Building with Nature - Hydrological impacts arising from the Eddleston catchment natural flood management (NFM) measures: empirical analysis

Summary report

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Primary research question

What changes have occurred in the flood response of the monitored catchments further to the installation of NFM measures? This question could focus on one or more aspects of hydrological response:

- 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.

The focus here is the first two of the listed aspects. 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 some duration of years.

Relevance to policy

Changes in land use and land management will impact on flooding characteristics within a catchment, something of critical importance to both policy and practice. In addition, with climate change comes the expectation of increases in the incidence of flooding and its associated social, financial and environmental impacts. The focus of the Eddleston study on Natural Flood Management and its effects is directly aligned to government requirements to understand the effectiveness and value of NFM measures as part of their overall approach to catchment based sustainable flood risk management. The results will assist responsible authorities to implement measures which are likely to prove effective in reducing flood risk alongside more traditional structural flood defence measures, and to also act as climate change mitigation measures in their respective areas of responsibility. Whilst the extent and depth of flooding are important in their own right, delaying a flood peak is also of direct relevance, as this gives more time for potentially impacted communities downstream to respond to flood warnings, something that can alleviate flood damage, and save property and even lives.

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. All 12 stream level gauges have been calibrated to produce a continuous series of stream flow data. The focus was on intensive data gathering in order to obtained detailed 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 7 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. These have focused on assessing the significance of differences in lag since the commencement of NFM measures, using a Mann-Whitney test of difference 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.

Also 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 with 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.

Results – lag time and event frequencies

Lag analysis results are shown in Figures 1 and 2 and Table 1.

- In catchment areas of less than 26 km^2, 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 1), 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.
- In larger catchments greater than 26 km^2 in area, 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.

- 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 km^2.(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.

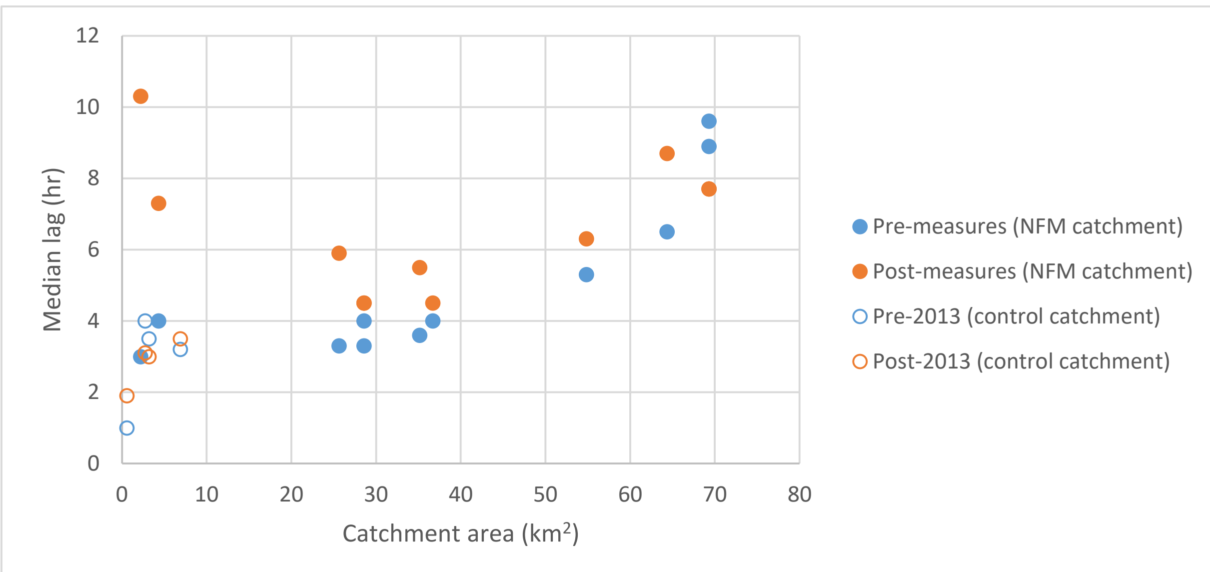
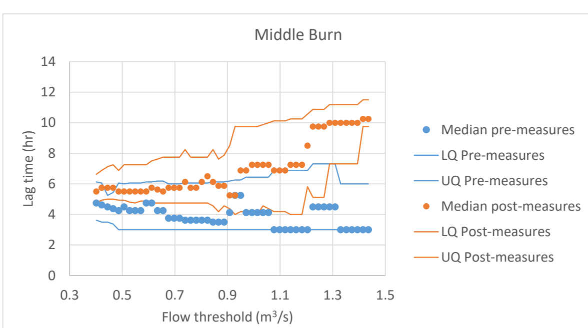
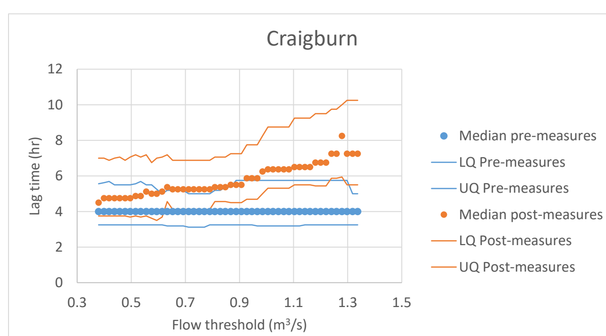


