Eddleston Water 2021 Report

Aerial photo of the Lake Wood and Cringletie meanders of the Eddleston Water looking south downstream towards Peebles, Oct 2021

This report was produced for Scottish Government by Tweed Forum and has been written by the main group of researchers working on the project during this time.

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1. Executive Summary

The Eddleston Water study, now in its 12th year, looks to assess the effectiveness of Natural Flood Management (NFM) to reduce flood risk and improve riparian habitats at a catchment scale. By taking an integrated approach to flood risk and habitat improvement, and through the use of a wide range of NFM measures in locations across the whole catchment, the Eddleston Water project has been able to recreate 'lost' hydrological and ecological processes at both the river reach and landscape level. The introduction of these measures has re-connected the river to its catchment both in the headwaters, through large scale riparian tree planting and the introduction of engineered log structures, and on the floodplain where the creation of flood storage ponds, remeandering of once-straightened channels, the removal of adjacent flood embankments and other measures all help temporarily store water and slow the flow. In addition, NFM can be seen to deliver a range of other benefits and ecosystem services and to act as an important climate change adaptation measure.

In this context, our work at Eddleston up to 2021 so far has shown:

- **NFM reduces the risk of flooding**
    - Strong empirical evidence demonstrates that engineered log structures and associated ponds and riparian planting significantly increase the lag time between rainfall events and rising river levels for catchments in the headwaters up to 25km^2. Increases in lag time can be regarded as synonymous with reductions in peak flows and give rise to greater opportunities to issue flood warnings and for responses on the part of recipients.
    - Reductions in the annual frequency of high flow events throughout the Eddleston system give positive indications regarding the effectiveness of NFM interventions, with initial findings suggesting that even in Peebles (catchment at 69 km^2), a reduction of 29% in high flow frequency can be seen (comparing 8 years baseline data with 7 years post NFM measures), while further upstream the effects are even more striking (50% reduction on a comparable basis for a 29 km^2 catchment area).
    - In response to a mix of NFM measures across the catchment, flood peak magnitudes are estimated to reduce by 5% at the catchment outlet, irrespective of the magnitude of the causal event.
    - Modelled and empirical evidence shows that remeandering, combined with embankment removal can provide additional temporary floodplain storage and so help reduce flood peaks, but remeandering on its own has limited flood reduction benefits
    - The creation of well-designed large floodplain storage ponds can provide temporary storage and so help reduce flood risk, as shown by modelled and empirical evidence
    - Infiltration under mature deciduous tree cover is much greater (up to 8 times) than under pine plantations and grassland on the same geology; and
    - Tree planting and similar NFM measures that seek to improve infiltration are most effective in responsive, low permeability catchments, as the effects are masked in catchments already benefiting from high soil and geology permeability.

- **NFM enhances habitat restoration, delivers nature recovery and climate change resilience**
  - NFM measures including the planting of >330,000 native trees, and the creation of 38 ponds provide direct habitat restoration benefits at the riparian and landscape scale. Environmental-DNA analyses show the Eddleston NFM ponds provide new habitats for aquatic invertebrates from over 50 families, including 25 high scoring water-quality indicator species of mayfly, stonefly and caddisfly.
  - Remeandering increases river length, which increases the total amount of riparian habitat available for salmon, otters and other species. In the Eddleston, different remeandered sections have added from 8% to 46 % length of new river habitat.
  - Remeandering increases in-stream channel habitat diversity by creating more pools and riffles, especially in reaches where more sinuous channels have been created
  - Remeandering leads to the gradual re-establishment of macroinvertebrate communities and suggested improvements to salmonid population health
  - Riparian tree planting provides a direct climate change adaptation through the creation of 'thermal refugia' from the eventual shading provided by bankside trees, whilst NFM at the landscape scale also helps reduce the impact of increasing climate change-derived flood events
- **NFM measures provide a range of other ecosystem services which, together with flood damages avoided, provide significant positive cost-benefit returns**
  - Appraisal of NFM measures already implemented in the Eddleston show a positive net present value (NPV) of £950k from flood damages avoided over 100 years
  - NFM co-benefits already delivered amount to £4.2million NPV on-top of flood damages avoided by the same NFM measures - mainly from water quality improvements, carbon management, recreation, biodiversity and fisheries
  - Modelling of an enhanced scenario of NFM measures shows very significant returns, potentially delivering £2.85million NPV from flood damages avoided and a further £17.7million NPV from additional benefits.

2. Introduction

The Eddleston Water project was established by Scottish Government in 2009 as one element of their programme to explore the potential contribution that natural flood management (NFM) could make to addressing increasing concerns of flooding and habitat degradation. This new focus on an integrated catchment scale approach to sustainable flood risk management reflects a fundamental change in how flood management is perceived in Scotland, as set out in the Flood Risk Management (Scotland) Act 2009. This Act mapped out a new approach that seeks to work with natural processes at a landscape scale to help reduce the risk of flooding, and also deliver other benefits, alongside the complementary use of more traditional structural flood defence measures and associated actions to increase awareness, preparedness and resilience of communities to flooding and climate change.

This report focuses on research and activities undertaken in the project between 2016 and 2021. It should be seen as a follow up to the Eddleston Water Project Report 2016 [1] and we have not repeated findings from this earlier report unless of key relevance. It focuses on the work undertaken on monitoring the effectiveness of NFM measures on surface water flood risk and on their associated hydromorphological and ecological impacts. During this time, the Eddleston Water catchment has also been the subject of many other studies, notably the complementary work undertaken by British Geological Survey on groundwater, as well as numerous research projects from UK and overseas universities. Many of these are ongoing and new results are emerging each year.

- ***Aims and Objectives***

The project has three main objectives:

a) To investigate the potential to reduce the risk of flooding to downstream communities through the utilisation of NFM measures;

b) To improve habitats for wildlife, including fish and raise the ecological status of the river; and

c) To work with landowners and farmers in the local community to maximise the benefits of the work, whilst sustaining farming livelihoods and practices.

In seeking to deliver these objectives, the project set out to generate robust evidence of the impact, cost and benefits of working with natural processes at a catchment scale. The project took an empirical approach from the outset, based on detailed data collection, measurement and monitoring, with the subsequent development of models, including a combined hydrologic and hydraulic catchment model to enable scaling up and comparison with other studies elsewhere.

Addressing these three objectives will help to meet the scientific challenges that were recognised in the recommendation of a Scottish Parliamentary Committee that "*the government establish further pilot studies to assess the contribution that natural flood management measures can make at the catchment scale*" [2].

- ***The Project Partnership – Governance and Funding***

From the outset, the project has been managed by Tweed Forum and directed by a small Project Board chaired by the Scottish Environment Protection Agency (SEPA) and the Scottish Government. The Board was subsequently expanded to include Scottish Borders Council (SBC), and is supported by the two main science providers, British Geological Survey (BGS) and the University of Dundee. Further advice is available from a Steering Group of key stakeholders, including Scottish Natural

Heritage (SNH), Forest and Land Scotland (FLS), Forest Research (FR), Tweed Foundation, National Farmers Union (Scotland), Scottish Land and Estates, and the Environment Agency.

The partnership effectively also includes the local farmers and landowners in the Eddleston valley and the communities with whom we work, as they are key to all aspects of project design and delivery. Their participation and support for the introduction of NFM measures and associated monitoring is entirely voluntary.

The project began with a Scoping Study in 2010 produced by the University of Dundee and cbec [3], which included a detailed characterisation of the current catchment, along with a restoration strategy indicating the types and locations of potential NFM measures that could be proposed across the catchment. The Scoping study included plans for Stakeholder engagement and a Monitoring strategy. This initial phase was followed by the installation of the main monitoring network in 2011, comprising a detailed surface hydrological monitoring network, along with meteorological, hydromorphological, ecological and ground water measurement, in order to provide a comprehensive baseline. From late 2012 new NFM measures were implemented, with the majority being introduced between 2103 and 2015, though more have been developed since.

Funding for the project has come from Scottish Government, including through relevant funding streams such as SEPA's Water Environment Fund and the Scottish Rural Development Programme. For the period 2016-2020, it was the recipient of funding through participation in the EU North Sea Region Interreg programme *Building with Nature*. In addition, very significant contributions have come from SEPA itself and from many of the partners noted above, including University of Dundee and BGS, not least in terms of in-house monitoring, research, analyses and advice. Other organisations, including SNH, SBC, FLS, FR, CEMEX, Scottish Power, Forest Carbon and Woodland Trust are important funders and supporters, as also are the land owners and managers themselves. The total cash cost of the project to date is approximately £2.6million, of which the initial scoping, set up and characterisation, along with monitoring, evaluation and modelling accounts for c. £1million, to which, as noted additional recognition also needs to be given to the partners' significant in-kind contributions.

- ***The Eddleston Water Catchment***

The Eddleston Water is a typical 69 km^2 catchment in the Scottish Borders, the main stem of which flows some 20km north-south to join the River Tweed in Peebles. Underlain by Silurian greywackes and recent glacial deposits, the topography is gently rolling to the west of the main stem, but steeper to the east (locally rising to 543 m where annual rainfall exceeds 1500 mm). The dominant soil types are brown forest earths and non-calcareous gleys, giving land capability classes of 4 and 5 which provide grazing for sheep on improved and semi-improved grassland [4]. Land use is varied, with extensive improved pasture along the main valley floor and conifer plantation forestry above 300 m in much of the western catchment.

Looking east towards Eddleston and the Longcote catchment behind, with the Eddleston Water flowing left to right in the foreground

Straightened reach of Eddleston Water in lower catchment at Chapelhill showing Water crowfoot in flower

The catchment has undergone extensive changes over the last 500 years, with clearing of native woodland, land drainage, river straightening and afforestation with non-native conifers [5] all contributing to alter how the land drains, both in the river valley and on the surrounding hill slopes. Much of the 12 km long main river stem from Waterheads to Peebles was straightened, channelised and embanked in the early and mid-19th century to enable the building of a road and later, a railway, such that connections with its floodplain have been lost. The river was classified by SEPA as at 'bad' ecological status in 2009 (using EU Water Framework Directive (WFD) criteria), largely due to these historical impacts on the physical structure of the channel and a loss of aquatic plant cover.

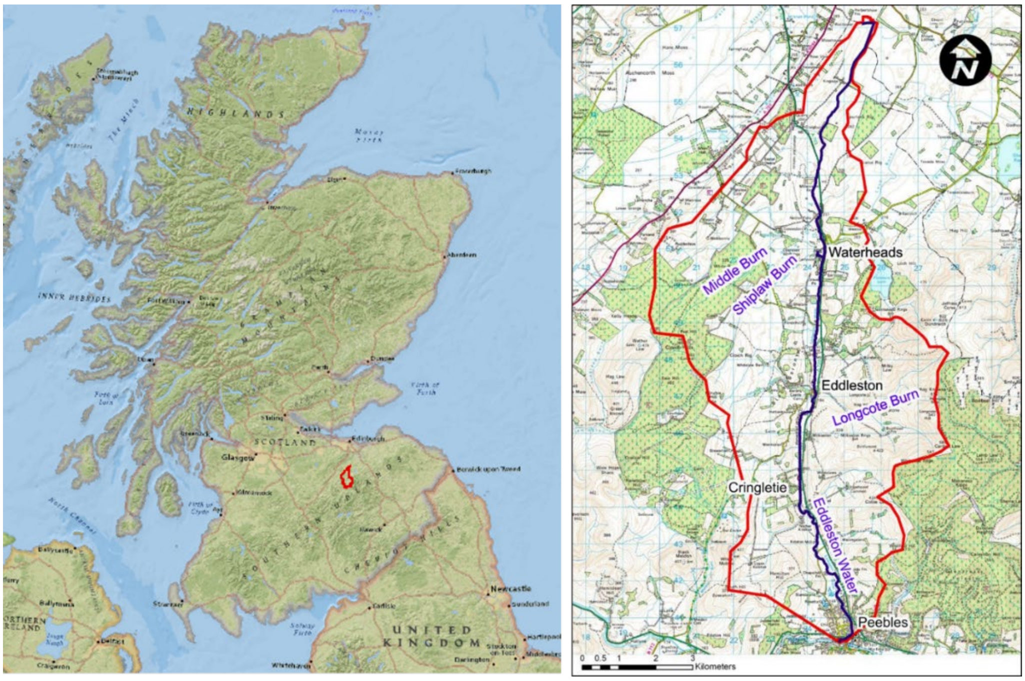


Figure 1. Left: Eddleston Water location (Catchment Boundary: FEH Web Service; Basemap: National Geographic). Right: Eddleston Water Catchment showing settlements and main water courses (Eddleston Water Project: 2016 Report [1])

Comparison of an old map showing a largely still-sinuous river course in the Darnhall section of Eddleston Water at the end of the 18th century with the watercourse in 2012 before works began reveals that this led to the loss of some 16% of the original 6.5 km channel length along that stretch of the valley bottom alone. In addition to shortening the length of channel, removing and damaging habitats for plants and animals, including salmon and trout, and other protected species such as otters and lamprey, this has led to surface water runoff generated upstream being quickly transmitted downstream, increasing the risk of inundation of the communities in Eddleston and Peebles. In 2010, SEPA's 1 in 200-year flood risk map showed 589 properties to be at risk of surface water flooding (521 of these being in Peebles).

Eddleston Water in flood, March street, Peebles Dec 2015

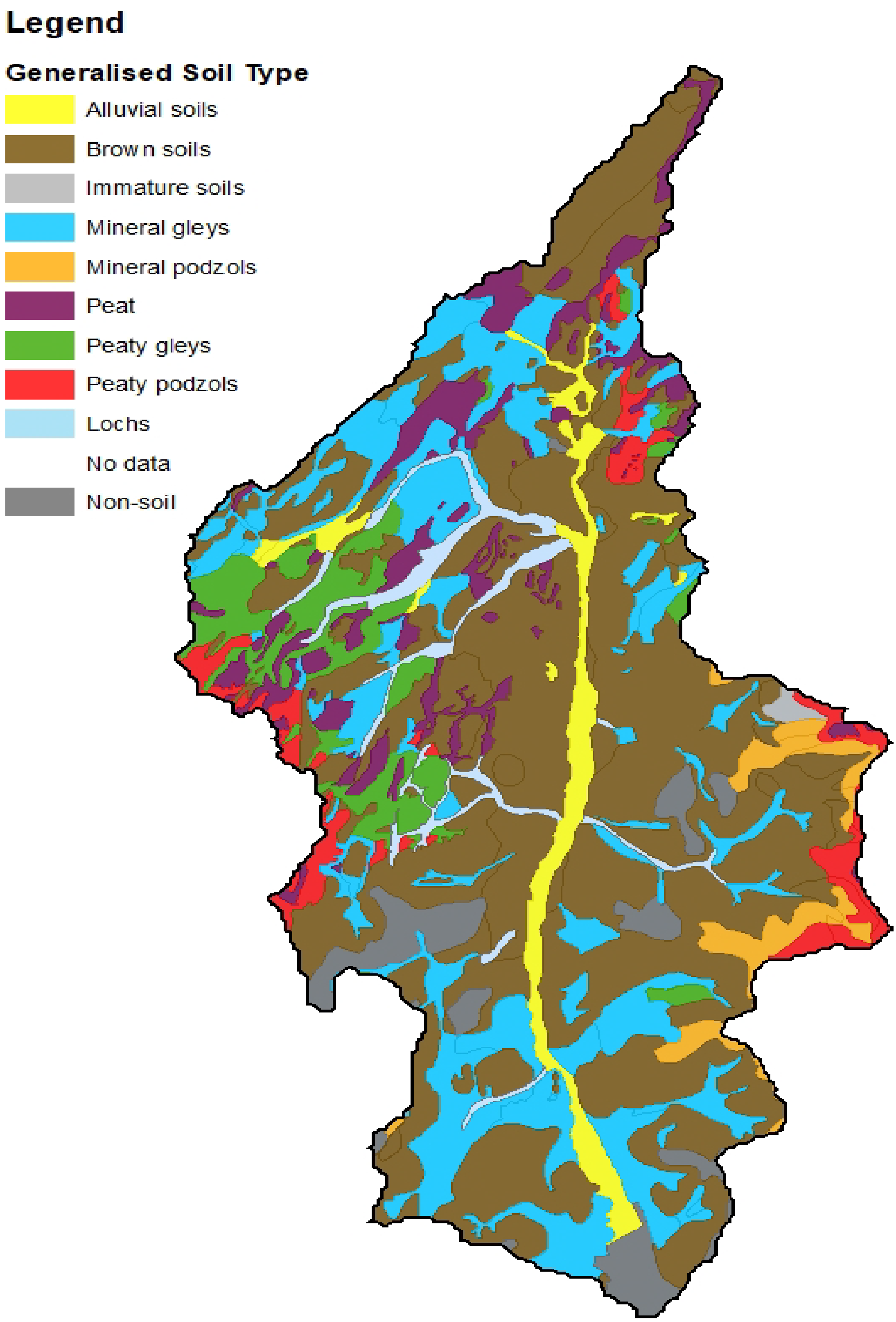


Figure 2. Generalised Soil Types within the Eddleston Water Catchment 1:25000 Soil Map (partial cover), The James Hutton Institute (Eddleston Water Project: 2016 Report [1])

