Plymouth Green Minds Natural Flood Management and Beaver Project

Hydrological Monitoring Report 2024

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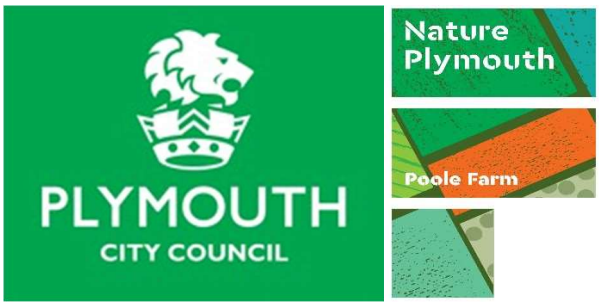

University *of* Exeter

- Front cover photo: a combination of beaver and human Nature-based Solution interventions on Bircham Stream ©Alan Puttock
- Rear cover photo: beavering away to create woody debris dams ©Plymouth Natural Grid.
- Site photography used throughout the report © Chris Parkes

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Introduction and Research Objectives

The Green Minds projects aims to put nature at the heart of our decision making, recognising its role in shaping a healthy future for all (https://greenmindsplymouth.com/). Working with Plymouth City Council and Green Minds project partners, University of Exeter researchers have been undertaking hydrological monitoring to understand the impact of nature-based solutions management interventions in Bircham Valley, Seaton Valley and downstream in Forder Valley, Plymouth. Initially this project was focused on the reintroduction of beavers into an enclosure on Bircham Stream, with the aim that their engineering activities such as dam building would deliver flow attenuation but has since expanded in scope to address a range of other natural flood management (NFM) interventions across the Forder Valley catchment as well. Explicitly monitoring results presented in this report seek to address the following research questions.

Research question 1: Has there been a change in flow regimes and storm event response following NFM interventions?

Research Question 2: Can changes in storm event response (as indicated by storm peaks) be attributed to the presence of NFM interventions?

Figure 1. Example of flashy Bircham stream pre any impact or restoration in 2017.

Methods

Study sites and NFM interventions including beaver activity

Examples of NFM interventions on Bircham Valley Stream are included in Table 1. Figures 2-11 provide examples of NFM interventions at the site alongside maps of the river network and contributing catchment area to key monitoring points of interest. The Bircham stream below Poole Farm and the core area of interest has a contributing area of ca 2.8 km^2 with a well wooded riparian zone, but otherwise a predominately urban landuse. The steep nature of the catchment combined with the urban landuse results in a historically flashy flow response to storm events and has resulted in an interest in management options to 'slow the flow'. Additionally, this study monitored the neighbouring Seaton Valley Stream, which whilst a much smaller contributing area (ca 1.1 km^2) but a similar landuse and pre impact management, making it potentially useful as a control site. Finally hydrological monitoring was undertaken further downstream in Forder Valley below the confluence of Bircham and Seaton Streams to see if any observed local impact on flow regimes persists downstream. The Forder Valley monitoring point has a modelled contributing area of ca 4.6 km^2 and is dominated by the contribution from Bircham Stream although as a note of caution some uncertainty must be accepted when delineating catchment areas based upon topography in highly modified urban environments.

Following extensive feasibility, licencing and public engagement work led by Plymouth City Council and project partners, beavers were released into the site starting with one animal in November 2020 (https://twitter.com/plymouthcc/status/1329057207795773442) and a following animal in early 2021. First reports of significant alterations to the site in the form of damming and tree felling occurred in March 2021. Regrettably beavers escaped in July 2021, with one animal being killed in car crash. Following this escape and accident, the beaver project was paused to consider fencing and management options before beavers were re-released back into the site in November 2023. The period from late 2020 to mid-2021 where the Bircham Stream site was beaver impacted is referred to 'Phase 1' for the sake of reporting and data analysis herein.

In parallel to the beaver project other NFM options were being considered for Bircham, Seaton and Forder Valley and following the pause in the beaver project increased in priority. As detailed in Table 1 and Figure 4 multiple leaky wood dams and other nature-based interventions have now been installed. These leaky dams along with the return of the beavers to the enclosure in November 2023 are collectively referred to as 'Impact 2' within reporting and analysis.

Collectively Bircham stream has seen most interventions with 33 leaky wood dams, 4 flow deflectors, 1 mid channel structure, 3 scrapes and also the reintroduction of a pair of beavers to the site in November 2023. After previously being only lightly impacted by restoration work Seaton stream also saw the installation of 22 leaky wood dams, 4 flow deflectors and more scrapes in September 2023. Downstream in Forder valley there have been less interventions, but 4 scrapes were created in 2022.

As most interventions to the site occurred in the Impact 2 period between May 2021 and the latest data collection of February 2024, the majority of analysis undertaken in this report considers this period with 'Yes' referring to the post May 2021 period when intervention was present and 'No' referring to the pre intervention period.

To allow further interpretation of results over time for some analysis the monitoring has been split into 3 time periods corresponding with internal reporting deadlines and interventions. These are:

- 'no' intervention baseline monitoring phase from November 2019 to November 2020

- ‘Phase 1’ or impact 1 stage when beavers were briefly present on site although no major damming or site interventions were recorded, and this is considered continued baseline. This ran between November 2020 and April 2021.
- ‘Phase 2’ The start of NFM interventions on Bircham stream primarily consisting of the installation of 13 leaky dams. This period also ended with an interim reporting deadline. April 2021 to May 2023.
- ‘Phase 3’ Continued installation of NFM interventions on both Bircham and Seaton streams along with the return of beavers to the enclosure on Bircham stream. May 2023 to February 2024.

Table 1. Monitoring and impact periods as referred to in analysis.

NFM Interventions Present (Impact 2)	Monitoring Phase	Date
No	Baseline/No Intervention	November 2019 - November 2020
	Phase 1	November 2020 - April 2021
Yes	Phase 2	April 2021 - May 2023
	Phase 3	May 2023 - February 2024

As shown in Table 2, it must be highlighted that continued phases of NFM intervention are planned for the coming months. These leaky dams combined with the return of beaver and likely future ecosystem engineering will mean that future impact upon hydrology will continue to evolve over time.

As a caveat it must be highlighted that downstream of the Bircham Monitoring site, but potentially affecting surface runoff to both the Seaton and Forder gauging stations a major road and related infrastructure construction was underway for large parts of this monitoring period. There are no clear indications in the data that this work had major impacts on runoff conditions, but it is important to highlight for completeness. It is also possible that current and planned enclosure fencing, and channel grilling will also impact upon hydrology.

Table 2. Details of Beaver and Impact Leaky Dam NFM interventions across the Bircham, Seaton and Forder monitoring locations. Details provided by Plymouth City Council.

Management prescription	Details	Date	Rationale
Beaver (Impact 1)	Initial Beaver Release	November 2020	Flow attenuation and habitat restoration
	Dam 1 construction and tree felling	March 2021	
	Beavers escaped/removed leading to pause in beaver project	July 2021	
Leaky woody dam and return of beaver (Impact 2)	(i) 10 leaky woody dams inserted in-channel along Bircham stream.	(i) June - Sept 2022	(i) Slow high energy water flows during high precipitation / storm events through storing excess in-channel and dissipating it across floodplain area to reduce the impacts of flooding downstream.
	(ii) 3 leaky debris/woody dams in-channel & spring-fed tributary within beaver enclosure.	(ii) April 2021 - June 2021	(ii) Create a greater variety of floodplain habitat mosaics to benefit a range of amphibians, invertebrates & birds, and to improve the woodland structure of the riparian edge.
	(iii) 30 - 40 more interventions (leaky dams and scrapes) inserted further upstream on both Bircham and Seaton between June - Sept 2023. This included a green skills bootcamp on 27th September when 4 dams installed and a willow pond NFM dam on 17th October.	(iii) June – October 2023	As above
	(iv) Aim to have a total of approx. 120 in stream in subsequent years. As of February 2024 80, interventions were installed across Bircham, Seaton and Forder valleys.	Ongoing	As above
	(v) Beavers return to site at Poole Farm (2nd release of a pair of 2-year-old beavers)	7th November 2023	Flow attenuation and habitat restoration

Figure 2. Looking down on the beaver enclosure area – April 2021

Figure 3. Looking down on beaver enclosure area with surface water visible in release pond.

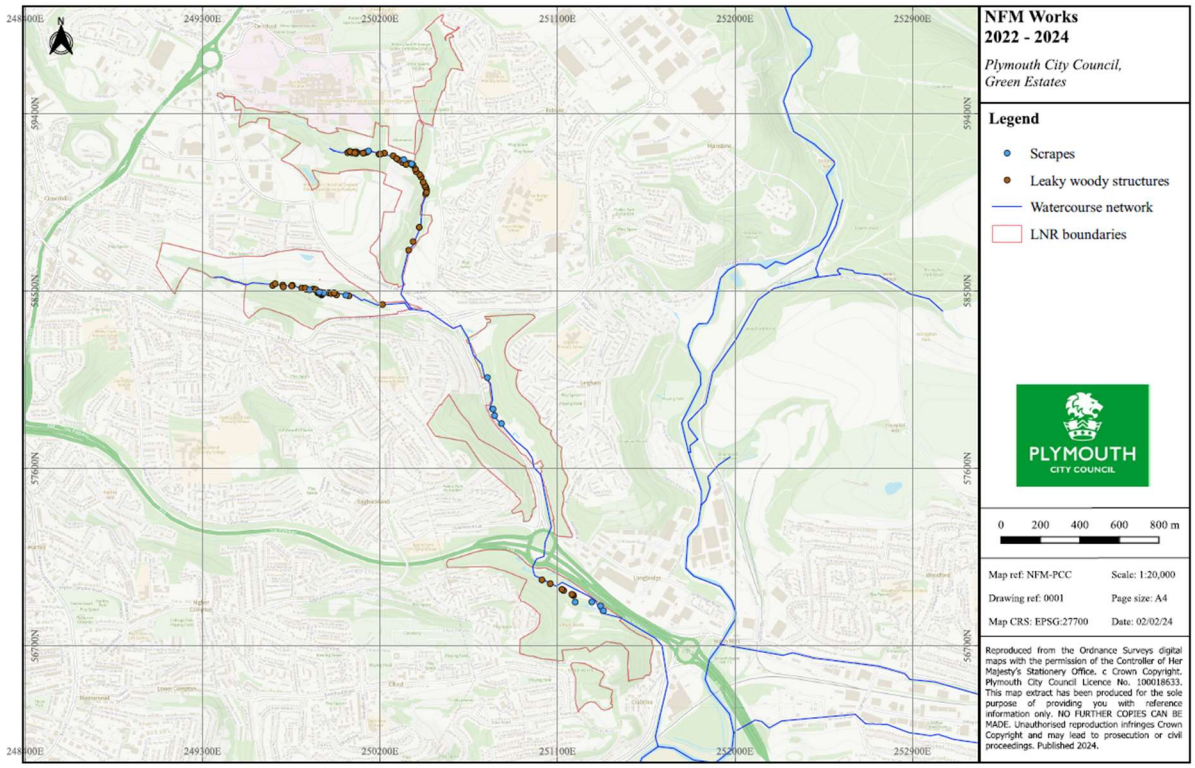


Figure 4. Location of NFM works to be installed 2022-2024 © Plymouth City Council. At time of reporting interventions were installed in Seaton and Bircham stream but not downstream in Forder valley.

