

Evaluating the effectiveness of natural flood management implemented within the Isbourne catchment



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BSc Geography

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Declaration

This dissertation is the product of my own work and does not infringe the ethical principles set out in the University's Handbook for Research Ethics. I agree that it may be made available for reference via any and all media by any and all means now known or developed in the future at the discretion of the university.

E. Godfrey

Signed: Emma Godfrey

Date: 10/04/2026

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I would like to thank my dissertation supervisor Ceri Davies for her support throughout the dissertation writing process.

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Abstract

The Isbourne catchment, located within the counties of Gloucestershire and Worcestershire, United Kingdom (UK), experienced a significant flash flood in 2007 leading to the implementation of natural flood management (NFM) in 2016 due to the unsuitability of traditional hard engineering. This study aims to evaluate the effectiveness of the NFM implemented within the Isbourne catchment in relation to flood risk reduction.

Precipitation and daily average flow data was collated and analysed in order to interpret long-term trends and seasonal variation within the Isbourne catchment. This data was filtered to identify the top ten precipitation events before and after the addition of NFM within the Isbourne catchment, during the intervals of 2000-2015 and 2017-2024, and for the control site, named the Coln catchment, which has not had any intervention, including hard engineering or NFM. Subsequently, hydrographs were created with features including peak flow, Lag time, discharge and return to baseflow then deciphered. Statistical analysis of before and after for each time period was conducted using the interquartile range (IQR) and 95% confidence intervals to determine if changes in data are statistically significantly and consequential of the NFM.

Overall, there is a statistically significant correlation between the implementation of NFM and the increase to Lag time and reductions in event discharge and peak flow. A general overall increase was observed in annual precipitation between 1961 and 2023 within both catchments. However, the implications of increasing future rainfall to the effectiveness of NFM is significant to short-term intense rainfall. However, there is also evidence of the exceedance of the NFM's capabilities specifically during events of extreme precipitation and preceding wet conditions. The occurrence of extreme precipitation events within the Isbourne catchment since the implication of NFM is significantly limited therefore NFM at low to medium size events can be recognised as effective whereas, extreme events require additional data to determine the NFM's potential limits.

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1. Introduction

Flooding is defined as the presence of a substantial quantity of water over land which is typically dry (Kundzewicz and Pinskiwar, 2022). Recognised as the most common natural disaster, flooding has significant impact on infrastructure, economies and threatens human life (Razavi et al., 2020). The two main, most impactful types of inland flooding are: fluvial and pluvial. Fluvial flooding describes the flow of water over a river's banks, characterised by heavy rainfall, saturated soils and high downstream flows, posing a threat to infrastructure developed on floodplains, therefore, measures are implemented to reduce the possibility of inundation (Dadson et al., 2017). Pluvial flooding is initiated by periods of heavy precipitation overwhelming drainage networks or exceeding the infiltration capacity of soils resulting in localised floods - typically in urban areas- and the accumulation of surface water (Kundzewicz and Pinskiwar, 2022).

Flooding results in an annual average global cost of \$388 billion and accounts for 35% of weather related disasters (UNDRR, 2025). Within Europe, these costs have rapidly increased as a result of climate and socioeconomic factors including population growth and urbanisation, causing the loss of wetlands and floodplains (Feyen, 2012). The risk of flooding is rising whilst it is acknowledged following the 2007 summer flash floods by the UK government reviewed flood defences noting the increasing flood risk cannot be met by building larger hard engineered defences with suggestions of natural, catchment based solutions (Kay et al., 2019). NFM is described as a catchment-based approach which harnesses hydrological processes through restoring natural environments with the aim of slowing the flow of water through the catchment (Vann et al., 2025).