Figure 1. Median lag as a function of catchment area for NFM and control catchments, for peaks occurring before and after the commencement of NFM implementation in August 2013.





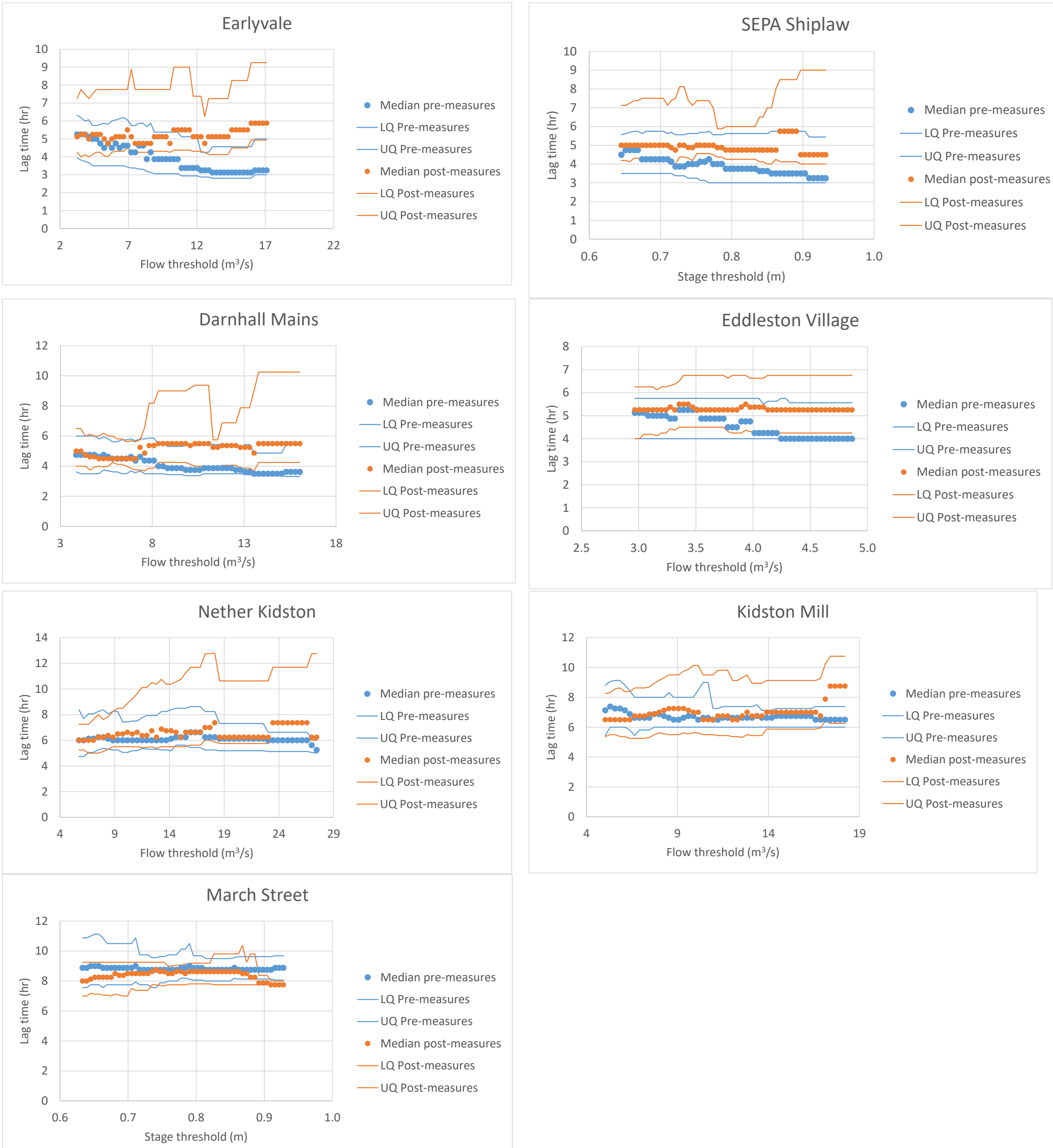


Figure 2. Median lag as a function of flood magnitude. Drainage areas associated with named catchments are listed in Table 1 while gauge sites can be located on Figure 3.