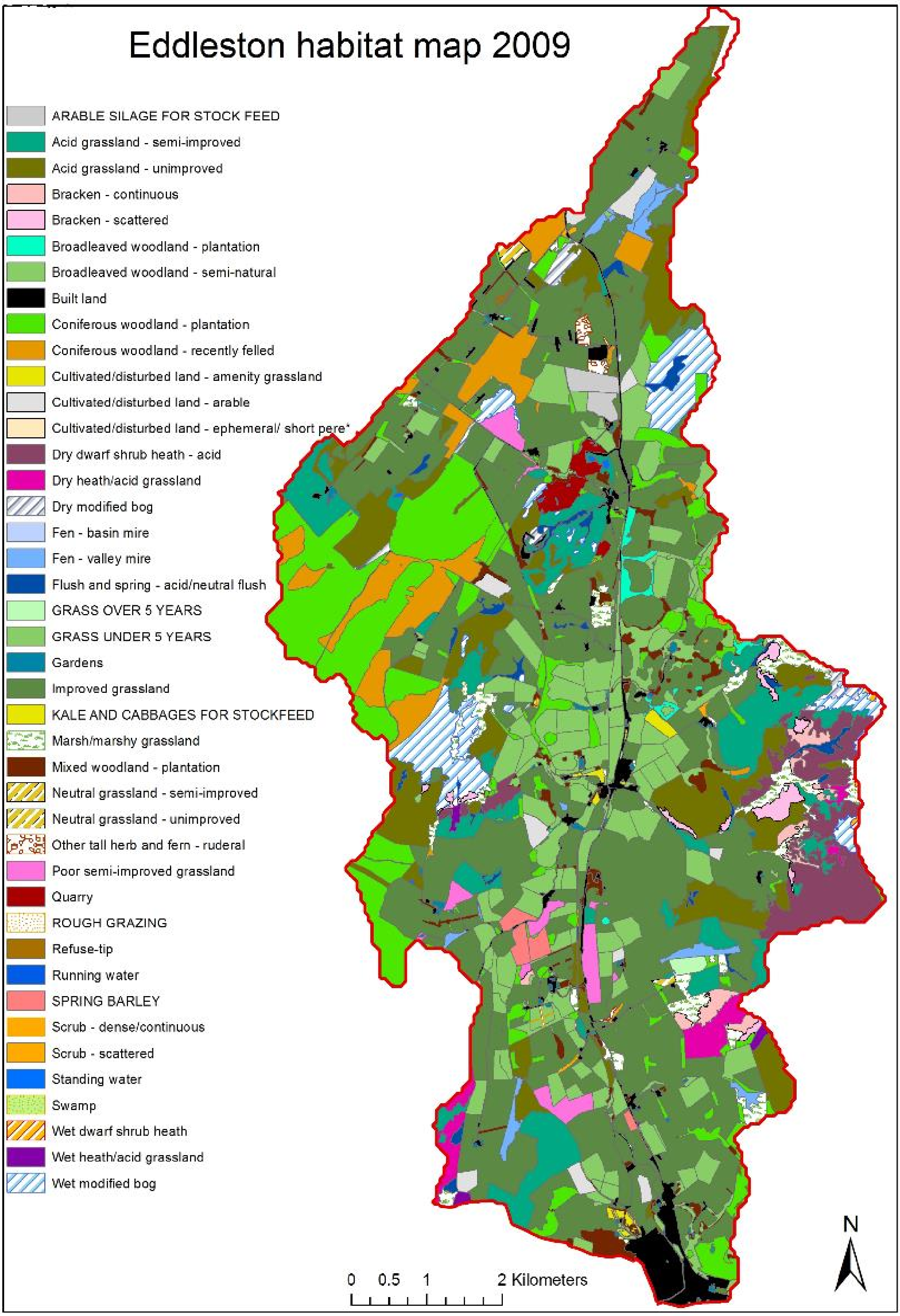


Figure 3. Eddleston Water Habitat Map 2009 produced by Environment Systems (Eddleston Water Project: 2016 Report [1])

- ***The Monitoring Strategy – overall view***

Full details of the overall monitoring strategy along with individual templates describing the sampling and surveys undertaken for each of its scientific components are available on the Eddleston Water website (https://tweedforum.org/eddleston-project-database/), as is the paper analysing lessons learned from its development and implementation [6]. The project took a process-based approach to assessing the impact of NFM restoration measures (Fig 4), with a strong emphasis placed on establishing a really robust and dense hydrological network capable of providing the fine-scale spatial platform upon which all other monitoring programmes have been built.

Main Automatic Weather Station at Darnhall – see Fig 7

This approach also enabled the comparison of the response to restoration measures from sub-catchments that had contrasting hydrological and environmental characteristics. This was complemented, wherever possible by co-location of monitoring sites for different parameters, thus further helping the integration of scientific disciplines, and where possible by the re-use of sites that had been monitored previously for other purposes prior to the project (Fig 5), thus 'extending' the period for which pre-implementation data was available.

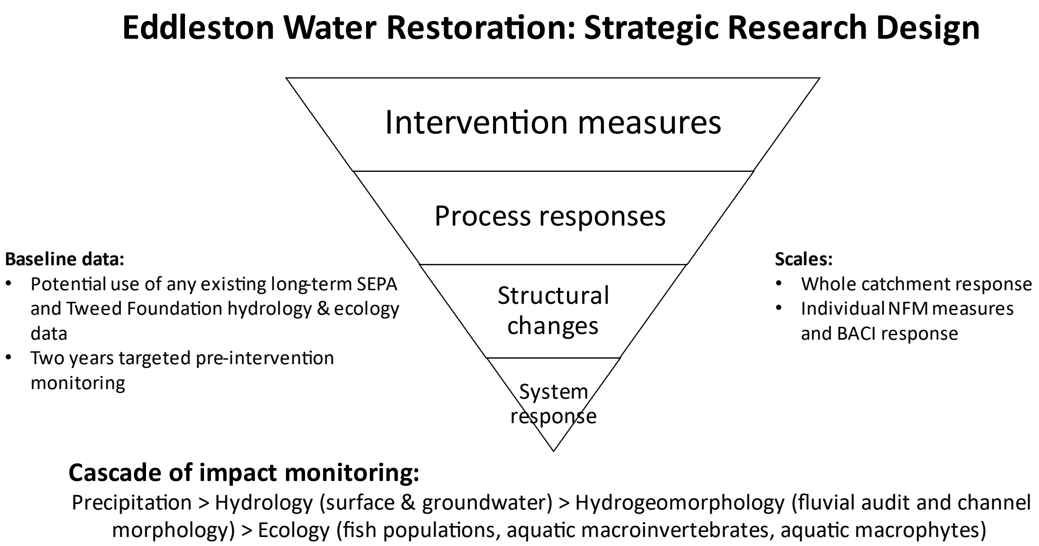


Figure 4. Eddleston Water Strategic Research Design (from Spray et al. 2022 [6])

The primary aim of the monitoring strategy is to assess the effectiveness of NFM measures to reduce flood risk and improve river and associated catchment habitats, and where possible to do so using a *Before-After-Control-Impact* (BACI) research design. Where this was not feasible, other approaches that incorporate examination of measures of change were used, with relevant research designs focussing on two scales: a) *The overall catchment scale* – so as to examine the cumulative impact of NFM measures introduced across the landscape; and b) *The individual NFM measures* – to assess the effectiveness of different types and designs of NFM in different locations within the catchment. Together, this addresses the requirement of Section 20 of the Flood Risk Management (Scotland) Act 2009 which is to 'assess the *possible contribution* of *alteration* etc. of natural features and characteristics' when assessing options for flood risk management.

In stream high flow monitoring during flood conditions

Delivery of the monitoring programme was undertaken by the main partners involved: SEPA, University of Dundee and BGS, along with contracts for specific work on for example fluvial audits (cbec), fish (Forth Rivers Trust/Tweed Foundation/Trex Ecology) and aquatic invertebrate analyses (Veritas Ecology Limited and Apem Ltd). In addition, monitoring of surface water hydrology was augmented by the development of the Eddleston Water combined Hydrologic and Hydraulic Catchment model [7].

The primary focus on flood risk reduction and habitat improvement is complemented by a range of other studies directly related to the wider catchment approach of integrated water and land management, including cost-benefit analyses, income foregone, exploration of farmers' attitudes to NFM and ecosystem services [6]. Over the years, the catchment has also become a Research Platform in its own right, supporting many student projects from the University of Dundee, as well as related studies from research partners outwith the core group, including the Universities of Newcastle, Edinburgh, Durham, Winchester, Edinburgh Napier, Delft, Western Switzerland, Ostrava, SRUC, the James Hutton Institute and others.

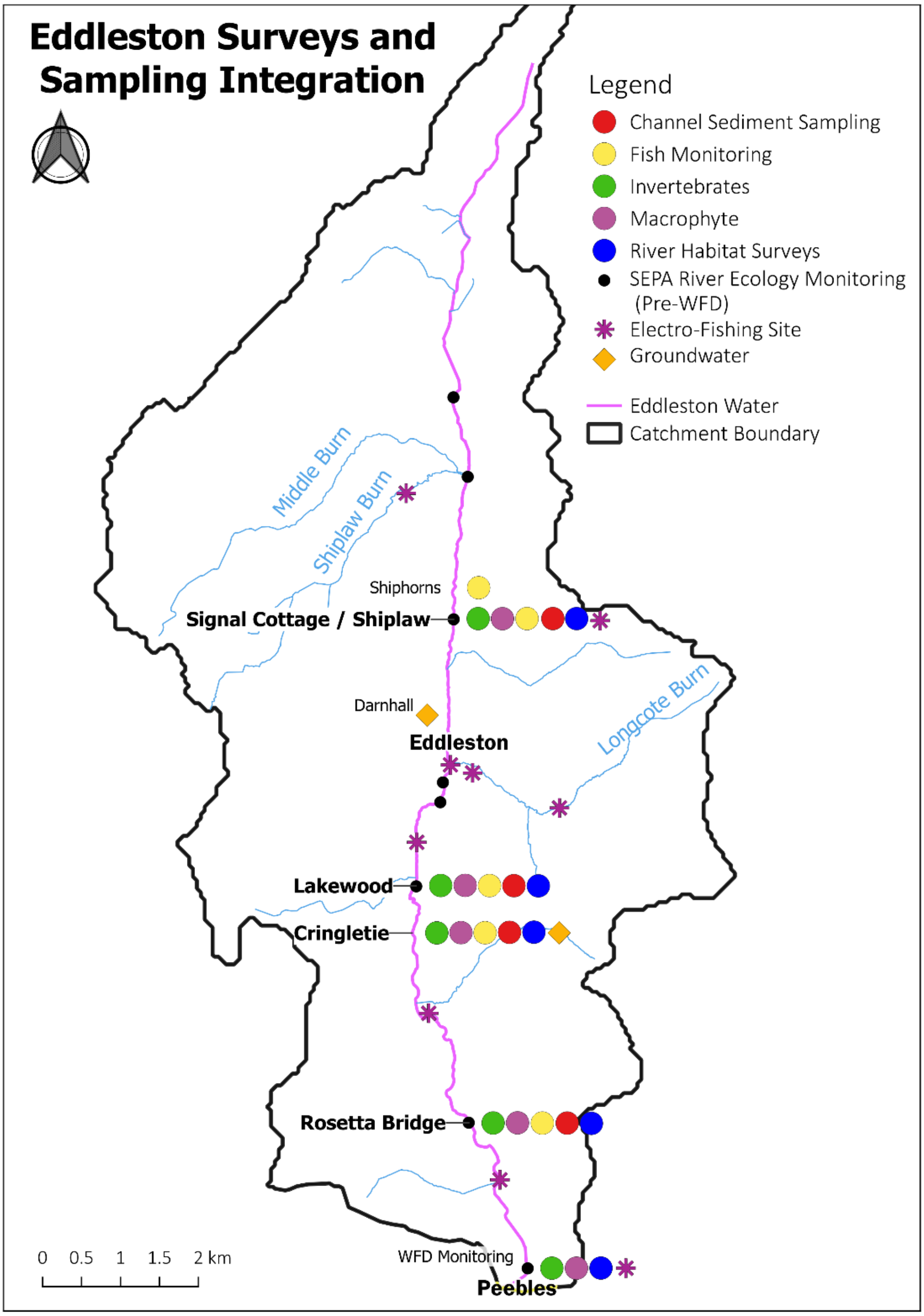


Figure 5. Eddleston Water integration of catchment restoration monitoring networks.

As with many other field-based research studies in the UK, the project had to contend with the impacts of the ongoing COVID-19 pandemic. This severely restricted access to the catchment in 2020, and to a lesser extent since, but although this had a minor impact on maintenance of some elements of the monitoring network, the majority of survey work was able to continue remotely or was scheduled for delivery in 2019 and 2021. A separate challenge occurred due to the cyber-attack on all SEPA's IT systems in December 2020 and the ongoing fall out of loss of access to stored and analysed data held by SEPA, leading to extensive delays and lost data.

- ***Implementation of Measures – overall view***

Working with 20 farmers across the catchment, since 2012 Tweed Forum and partners have been able to install a wide range of NFM measures (Fig 6), including:

  - 207 hectares of woodland planting, with over 330,000 native trees

Native tree planting as an NFM measure along Shiplaw burn

  - 116 large high-flow log structures, positioned on upper tributary streams

High flow log structure in the upper catchment on the Middle burn

  - 36 flow attenuation ponds located in the headwaters and tributaries, and 2 large ones on the lower floodplain

Aerial view of small flood storage ponds in upper catchment at Ruddenleys

Large flood storage and biodiversity pond on lower floodplain at Kidston Mill

  - Three lengths totalling c 3.5 km of previously straightened river channel re-meandered, with adjacent flood banks removed. This has added a total of c 362m of new channel to the main river.

As noted, the majority of these NFM measures were introduced between 2013 and 2015, but some have occurred since, including in 2021, and more are planned. Monitoring the impact of these individual NFM measures as they have been deployed has been the objective of the study, along with assessing the total catchment response to their combined implementation.