Figure 5. Example of NFM woody dams installed on Bircham Stream © Plymouth Natural Grid. Text refers to what3words locations.

Figure 6. Work underway at the site to install NFM features. © Plymouth Natural Grid.

Figure 7. Combined beaver and human wetland creation/modification on Bircham Stream – January 2024

Figure 8. Wednesday green skills boot camp – 4 dams installed inside the enclosure - 27th September (photos on Facebook)

Figure 9. Willow pond NFM Dam below inside the enclosure - 17th October. This has since had the most beaver activity on it © Chris Parkes.

Figure 10. Grill downstream of the beaver enclosure installed in Phase 3, during 2023. Whilst not in itself an NFM intervention it is worth noting the installation of this grill (and a comparative one on the beaver enclosure inflow) could also have an impact upon flow regimes.

Figure 11. Beaver release into enclosure at Poole Farm © Chris Parkes.

Hydrological monitoring sites and methodology

In this report data is presented from undertaken between November 2019 up until February 2024. The locations of the three hydrological monitoring stations are illustrated in Figure 12 and Figure 13. At each of the monitoring stations a stilling well was constructed and instrumented with an in-situ submersible pressure transducer (U20L, HOBO ONSET, USA) recording on a 15 min time step (Figure 14). A further U20L pressure transducer was located at Poole Farm to record local barometric pressure allowing pressure recorded in the stilling wells to be converted to water level/stage (recorded in metres). In combination with surveying of channel dimensions and the use of the manning's equation, water level was converted to discharge as detailed in Puttock et al., 2021. In November 2022 backup level sensors were installed (Rugged Troll 100, Insitu USA) to increase redundancy and minimise the chance of any future data gaps. Monitoring equipment remains at the site so monitoring of NFM interventions going forward is possible if deemed desirable.

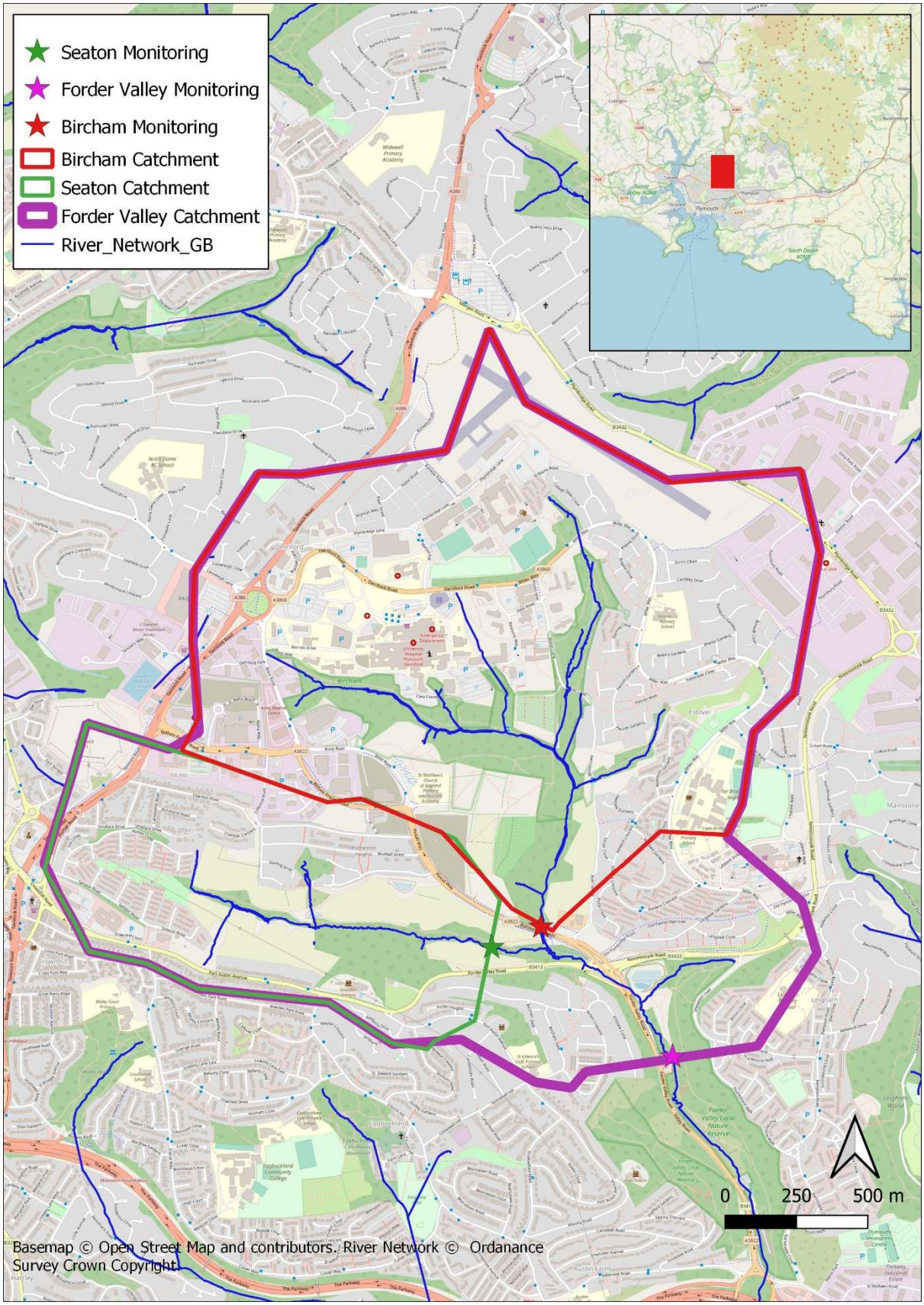


Figure 12. Approximate intervention location and intervention type. In 2021/2022 a further hydrological monitoring station was installed below the retention pond (Orange point). Aerial imagery: Open-Source Google imagery © OpenStreetmap (and) contributors CC-BY-SA.

Figure 13. Location of core hydrological monitoring stations where pre and post NFM intervention data exists. Aerial imagery: Open-Source Google imagery © OpenStreetmap (and) contributors CC-BY-SA.

Figure 14. Examples of hydrological monitoring stations at the site. Top left: Bircham Stream, Bottom Left: Seaton Stream, right: Downstream in Forder Valley.

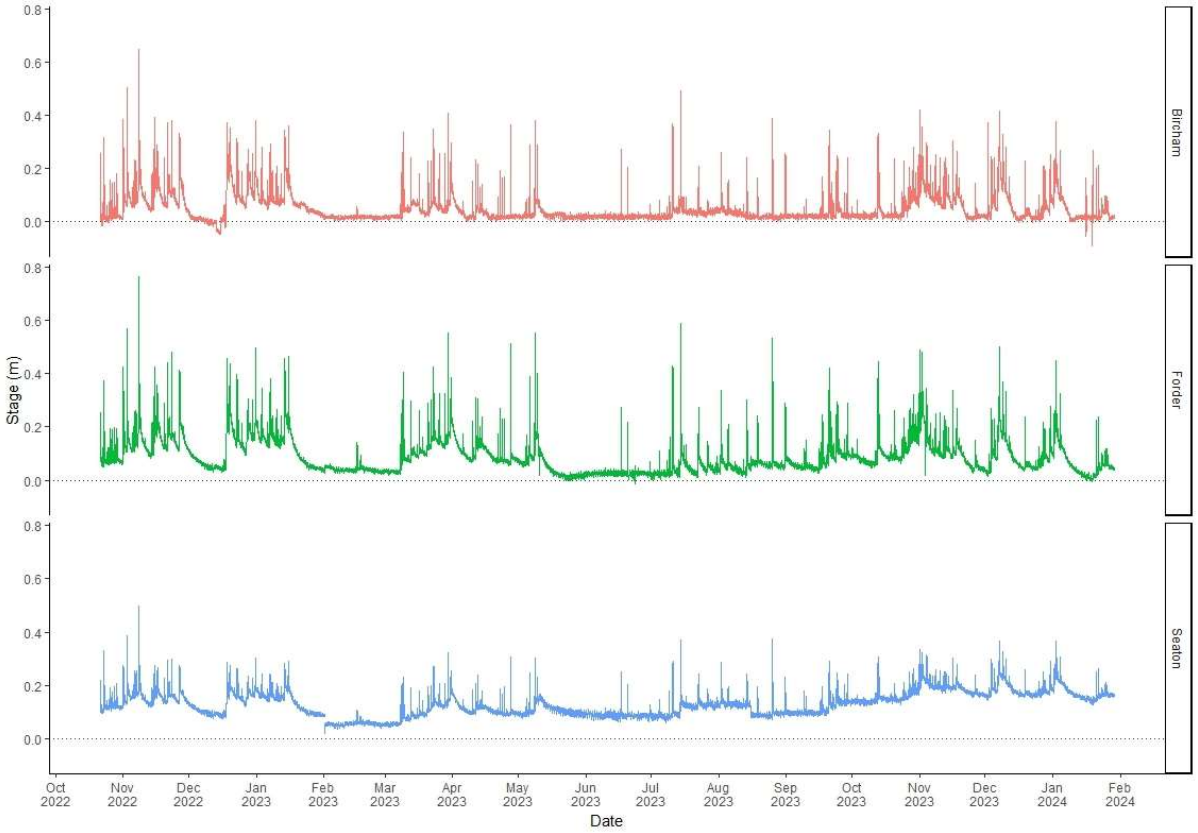


Figure 15. Example raw level data from all three monitoring stations, October 2022 - February 2024

Rainfall data collection

Rainfall is spatially variable and data from a single rain gauge can be non-representative, particularly in forested catchments (Younger et al., 2009; Zeng et al., 2018). Therefore, rainfall radar data, derived from the NIMROD system (Met_Office, 2003), was used across sites. NIMROD data are provided as gridded total rainfall with resolutions of 1km and 5 minutes respectively. Total rainfall for each time step was extracted for the sites contributing catchment area and converted to mean rainfall rate, before aggregating to 15 minutes to align with the temporal resolution of flow data. Data download and conversion was conducted using python 3 and raster statistics - intensity (mm hr^{-1}) and volume (m^3) were extracted with R using the exactextractr package (Bastion, 2020). A backup rain gauge was also installed at the site for redundancy (Onset Hobo, USA).

