review the impacts of tree cover on flood characteristics in general, to determine if tree cover has an observable effect upon the volume of runoff generated and the response times of catchments

iv. measurements of hydrological response should be carried out over the full range of conditions likely to occur (e.g. dry landscape to saturated landscape) and at multiple scales

v. consider how to objectively compare and consider studies undertaken at a particular site, but over a number of years and through subsequent development of forest cover

vi. existing observational studies could have a role in continuing to provide useful data particularly in cases where modifications to the tree cover are ongoing

vii. future work should focus on trees as one part of the flood mitigation solution and work with other sectors (e.g. engineering) understanding of how different measures interact and best combine to reduce flood risk

viii. endeavour to uncover any relevant unpublished studies. Researchers and journals should be encouraged to publish null results

ix. consider the wider context and implications of this work to inform future policy development on flood risk management

6 Summary

NFM aims to restore, conserve and enhance natural processes that mitigate flood flows. The diversity of potential measures, many contexts of application and the lack, or inconsistency, of evidence mean that this is a challenging area to review. The current review is largely based on the Environment Agencies WWNP Evidence Directory (with additional literature added that has been published alongside or since that review); thus, it does not represent a comprehensive independent assessment of the scientific literature. However, it does provide a useful updated synthesis of the most comprehensive evidence review available to underpin the Welsh Government's consultation on their new Sustainable Farming Scheme.

Given that the hydrological response of catchments to rainfall is complex in space and dynamic in time (Dadson et al., 2017) it is challenging to monitor the effect of natural processes on flood flows, and in particular, at large scales and for extreme flows. Observations at the small scale (<100km^2) for small events (5-20 year return period) suggest NFM can mitigate floods. However, care should be taken when extrapolating evidence to areas with different soils and/or vegetation (Dadson et al., 2017). At larger scales, the observed benefits at the small scale do not necessarily combine due to catchment scale effects such as the synchronisation of subcatchment flood waves (Dadson et al., 2017). The lack of evidence at the large scale may be due to the lack of sufficiently large-scale interventions (Dadson et al., 2017). Most evidence for the effect of NFM at the catchment scale for large flood events is model based and requires further validation. Therefore, we assign an 'amber' rating to all interventions in Table 6.1, reflecting the fact that a logic chain exists for each but evidence for effect on flooding is either only available at the small scale or is model based. NFM interventions may play a role in climate change adaptation. The potential for NFM interventions to mitigate the effects of climate change on future flood risk depend on the catchment response type and its location (Kay et al., 2019). NFM is most likely to mitigate low emission climate change scenarios over short time scales.

All evidence of the effectiveness of NFM interventions must be carefully considered with their contextual information. For example, intervention functioning will be highly dependent on antecedent weather conditions, catchment characteristics and spatial/temporal distribution and amount of rainfall during a specific event. Dadson et al. (2017) emphasised the potential importance of management practices (e.g. forestry roads and machinery used).

It is clear from NFM case studies that most catchments adopt a suite of measures. In many cases, interventions are complimentary (e.g., leaky barriers may enhance river floodplain interaction and this may be particularly effective where floodplains have been restored to enhance their roughness). Furthermore, where NFM interventions have a logic chain, but an unquantified effect on flood flows, they may be justified on their additional benefits (e.g. reduced soil erosion). As the effect of specific intervention types becomes clearer models are likely to play an important role in evaluating the effects of suites of different measures. There is a lack of information on the longevity and maintenance requirements of NFM interventions.

It is important to note that the lack of direct observed evidence for the effectiveness of many interventions, particularly at larger scales and for larger floods, should not result in them being dismissed as potential flood mitigation options. Instead, their adoption should be encouraged in a programme of adaptive management with a robust monitoring programme so evidence can be collected and used to inform further implementation policies. It is important that monitoring is long-term to capture the dynamics of the interventions themselves and the full range of climatic conditions that may occur. However, it should also be acknowledged that evidence on the effectiveness of NFM interventions does not support them having a major effect on the most extreme events (Dadson et al., 2017). The need to encourage/resource hydrological monitoring of NFM schemes was illustrated by a survey undertaken by the JBA (JBA Trust, 2016) who found that as little as 6% of the schemes in the UK were intensively monitored.

Table 6.1 Flood risk management interventions

Note: Most evidence for the effect of NFM at the catchment scale for large flood events is model based and requires further validation. Therefore, we assign an 'amber' rating (see key) to all interventions in this table reflecting the fact that a logic chain exists for each but evidence for effect on flooding is either only available at the small scale or is model based. The summary assessments in Table 6.1 are based on the findings of this review and expert assessment of these by the wider ERAMMP group. In the table 'key outcomes' refers to FRM outcomes and 'key benefits' refers to co-benefits for other topics covered by the wider review such as water quality, biodiversity habitats climate mitigation and adaptation.