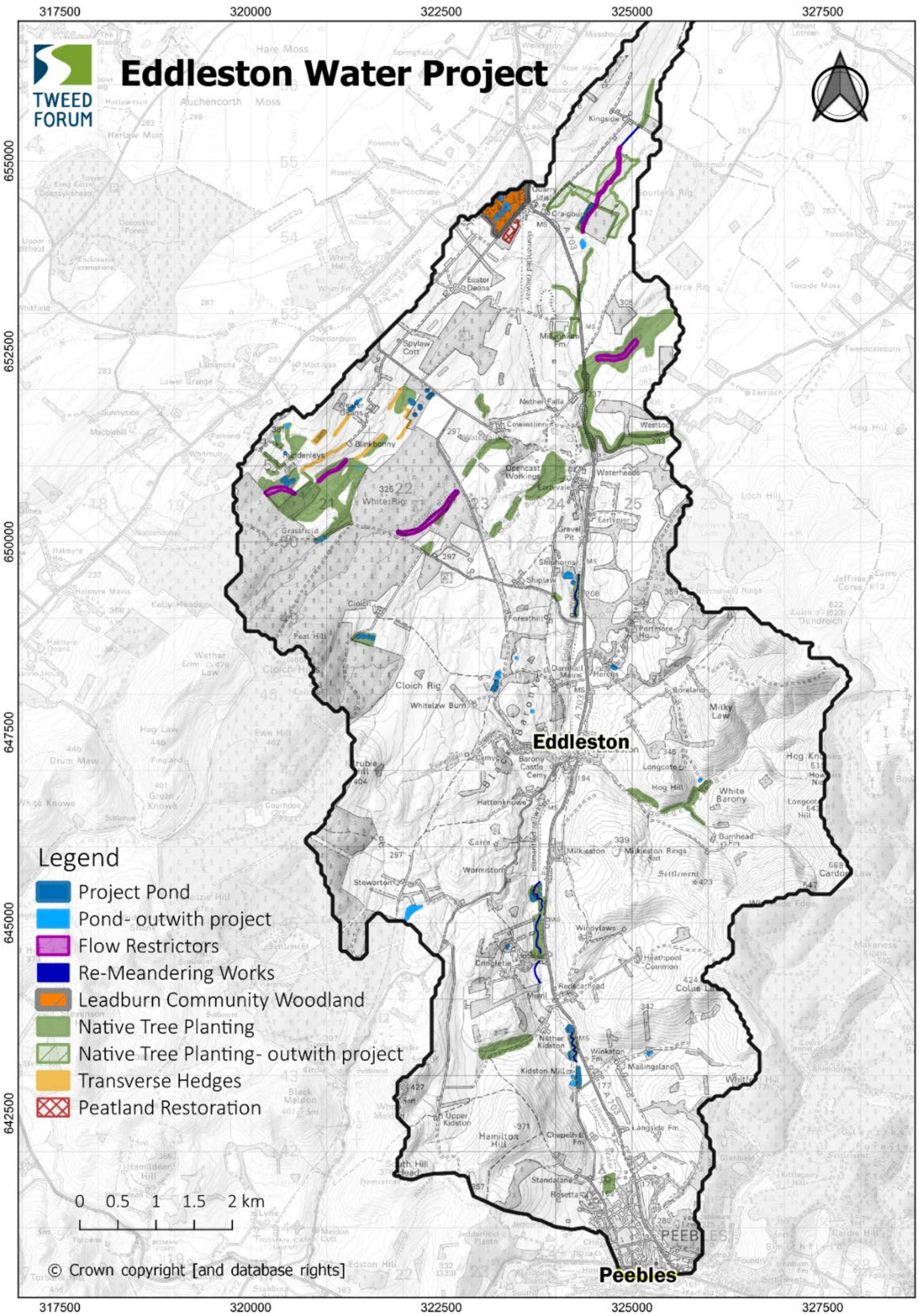


Figure 6 – NFM and Habitat enhancement measures across the Eddleston water catchment

Newly completed meanders at Nether Kidston, showing root wads used to stabilise the banksides and create instream habitat

3. Assessing the Hydrological impacts of Natural Flood Management measures – the empirical evidence

The question as to what changes have occurred in the flood response of the catchment as a result of the installation of NFM measures could focus on one or more aspects of hydrological response, including:

- the lag between rainfall and peak of the following hydrograph;
- the size of the flood peak;
- the total volume of storm runoff (excluding water which is temporarily stored and later released into the watercourse); and
- the duration of the runoff response.

Frequency of occurrence of events above some identified threshold could also be examined. Each of these aspects is interlinked, but the focus here is the first two of these listed aspects, whilst further detailed results can be found elsewhere [8].

It should also be noted that the impact of NFM measures on different aspects of flood risk is the subject of ongoing study, and further results can be expected in the near future from current work being undertaken by BGS and University of Dundee.

Hydrological lag is a robust indicator of change, useful for assessing the extent of NFM impact, in the sense that it does not depend on assumptions of modelling or the accuracy of streamflow measurement. It is a simple and clearly communicated measure of hydrological response which is commensurate with flow attenuation: - as flood water is increasingly held back in a catchment, lag increases and accordingly peak flow rate is reduced. The hydrological effectiveness of NFM measures is often thought to be greatest in small catchments <20 km^2 and in less rare flood events, say with annual exceedance probabilities of greater than 1 in 5 years (20% AEP). Therefore, the results are investigated in the context of catchment scale and the magnitude of peak events.

Flood peak is clearly of critical importance to the assessment of flood risk at locations downstream of NFM interventions: - change in flood peak magnitudes corresponds to changes in the number of properties which may be flooded in one event and the likelihood of individual properties being flooded over a run of years.

Methods

A dense monitoring network was established in 2011 comprising 11 stream level gauges and four rain gauge sites, subsequently extended to 12 stream level gauges and five rain gauge sites (Fig 7). All 12 stream level gauges have been calibrated to produce a continuous series of stream flow data. The focus has been on intensive data gathering in order to obtain detailed, robust and abundant field data from which to observe changes in hydrological response characteristics. The network was operated for 2 years of a baseline period before any NFM measures were implemented and has subsequently been operated for a further 10 years to date.

Statistical analyses have been undertaken for each site affected by the NFM measures to explore the changes in hydrological lag since the introduction of measures from 2013 onwards. The focus has been on assessing the significance of differences in lag since the commencement of NFM measures, and employing a range of sampling thresholds with a focus on the highest flows. Medians and inter-quartile ranges have been plotted as a function of flow threshold in order to explore the sensitivity of lag to flow peak. In addition, changes in annual peak frequency have been tabulated to allow comparisons before and after the commencement of measures and to allow comparisons between and among experimental and control sub-catchments (in which no measures were implemented).

Changes in flood magnitude are presented for sites in the catchment utilising data from SEPA monitoring records beginning in 2001 and 2005, long before the NFM project began, since these allow the most robust comparisons possible using annual maximum flood flow data. These are presented with the results of similar comparisons for adjacent catchments to the north, west and south of the Eddleston catchment, in order to allow the findings to be placed in context, given the possibility of chance variations in rainfall and snowmelt affecting the results.

While the changes of flood magnitude mentioned above present the results of all measures within the catchments examined, further results are presented for a comparison of flood magnitudes after a single off-line pond was installed in the lower main stem of the Eddleston Water, just 3 km upstream of the catchment outlet. This is one of the largest single interventions in the catchment and complements the results of combined interventions upstream involving the installation of flow restrictors, on-line ponds and riparian planting and fencing.

In addition, recent work by Isabelle Costaz as part of her PhD study funded by University of Dundee has focussed on the potential of channel re-meandering on Eddleston Water for flood attenuation, initial results of which can also be referenced [9].

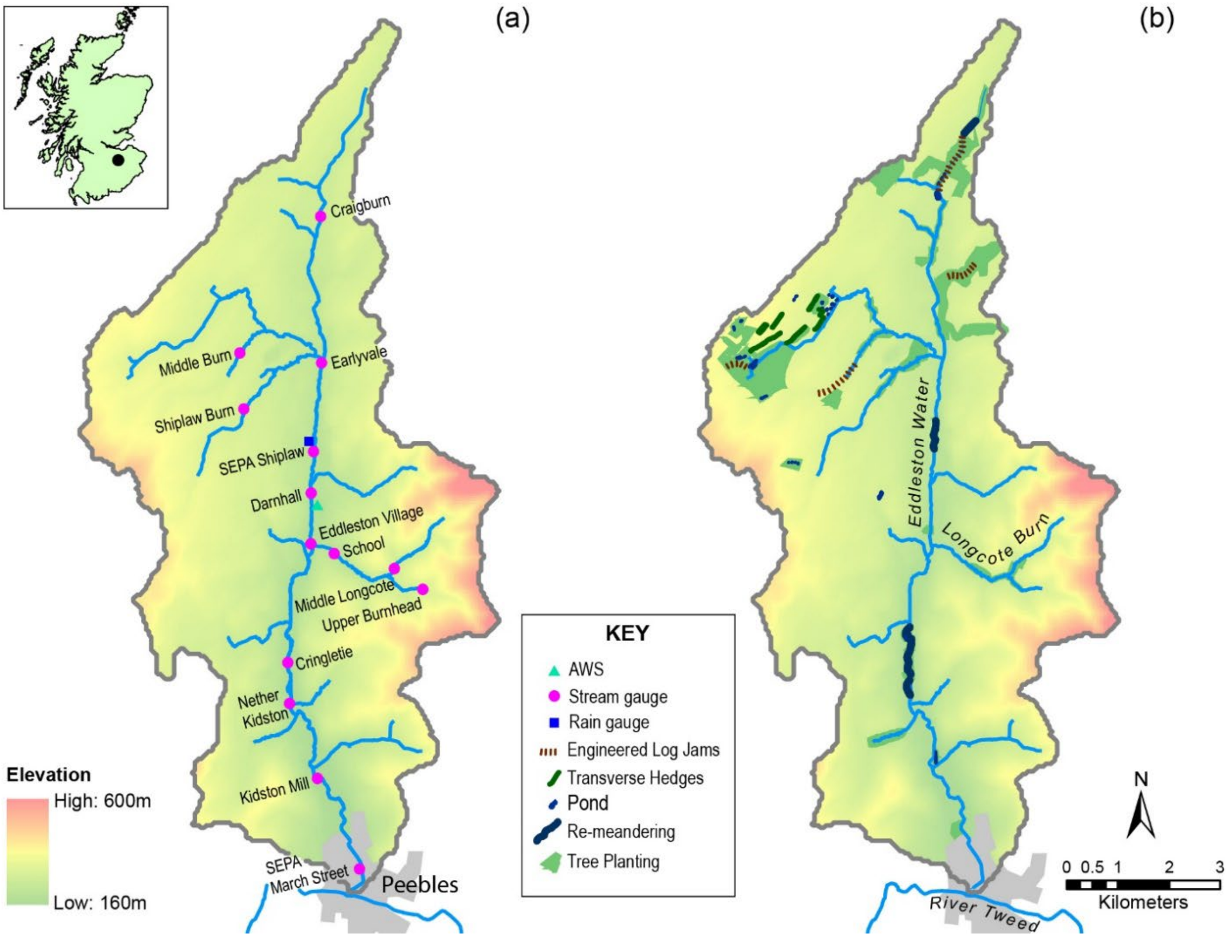


Figure 7. Gauging sites used in the analysis and location of NFM measures

Results – lag time and event frequencies

Lag analysis results are shown in Figure 8 and Table 1.

a) In catchment areas of less than 26 km², all three NFM experimental catchments treated with a mix of flow restrictors, ponds and riparian planting show increases in median lag times from 4 hours or fewer to 6 hours or more (Figure 8) following the introduction of measures. By contrast, two control catchments showed median lag times of less than 4 hours in both the baseline period and also in the years following interventions in the adjacent experimental catchments.

b) In larger catchments greater than 26 km², median lag times are 5 hours or more in the period before NFM measures were introduced while, in the period after measures, median lag time increases by at least 0.5 hour except in the furthest downstream site. For catchments greater than 26 km², median lag time increases with catchment area, as would be expected given the increases in distance downstream.

c) The differences observed between pre- and post-NFM lag values are shown to be statistically significant at a 5% significance level for all three catchments < 26 km² (Table 1).

In all NFM catchments, the annual frequency of events reduces substantially after the 2-year baseline period. Whilst this may be a direct result of the implementation of the NFM measures, other concurrent changes such as climatic variability or alteration in land management may also play a part. Nevertheless, the typical reduction in event frequency in NFM catchments, in excess of 70%, makes a striking contrast with the typical change in the control catchments, ~ 35%, noting that in such small catchments, volatility in hydrological response is not unexpected due to potentially significant changes either locally in the stream channel or the catchment.

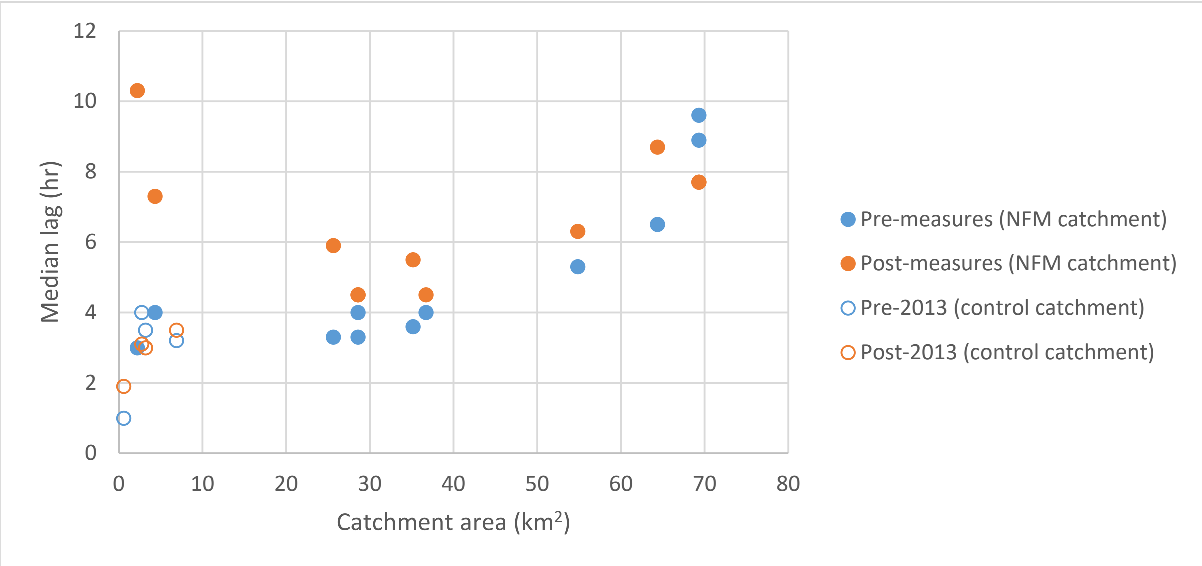


Figure 8. Median lag as a function of catchment area for NFM and control catchments, for peaks occurring before and after the commencement of NFM implementation in August 2013.

Table 1. Median lag time, change in annual event frequencies and significance of differences before and after commencement of NFM measures in August 2013 (bold signifies increases in median lag > 2.5 hr and differences in lag values significant at p<0.05)

	Catchment area (km^2)	Median lag (hr) at ~1-year sampling threshold		δ median lag (hr)	Number of events above highest threshold (*n*)		δ annual frequency	Record length (yrs)	p-statistic for significance of differences between samples of *n* observations		
		Pre-measures	Post-measures		Pre-measures	Post-measures			*n*>=5	*n*>=10	*n*>=20
NFM catchments											
Middle Burn	2.21	3.0	10.3	**7.3**	5	5	-71%	9.0	**0.011**	**0.043**	**0.002**
Craigburn	4.34	4.0	7.3	**3.3**	15	5	-90%	9.0	0.069	**0.008**	**0.024**
Earlyvale	25.64	3.3	5.9	**2.6**	5	6	-66%	9.0	0.061	**0.046**	**0.020**
SEPA Shiplaw (18 yrs)	28.57	4.0	4.5	0.5	17	5	-50%	18.5	0.127	0.258	0.102
SEPA Shiplaw (9 yrs only)	28.57	3.3	4.5	1.2	8	5	-82%	9.0	0.072	0.080	**0.021**
Darnhall	35.16	3.6	5.5	1.9	6	5	-76%	9.0	0.206	0.129	0.264
Village	36.69	4.0	4.5	0.5	8	5	-82%	9.0	0.464	0.171	**0.011**
Nether Kidston	54.84	5.3	6.3	1	5	5	-71%	9.0	0.058	0.326	0.192
Kidston Mill	64.38	6.5	8.7	2.2	6	5	-76%	9.0	0.181	0.397	0.268
March Street (15 yrs)	69.3	9.6	7.7	-1.9	8	5	-29%	15.0	0.394	0.309	0.179
March Street (9 yrs only)	69.3	8.9	7.7	-1.2	6	5	-76%	15.0	0.323	0.174	0.230
Control catchments											
Shiplaw Burn	3.18	3.5	3.0	-0.5	12	5	-88%	*9.0*	0.456	0.484	0.476
School	6.89	3.2	3.5	0.3	5	11	-37%	8.7	0.140	0.152	0.078
Middle Longcote	2.75	4.0	3.1	-0.9	5	24	37%	9.0	0.444	0.386	0.187
Upper Burnhead	0.59	1.0	1.9	0.9	5	*8*	-54%	6.6	0.484	0.409	0.448

Results – flood peak magnitudes

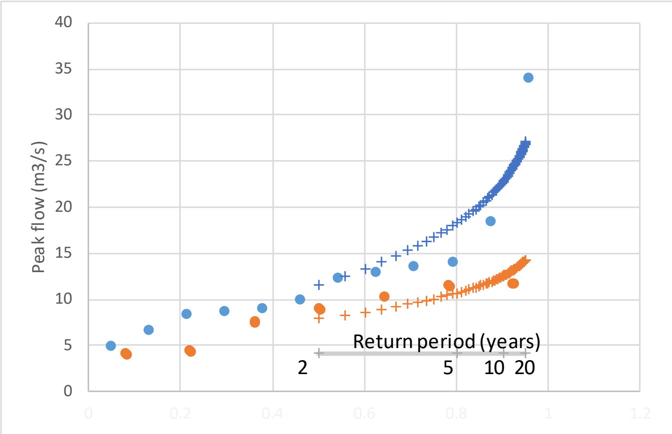
The analyses in Figure 9 show a dramatic reduction in estimated flood risks at the Shiplaw gauging station post-2013 when comparing with pre-2013 data. The reduction in the 10-year flood is in the order of 45% in flow terms. At the March Street gauging station downstream, a lesser reduction is seen, equivalent to a reduction in flood risk of 9% comparing data from either side of the same 2013 division in the annual maximum flow series.