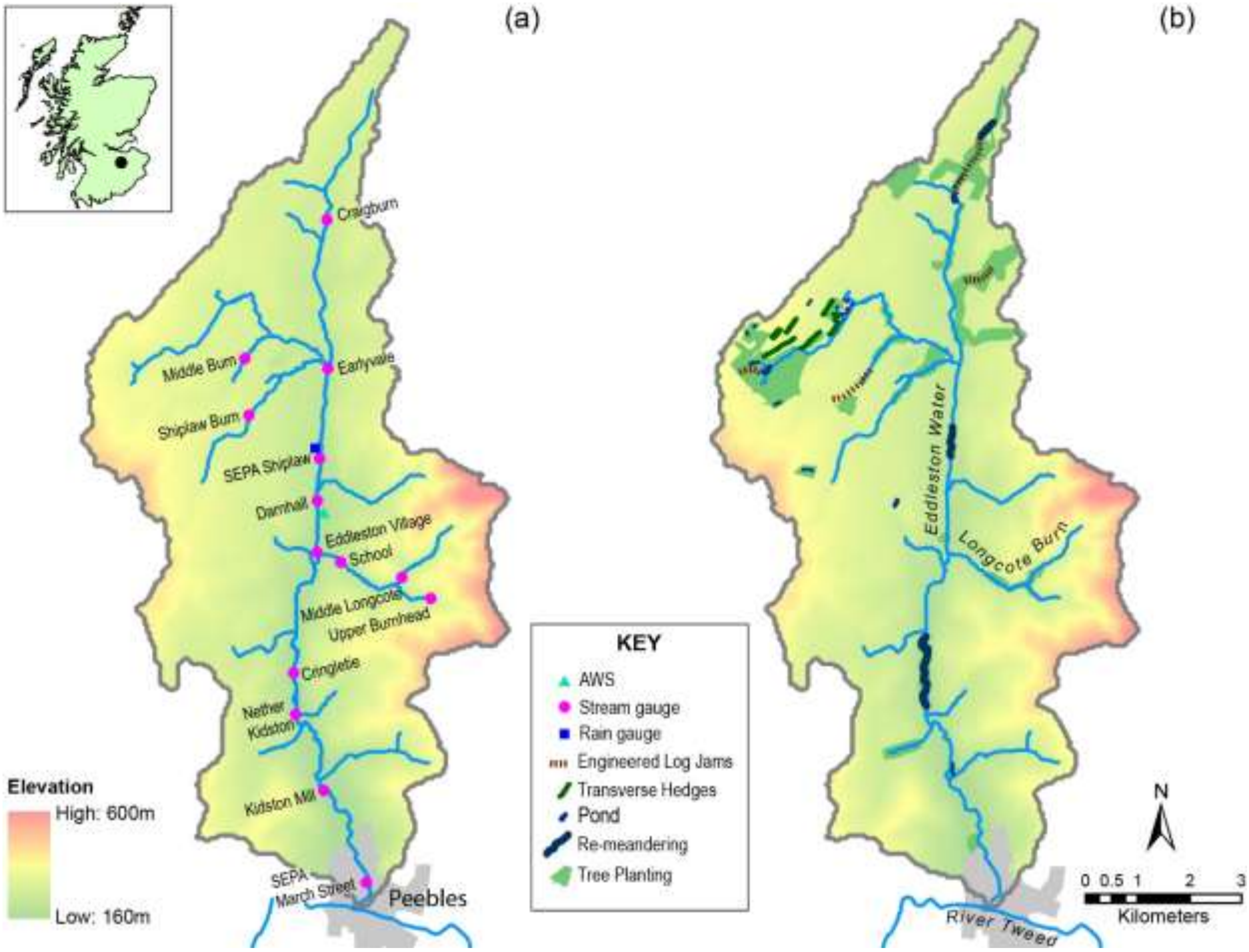