Figure 16. Rain gauge and barometric sensors installed at Poole Farm.

Data cleaning and storm event extraction

As in Puttock et al., (2021) and previous reporting for this project, the extraction of rainfall-runoff events and corresponding metrics was undertaken using a semi-automated rules-based approach for the identification and pairing of rainfall and flow/stage geometries from sub-hourly observations (Ashe et al., 2019; Deasy et al., 2009; Glendell et al., 2014; Ladson et al., 2013; Luscombe, 2014; Puttock et al., 2017) summarised in Figure 17. Data were sub-sampled at 15 minute intervals and pre-processed for quality control (i.e. cleaned of noise, outliers and periods of other anomalous observations (Ashe et al., 2019). Stormflow was estimated by implementing flow separation on the time series (Ladson et al., 2013). Analysis was done in R 4.0.5. (R Core Team, 2020). Event extraction time series for each site are included and event metrics were calculated for each event.

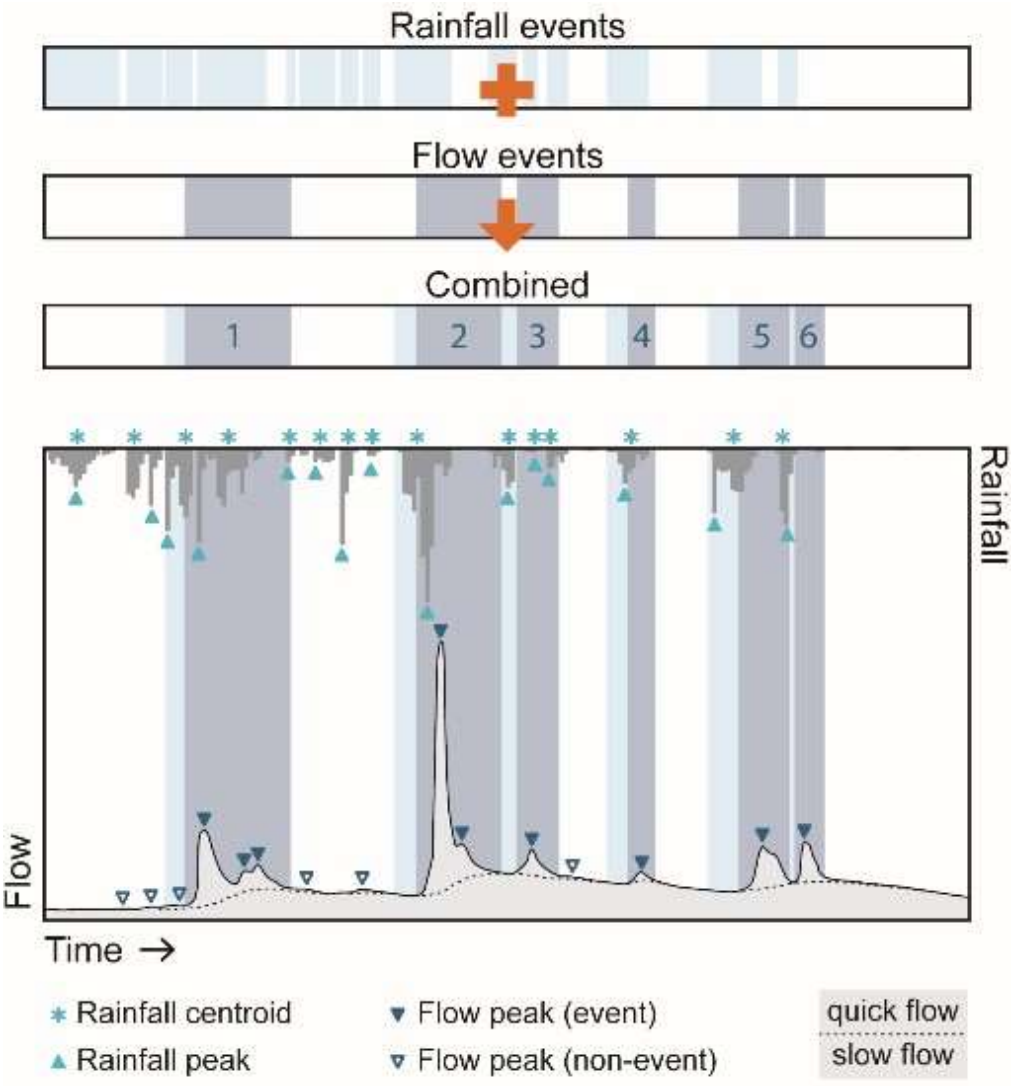


Figure 17. A conceptual figure depicting the event extraction methodology. Periods of continuous rainfall are identified alongside corresponding flow events where quick flow exceeds slow flow. The durations of both rainfall and elevated flow are combined to create an event window which is used to extract hydrological information for a given storm event. Adapted from Ashe et al., 2019.

Statistical analysis

Statistical analysis was undertaken in R 4.0.5. (R Core Team, 2020) with data manipulation, summary statistics and plotting being undertaken using the ggplot2 and cowplot packages (Wickham et al., 2019; Wilke, 2019). The statistical significance for differences between pre- and post-intervention sets for summary statistics were determined using the non-parametric Wilcoxon test. Direct comparison of means and distributions of hydrological metrics pre- and post-intervention, provides an indication as to the impact of intervention. However, this does not consider the amount of rainfall. We therefore used Generalised linear models (GLMs), with a Gamma error distribution and identity link functions, where event rainfall is the control variable, event peak stage is the response variable and intervention presence are considered as an additive covariate. The model form equation is shown below:

Peak flow ~ Total Rainfall + Intervention Presence

This allows for testing the effect of intervention on event peak flows, relative to contributing event rainfall. GLMs were chosen over linear regression, due to their ability to cope with a non-normally distributed response variable. As smaller flow events are more common than large events the error distribution of event peak flows for all sites has a Gamma distribution. Analysis was undertaken using the glm2 package (Marschner, 2011).

Estimated marginal means (i.e. adjusted or least-squares means), along with associated standard errors, were calculated using the emmeans R package (Length, 2020) for all GLMs to compare differences in mean peak flow before and after intervention, over different hydrological seasons and, where the control is used, between control and impacted sites. Estimated marginal means are useful for interpreting the outputs of regression analysis where the difference between, or the effect of, factor levels is of interest (Castorani et al., 2018; Piepho & Edmondson, 2018).

Results

The following sections present summary statistics for monitored flow records, followed by further analysis to investigate whether flow regimes have quantifiably changed following NFM interventions. Figures 18 to 20 summarise the entire flow monitoring period analysed in this report, include the baseline period from November 2019 to November 2020, the initial period of beaver introduction and the Impact 2 of Leaky dam and other NFM constructions and return of beaver up until February 2024 (expanding analysis from the previously delivered May 2023 interim update reporting which also coincides with a greater number of interventions). Gaps in data record represent periods of equipment failure or download issue, however, due to the focus on automated extraction of storm response vents these gaps do not affect the analysis undertaken. The monitoring period presented consists of 148,314 15 min timestep datapoints, for the Bircham Stream monitoring station, 474 storm events were extracted. For Seaton 457 storm events were extracted, whilst for Forder Valley they were 435 extracted events. Over 400 events per site gives a solid foundation for the subsequent analysis presented.

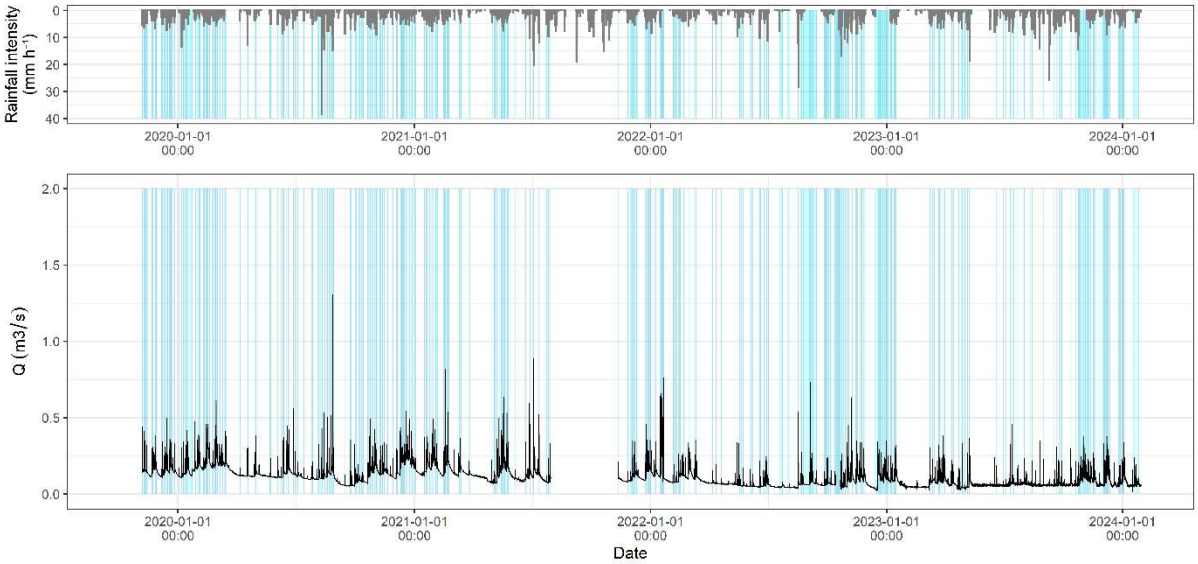


Figure 18. Bircham flow and rainfall monitoring record from November 2019 to February 2024. Blue bars indicate where event extraction has identified rainstorm events and corresponding hydrological response events.