High flood levels In Peebles at March Street

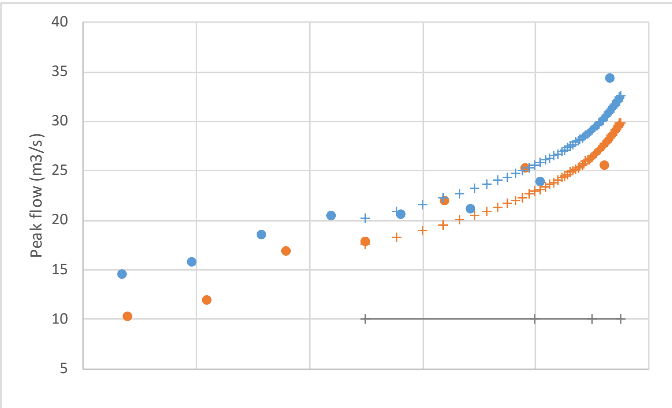
Comparing these changes with gauging stations in neighbouring catchments, increases in estimated flood risk are seen for the Lyne Water and Manor Water (+ 97 mm in level terms, and +22% in flow terms, respectively) while for the North Esk to the north of Eddleston, the corresponding change is a 23% reduction in flood risk. While climatic or other random effects must affect estimates of flood risk using any period of record, it is striking that the largest reduction in flood risk among any of the sites examined is for the Eddleston above Shiplaw – a catchment which also shows a major increase in lag time.

Figure 9. Flood frequency analyses for annual maximum floods on the Eddleston Water and in adjacent catchments:

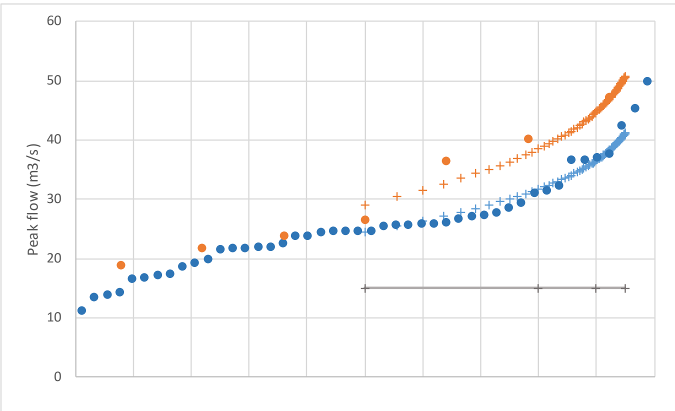
(a) Eddleston Water at Shiplaw (26 km²)



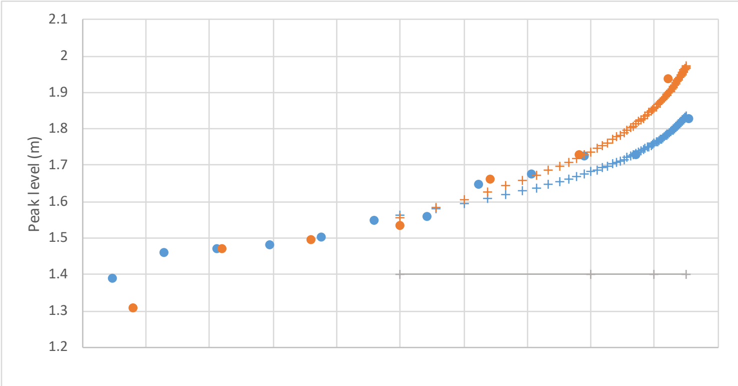
(b) Eddleston Water at March Street (69 km²)



(c) Manor Water at Cademuir (62 km², south of Eddleston)



(d) Lyne Water at Lyne Station (175 km², west of Eddleston)



(e) North Esk at Dalmore Weir (82 km², north of Eddleston).

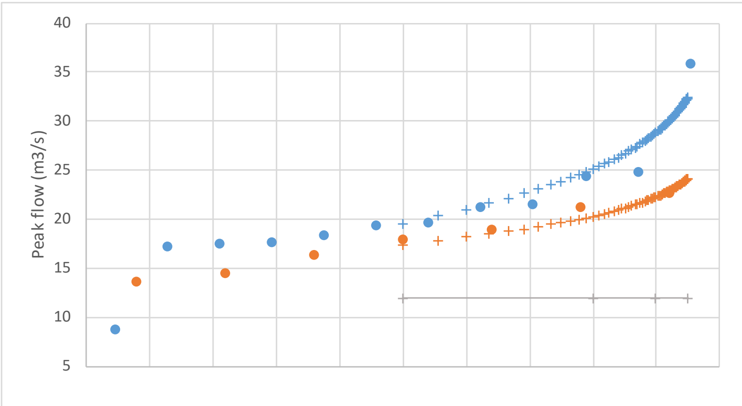


Figure 9 - a Generalised Extreme Value distribution (+) is fitted to observed annual maxima (●) plotted using Gringorten plotting positions for each site. Blue: pre-2013, orange: post-2013. Given the short record lengths, uncertainties are large.

Results - Impact of creation of Ponds for temporary flood storage:

The creation of ponds across catchments to temporarily store water in times of flood is a well-known NFM measure and this is now the focus of ongoing detailed study being undertaken for the project by BGS. Meanwhile, one recent intervention in the Eddleston which is readily analysed is the building of such a pond at Kidston Mill, designed to attenuate flood peaks downstream of most of the other measures.

Aerial view of large flood storage pond at Kidston Mill – under construction

Kidston Mill flood pond under flood conditions Nov 2021. Note also flooded new meanders upstream at Nether Kidston

Figure 10 shows a striking reduction in flood peaks at the Peebles March Street gauge since completion of the pond in May 2017, relative to water levels at the upstream Cringletie gauge. At a threshold value of 1.1 m above datum at the Cringletie gauge (equivalent to the median flood), the corresponding peak flood flow at Peebles March Street had reduced since 2017 by ~ 21%. The direction of change is consistent with the reduction in flood risk since 2013 reported in Figure 6.

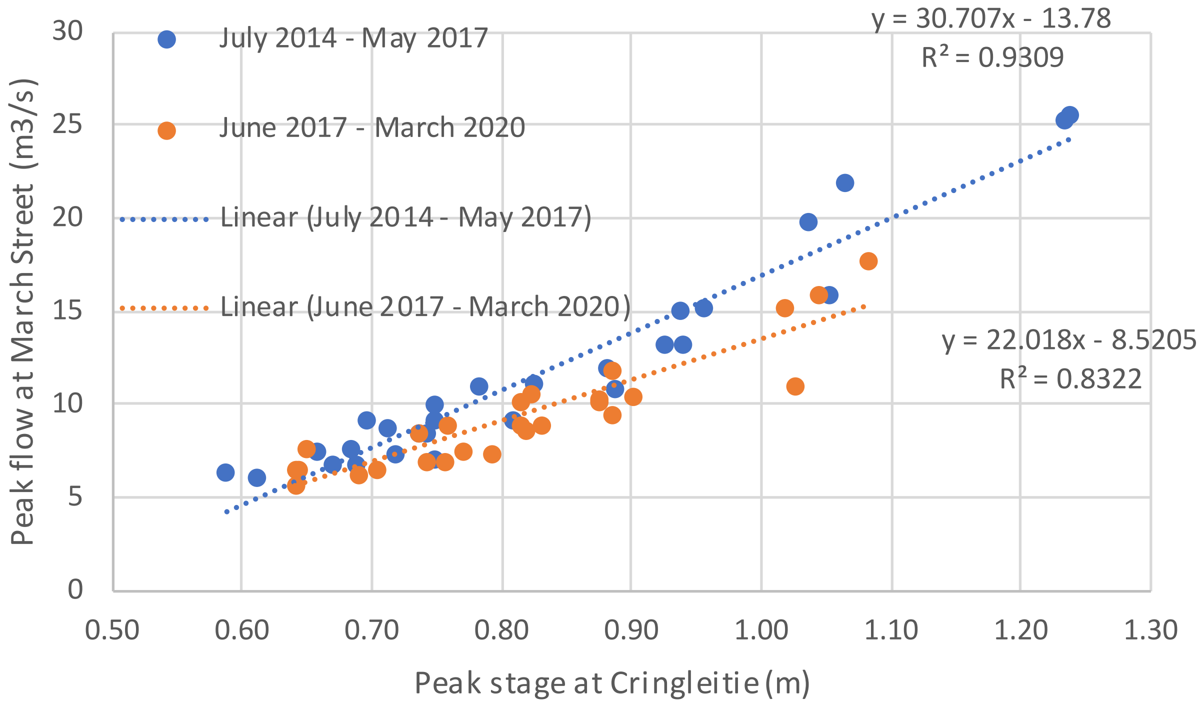


Figure 10. Flood peaks at Peebles March Street relative to an upstream gauge at Cringletie, following provision of off-line storage at Kidston Mill Flood pond in May 2017. No other measures have subsequently been introduced between these gauges.

This empirical result complements initial modelling results of the potential impact of both this single flood pond and a series of such large floodplain ponds undertaken by cbec in 2017 [10]. At the peak 1.5yr inundation, they calculated that the pond as designed for Kidston Mill would theoretically store 19,600m^3 of water, whereas at peak inundation for existing conditions, the same area of floodplain stores only 3730m^3. Extending the modelling to a catchment scale showed that the potential impact of a series of large ponds situated on the floodplain suggests that, for a 1.5-year return interval flow event, five such ponds in series could locally reduce the discharge peak by some 18-20% and theoretically delay it by up to 6 hours.

Results - Impact of remeandering on flood hydrology:

Meanders have been introduced at a number of locations along the main stem over the years since 2013 (Fig 7), as well as downstream at Kidston Mill in 2021, but at the catchment scale they are difficult to associate with specific changes in flood peaks. However, in 2018 a Dundee University funded PhD project began investigating the impact of the re-meandering of a 1.6 km long reach (final length) of the Eddleston Water in its central part [9].

Detailed aerial view of new meanders at Lake Wood 2022

The research assesses the impact of this re-meandered reach on flood attenuation using a combination of three methodologies: observed hydrologic time series analyses, studies of geomorphic changes within the reach, and 2D hydrodynamic modelling (HEC-RAS).

The results show that NFM remeandering alone leads to only a limited increase in flood attenuation both in terms of maximum peak flow attenuation and delays in peak travel time for a Q5y event. Topographic features within the floodplain play a major role in interacting with the flow dynamics and limiting the space available for the flood to expand and as a consequence limit flood attenuation. Without the concurrent removal of all flood banks and reinstatement of unhindered reconnection with the floodplain, channel incision is identified as having a key role in constraining potential flood attenuation from remeandering as an NFM measure.

4. Modelling the Hydrological impacts of Natural Flood Management

Model construction

As part of the work undertaken within the EU *Building with Nature* programme, JBA were commissioned to review the range of catchment information, reports and previous studies from the Eddleston, alongside a wider literature review of approaches that could combine data and modelling with sufficient accuracy to enable the construction of a new catchment model capable of representing a whole-system response to changes resulting from NFM measures in the Eddleston [7]. This concluded that whilst a range of modelling packages are capable of representing NFM in the whole catchment, HEC-RAS 2D makes best use of new high-resolution LiDAR data, has a flexible mesh allowing refinement where necessary, and can be exchanged between partners without licensing restrictions. It was also noted that whilst the current version of the software (5.07) did not include distributed hydrological losses, the next release includes this functionality – something that has now been added to the Eddleston model through the work of BGS in 2022.

JBA then constructed a combined Hydrologic and Hydraulic model of the Eddleston catchment using HEC-RAS 2D [7]. Although this integrated modelling approach helps understand the "whole system response" to the mix of distributed NFM measures, representing NFM in models continues to be the subject of much on-going research, especially in terms of its effectiveness at larger scales greater than ten square kilometres. In the current study, it was found there are trade-offs between representing hydraulic structures, such as engineered log jams more precisely, requiring detailed data to calibrate loss coefficients and long model run-times to ensure stability, or more simply using increased roughness which could risk overlooking more subtle changes in response. These findings were subsequently built into a decision-tree and accompanying user-guide developed in this study to help others intending to represent NFM in scheme appraisal.

New hydrological approaches were used (DAYMOD / ReFH2.2 Calibration Utility) in order to estimate antecedent soil moisture conditions and estimate a realistic net-rainfall for six real high-flow events. These were used as inputs into the whole catchment model, using existing Eddleston data to calibrate the friction loss coefficients across the catchment. A pre-NFM (2012) and post-NFM (2015) terrain model and roughness grid were constructed that represented the changes over the period of NFM installation. The new model was compared against a range of data including the measured hydrographs at small, intermediate and whole-catchment scales, analysis of peak flow time delay along the system, and a trash line survey.

Results of model runs

Overall, the performance of the model was considered to be reasonable for a catchment of this size, and it has been possible to model its response to many distributed changes on the basis of the multi-scale monitoring data. A limited uncertainty analysis was also undertaken to understand the influence of uncertainty in the distributed roughness parameter measurements on model predictions, which helps to contextualise estimates of risk-reduction using the model. For example, when making predictions at the whole catchment scale, uncertainties due to roughness alone can be as large or greater than the change in peak flows that we are aiming to quantify. This does not mean that the relative change cannot be detected, as evident in the consistent reduction in the mean peak flows between pre-NFM and post-NFM, it means that it is harder to detect, and that predictions using a wider range of combinations should generally be considered to understand change. It was also recognised that further improvements to calibration could be made in the future, using distributed rainfall runoff modelling capable of continuous simulations such as ReFH 2.3 calibration utility, or models such as Dynamic Topmodel, and these are being considered in the current project work through BGS.

Nine design events (10, 25, 30, 50, 75, 100, 200, 1000 Return Periods (RP) respectively) were computed using ReFH2, and the pre-NFM and post-NFM scenarios were simulated with a broad-scale representation of the NFM in terms of storage, changes to bathymetry with re-meandering work, and friction, based on published ranges and considering the fine-scale model results. The relative changes to the peak flows vary between 6.9% for RP5 and 5% for RP1000, and these should be expressed with the model uncertainty, for example: peak flow reduction is 7% +/- 5%. Whilst this shows relatively small changes for the large number of interventions in Eddleston, this is perhaps to be expected without large areas of land use change or more storage in the headwaters. However, the fact the changes are predicted to keep working at extreme flows (land-use change may not have the same effect as larger events may wet up the extra soil storage) suggests that NFM is a useful, complimentary measure that can be used in combination with traditional risk reduction measures such as defences, especially to help reduce the growing impacts of climate change.

Further analyses, bringing in results using this same whole-catchment direct-runoff modelling approach from other catchments has been used to analyse how the storage on the floodplain can expand with flood magnitude, and can be enhanced with appropriately designed NFM [11]. For Eddleston and other large catchments it is evident that with more rainfall and flows, more areas of the floodplain come into play as storage, especially where re-meandering is concerned. For example, at Cringletie the additional floodplain storage before (8700 m^3) and after (9216 m^3) restoration of the meanders was estimated using zonal statistics, giving an increase in 6% of the original storage for the same event [11].

New meanders at upper Nether Kidston (foreground) and Cringletie upstream in flood conditions. The yellow line shows the line of the old straightened channel.

5. Fluvial Audit

cbec undertook a detailed fluvial audit of the whole river system in 2018, repeating their earlier full survey in 2009 and partial surveys in 2015/2016, along with fixed-point photography. In addition, they undertook topographic surveys of specified sections of the Eddleston Water which together aims to assess the physical and biological changes that have occurred within the active river corridor following the implementation of the various restoration and NFM measures across the catchment [10].