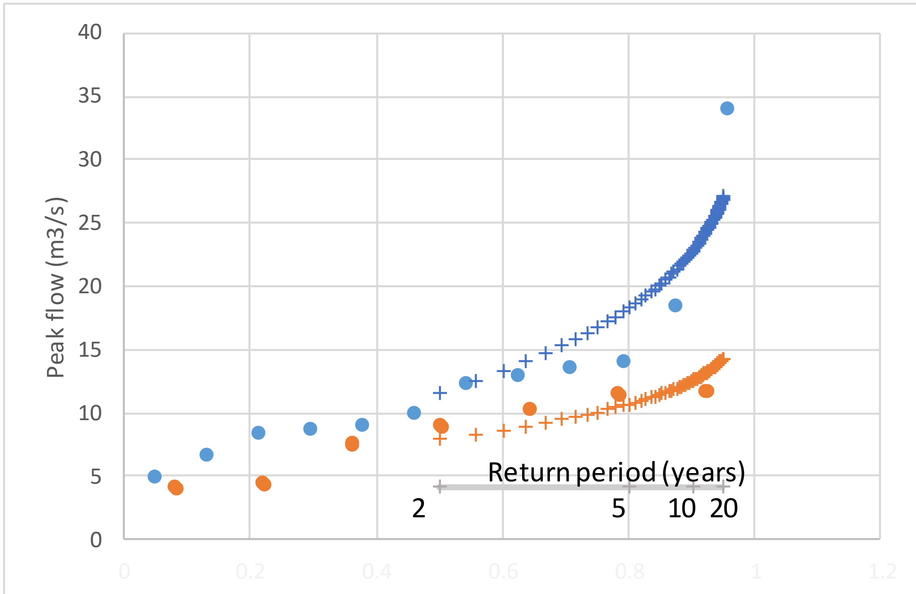