Confidence	Intervention name	Key Outcomes*	Key Benefits**	Critical concerns
River and floodplain management (section 4.1).				
Amber	Restoration of floodplain functions and creation of wetlands	Enhancing the river - floodplain connection stores flood water and slows the flow.	Biodiversity Removes sediment and nutrients.	Risk of synchronisation of flood waves in catchment.
Amber	Leaky barriers	Enhance floodplain connection. Slow flood flows where floodplain is rough.	Biodiversity Reduced sediment transport	In channel mid and upper catchment measure. Much of evidence base is modelling. Risk of synchronisation of flood waves in catchment.
Amber	Offline storage areas	Store and attenuate flood flows in a managed way.	Water quality benefits	Design criteria may be an important consideration (draining and filling around anticipated peak flow periods -- cannot be left full e.g. in winter). Few studies of their effect on flood flows.

Confidence	Intervention name	Key Outcomes*	Key Benefits**	Critical concerns
				Cooperation between adjacent landholders may be needed.
Woodland management and woodland creation for the purpose of flood alleviation (section 4.2).				
Amber	Floodplain woodland	Increase floodplain roughness and slow flow	Biodiversity	Risk of synchronisation of flood waves in catchment.
Amber	Catchment woodland	Available evidence, although limited, highlights importance for "smaller" rainfall events.	Helps to mitigate (uncertain) risks of more extreme climate change impacts	Evidence for effects on mitigating flow from larger rainfall events is less well established. Majority of evidence is model based.
Amber	Cross-slope woodland	Reduces rapid runoff from improved grassland upslope.	Water quality benefits. Reduces diffuse pollution.	Evidence from one observational study of effect in many rainfall events, but not clear if equally effective if flood event occurs when soil is already very wet.
Amber	Riparian woodland	Slows floodplain flows. Can have significant influence on fluvial geomorphological processes.	Biodiversity gain compared to intensive farmland systems - improve habitat for aquatic & terrestrial biota.	Evidence is mainly modelling. Careful modelling required to understand impact on river channel morphology. Can alter in-stream primary production and invertebrate detrivores. Management may be required to ensure trees do not block flow in certain places.
Run-off management (section 4.3).				
Amber	Run-off pathway management in field bunds: individually may be minor impact, so significant number, across	Store and slow runoff before it enters river	Water quality benefit. Reduces diffuse pollution.	Measures: swales, sediment traps, ponds/bunds. Design criteria may be important

Confidence	Intervention name	Key Outcomes*	Key Benefits**	Critical concerns
	multiple adjoining farms, needed.			considerations (draining and filling around anticipated peak flow periods -- cannot be left full e.g. in winter).
Amber	Headwater drainage management	Often a flood source area thus active management (vegetation, ditch blocking, etc.) has potential to temporarily store water.		Peat bog capacity depends on condition and vegetation type
Amber	Soil and land management (arable) Minimum tillage. Contour ploughing. Vegetative cover in winter. Buffer strips with permanent vegetation.	Increase infiltration and reduce runoff	Water quality benefit. Reduced diffuse pollution.	Limited evidence for impact on flooding. Likely to have impacts on other things (positive and negative), e.g. biodiversity (+ve for buffer strips, -ve for birds for vegetative cover over winter)
Amber	Soil and land management (grassland) Stocking density, underdrainage, vegetation management	Increase infiltration and reduce runoff	Water quality benefit. Reduced diffuse pollution.	Limited evidence for impact on flooding. Soil type needs to be considered
Amber	Woody landscape features.	Hedges and buffer strips can slow runoff.	Biodiversity. Possibly reduced pollution.	Strategic location is important when creating new features.

* Key outcomes – captures information of the mechanism by which the interventions reduce flood risk.
** Key benefits – examples of widely accepted benefits are given here as opposed to a comprehensive list.

Colour Key:

- Blue = well tested at multiple sites with outcomes consistent with accepted logic chain. No reasonable dis-benefits or practical limitations relating to successful implementation.
- Amber = agreement in the expert community there is an intervention logic chain which can be supported but either evidence is currently limited and/or there are some trade-offs or dis-benefits which WG need to consider.
- Pink = either expert judgement does not support logic chain and/or whilst logic chain would suggest it should work there is evidence of one or more of the following:
  - its practical potential is limited due to a range of issues (e.g. beyond reasonable expectation of advisory support which can be supplied and/or highly variable outcome beyond current understanding or ability to target),
  - the outcome/benefit is so small in magnitude with few co-benefits that it may not be worth the administration costs,
  - there are significant trade-offs.

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