The 2018 fluvial audit was undertaken in March/April and follows the same method used in 2009. This is a modified version of the more standard 'Fluvial Audit' methodology developed by cbec for the Eddleston project to allow for the identification of the physical condition of the river and, specifically, the engineering impacts along its length (with the view to prioritising restoration efforts). This methodology classifies channel character in terms of observed morphology, the physical expression and integration of fluvial processes, and is thus more process-based than some 'Fluvial Audits' such as the River Habitat Survey which is essentially just an inventory of components of the channel/ riparian zone. The survey was undertaken at a high spatial resolution that involved recording morphology down to the scale of individual habitat/ morphological units and alluvial bar forms and provides a spatially-referenced, digitised inventory of the physical form of the river (morphology and sedimentology), key habitats and all likely relevant influencing factors (e.g. sediment dynamics including erosional and depositional patterns, sediment sources, tributaries inputs, river corridor confinement, sediment size, riparian vegetation structure, bank erosion, engineering pressures). The survey covered the main 12 km section of the river extending from Waterheads (NT 2446 5100) downstream to the footbridge (NT 2519 4080) at March Street in Peebles. Fixed point photography was undertaken to supplement the physical condition monitoring of the channel and riparian areas. A set of 50 photographs were provided with their location and orientation recorded, which will be particularly beneficial after large flood events, when the channel has more energy to actively carry out work.

The topographic surveys of the active channel corridor and floodplain were undertaken at key locations along the river. This covered all the remeandered sites (Shiphorn – 570m; Lakewood/Milkieston/Cringletie/Nether Kidston – 1.5km); five control locations up and downstream of the remeandered sites (Shiphorn 440 + 540m; Lake Wood 530 + 461m; Rosetta Bridge 490m); and at four gauging stations (Craigburn 142m; Darnhall 160m; Eddleston 100m; Earlyvale 115m). A non-cross-sectional, grid-based survey protocol was employed, to provide optimal coverage of the site and allow a detailed 3D surface of control and restoration reaches to be generated.

New channel form and placement of woody structures in newly created meander at Nether Kidston

The greater level of detail captured using a grid-based survey (over a typical cross-sectional) approach allows for greater accuracy when meshing together collected topographic survey data with existing LiDAR data, producing a continuous, detailed surface along the specific reaches of the river. In addition, two fixed control points were surveyed-in over the duration of the survey, enabling subsequent monitoring of key fluvial processes (e.g., the development of alluvial bars or bank erosion leading to lateral channel migration).

Full details of channel changes are presented in the Monitoring Report [10] which also establishes a detailed baseline for further surveys. In summary, it shows that morphological diversity is greater than in pre restoration conditions (2009 survey). This shows that restoration measures have allowed natural fluvial processes to return, which has increased morphological diversity which, in turn can be expected to lead to associated ecological benefits. In the later time period between the two post restorations surveys (2015/2016 and 2018) there has been a slight simplification in the restoration reaches, with a small reduction in morphological unit complexity. This would be expected to occur as following restoration lack of vegetation and rapid channel adjustment will initially create a very unstable but diverse set of morphological units as the channel attempts to restabilise. As vegetation recolonises banks and alluvial bar forms, these features will become more stabilised, therefore increasing the amount of energy required for ongoing morphological adjustment and creating a more stable but less morphologically diverse channel. This simplification of the channel has been amplified by the fact that there have only been moderate magnitude flow events since the implementation of restoration measures. A high magnitude flow event is required to a properly test the system in terms of how it adjusts from such an event.

6. Groundwater and Soils

The Eddleston Water Catchment is largely underlain by fractured greywacke sandstones that have been eroded and partially infilled by subsequent glacial and alluvial processes.

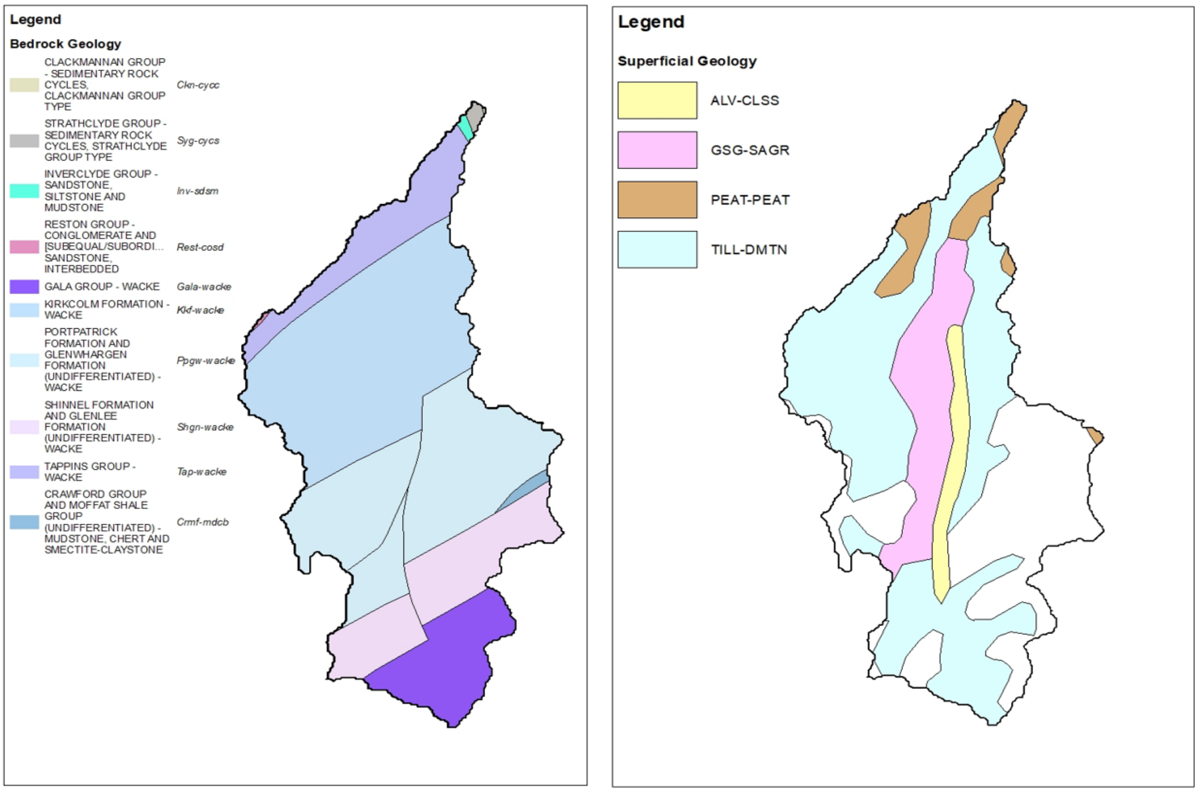


Figure 11. The Eddleston Water Catchment. Left: Bedrock Geology; Right: Superficial Geology (Reproduced with the permission of the British Geological Survey ©UKRI. All rights Reserved (from Eddleston Report 2016)

The British Geological Survey (BGS) has been leading the groundwater research involved with the project since its inception, initially with University of Dundee and latterly bringing in other partners, including University of Edinburgh. There have been three main aspects to their work: (1) monitoring how floodplain aquifers interact with the runoff and the river; (2) examining variations in soil permeability with landcover and geology; and (3) estimating the significance of subsurface flow throughout the catchment and in relation to storms and changes in landcover. The studies have involved: detailed 3D characterisation using geophysics, drilling, geological and hydrochemical surveys; long term monitoring of groundwater and soil moisture on both a hillslope and floodplain observatory; targeted surveys of soil permeability; and multiyear high frequency measurements of stable isotopes. Key learnings have been published in a series of papers, as referenced below.

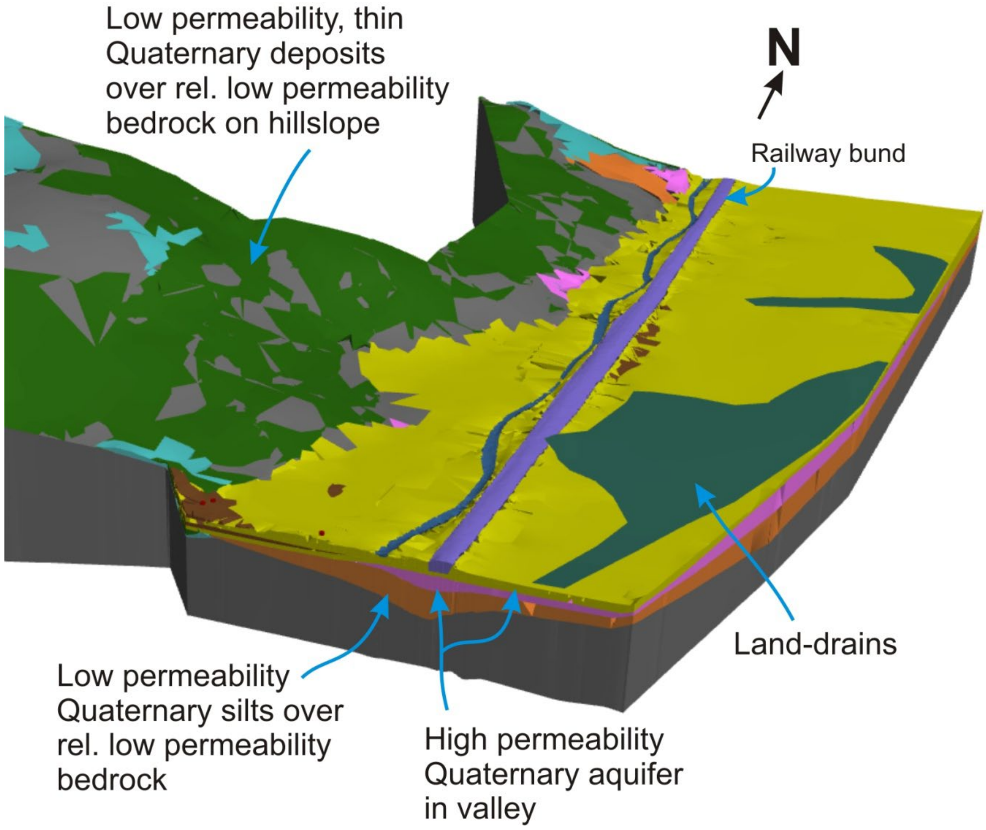


Figure 12 - The 3D hydrogeological model of the Darnhall floodplain and hillslope used to identify sub-surface coupling between hillslope and river (from Ó Dochartaigh et al. 2019 [12]).

Most of the floodplain groundwater is more closely coupled to river flow than local rainfall, and groundwater levels rise within hours of river level rise, but quickly recede after river levels fall. However, at the edge of the floodplain, groundwater is much more closely coupled to the hillslope with groundwater levels rising slowly after local rainfall and receding after several weeks – leading to localised groundwater flooding [12]. This is strongly controlled by the nature of the geology and shows the importance of understanding the 3D geology of floodplains in forecasting hillslope river coupling (Fig 12).

There is a strong relationship between land use, type of woodland and soil permeability [13]. Soils under mature broadleaf woodland have a much higher permeability (5 – 8 times) than under neighbouring grazed pasture or under coniferous forest plantation. Further study of the role of coniferous plantations in the catchment showed that although plantation forest cover could reduce total storm rainfall fraction by 11%, a much larger control was exerted by differences in geology and soil type [14]. Similar results were given from a distributed hydrological model study in 2021 [15] which showed that whilst variation in superficial geology was generally more important in controlling flooding than land use at a large scale, within two sub-catchments of similar geology, land use exerted a strong control

By comparing groundwater flow and soil moisture characteristics of a slope with and without a transverse forest strip, sub surface flow dynamics could be investigated. Although sub surface soil moisture dynamics and water table depth were altered within the strip, there was little evidence of the effect persisting more than 15 m downslope. This experiment also showed that the presence of the forest strip had no impact on groundwater connectivity through larger storms [13]. Wider research across the catchment showed during storm events, pre-event soil and groundwater often comprised more than 50% of runoff [16].

7. Assessing the Ecological and Hydromorphological impacts of NFM restoration at the catchment scale

The Eddleston Water Monitoring Strategy identified that the impact of restoration should be assessed at both the whole catchment and individual NFM scale. For whole catchment impact, biology and hydromorphology were examined by reference to the ongoing assessment of 'Ecological status' as measured by SEPA using standard methods for monitoring of waterbodies for EU Water Framework Directive (WFD) reporting. In the context of WFD reporting, the Eddleston Water catchment is actually recorded as two separate water bodies: the *Cowieslinn Burn* (7.3km, SEPA id. 5308) which is the largest northwest tributary, and the main stem *Eddleston Water/Cuddy Burn* (19.2km, SEPA id 5307). The Cowieslinn Burn, which is not specifically monitored is recorded as good ecological status in all years pre and post the Eddleston project, so is not examined further. The classification and status of the main stem is more complex, partly due to changes in methodology introduced by SEPA during this period (see below).

For biology, information on macroinvertebrates, macrophytes and fish were collected. SEPA collected samples of aquatic macroinvertebrates for routine monitoring from a single location on the main stem of the Eddleston Water at the downstream end of the river in Peebles. Results from this monitoring had shown that aquatic macroinvertebrate indicators were of consistently good status. At this scale (i.e. 5km downstream from the restoration sites) no changes from restoration were expected to be evident. Macrophyte monitoring still occurred at five locations, including the original sites up and downstream. Fish were monitored by Tweed Foundation every three years, as spot sampling for salmonid fry at sites along the Eddleston Water. No WFD monitoring data is presented for fish by SEPA prior to 2013.

Fish sampling using electrofishing at Lake Wood

For hydromorphology, SEPA's Morphological Impact Assessment System (MImAS) was used to assess the 'hydromorphological status' of the river channel for the WFD. The process determines the morphological impact resulting from single or combinations of activities (such as artificial bank revetments) within a given length of channel. Along the Eddleston Water, much of this is a legacy from channel realignment 200 years ago. Using MImAS, a detailed survey was undertaken by SEPA in 2012 before any NFM works began which resulted in a downgrading of the WFD score to 'Bad' status. As WFD monitoring employs a 'one out all out' to assessment, such a Bad status for hydromorphology results in this same score for the entirety of the waterbody, irrespective of the status of other elements. Along with the earlier Fluvial Audit undertaken by cbec as part of the Scoping Study, the 2012 MImAS survey was used to help identify potential reaches for channel restoration.

The other aspect of river restoration that needs to be considered is the length of channel that has been restored and recreated as part of the project. The comparison is not only to the total length in 2012 before any NFM measures were implemented, but also to the watercourse's original course and the lengths of channel that were 'lost' in the intervening decades due to straightening and the creation of hard embankments that cut off connectivity to its floodplain.

Methods

At the catchment level, ecological monitoring followed closely existing methodologies and locations, providing continuity with previous data streams. For biology, macroinvertebrate standard 3 minute kick samples collected in Spring and Autumn were available (identified to taxonomic family level), and accompanied by the associated RIVPACS environmental information (wet width and mean depth of channel, substrate (Wentworth categories), hydromorphological unit and bed stability). Therefore, to build on this source of information, macroinvertebrate sampling was undertaken as one of the key ecological assessment units Aquatic macrophyte monitoring used the WFD LEAFPACS methodology at the five 100m locations. Fish monitoring followed the spot sampling programme for salmonid fry undertaken by Tweed Foundation. Analyses followed WFD protocols and indicators for assessing waterbody 'status'.

For Hydromorphology MImAS was used to build on existing information, though throughout the assessment period modifications to the exact methodology were being considered, and updated surveys are ongoing. Measurement of the original water course and the lengths of channel recreated was done using old maps and the detailed hydromorphological surveys done pre and post creation of the new re-meanders.

Monitoring of other species, including otters, water voles and lamprey was discounted as were any proposals to monitor INNS as any changes were unlikely to be consequent upon introduction of NFM.

Results

As noted in the 2016 Eddleston Report, comparison of the old Turnpike road map produced at the very end of the eighteenth century with the watercourse as in 2012 reveals that by 1801 works to enable the building of the new road and smaller areas of agricultural 'improvement' had already led to the loss of some 16% of the original 6.5 km channel length along that stretch of the valley bottom from Waterheads to Eddleston village.