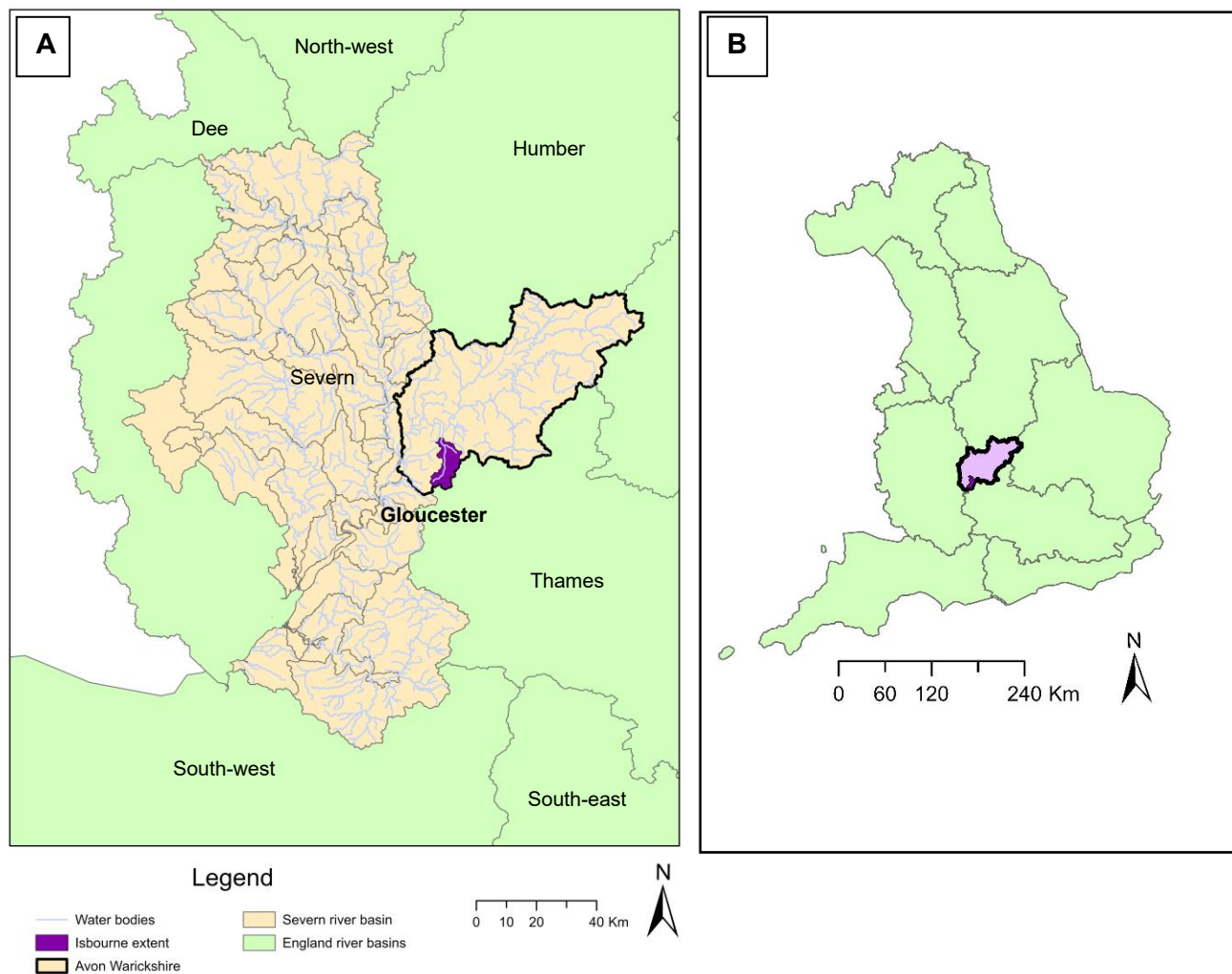


Figure 1: Positioning of the Ibsourne catchment in proximity to the English River basins and operational catchments (B) position within the UK.

The Ibsourne catchment is located to the North of Cheltenham in the south-west of England, within the counties of Gloucestershire and Worcestershire. The catchment is a waterbody located in the Avon Warwickshire management catchment which is a subdivision of the Severn river basin district, as seen in Figure 1.