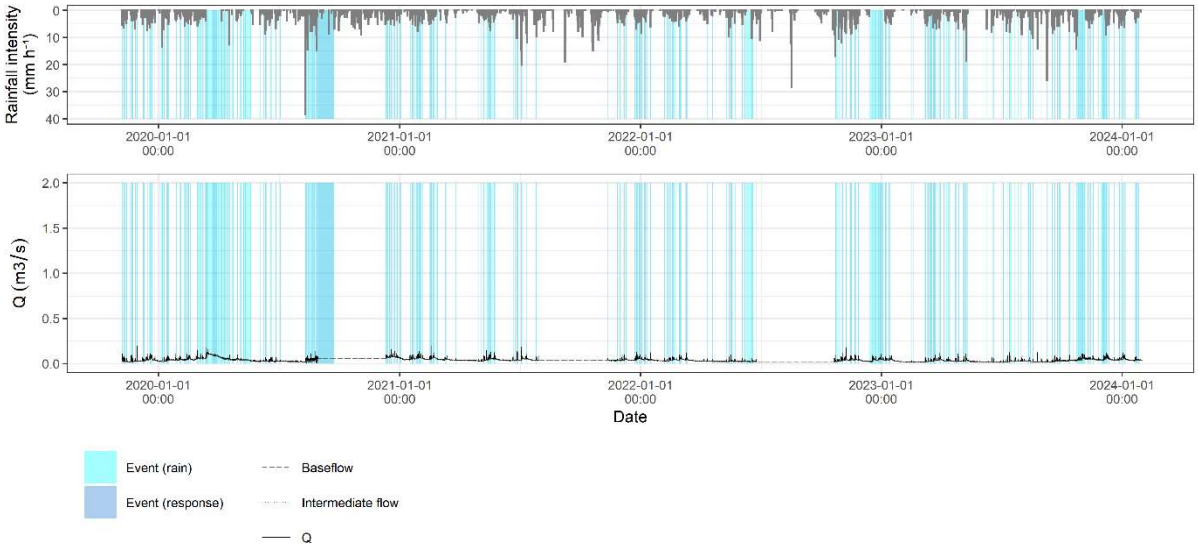


Figure 19. Seaton flow monitoring record from November 2019 to February 2024. Blue bars indicate where event extraction has identified rainstorm events and corresponding hydrological response events.

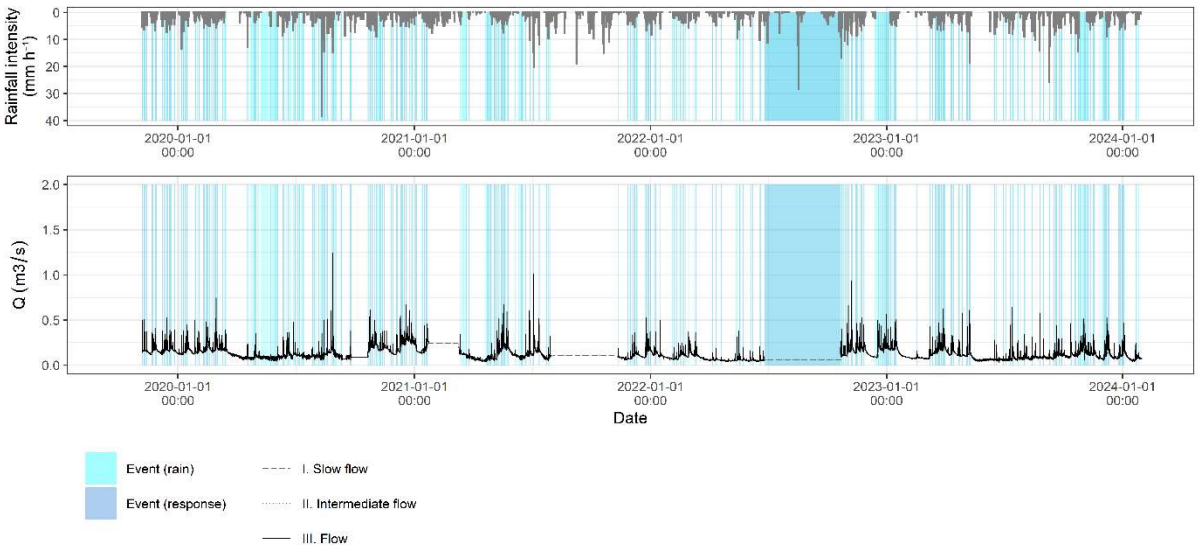


Figure 20. Forder Valley flow monitoring record from November 2019 to February 2024. Blue bars indicate where event extraction has identified rainstorm events and corresponding hydrological response events.

Data summary

Figure 21 summarises peak discharge extracted from storm events across the sites for the different periods monitored, whilst Figure 22 provides a condensed version focusing on the overall presence of NFM interventions. Further statistics for the baseline versus two impact phases are presented in Table 2. It is important to note these are not normalised by event rainfall, which will be addressed further in the regression analysis section.

Across all sites rainfall event size was greater in the Phase 1 phase corresponding with the brief beaver presence on the Bircham site and summary statistics showing increasing in peak Q across all sites most likely correspond with rainfall i.e., as shown in both the beaver and non-beaver impact Bircham and Seaton monitoring stations. Given the relatively brief and minor impact of beavers at the site (i.e., only one temporary dam) it doesn't appear they significantly altered downstream flow regimes in the period they were present.

Summary statistics in Table 3 and Table 4 show a reduction both mean and median peak flows and a (small) increase in lag times following the Impact 2 introduction of leaky dams into the Bircham Stream site. Interestingly following the initial phase of NFM interventions (Phase 2) only Bircham Stream shows a change whilst the as then mostly non-impacted Seaton Stream, didn't show a reduction in peak flow for the same time. The downstream site in Forder Valley also showed no difference in mean peak flows but a small reduction in median peak flows and a small increase in lag times in Phase 2. However, in Phase 3 monitoring during which significantly more NFM interventions were installed in Bircham Stream, some were installed in Seaton Stream and also beavers returned to the site all sites now show a reduction in Peak flows indicating the NFM impact has increased over time.

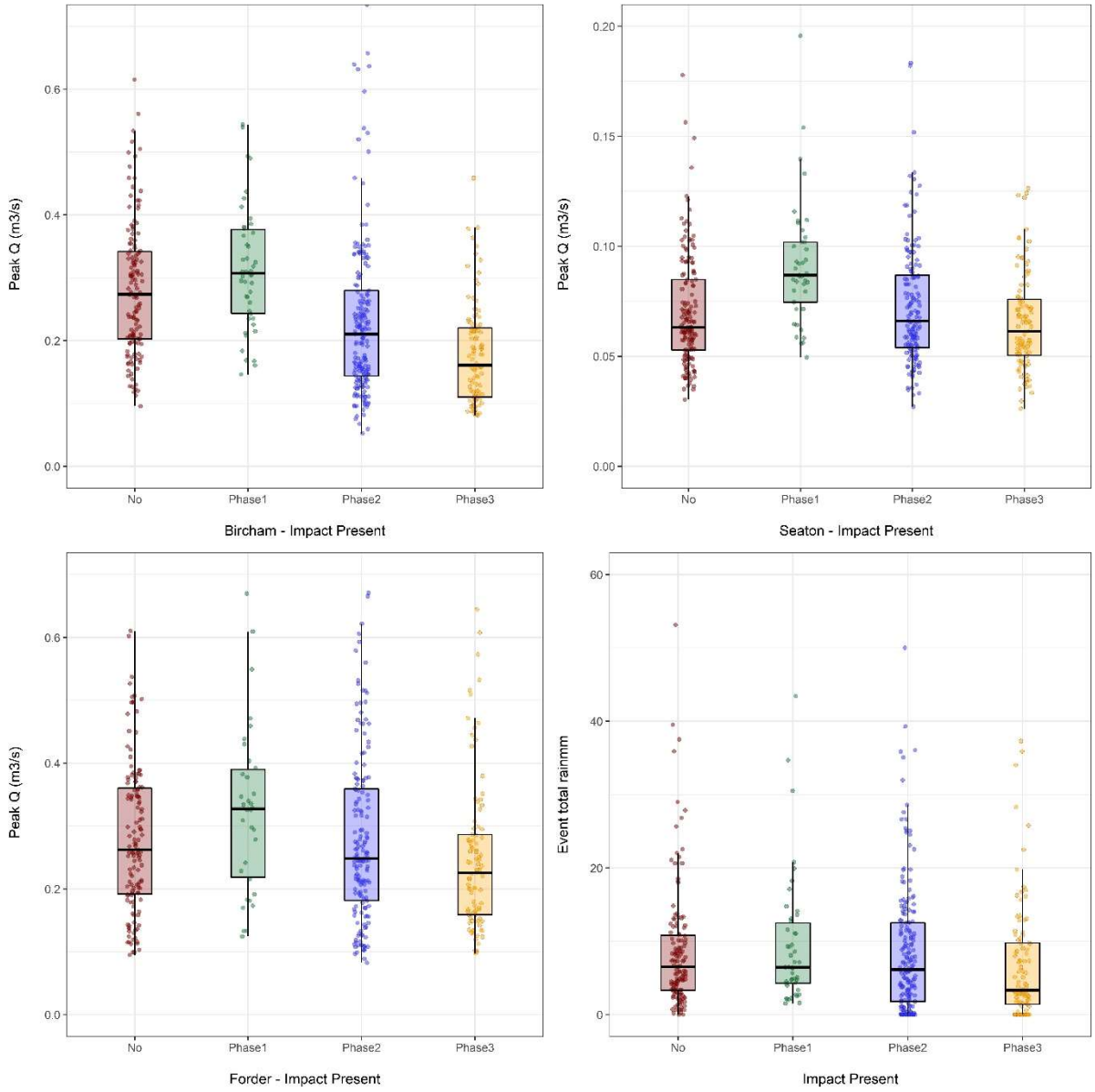


Figure 21. Boxplots summarising peak flow results across the different monitoring phases. The bottom right boxplot also summarises event rainfall for the two monitoring periods.