Since 2012, some 362 m of 'new channel' has been re-instated (Table 2) along different stretches where remeandering has occurred. In addition, some lengths of channel have been left open as ponds along the old line of the river, such as at Lake Wood. As a percentage of the total water course, 362m is only a 2.0% increase in channel length, but it represents 3.3% along the main floodplain (Shiphorns to Peebles), and 10.9% of the three main sections that were remeandered (Shiphorns; Lake Wood-Milkieston-Cringletie-Nether Kidston upper; Nether Kidston lower – less 116m section at Cringletie hotel that could not be altered because of potential bridge stability.

Location	Length 2007	Length 2021	Difference	% Increase
Shiphorns to Leadburn	7192	7192	0	-
Shiphorns	556	605	49	8.8
Eddleston Village	3834	3834	0	-
Lake Wood	272	398	126	46.3
Milkieston	170	196	26	15.3
Cringletie	516	556	40	7.8
Cringletie Hotel bridge	116	116	0	-
Nether Kidston upper	297	335	38	12.8
Redscarhead	1078	1084	6	0.5
Nether Kidston lower	425	502	77	18.1
Peebles to Kidston Mill	3661	3661	0	-

Table 2 Length (in metres) of channel that has been restored or newly recreated along the main stem of the Eddleston water from north to south since 2012

Three remeander reaches looking downstream from Lake Wood, through Milkieston to Cringletie and showing line of old course.

WFD reporting results are summarised for key years in Table 3, with the full picture available on https://www.sepa.org.uk/data-visualisation/water-classification-hub/. Overall, the waterbody has improved from Bad (the poorest category in WFD monitoring) immediately prior to any NFM measures being implemented (2012), initially to Poor (2018) and latterly to Moderate Potential (2020). This last change of 'category' introduced by SEPA in 2019 identifies Eddleston as a 'Heavily Modified Water Body' (HMWB), for which 'potential status' as opposed to 'actual status' is set as the eventual goal of improvement through river basin management. As noted by SEPA, '*The water body has been designated as a heavily modified water body on account of physical alterations that cannot be addressed without a significant impact on the drainage of agricultural land*'.

Parameter / Year	**2009**	**2012**	**2018**	**2020**
Overall Ecological status	**Poor**	**Bad**	**Poor**	**Moderate Ecological Potential**
Physico-chemical	high	high	high	high
Overall Biological elements	Poor	Bad	Moderate	Moderate
Specific pollutants	pass	pass	pass	pass
Hydromorphology	Moderate	Bad	Poor	Poor
Hydrology	Good	Moderate	Good	Good
Water quality	-	-	Moderate	Moderate

Table 3: Summary WFD classification of the Eddleston Water/Cuddy Burn (ID:5307) over time. From SEPA's Water hub available at https://www.sepa.org.uk/data-visualisation/water-classification-hub/.

This overall improvement in classification hides some slightly confusing changes between years. Some elements show diverging and in places inconsistent variations. Within the suite of sub-elements that make up Biology, Macroinvertebrates have consistently been at 'High' status ever since records began; Aquatic plants have maintained 'moderate' status throughout; but Fish ecology which began at 'high' in 2012 dropped to 'good' in 2017 and down to 'moderate' in 2016 and since. And whilst Hydrology has been high or good throughout, Hydromorphology changed from Moderate in 2009-2011, to Bad in 2012 (all years prior to any NFM measures) and then improved to 'Poor' for all years since the implementation of NFM measures.

As noted, measurements of aquatic macrophytes continued at five sites along the Eddleston Water, not only the main WFD monitoring location downstream, so it will be interesting to see the results of this wider monitoring in due course.

Water Temperature

Though not a part of the main project monitoring, reference should also be made to a study in 2021 by Demi Payne, a University of Dundee student [17] which utilised the hydrological monitoring network established by the Project along with a 34-year data set collected by SEPA to examine how stream water temperatures are changing in the Eddleston Water catchment and identify the possible drivers.

Whilst no evidence was found to show that water temperatures have been significantly impacted by climate change in the past 34-years, local topography was found to influence temperatures between sampling points. Of particular relevance, the NFM measures implemented at four specific sites, were shown to have significantly lowered localised water temperatures, particularly in summer months, with one site, Craigburn Farm exhibiting a 1.5°C decrease in daily maximum water temperatures after modification. This work highlights the potential importance of NFM measures such as riparian tree cover, engineered log jams and fencing in creating areas of thermal resilience.

NFM flood storage Ponds

Another complementary study undertaken in 2021 by a Swiss university student, Malika Gyger working through Dundee University has investigated the ecological benefits provided by the creation of NFM ponds across the Eddleston catchment [18]. She examined whether ponds primarily designed for the attenuation of flood risk, host communities of aquatic macroinvertebrates that are rich and diversified. The student also investigated whether environmental predictors and pond connectivity might be driving the biodiversity of these ponds.

Through detailed surveying of the macroinvertebrate communities in 12 ponds, the student was able to show that when identified to the taxonomic 'family' level, the mean richness of NFM ponds (27.5 families) was similar or better than that found in many other 'natural' or conservation ponds across the UK. NFM ponds have the ability to play a dual role, functioning both to alleviate flooding and to enhance catchment biodiversity. Ongoing studies using analyses of environmental DNA taken from 18 ponds are now also being compared with e-DNA results from samples taken in 2021 from the different habitats in the four standard river macroinvertebrate sampling locations. The results from this work will provide evidence at the species level of the added value of NFM flood storage ponds in terms of their contribution to overall catchment wetland biodiversity.

Sampling for aquatic invertebrates in Kidston Mill Flood pond 2021

8. Assessing the Hydromorphological impacts of NFM restoration through re-meandering

A key aim of river restoration is to create a greater diversity and spatial extent of geomorphic units within rivers where physical structures such as pools and riffles have been lost, become oversimplified or degraded. As well as improving river habitat quality, quantity and, ultimately aquatic biodiversity, it may also help reduce flood risk through lengthening the channel, and potentially increasing roughness and the storage of water on the floodplain. Returning bends to rivers creates helical flow, driving a greater variation of flow velocity patterns. Longer term, this increased flow diversity should drive variable patterns of sediment erosion, transport and deposition, further increasing geomorphic structural diversity, and be reflected in distinct differences in grain size. As a result, this should lead to an increase in habitats and ecological niches, and therefore an increase in diversity of aquatic macroinvertebrates and fish. Areas of deeper water such as pools also play an important role in regulating water temperature as the climate warms, increasing system resilience to this warming.

Methods

Monitoring aimed to investigate the changes to the physical structure of the river following restoration [19], and, in particular: a) whether restored sites have greater geomorphic diversity than the unrestored, control sites; and b) if geomorphic units within the restored sites display distinct differences in the grain size distribution for each unit (compared to geomorphic units present in the reaches prior to restoration and to those situated within the unrestored, control sites)? Four 100 m long sites were monitored; two control sites (Signal Cottage – upstream; Rosetta Bridge - downstream) and two restored sites (Lake Wood – upstream; Cringletie – downstream). Geomorphic unit mapping and sediment sieving were carried out for each sampling reach. Sampling was carried out in 2013 prior to restoration (pre) and at 1, 3, 5 and 7 years following restoration: 2015 (Post1), 2017 (Post3), 2019 (Post5) and 2021 (Post7).

Geomorphic unit mapping - Geomorphic units may be defined as distinct morphodynamic entities that have been formed by either erosional (i.e. pools) or depositional (riffles and bars) processes, and they have distinct characteristics (i.e. flow-sediment relationships) which reflect the energy of a reach and the type of river. Analysis using the Geomorphic Unit Toolbox (GUT) was undertaken by Dr. Richard Williams from University of Glasgow. GUT uses high-resolution topographic data to map the distribution of geomorphic units within a reach, and as this analysis is based on the topography of the channel, GUT does not have the user variability and error often found in other methods of mapping. (see https://github.com/Riverscapes/pyGUT). A high-resolution topographic survey of the channel was undertaken by cbec in May 2018 which was interpolated to create a 0.1 m resolution grid, enabling the model to analyse the three-dimensional geometry of the bed. The Shannon-diversity Index was used to quantify the channel diversity.

Sediment sieving - Sediment sieving involved digging up sections of the channel bed and passing the sediment through multiple sieves to determine the distribution of grain sizes.

Sieving and weighing channel bed sediment samples at Shiplaw meander

Sediment was sampled at all four sites from each in-channel geomorphic unit present - slacks, pools, glides, runs and riffles - with the number of samples taken reflecting the proportion of the site made up of that unit. A target sample weight of sediment to be sieved was calculated using the average weight of the three largest grains and multiplying this by 20. Sieve mesh sizes were 2, 4, 8, 16, 32, 64, 128 and 256 mm. The resulting data reflects the weight of material in each of the categories, enabling percentile information to be extracted statistically from this distribution. The data was also analysed using PCA analysis, using the substrate distribution measurements (percentiles of 5, 10, 25, 50, 75, 90 and 95) to create indices of substrate distribution. Principal components one and two (PC1 and PC2) explained 80.6% and 15.0% of the variation in the dataset.

Results

a) *Do restored sites have greater geomorphic diversity than the unrestored, control sites?*

Figure 13 shows that, four years post restoration, the diversity in geomorphic units differed between the sites 19. However, this relationship was not simple, as the sites could be placed along a continuum of decreasing geomorphic diversity - from Signal Cottage (upstream control) to Lake Wood (upstream restored) to Cringletie (downstream restored) with the most homogeneous being Rosetta Bridge (downstream control).

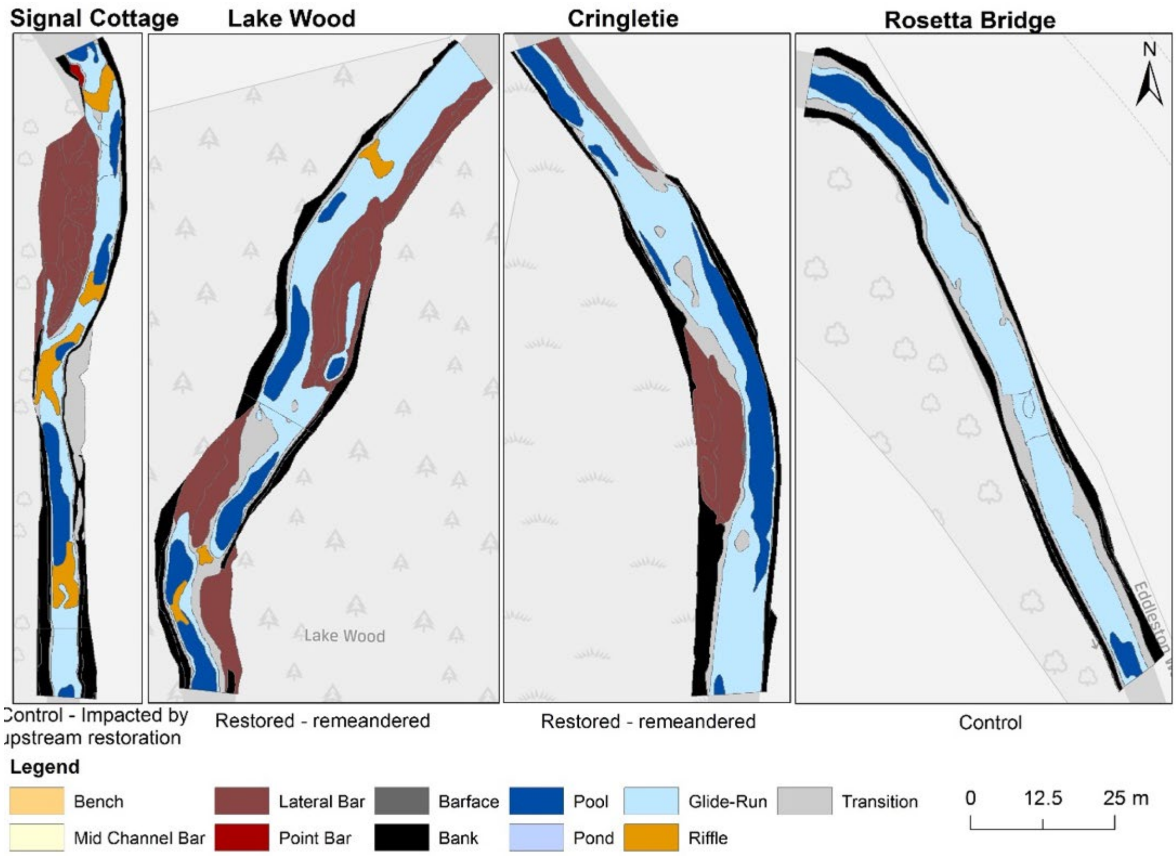


Figure 13: Distribution of geomorphic units as derived from the GUT analysis for Signal Cottage and Rosetta controls site and Lake Wood and Cringletie restoration sites. Sites are presented from upstream to downstream, left to right. Analysis carried out by Richard Williams, University of Glasgow.

b) Do geomorphic units within the restored sites display distinct difference in the grain size distribution for each unit?

Lake Wood, the upstream restored site, only had glide units prior to restoration, seen in a small ellipse size (Fig 14). Following restoration, pools and runs have also formed. Despite overlap in size, a clear trend in coarsening from pools to glides to runs is clear, which has been mirrored by an increase in ellipse size. The Cringletie restoration site shows a similar pattern of coarsening, with runs becoming coarser than glides following restoration. This pattern was distinct at 3 years post restoration, mirrored in a larger ellipse size. However, a lack of high flows and a dense cover of macrophytes on the bed are likely to have decreased the extent of these grain size differences seen at Post 5 at Cringletie and to a lesser extent Lake Wood (though they are still at a level greater than prior to restoration based on ellipse size).

Of the two control sites, Signal cottage had very similar grain size distributions at the initial survey for all units. Over the sampling period the differences in grain size between units have become more distinct, with glides exhibiting fining and riffles coarsening. This is echoed in the PCA analysis, but with a much smaller ellipse for the pre sample, which has become larger over time, especially for the Post 3 sample. In contrast, at Rosetta Bridge, grain size distributions for the different units have remained very similar, with considerable overlap observed, across all time periods in the raw data. In the PCA analysis, the overlap of the samples remains similar for the time-points, despite the ellipse increasing in size for the Post 3 sample (this increase is not supported by analysis of the raw data).

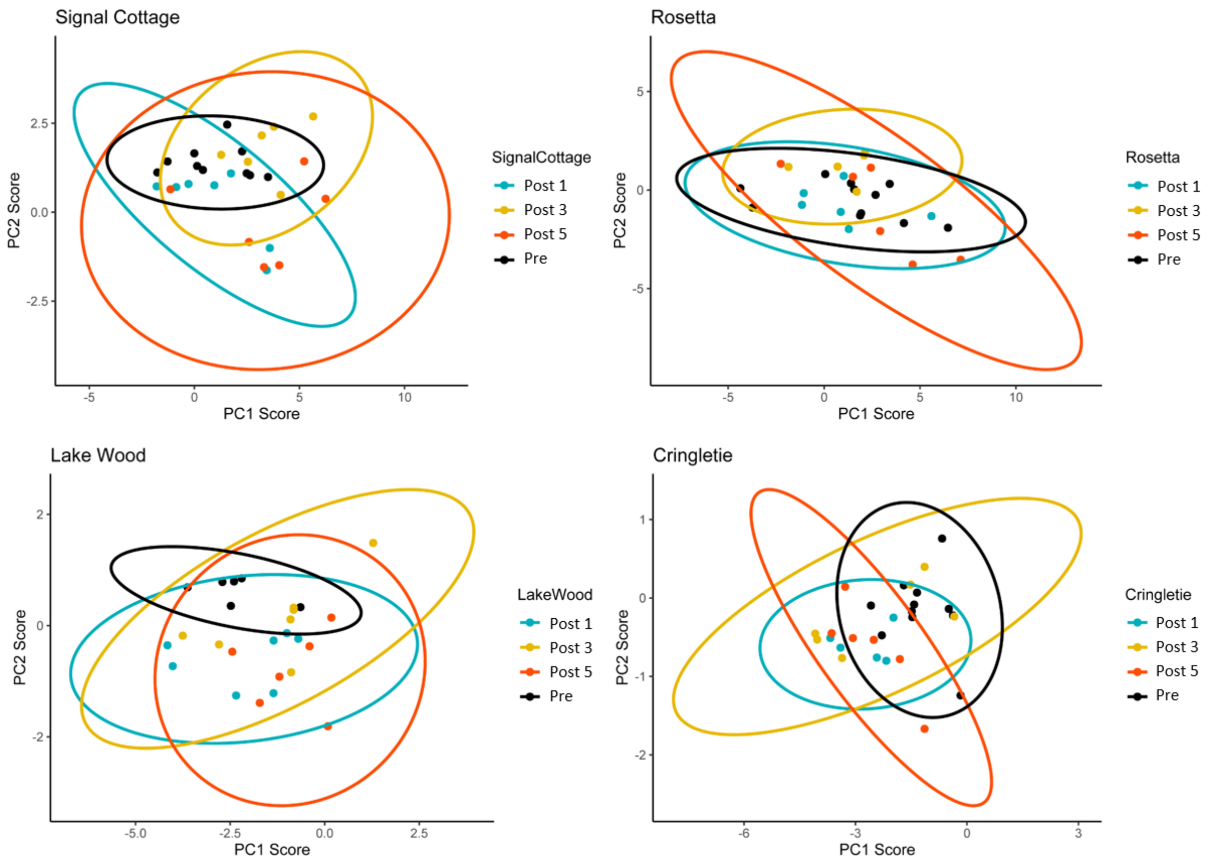


Figure 14. 95% ellipses based on sediment distribution data for the four sites at each of 4 sampling time-points.