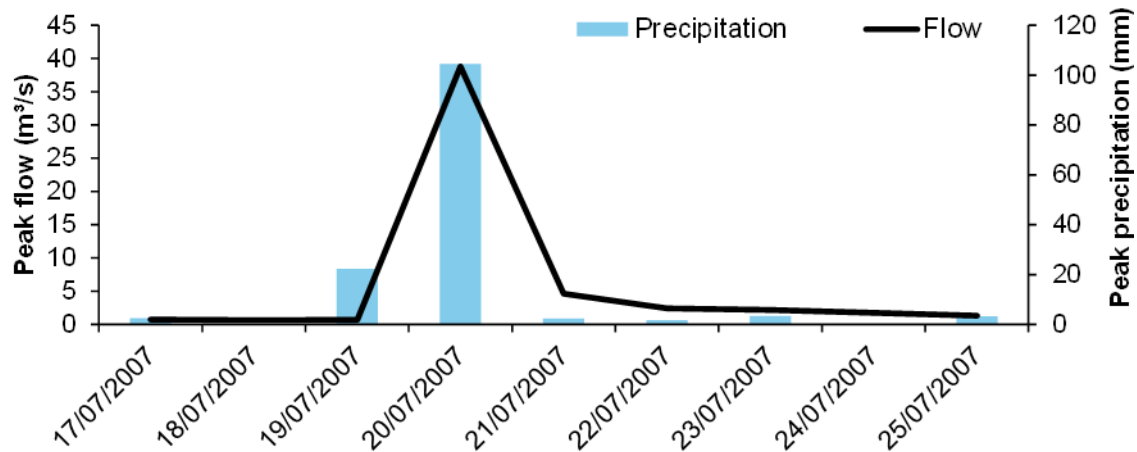


Figure 2: Hydrograph of the July 2007 flood event showing flow and precipitation data from the Hinton on the Green gauging station. Data sourced from (NRFA, N.D).

The Isbourne catchment has a history of fluvial and surface water flooding with the largest flood event recorded in the summer of 2007. This flash flood, caused by heavy rainfall, significantly affected the village of Sedgeberrow, flooding 90 residential properties, with a rise in the river level of 4.6m in 12 hours recorded at the gauge station at Hinton on the Green (Environment Agency, 2009). As indicated in Figure 2, the flooding event in 2007 was a result of 104.5mm of rainfall in one day and subsequent peak flow of 38.3m³/s on the day of the rainfall event.

The majority of flood events occur within the floodplain river valley areas in which the majority of housing are located, with villages to the north of the catchment most at risk to flooding (Clarke et al., 2016). The addition of NFM management within the catchment commenced in 2016, with a total of 170 interventions completed by 2025 including leaky woody dams, storage areas, ponds, a ditch and a bund (Isbourne Catchment Group, 2025).

A report investigating the potential of NFM introduction in the Isbourne catchment by Clarke et al. (2016) suggested future intentions to assess and quantify the effect of any future NFM implemented. There is no quantitative desk based approach to assess the effectiveness of NFM projects at a catchment scale (Connely et al., 2023). The effectiveness of NFM at different scales and between catchments is unproven, with some studies concluding there is insignificant quantitative evidence of the same level of effectiveness of flood risk reduction between plot, hillslopes and at a catchment scale (Zhu et al., 2024). The lack of long-term quantitative data for the effectiveness within larger catchments is the main limiting factor preventing the implementation of NFM on a wider scale, therefore, quantifying the effect of NFM on directly related flood characteristics is critical, specifically the effect on peak flow reduction and Lag times (Zhu et al., 2024). Consequently, this study is relevant in a wider context as a method to be applied to other catchments to assess effectiveness.

This study aims to evaluate the effectiveness of natural flood management implemented within the Isbourne Catchment to reduce flood risk. The objectives include:

- Analyse seasonal and temporal changes to precipitation and flow between 1961 and 2023.
- Statistically analyse peak flow and total event discharge of the top ten highest precipitation events, before and after the NFM intervention within the Isbourne Catchment.
- Statistically analyse peak flow and total event discharge of the top ten highest precipitation events, to the control, Coln catchment.
- Evaluate hydrograph shape under various conditions before and after the implementation of NFM including Lag time, rising and falling limb.