Figure 3. Gauging sites used in the analysis and location of NFM measures

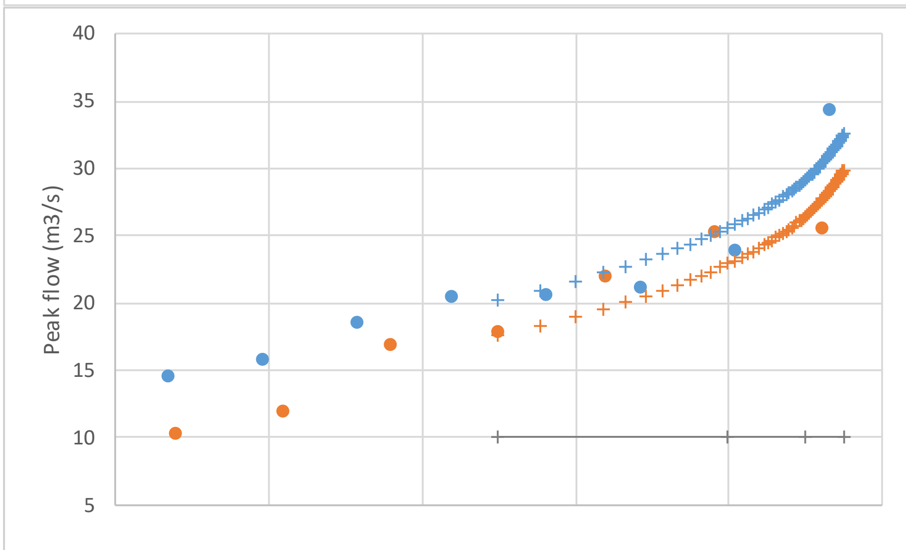
Table 1. Median lag time, change in annual event frequencies and significance of differences before and after commencement of NFM measures in August 2013 (bold signifies increases in median lag > 2.5 hr and differences in lag values significant at p<0.05)

	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

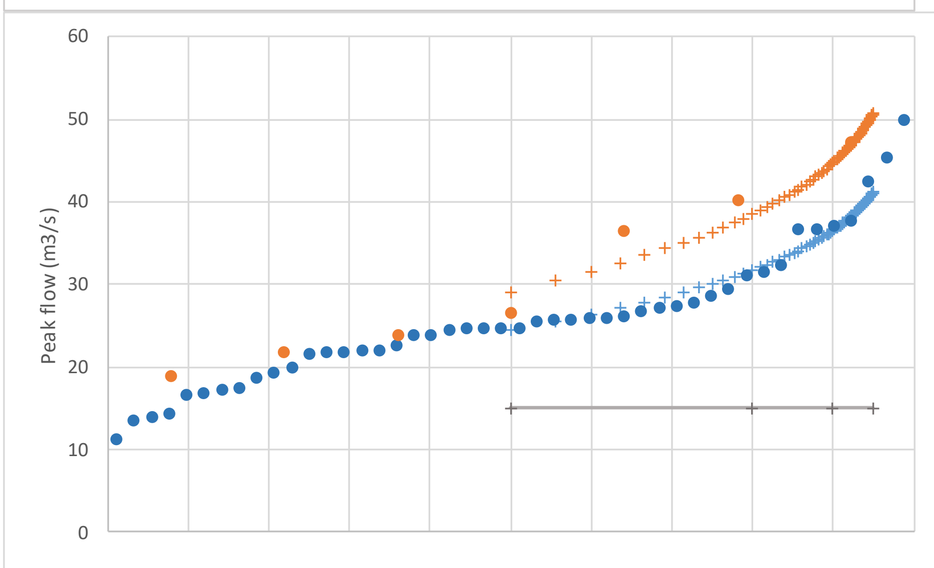
a)


Peak flow (m3/s)
40
35
30
25
20
15
10
5
0
Return period (years)
2
5
10
20
0
0.2
0.4
0.6
0.8
1
1.2

b)


Peak flow (m3/s)
40
35
30
25
20
15
10
5

c)