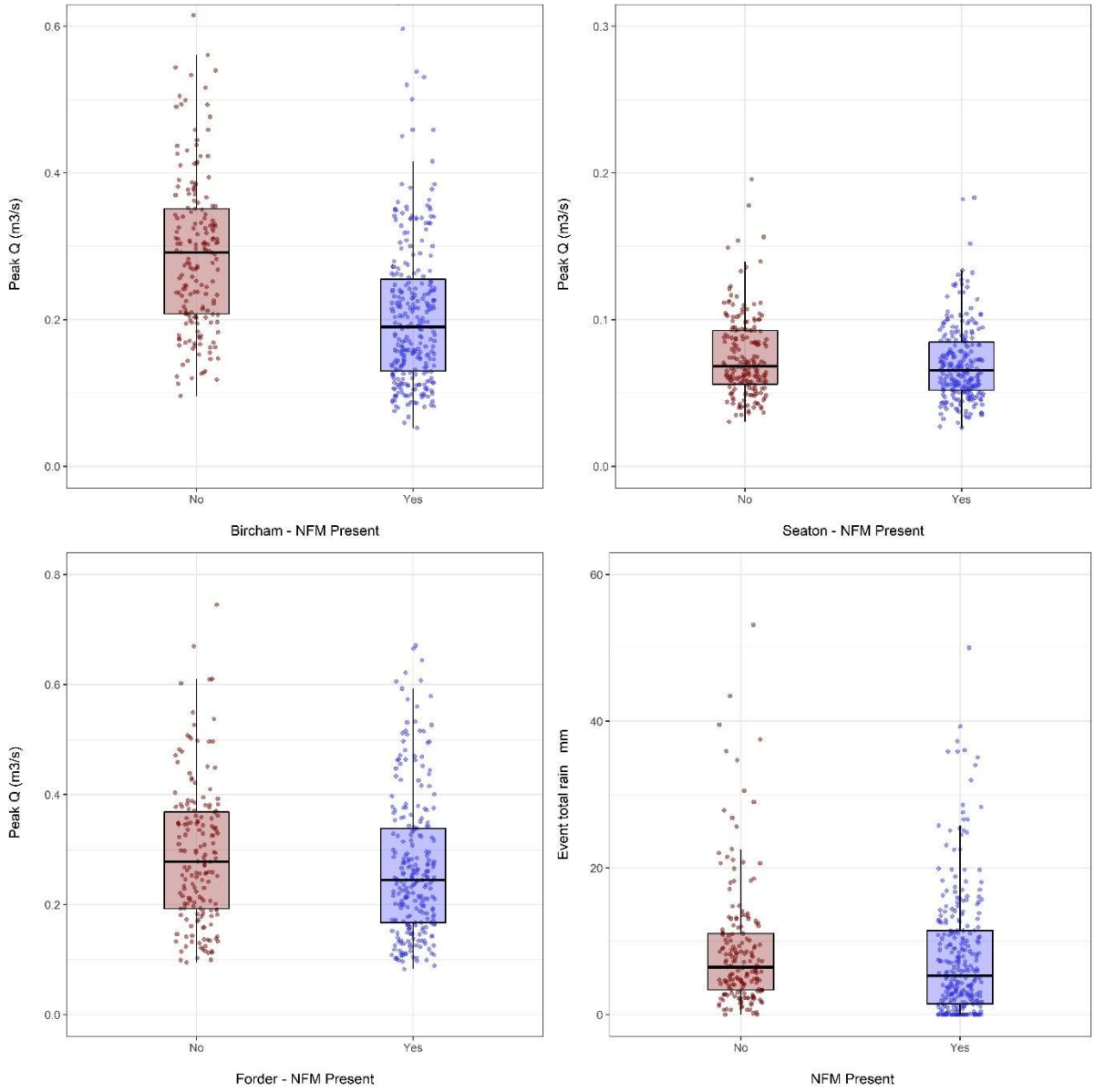


Figure 22. Boxplots summarising peak flow results across the 3 core monitoring sites for Impact 2 NFM leaky dams monitoring phases. The bottom right boxplot also summarises event rainfall for monitoring periods.

Table 3. Summary statistics for peak discahrge, rainfall event magnitude and lag times (rain start to response event) across the monitoring stations. Impact 2 refers to NFM intervention presence and return of beavers to Bircham.

		Peak Q $m^3 s^{-1}$			Event Rain (mm)		Lag Time (hrs)	
Site	Impact	Mean	Median	SD	Mean	Max	Median	SD
Bircham	No	0.292	0.291	0.111	8.9	53.1	2.8	10.9
	Impact 2	0.215	0.190	0.123	7.9	50.0	2.8	16.6
Seaton	No	0.075	0.068	0.027	7.0	43.4	3.1	19.5
	Impact 2	0.070	0.065	0.026	8.6	37.2	3.3	18.2
Forder Valley	No	0.291	0.278	0.127	7.8	39.5	2.5	30.3
	Impact 2	0.272	0.245	0.143	9.0	37.2	2.75	12.4

Table 4. Summary statistics for peak discahrge, rainfall event magnitude and lag times (rain start to response event) across the monitoring stations in relation to phases of montioring. 'no' intervention baseline monitoring phase from November 2019 to November 2020. 'Phase 1' or impact 1 stage when beavers were briefly present on site although no major damming or site interventions were recorded and this is considered continued baseline. This ran between November 2020 and April 2021. 'Phase 2' The start of NFM interventions on Bircham stream primarily consisting of the installation of 13 leaky dams. This period also ended with an interim reporting deadline. April 2021 to May 2023. 'Phase 3' Continued installation of NFM interventions on both Bircham and Seaton streams along with the return of beavers to the enclosure on Bircham stream. May 2023 to February 2024.

		Peak Q $m^3 s^{-1}$			Event Rain (mm)		Lag Time (hrs)	
Site	Impact	Mean	Median	SD	Mean	Max	Median	SD
Bircham	No/Baseline	0.282	0.274	0.105	8.7	53.1	2.5	11.8
	Phase 1	0.324	0.307	0.122	9.6	43.4	3.5	7.5
	Phase 2	0.235	0.211	0.138	8.6	50.0	2.8	19.8
	Phase 3	0.178	0.161	0.080	6.8	37.3	3.1	7.6
Seaton	No/Baseline	0.070	0.063	0.025	6.3	36.7	3.8	21.5
	Phase 1	0.092	0.087	0.028	9.3	43.4	2.3	8.5
	Phase 2	0.073	0.066	0.027	9.6	36.1	3.0	22.5
	Phase 3	0.065	0.061	0.022	7.1	37.2	3.3	8.7
Forder Valley	No/Baseline	0.283	0.262	0.124	8.0	39.3	2.5	31.6
	Phase 1	0.324	0.328	0.133	6.9	34.6	2.75	24.8
	Phase 2	0.285	0.248	0.153	8.9	36.1	2.5	13.7
	Phase 3	0.249	0.226	0.122	7.9	37.2	2.75	9.7

Flow Duration Curves

Flow duration curves (aka cumulative frequency curves) show the percentage of time a given flow was equalled or exceeded. They are useful for visually representing the hydrological behaviour of a

monitored system throughout the full range of flow conditions observed (i.e., rather than just extracted storm events). Smaller values represent rarer high flow conditions (with 1 %, 2%, 5% and 10 % all used to represent stormflow conditions). Conversely, high values show more low flow conditions with 95 % often used to represent low flow conditions (Addor et al., 2018; Gnann et al., 2021). The slope of the flow duration curve can also be analysed with a steeper slope indicating a flashier hydrological response (Addor et al., 2018; Ochoa-Tocachi et al., 2016). Duration curves for the 3 core sites are presented in Figure 23, focussing on the Impact 2 phase where leaky dams were present within the site. Statistics for both impact phases are presented in Table 5. Results illustrate that all sites show a reduction in high flow metrics following Impact 2 NFM interventions. However, results also show overall reductions in all water levels and large reductions in the 95 % low flow value, again potentially reflecting the likely impact of drought periods in recent years.