Whilst both geomorphic diversity and the extent of grain size sorting between sites displayed differences, these are not as simple as control versus restoration. Instead, the role of site history and local scale conditions were contributors. Whilst both restored sites displayed an increase in sorting for geomorphic units following restoration, this was more defined for Lake Wood compared with Cringletie. These units also demonstrated greater sorting, though the same pattern of coarsening from glides to runs was apparent at both sites. Lake Wood was restored to a greater sinuosity (1.46) than Cringletie (1.08), with a straight line having a sinuosity of 1, which has resulted in increased geomorphic unit diversity and a greater number of units. Lake Wood also underwent a greater increase in channel length (46%) compared to only 8% at Cringletie, which resulted in an increase in both quantity and quality of habitat available. Lake Wood also has more energy with the pre-restoration alignment having 408 W/m^2 compared with Cringletie's 67 W/m^2.

Temporal variation is also likely to have impacted channel recovery. The median high flow at the Shiplaw gauge (close to Signal Cottage) is 12 m^3s^{-1}. However, high flows for 2017 and 2018 were only 3.5 and 5.2 m^3s^{-1} respectively. Without larger flows, less adjustment and therefore recovery can occur. In addition, macrophytes have colonised the bed of the restored sites. This is impeding sediment entrainment and sorting and decreasing the differences in grain size between the different units. A large flow would be needed to remove this plant material and sort the underlying sediment.

In summary, this study indicates that restoration has increased the diversity of geomorphic units and how well sorted these units are [19]. Restoring the correct sinuosity for a reach of river is essential for rivers to recover diverse morphology. The restored sinuosity at Cringletie is lower than what would be expected naturally for this site, and less than that of Lake Wood, which has been mirrored in less recovery and a lower diversity and sorting of geomorphic units. Increasing the sinuosity also increases the length of river restored, increasing the quantity of habitat as well as the quality.

It also highlights that these sites are not fully recovered, and more adjustment is necessary to improve condition as recovery takes time and recovery trajectories are not always linear and can vary between sites. Continuing monitoring into the future, and especially following a flood event would help further understand the complexities of restoration. Key findings to be applied to other restoration schemes also include recognition that individual sites vary, and Controls are not operating in a static world and may themselves also change. Just looking at treatment and control for sites will not take into account differences in morphology, history and characteristics of restoration, all of which play a part.

Creation and subsequent evolution of the new meanders at Cringletie

The river along the Eddleston valley was straightened at the end of the Seventeenth century to enable the building of a turnpike road between Peebles and Edinburgh. Subsequently, with the building of the railway in 1855, the channel became entrenched between solid flood embankments. As part of the project, 3.5km of river have been remeandered, starting with this section at Cringletie in 2013.


2012 - straightened course of river


2013 July - cutting the new channel


2013 old (left) & new (right) channels



2013 August - Opening of new meander & first flow going down the channel


2014 May - freshly deposited gravel bar


2014 Oct - vegetation on gravel bar


2016 May - looking upstream


2016 May - looking downstream


2017 - September


2019 - September


2021 - September

9. (a) Assessing the Ecological impacts of NFM restoration through re-meandering – aquatic macroinvertebrates

Channel re-configuration or re-meandering is common and widespread feature of river restoration projects. As such, at the level of individual NFM measures, ecological and hydromorphological monitoring focussed on this aspect of the Project. To assess impacts on ecology for both macroinvertebrates and fish a BACI design was developed centred on the 'treatment' stretches of remeandered (experimental) channel, combined with the monitoring of control stretches, one upstream and one downstream (Fig 15).

Methods

The choice of remeandering sites was informed by the hydromorphological surveys in the Scoping study which identified the reaches most severely impacted by historical alterations to the banksides and channel. In addition, landowner agreement to the remeandering proposals was a significant consideration. The choice of Control sites was based on co-location with SEPA's existing aquatic macrophyte survey sites and pre-WFD ecology sites. In each case, a "site" was defined by the appropriate methodology used so that all relevant measurements could be physically co-located within the bounds of each site. For this purpose, each site was c.100m long to encompass at least two full pool-riffle sequences (assessed as 12 x restored channel width of 9m = 108m) and the standard survey reach length used for macrophytes.

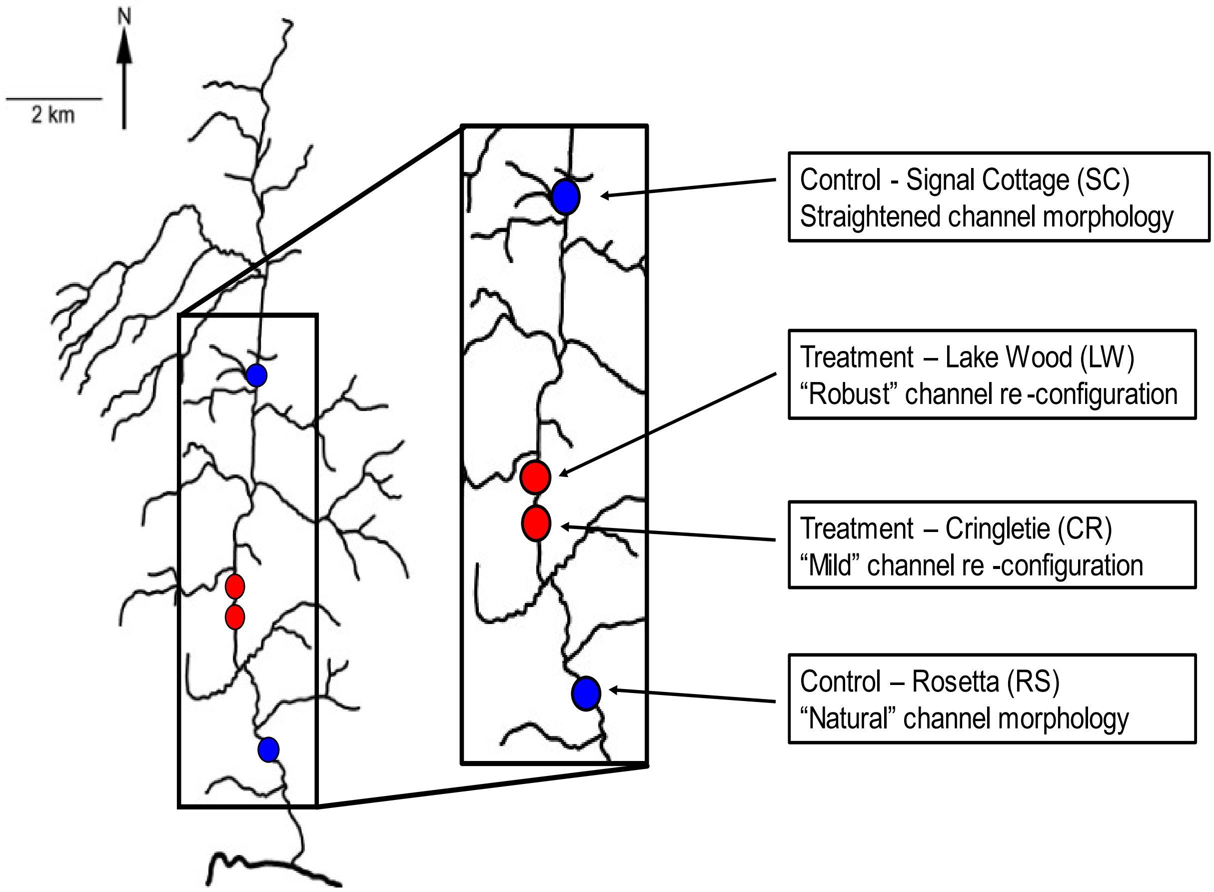


Figure 15. Schematic diagram of the experimental design showing the treatment (red circles) and control (blue circles) sites where macroinvertebrate samples were collected

Period	Year	Season	Month	Cringletie	Lake Wood	Signal Cottage	Rosetta
Before	2012	Spring	May	1 x3 min sample		1 x3 min sample	1 x3 min sample
		Summer	Aug	1 x3 min sample		1 x3 min sample	1 x3 min sample
		Autumn					
	2013	Spring	May				
		Summer	Jun				
Follow		Autumn	Nov				
	2014	Spring	Apr				
		Spring	May*	Family level only	Family level only	Only 1 pool rep	
		Summer	Aug			**	
		Autumn	Nov				
After	2015	Spring	May				
		Autumn					
	2016	Spring	May				
		Autumn	Nov				
	2017	Spring	May				
		Autumn	Nov				
	2019	Spring	May				
		Autumn	Nov				
	2021	Spring	May				
		Autumn	Nov				

Table 4. Summary of Ecological Sampling Programme

20 kicks x 3 repeats at each site in each season, unless otherwise stated. Grey = no sampling.

** Excluded from analysis in preference to April 2014, to match species-level identification used in other years.*

*** No sampling because site impacted by channel reconfiguration immediately upstream.*

As seen in Table 4, monitoring occurred one or two (2012/2013) years pre NFM intervention; immediately following restoration (2013-2017), and then in alternate years (2019, 2021) so as to describe the trajectory of recovery. Initial plans to undertake sampling three times a year were replaced by Spring and Autumn sampling only from 2015. The WFD methodology was also refined so that precise locations better matched habitat types and were the same as used for the hydromorphological sampling. Instead of taking 3min kick samples, the sampler undertook 20 x individual kicks split between flow habitats (run, riffle, glide, slack, pool) in proportion to their occurrence within the 100metres section, with three replicates collected from each reach each sampling occasion.

Level of identification, laboratory analysis and calculation of metrics of species abundance, diversity and richness used relevant indices is described in the Report by Alem on Macroinvertebrate responses 2012-2019 [20]. Macroinvertebrate community composition was measured at the mesohabitat-scale and reach-scale using a suite of eight biotic metrics (WHPT-ASPT, LIFE-species, PSI-species, taxon richness, total abundance, CCI, % of total abundance of Ephemeroptera, Plecoptera and Trichoptera

(%EPT), % of total abundance of oligochaetes and chironomids (%OligoChiro)). The effect of the channel reconfiguration work on each biotic index at a reach scale was evaluated using a mixed-effects regression model to test for a statistically significant interaction between treatment (Control or Impact) and time period (Before, Following and After channel reconfiguration). The results were interpreted in terms of changes in mesohabitat composition at the four sites, and by comparing the habitat-level indices among sites.

Results

Analyses of results has not yet included the 2021 samples, but looking at the data up to 2019, the benthic macroinvertebrate community in Eddleston Water appears to be strongly influenced by mesohabitat composition. Channel reconfiguration has led to a partial improvement

Figure 16 Changes in proportional mesohabitat composition 2012-2019, based on the allocation of kicks to habitat units. Note: remeandering was completed on 25/07/2013 at Cringletie and on 11/09/2013 at Lake Wood

in macroinvertebrate community status (as measured by a variety of standard biotic indices), but full recovery from historical channel straightening is thought to have been constrained to date by the limited geomorphological changes so far seen at Lake Wood and particularly at Cringletie. The inclusion of the 2021 and later 2023 results should give a better picture of the trajectory of recovery, and particularly if this latter period includes some high flow events.

Aerial view of Lake Wood meander aquatic macroinvertebrate sampling site, showing habitat diversity already developed.

Key results to emerge so far include:

- Prior to channel reconfiguration, the two experimental sites – Lake Wood and Cringletie – had much less riffle/run and more glide habitat than the two control sites and had lower values than the two control sites for seven out of the eight biotic metrics (exception was %EPT).
- Channel reconfiguration in 2013 initially increased the proportion of riffle and run habitat and increased overall habitat diversity, but subsequent geomorphological adjustment appears to have partially reversed these changes. This mirrors the results of the Fluvial Audit undertaken by cbec [10].
- Against a background of rapidly increasing taxon richness at all sites, channel reconfiguration caused an initial abrupt shift in macroinvertebrate community composition at the experimental sites from one dominated numerically by mayflies, stoneflies and caddisflies to one dominated by oligochaetes and chironomids.
- Following the initial disturbance caused by the channel reconfiguration work, the experimental and control sites have partially converged in macroinvertebrate composition, but to date only total abundance and the %OligoChro have increased significantly as a result of the remeandering.
- Six years after the remeandering, four of the biotic indices (WHPT-ASPT, LIFE-species, PSI-species, and %EPT) remain significantly lower at the experimental sites compared with the control sites.

The results have also provided some key lessons in terms of other studies, notably that Control sites are essential. Over the study period, there was a strong and consistent increase in taxon richness at all four sites, which drove changes in some of the other biotic indices. If control sites had not been established, then the effect of channel reconfiguration would have been confounded by these background changes in macroinvertebrate community composition, and erroneous conclusions could have been drawn. Ideally, a longer period of baseline (pre-intervention) monitoring could have provided a more robust assessment of the impact of channel straightening at Lake Wood and Cringletie, especially as it is clear that geomorphological and biological responses to channel reconfiguration can take place over many years. In this respect the extended period of post-intervention monitoring conducted at Eddleston Water has been significantly valuable in revealing both short-term and longer-term effects of NFM measures. And finally, the use of a dis-aggregated sampling method to gather data from individual mesohabitat types provided valuable insight into the importance of physical habitat in structuring the benthic macroinvertebrate community, yet still allows responses to be assessed at a reach level.

9. (b) Assessing the Ecological impacts of NFM restoration through re-meandering – fish populations

In 2017, Forth Rivers Trust were commissioned to develop and execute a three-year monitoring programme investigating the response of native fish species to river restoration efforts on the Eddleston Water, focussing on the channel re-meandering carried out at Cringletie, Lakewood and Shiphorns (Fig 17). An additional element involved timed semiquantitative fishing at 23 sites in two tributaries (Longcote and Shiplaw) is not summarised here.