Peak flow (m3/s)
60
50
40
30
20
10
0

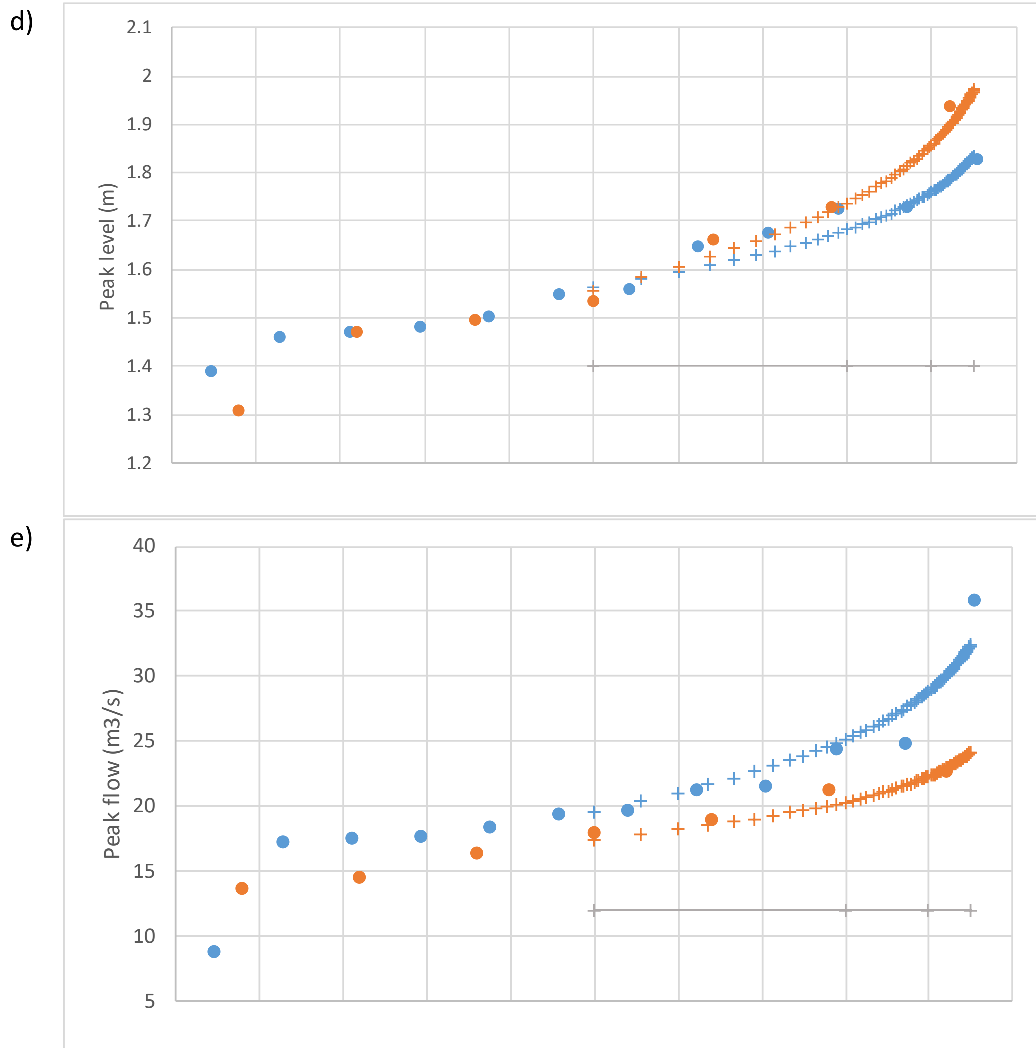


Figure 4. Flood frequency analyses for annual maximum floods on the Eddleston Water and in adjacent catchments. A Generalised Extreme Value distribution (+) is fitted to observed annual maxima (●) plotted using Gringorten plotting positions for each site. (a) Eddleston Water at Shiplaw (26 km^2), Eddleston Water at March Street (69 km^2), (c) Manor Water at Cademuir (62 km^2, south of Eddleston), (d) Lyne Water at Lyne Station (175 km^2, west of Eddleston), (e) North Esk at Dalmore Weir (82 km^2, north of Eddleston). Blue: pre-2013, orange: post-2013. Given the short record lengths, uncertainties are large.

Results – flood peak magnitudes

The analyses in Figure 4 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. 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.