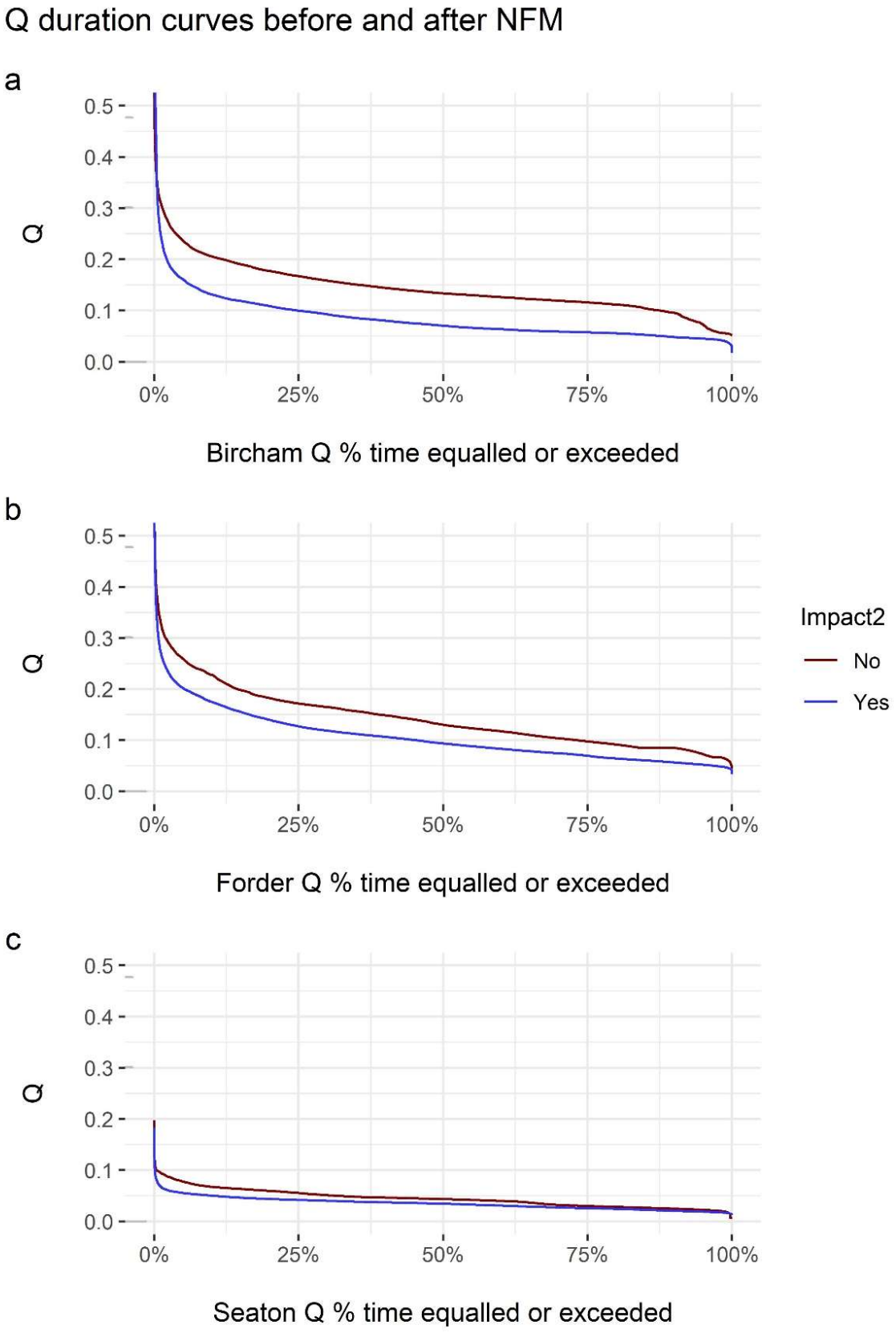


Figure 23. Cumulative frequency curves for 3 monitoring sites comparing pre and post NFM Impact 2. A = Bircham impacted stream, B = Forder downstream, C = Seaton non impacted control.

Table 5. Flow Duration Curve and overall data record summary statistics for the core monitoring points where pre and post NFM intervention monitoring data exists.

	Impact 2	Mean	Median	Q5	Q2	Q95
Bircham	No	0.144	0.133	0.236	0.283	0.073
	Yes	0.085	0.07	0.161	0.205	0.045
Seaton	No	0.045	0.043	0.077	0.0895	0.022
	Yes	0.035	0.034	0.055	0.0623	0.019
Forder	No	0.144	0.13	0.259	0.299	0.073
	Yes	0.107	0.094	0.202	0.243	0.052

Regression analysis

Whilst summary boxplot results are indicative of a change following NFM intervention they do not prove a causal relationship. Specifically, they do not account for any variability in rainfall the key driver of flow regimes that may have occurred between the monitoring periods. This section focuses on research question 2, seeking to test whether any changes in peak stage can be attributed to the presence of NFM.

To visualise relationships between rainfall and runoff undertake across the monitoring stations throughout the different monitoring phases, Figure 24 plots linear regression relationships for all 3 sites, whilst Figure 25 focuses on the core site of Bircham stream which has been most impacted by a combination of installed interventions and the enclosed beaver project.

GLM analysis was undertaken across sites using the model formulations detailed in the methods and is presented along with output statistics in Figure 26 and Figure 27. This analysis focus on pre and post Impact 2 NFM intervention installation and the return of beaver to the site. Supporting summary statistic results, model and marginal mean values from GLM analysis at Bircham Stream, immediately below leaky dam installation indicates the combined interventions have had a significant (**0.01) impact in reducing peak flows with marginal means showing an event peak flow reduction from 0.285 $m^3 s^{-1}$ to 0.219 $m^3 s^{-1}$ (23 % reduction). The less impacted control site on Seaton Stream also saw a smaller but still notable and statistically significant (*0.05) reduction over the same period (11.6 % reduction) indicating the recent interventions on that reach, are also having an impact on event peak flow response during the monitoring periods. Downstream in Forder Valley in the Impact 2 phase of analysis GLM results again show a reduction in peak flows and marginal means showing a reduction from 0.291 $m^3 s^{-1}$ to 0.271 $m^3 s^{-1}$ (6.8 %) although this result was not statistically significant, indicating thus far the impact observed directly below the interventions on Bircham Stream and Seaton Stream are only having a much smaller reduction in peak flows further downstream.

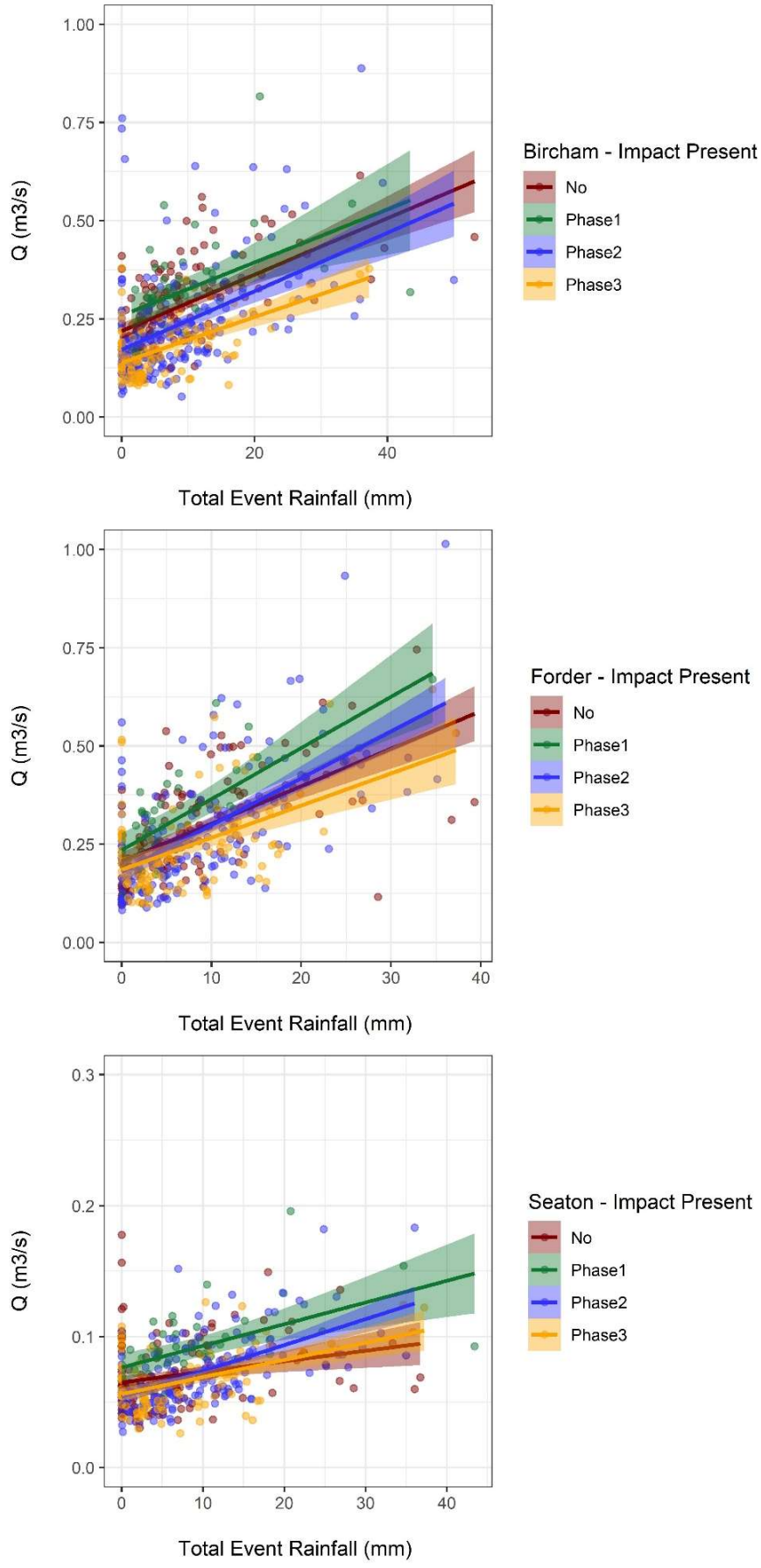


Figure 24. Linear regression relationships between total event rainfall and discharge for different phases of monitoring.