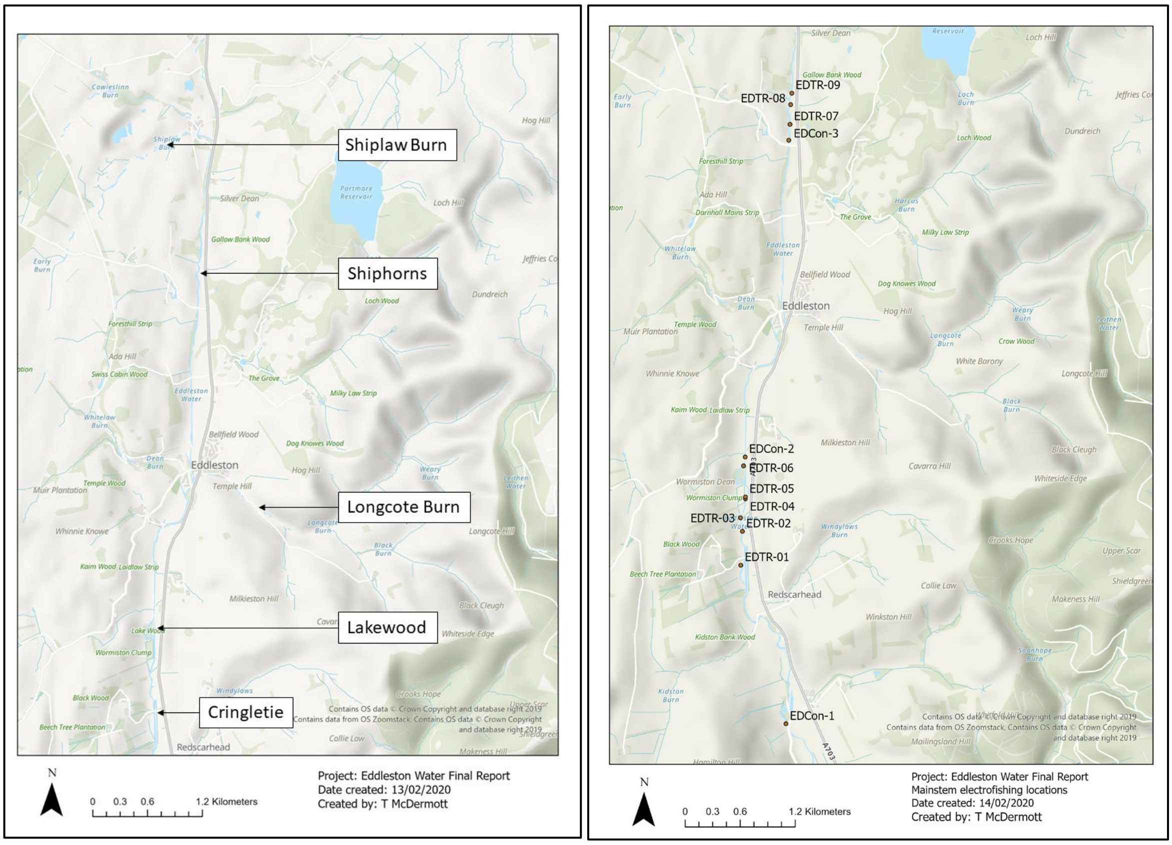


Figure 17. Outline of relevant fish survey locations and Location of electrofishing sites 2017-2019 (incl.). TR – treatment, Con – control

Methods

A fish-habitat walkover was carried out in July 2017 from Cringletie to Shiplaw to describe and quantify the available habitat for different life stages of salmonids in areas of restored and unrestored channel and to identify potential monitoring locations based on channel depth, channel area and general location. *A priori* Power Analysis identified the potential for a grouped Control-Treatment based sampling design to identify differences in fish density between restored and unrestored sites, and the following sampling programme was proposed based on a Control-Treatment basis, with a total of 12 samples (table 5) collected for each year of the programme.

	Control sites	Treatment sites	Years
Cringletie	1	3	3
Lakewood	1	3	3
Shiphorns	1	3	3

Table 5. Sampling site structure on main stem

Fully quantitative electrofishing sampling based on Scottish Fisheries Co-ordination Centre (SFCC) protocols was undertaken at the sites chosen for each of the three years 2017, 2018 and 2019. Fish were identified to species (or genus for Petromyzon lamprey juveniles), measured and the first 50 weighed, prior to return. Only data on salmon and trout fry (juvenile fish hatched during the survey year) were used in analysis as catches of other species were low. Habitat data was recorded as per SFCC recording form. Redd surveys were undertaken using a method developed from the American Salmonid Field Protocols handbook. The channel was walked during the spawning season (Nov - Dec) and redd presence, along with associated descriptive data, was recorded.

Results

The relationships between fish populations from Control and Treatment locations were analysed using mixed effects regression models with random factors. The results showed no difference in standardised salmonid production between control and treatment reaches based on densities of fish per $100m^2$. Similarly, there was no difference in size (i.e. complete recovery from channel construction). However, using density as a measure does not consider the relative abundance of habitat for the trout and salmon fry life stage. Restored lengths of channel have an area that is least 10% greater than the area of the original unrestored channel (and increases in length varying from 8-46%), so it is very likely that the restored sections are now producing more fry than if they remained unrestored - based on the absence of a difference between restored and unrestored sample locations throughout the study period. However, the Eddleston was a productive river for salmonids prior to restoration.

There was however a strong difference between years for Atlantic salmon fry, with electrofishing data from 2018 related to significant reductions in density (of salmon fry), length (of trout) and length variance (of salmon fry). Indeed, interannual variation is a strong signal emerging from the data and was probably most notable for redd counts with a year-on-year decline. However, collecting robust redd data is difficult and related to factors such as general flow patterns, spawning timing, water clarity and on-the-day light conditions. Nonetheless the results are consistent with the yearly decline in returning adult salmon on the Tweed during the study period.

Differences in habitat data collected as part of the SFCC recording form were reviewed using Principal Component Analysis (PCA). The extracted components from each data class were then compared and a significant difference was observed for the 1st component (33%) between control and treatment sites. However, the elements included within this component (stream energy, instream and bank macrophytes structures) suggest that this result is describing the mature state of the control sites with the still-to-mature state of the treatment locations.

The results highlight the often-overwhelming role played by interannual and life history factors in salmonid survival and production which potentially can mask other factors such as improvements in habitat. In addition, while salmonids are a key component of Scottish aquatic ecosystems, other species such as eel, lamprey, stickleback and minnow are not confidently enumerated using the standard SFCC approach, which is specifically tailored for juvenile salmonids. The limitations of this approach were also highlighted as it did not permit survey of the increasing areas of deep pools as channel bed heterogeneity increased following restoration, particularly in Lake Wood. However, it should be noted that the results obtained are consistent with the literature, reflecting the effect of limited budgets and timescales on monitoring responses of highly mobile fish species to restoration. This study also highlighted the limitations of channel area for such programmes in small channels, as there was physically no additional space to increase the number of monitoring locations.

New flood storage pond and downstream meanders at Nether Kidston during high flow conditions.

10. Evaluating costs and benefits

Although primarily aimed at temporarily storing excess flood water, delaying the arrival of flood peaks downstream and reducing peak flood levels, NFM can also provide a wide range of other benefits to society, such as improving water quality, increasing biodiversity, carbon storage, recreational and landscape enhancement. To date however, methods to assess the value of both the flood damages avoided by NFM measures and the value of these additional ecosystem services, and subsequently to integrate consideration of their respective values into decision-making processes for appraisal of flood risk measures have been lacking.

Tweed Forum, as Project Managers have details of the cost of installing and maintaining the many NFM measures that have been introduced in to the catchment over the years, along with associated ground works and other habitat improvement costs. The project is thus able to accurately measure costs as already spent and, in looking at flood risk reduction options, identify future costs with a high degree of certainty. In comparison, the benefits of NFM are less easy to identify or, at least to quantify but can be seen as being of two types:

a) Costs of flood damage that have been avoided due to the introduction of NFM measures; and

b) Additional benefits that arise from the introduction of NFM measures in the catchment.

It is important to note that in both the costs avoided and the benefits derived are not only direct economic ones, but include less tangible indirect aspects, such as reduction in stress and health benefits from not being flooded, and improvements to recreational experiences and landscapes. In addition, these are relevant not only as direct cost-benefit calculations (is it worth doing?), but also in comparison with other options for flood risk reduction (structural, NFM or a combination).

Initial research has already provided a cost-benefit analysis of the impacts of *theoretical* afforestation on peak river flows in the Eddleston under UKCP09 climate change projections, and on additional ecosystem services [21]. This found significant positive net present values (NPV) for all alternatives considered. They note that benefits were often dominated by ecosystem services other than flood regulation, with values related to climate regulation, aesthetic appeal, recreation and water quality contributing to a high positive NPV. The study suggests that whilst afforestation as a sole NFM measure provides a positive NPV in some cases, it highlights the importance of identifying and quantifying additional ecosystem co-benefits.

Methods

Tweed Forum commissioned JBA to investigate how best to model the different benefits arising from the use of NFM measures [7], and subsequently worked with Mott MacDonald in 2021 to explore how such multiple benefits from NFM can be effectively integrated into current decision-making processes for the appraisal of flood risk management measures in Scotland [22]. A detailed review of existing current environmental and social appraisal methodologies within the flood management sector was undertaken to provide a single agreed methodology for assessing additional ecosystem services. Information from the Ecosystems Knowledge Network Tool Assessor was supplemented by the expert knowledge of the project steering group and the results of a stakeholder engagement survey. The potential environmental evaluation methods underwent a two-stage assessment: firstly, to ensure the methodologies were suitable and secondly, to identify the preferred methodology, enabling a detailed assessment to be made of the additional benefits provided by NFM measures across the Eddleston Water catchment.

Results

The review concluded that CIRIA B£ST was the leading appraisal tool to support the evaluation of multiple benefits within flood risk management appraisals. As part of the project, B£ST was then tested on the Eddleston Water to trial its suitability. The tool was able to reliably quantify all significant multiple benefits in the form of ecosystem services for the project.

NFM measures already implemented by the project between 2010 and 2020 were shown to provide benefits from whole-life flood damages avoided of £950k positive NPV over a 100-year appraisal period. A second modelled enhanced option was also assessed which significantly increased the theoretical number and extent of NFM measures (some since implemented): - further afforestation of 25% of the catchment, double the length of channel works already implemented, five times the number of flow restrictors and log jams, and five times the number of runoff attenuation features and ponds already constructed. The benefits from whole-life flood damages avoided under this enhanced scenario were calculated as £2,850k NPV.

The same NFM measures were identified as also providing a whole range of other ecosystem services benefits across amenity, biodiversity and ecology, carbon sequestration, education, flows in watercourse, water quality and pollution (Table 6). Using the same 100-year appraisal period the *additional* Net Present Value benefits provided by the ecosystem services associated with the existing implemented NFM measures were estimated to be approximately £4.2M, and for the second modelled scenario of enhanced NFM measures, an additional £17.7M positive NPV.

Benefit category	**Actual NFM implemented (£k)**	**Additional NFM (£k)**
Amenity	1,489	3,724
Biodiversity and ecology	627	4,594
Carbon sequestration	717	4,857
Education	383	383
Flows in watercourse	365	2,678
Water quality and pollution	628	1,424
Total	**4,201**	**17,660**

Table 6. Estimated ecosystem services benefits for the NFM options (£k, Net Present Value, 100-year Appraisal Period)

It is clear from the results obtained that there is a need to include assessment of the multiple value of NFM measures in flood risk management appraisal to enable a 'fair' comparison of the costs and total benefits of flood risk management measures (not just NFM) in appraisals [23].

Cycle and footpath under construction alongside new meanders below Cringletie, increasing access and amenity value of NFM measures

It is also important to stress that NFM should not be seen as a competing alternative to other flood risk management options, such as structural defences and flood warning systems, but as a complementary tool that can be utilised alongside these infrastructure options within a whole catchment approach to sustainable flood risk management.

11. Conclusions

This is the second major report covering the full range of studies within the Eddleston Water project and builds on the earlier one reporting progress up to 2016 [1], as well as an expanding range of individual reports and published papers in the intervening period (see references for examples). As an empirically-based study, underpinned by one of the densest hydrological monitoring networks of its kind in the UK, it is supported by increasingly detailed and focussed modelling which includes ongoing development and refinement of surface and groundwater models to describe the effectiveness of NFM measures under differing antecedent moisture conditions and in different land uses. This is helping to ensure that results are transferable to other catchments, as well as enabling the exploration of different scenarios for land use and NFM deployment.

In this context, our recent work at Eddleston has shown that:

- **NFM reduces the risk of flooding**
    - Strong empirical evidence demonstrates that engineered log structures and associated ponds and riparian planting significantly increase the lag time between rainfall events and rising river levels for catchments in the headwaters up to 25km^2. Increases in lag time can be regarded as synonymous with reductions in peak flows and give rise to greater opportunities to issue flood warnings and for responses on the part of recipients.
    - Reductions in the annual frequency of high flow events throughout the Eddleston system give positive indications regarding the effectiveness of NFM interventions, with initial findings suggesting that even in Peebles (catchment at 69 km^2), a reduction of 29% in high flow frequency can be seen (comparing 8 years baseline data with 7 years post NFM measures), while further upstream the effects are even more striking (50% reduction on a comparable basis for a 29 km^2 catchment area).
    - In response to a mix of NFM measures across the catchment, flood peak magnitudes are estimated to reduce by 5% at the catchment outlet, irrespective of the magnitude of the causal event.
    - Modelled and empirical evidence shows that remeandering, combined with embankment removal can provide additional temporary floodplain storage and so help reduce flood peaks, but remeandering on its own has limited flood reduction benefits
    - The creation of well-designed large floodplain storage ponds can provide temporary storage and so help reduce flood risk, as shown by modelled and empirical evidence
    - Infiltration under mature deciduous tree cover is much greater (up to 8 times) than under pine plantations and grassland on the same geology; and
    - Tree planting and similar NFM measures that seek to improve infiltration are most effective in responsive, low permeability catchments, as the effects are masked in catchments already benefiting from high soil and geology permeability.
- **NFM enhances habitat restoration, delivers nature recovery and climate change resilience**
    - NFM measures including the planting of >330,000 native trees, and the creation of 38 ponds provide direct habitat restoration benefits at the riparian and landscape scale. Environmental-DNA analyses show the Eddleston NFM ponds provide new habitats

for aquatic invertebrates from over 50 families, including 25 high scoring water-quality indicator species of mayfly, stonefly and caddisfly.

- Remeandering increases river length, which increases the total amount of riparian habitat available for salmon, otters and other species. In the Eddleston, different remeandered sections have added from 8% to 46 % length of new river habitat.
- Remeandering increases in-stream channel habitat diversity by creating more pools and riffles, especially in reaches where more sinuous channels have been created
- Remeandering leads to the gradual re-establishment of macroinvertebrate communities and suggested improvements to salmonid population health
- Riparian tree planting provides a direct climate change adaptation through the creation of 'thermal refugia' from the eventual shading provided by bankside trees, whilst NFM at the landscape scale also helps reduce the impact of increasing climate change-derived flood events

- **NFM measures provide a range of other ecosystem services which, together with flood damages avoided, provide significant positive cost-benefit returns**
    - Appraisal of NFM measures already implemented in the Eddleston show a positive net present value (NPV) of £950k from flood damages avoided over 100 years
    - NFM co-benefits already delivered amount to £4.2million NPV on-top of flood damages avoided by the same NFM measures - mainly from water quality improvements, carbon management, recreation, biodiversity and fisheries
    - Modelling of an enhanced scenario of NFM measures shows very significant returns, potentially delivering £2.85million NPV from flood damages avoided and a further £17.7million NPV from additional benefits.

Twelve years since the project's origin and the production of the initial Scoping Study, we have also been able to review the successes and challenges that have arisen from the overall monitoring programme strategy and its implementation [6]; information that will help inform not only future research at Eddleston, but also studies elsewhere.

Detail of meander at Lake Wood in flood conditions

12. Acknowledgements

The Eddleston Water study is funded by the Scottish Government both directly and through relevant funding streams, such as the Scottish Rural Development Programme. For the period 2016–2020, it was the recipient of funding through participation in the EU North Sea Region Interreg programme *Building with Nature*. In addition, very significant contributions have come from the Scottish Environment Protection Agency and from key partners, including the University of Dundee and the British Geological Survey, not least in terms of in-house monitoring, research, analyses and advice. Other organisations, including the Scottish Borders Council, Scottish Natural Heritage (now NatureScot), Forestry and Land Scotland, Forest Research, CEMEX, Scottish Power, Forest Carbon and Woodland Trust are also important funders and supporters, as indeed are the land owners and land managers themselves.

The project is managed by Tweed Forum and directed by a small Project Board chaired by the Scottish Environment Protection Agency and the Scottish Government, with additional contributions from Scottish Borders Council and the two main science providers; the British Geological Survey and the University of Dundee. Acknowledgement is gladly given to Luke Comins (Tweed Forum), Debi Garft (Scottish Government), Heather Forbes and Roy Richardson (SEPA) not only for comments on the draft but for their many contributions throughout the life of the study. David Bradley (Apem Ltd) and James Hunt (Tweed Foundation) also made useful comments on early drafts, Hamish Robertson and Lucy Ramsay (Tweed Forum) assisted with the maps and report layout, which we are happy to acknowledge.

The partnership effectively also includes the local farmers and landowners in the Eddleston valley and the communities with whom we work, as they are key to all aspects of project design and delivery. We are pleased to acknowledge their participation and support for the introduction of NFM measures and associated monitoring.

13. Main project reports, publications and weblinks for this study:

- **Eddleston Water website**: https://tweedforum.org/our-work/projects/the-eddleston-water-project/
- **All Eddleston Water project reports are available online at:** https://tweedforum.org/eddleston-project-database/

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