The NFM interventions in the upper Eddleston catchment involve flow restrictors, ponds and riparian planting and fencing, and are linked to increases in lag which propagate along much of the length of the Eddleston Water. Meanders have been introduced at four locations along the lower main stem over a number of years and are difficult to associate with specific changes in flood peaks. However, one recent intervention which is readily analysed is the building of a pond at Kidston Mill, designed to attenuate flood peaks downstream of most of the other measures. Figure 5 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 consitent with the reduction in flood risk since 2013 reported in Figure 4.

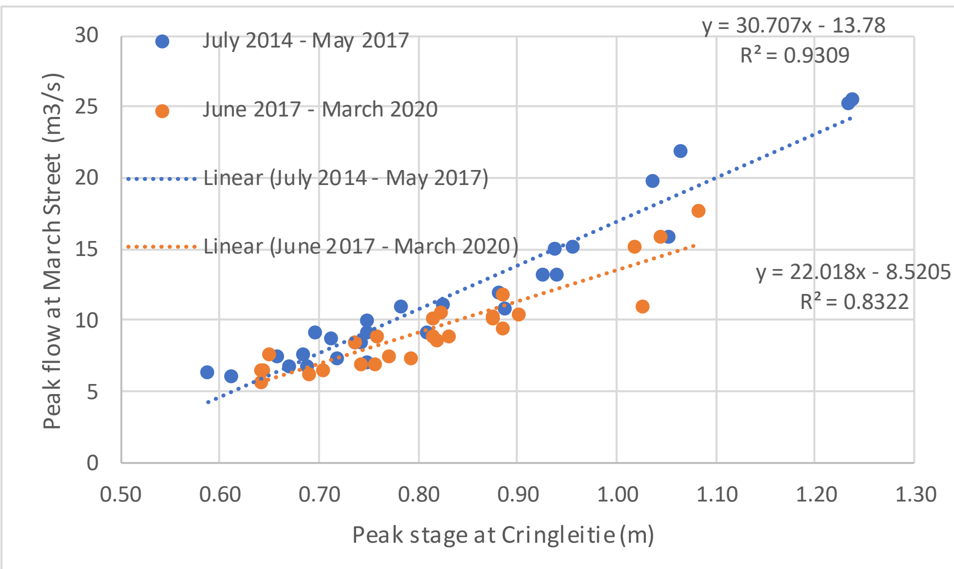


Figure 5. Flood peaks at Peebles March Street relative to an upstream gauge at Cringletie, following provision of off-line storage in May 2017. No other measures have subsequently been introduced between these gauges.

Discussion

The research background against which this work has been planned has emphasised for years the general lack of observational studies gathering and analysing data on the ground, to see how NFM measures actually perform. They note that NFM is expected to be effective in small spates and in small catchments, often without being specific. The results presented above show a generally-expected pattern with the greatest increases in lag being found in the smallest catchments analysed, up to a catchment area of 25.64 km^2: larger than some studies suggest may be possible. Insofar as the available data permit further analysis, the three most upstream sites (Earlyvale at 25.64 km^2 and its two NFM tributary streams at Craigburn and Middle Burn) show that the increase in lag increases with the magnitude of the sampling threshold (flood magnitude), up to about a 1-year return period, in each case showing an increase of at least 2.5 hours. This raises the possibility of NFM effectiveness at higher event magnitudes, though it is not possible by this analysis to predict the maximum extent of NFM effectiveness.

An important proviso is that the period post-measures has not been as wet as the baseline period, so some of the observed differences could be attributed to, or at least influenced by climatic variability. An insight can be found by comparing the increase in median lag at the SEPA Shiplaw gauging station (28.57 km^2) using the entire period of record 2001-2013 rather than just the usual 2-year baseline period 2011-13 (Table 1). While the normal before-and-after comparison shows an increase of 1.2 hours, this falls to only 0.5 hours when comparing the post-measured period with the entire prior 12 years. At the SEPA March Street gauge at the catchment outlet in Peebles (69 km^2), there is a reduction in the median lag time of 1.2 hr using the standard 9-year duration, which increases to 1.9 hr if using the entire period of available record.