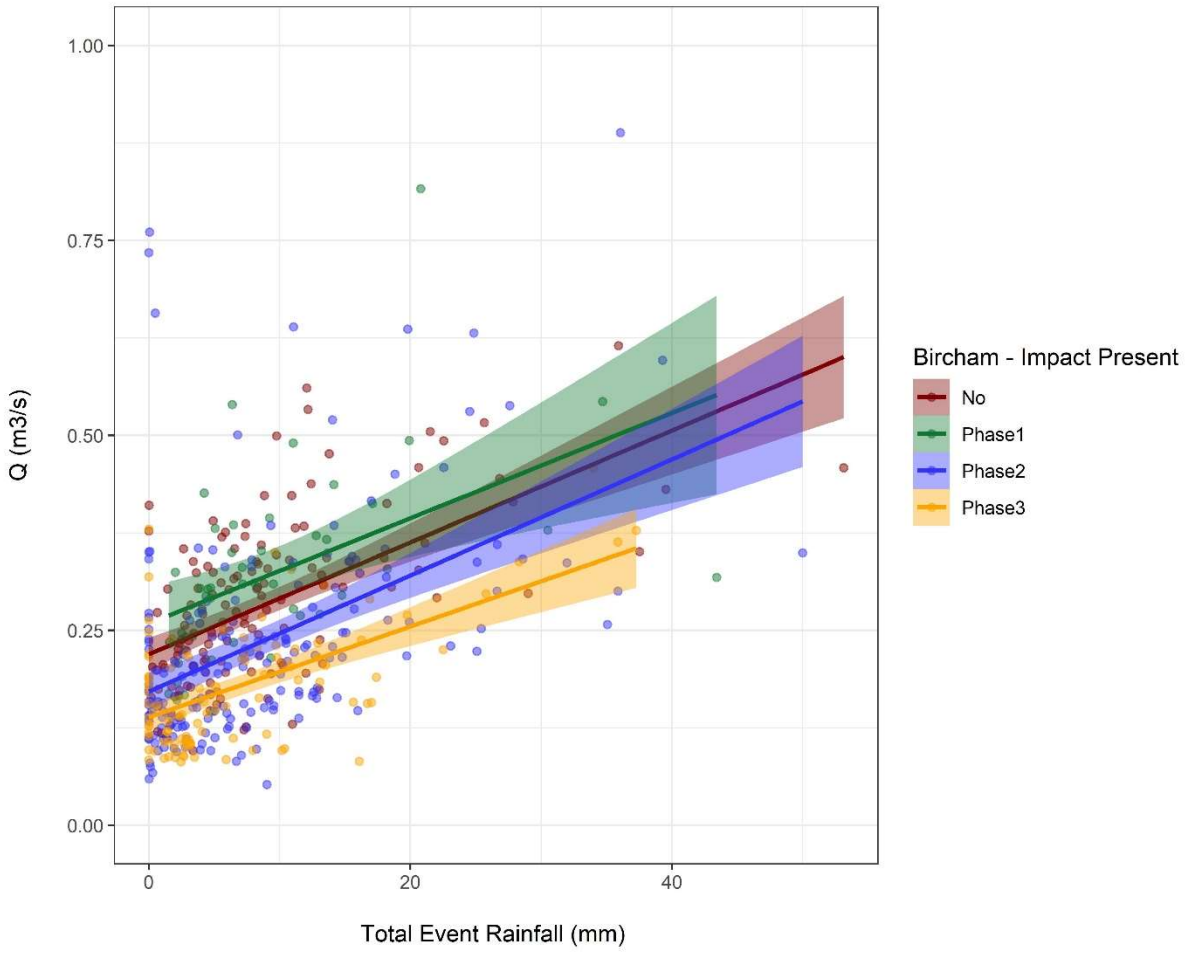
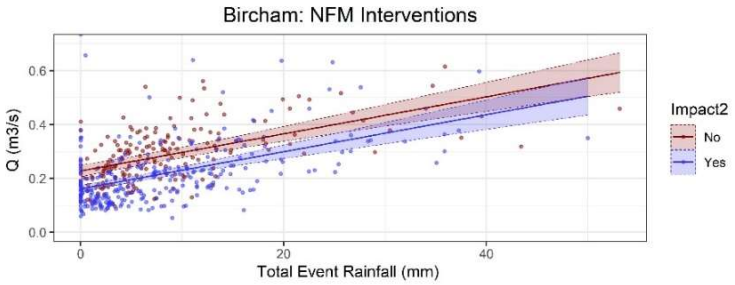


Figure 25. Linear regression relationships for key Bircham stretch between total event rainfall and discharge for different phases of monitoring.

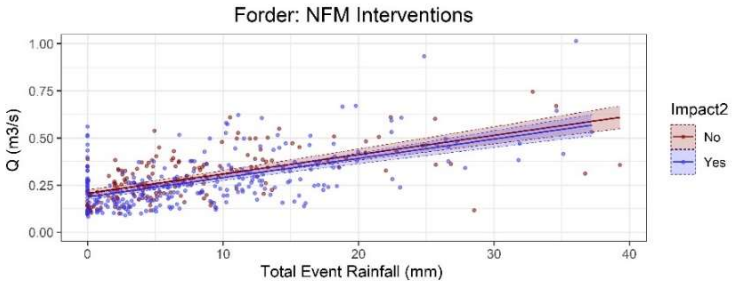


Bircham Regression Summary

term	estimate	std.error	T.statistic	p.value
Intercept	0.225	0.011	20.449	< 0.001 **
Impact2	-0.052	0.012	-4.385	< 0.001 **
Rainfall	0.008	0.001	8.231	< 0.001 **

Marginal Means

Impact2	estimate	std.error	statistic	p.value
No	0.285	0.010	29.66563	2.132417e-193
Yes	0.219	0.006	36.06862	7.042505e-285

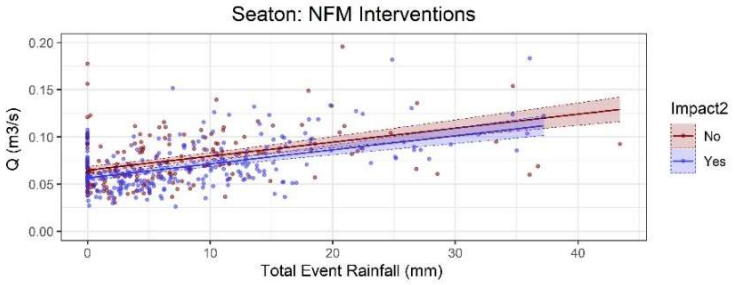


Forder Regression Summary

term	estimate	std.error	T.statistic	p.value
Intercept	0.204	0.009	21.882	< 0.001 **
Impact2	-0.018	0.011	-1.635	0.103
Rainfall	0.012	0.001	11.743	< 0.001 **

Marginal Means

Impact2	estimate	std.error	statistic	p.value
No	0.291	0.009	33.51112	3.318929e-246
Yes	0.271	0.007	40.01306	0.000000e+00



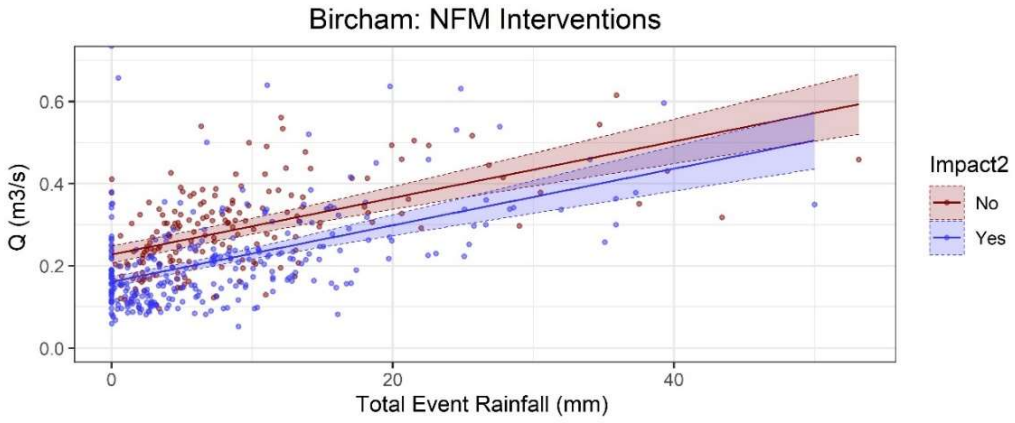
Seaton Regression Summary

term	estimate	std.error	T.statistic	p.value
Intercept	0.065	0.002	31.826	< 0.001 **
Impact2	-0.007	0.003	-2.850	0.005 *
Rainfall	0.002	0.000	7.963	< 0.001 **

Marginal Means

Impact2	estimate	std.error	statistic	p.value
No	0.077	0.002	43.05780	0
Yes	0.068	0.001	48.73128	0

Figure 26. GLM model results between peak stage and total event rainfall, before and after Impact 2 NFM impact across all sites for all recorded storm events. Top: model output plots; Bottom: model summary and marginal mean values for each site.

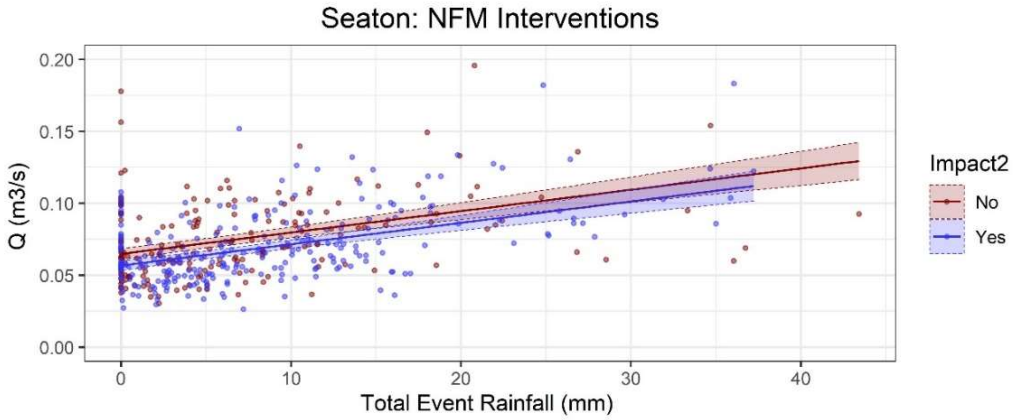


Bircham Regression Summary

term	estimate	std.error	T.statistic	p.value
Intercept	0.225	0.011	20.449	< 0.001 **
Impact2	-0.052	0.012	-4.385	< 0.001 **
Rainfall	0.008	0.001	8.231	< 0.001 **

Marginal Means

Impact2	estimate	std.error	statistic	p.value
No	0.285	0.010	29.66563	2.132417e-193
Yes	0.219	0.006	36.06862	7.042505e-285



Seaton Regression Summary

term	estimate	std.error	T.statistic	p.value
Intercept	0.065	0.002	31.826	< 0.001 **
Impact2	-0.007	0.003	-2.850	0.005 *
Rainfall	0.002	0.000	7.963	< 0.001 **

Marginal Means

Impact2	estimate	std.error	statistic	p.value
No	0.077	0.002	43.05780	0
Yes	0.068	0.001	48.73128	0