Results for comparisons of flood magnitudes are also consistent with expectations, with reductions being found when comparing flood magnitudes before and after the commencement of NFM works in 2013, using the full period of existing SEPA records from 2001/2005. The change of -9% seen in the 10-year flood (10% annual exceedance probability) in the lower Eddleston catchment is within the range of variability found in adjacent catchments, but the corresponding reduction of 45% in the upper Eddleston represents a dramatic reduction, well beyond findings in any of the neighbouring areas.

It is perhaps fortuitous that the study catchment has baseline monitoring data extending to 12 years before the start of catchment works. Many NFM studies are informed only by model predictions without necessarily any local data, and it is not realistic to expect such lengths of monitoring and the associated expense to be incurred before measures are designed and implemented.

Attention should also be directed to the uncertainties surrounding changes in median lag times. The plots in Figure 2 reveal interquartile ranges of several hours at the highest event magnitudes, and of course the rest of the sample is found outside these bounds. No two flood events are the same: there are differences in antecedent conditions, the duration, extent and intensity of the rainfall causing a peak, and also in complications arising from any snowmelt effects (which affect perhaps 25% of the largest events in the Eddleston catchment). Such complexity and the uniqueness of each peak flow event underlie the difficulties in making precise statements about the magnitude of change in response to NFM interventions. Ongoing monitoring will help increase the length of records in the Eddleston Water and will help the observed changes in flood magnitude and risk to be more confidently defined.

Conclusions

These results show strong evidence of an increase in catchment lag time, in excess of 2.5 hr, in the headwater catchments in which NFM measures have been implemented, and in the upper Eddleston Water to a catchment area of 26 km^2. These results are significant at 95% confidence level and expected to be caused by the attenuating effects of the measures deployed. Also in the upper Eddleston Water, estimated flood risk has reduced sharply, with the magnitude of the 10% annual exceedance flood reducing by 45%.

The two tributary catchments (Middle Burn and Craigburn) affected by NFM interventions show similar baseline lag times, 3-4 hours, but the former shows an increase of 7 hours whereas the latter shows an increase of only 3 hours. The measures deployed differ, with only log jams in the former and a combination of log jams and ponds in the latter, while there are also differences in the numbers of NFM features in each. The measures to be deployed in future catchments may differ according to physical characteristics and landowner priorities. Meantime the increased roughness of floodplain flow associated with log jams may be considered as a possible explanation for the dramatic increase in lag observed, and a reason to look for further locations in which to install log jams.

Increases in lag time can be regarded as synonymous with reductions in peak flows while flood frequency analysis has not been attempted for these tributary catchments. They also give rise to greater opportunities for the issue of flood warnings and for responses on the part of recipients.

Reductions in the annual frequency of high flow events throughout the Eddleston system also give positive indications regarding the effectiveness of the NFM interventions. Even in Peebles at the 69 km^2 March Street gauge, and using the full 8 years of baseline data for comparison with 7 years of post-measures data, a reduction of 29% in high flow frequency can be seen (at a ~1-year return period), while further upstream the effects are more striking (50% reduction on a comparable basis using the 19-year SEPA Shiplaw record at a 29 km^2 catchment area). Hydrological lag tends towards irrelevance when the runoff peak does not even rise sufficiently to be counted as a peak at all.

The Eddleston Water dataset is unique in Scotland and probably the UK in terms of the density, length and quality of monitoring data which has been amassed. Its value as a resource for the testing of models in likely to only increase, and steps should be taken to get greater recognition for this. Empirical analysis has shown evidence of substantial change up to 26 km^2, which is beyond the scale of prior studies. As the data continue to be collected at a growing number of sites, opportunities to better understand linkages between cause and effect within the catchment are expected to increase.