Figure 27. GLM model results between peak stage and total event rainfall, before and after NFM impact at the impacted Bircham Stream and compared to a control site (Seaton Stream). Top: model output plots; Bottom: model summary and marginal mean values for each site

Results Summary

- Hydrological monitoring results between November 2019 and February 2024 are presented and analysed as part of research undertaken by University of Exeter for the Plymouth Green Minds project.
- The project experimental design was initially designed to focus on beaver engineering at the site but following a pause in the beaver project and the installation of leaky dams on the site, the project has expanded to have a wider natural flood management focus.
- Monitoring was also undertaken on a neighbouring stream (Seaton) which initially was unimpacted so could act as a control. However, now project NFM intervention installation has now expanded to cover that reach, so a before-after experimental deign is adopted across all monitoring sites.
- Downstream monitoring in Forder Valley aims to see if any observed impacts in flow regimes on Bircham and Seaton streams persist beyond the local/site scale and are observable downstream.
- Water level at each of the 3 monitoring points was recorded continuously (apart from small gaps due to logger or download issue) on a 15-minute timestep and converted to discharge for hydrological analysis. Combined with rainfall radar data, the hydrological monitoring data was analysed using a standardised and semi-automated approach to extract rainstorm events and their related flow response events.
- Over 400 storm events were extracted for each of the monitoring sites.
- Given the minor and temporary initial phase of presence of beavers on the site, during which no major interventions or ecosystem engineering was observed this time period (Phase 1 monitoring) has been combined with the baseline data and the main focus of further hydrological analysis was the 'Impact 2' installation of leaky dams, other NFM interventions and return of beavers to the site. All these interventions have been undertaken since April 2021.
- Summary statistics and flow duration curves showed that peak flow levels in storm response events and high flow metrics (i.e., Q2 and Q5) showed a reduction on Bircham Stream in the initial period following leaky dam installation and this trend continued and accelerated with the installation of further NFM interventions and the return of beaver to the site.
- As with other sites recently studied, analysis of flow duration curves and the overall flow record indicates high flow metrics have all reduced following NFM interventions, but so have low flow metrics. The reductions in the 95th percentile most likely represents the recent drought and dry periods experienced recently coinciding with parts of the Impact 2 monitoring period.
- Regression analysis was undertaken using generalised linear models (GLMs) to consider rainfall variability (the key drive of hydrological response) and see if changes in peaks could be attributed directly to NFM interventions.
- GLM analysis indicates NFM Impact is responsible for statistically significant reductions in peak flow levels on Bircham Stream (23 %) indicating that the combined presence of installed NFM interventions and the enclosed beaver project is leading to attenuation in peak flows during rainstorm events.
- This key value of an 23 % peak flow reduction is an increase from the 17 % observed in interim reporting undertaken in May 2023 indicating continued intervention at the site since then has become increasingly impactful.
- Seaton Stream also now shows a reduction in peak flow values of 11.6 % during storm events following installation of NFM interventions on that previously non-impacted site.

- Lag times were also shown to be slightly longer following leaky dam installation. For example, on Bircham stream, start of rainstorm to peak flow times increased from 2.5 hours in the baseline monitoring to 3.1 hours in the phase 3 monitoring in 2023/2024 indicating NFM interventions may be 'slowing the flow'.
- The reductions in peak flow observed further downstream in Forder Valley were smaller (6.8 %) and not statistically significant. These updated values show a small increase from the 6 % reported in interim analysis in May 2023 but do show a downstream dilution effect indicating a more minor impact downstream.
- Since interim reporting delivered in May 2023 peak flow reductions have increased at all monitoring locations indicating the increase in level of NFM interventions at the site is resulting in an increased impact upon downstream flow regimes.
- It is critical to note that installation of NFM interventions continues and beavers have only recently returned to the site. meaning a larger hydrological impact could be observed in the future, building upon these promising current findings.

Figure 28. Bircham Stream in flood, prior to NFM installation 27th August 2020. There was known flooding downstream of Poole Farm on that day, with the Forder Valley Link road construction site being inundated, and £10k + damage caused to vehicles and infrastructure. The Bircham river was so swollen that a Forest School group had to be rescued – being escorted across the construction site to use the only bridge big enough to get back to Poole farm (Source per comms Plymouth City Council). Floods across Devon and Cornwall after 'biblical' rainfall - BBC New: https://www.bbc.co.uk/news/uk-england-devon-53936684

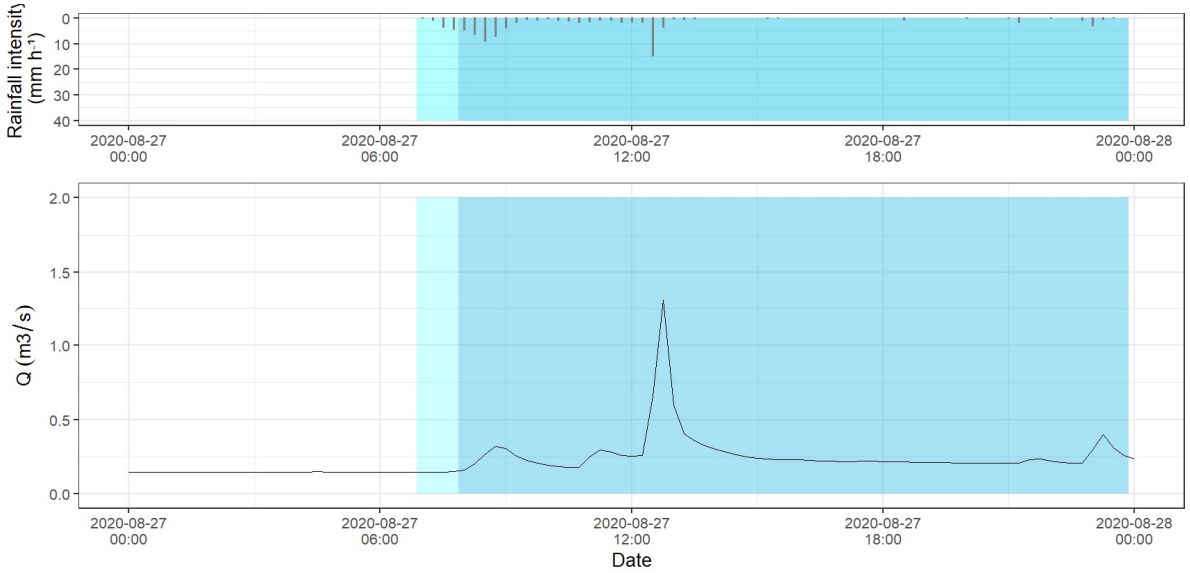
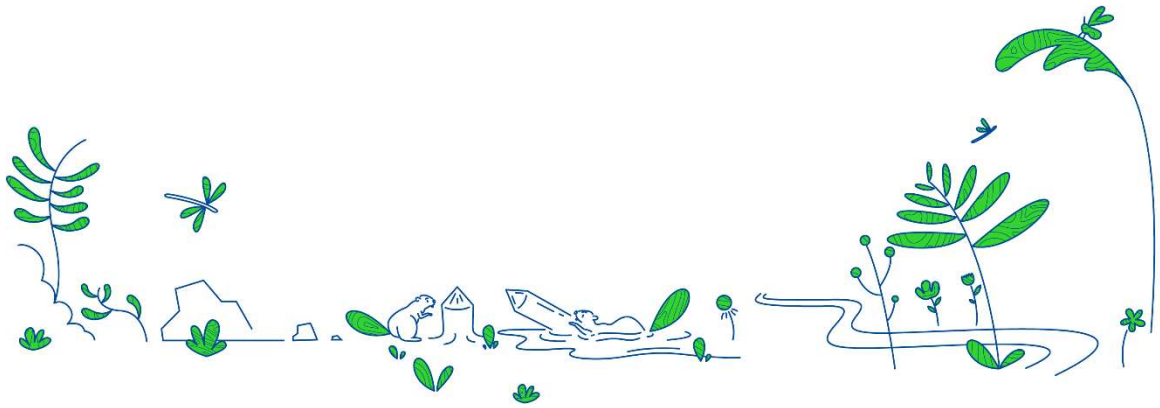


Figure 29. Hydrograph showing rapid response on the 27th August 2020.

Figure 30. Bircham River 2024 during wet conditions with new infrastructure and information boards installed. This photo is taken from a similar viewpoint to Figure 28, following installation of NFM Interventions. Anecdotal accounts and imagery such as this support the data presented in this report indicating flow attenuation since NFM installation. The new bridge and notice board infrastructure that has been installed to enable visitors access to the Bircham river/enclosure and education of the benefits of beavers and wetlands.



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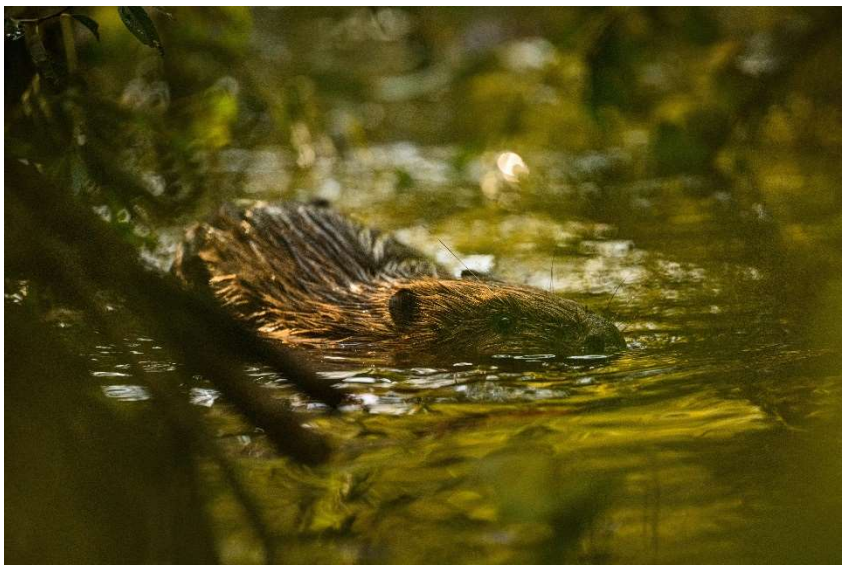

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