2. Literature Review

2.1 Flooding in a global context

The Intergovernmental Panel on Climate Change's latest report states a strong likelihood of the increase in frequency and intensity of heavy precipitation events, consequential to climate change, on a regional and global scale (Seneviratne et al., 2021). Extreme precipitation is the main contributor to flooding, with projected increases in pluvial and fluvial flood events, greater peak flows and uncertainties to the coverage of areas that will be significantly affected (Seneviratne et al., 2021). There is high confidence that the holding capacity of atmospheric water will increase between six to seven%/°C rise in temperature, resulting in an increase to future global flood risk (Tabari, 2020). Extreme precipitation events are predicted to significantly impact regions experiencing high moisture availability, with a further increase during wet months, but there are regions with overall reduction in annual precipitation (Gimeno et al., 2022). It is acknowledged globally that there is a significant gap between future predicted flood risk and the level of adaptation implemented, with current management failing to provide a sufficient response (Climate Change Committee, 2021). Sharma et al. (2018) states a non-direct relationship attributed to increased precipitation and flood magnitude, whilst stream flow increases to a lesser extent in comparison to the rise in temperature.

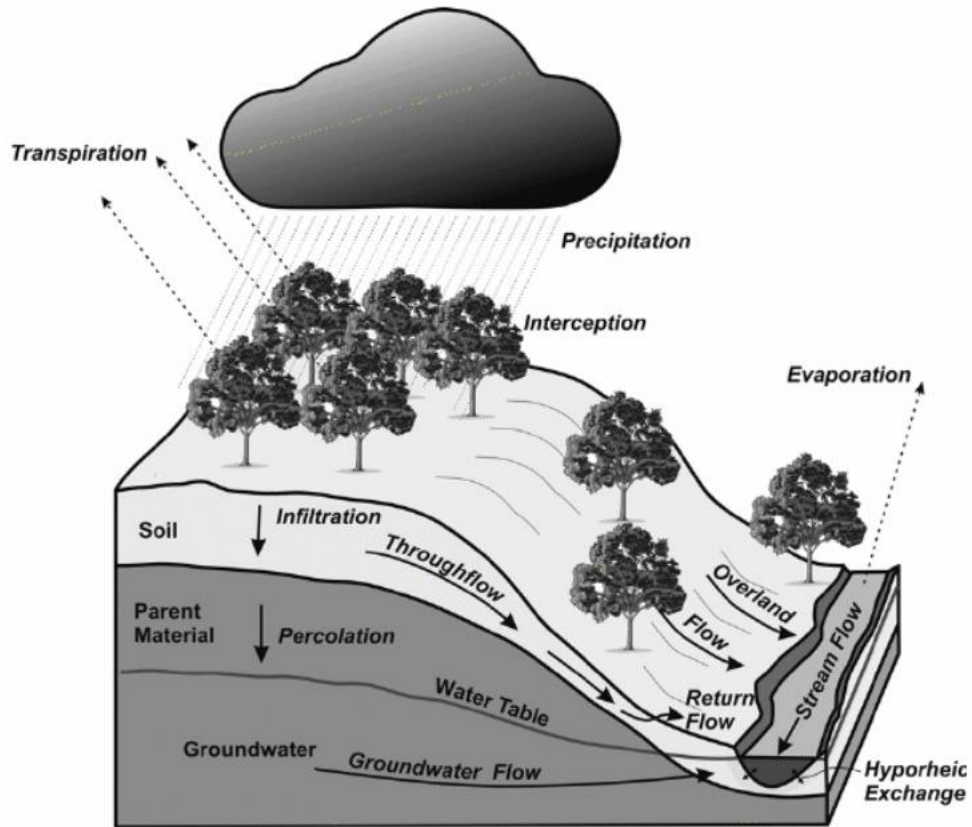


Figure 3: Water pathways within the terrestrial water cycle. Source: (Rhoads, 2020)

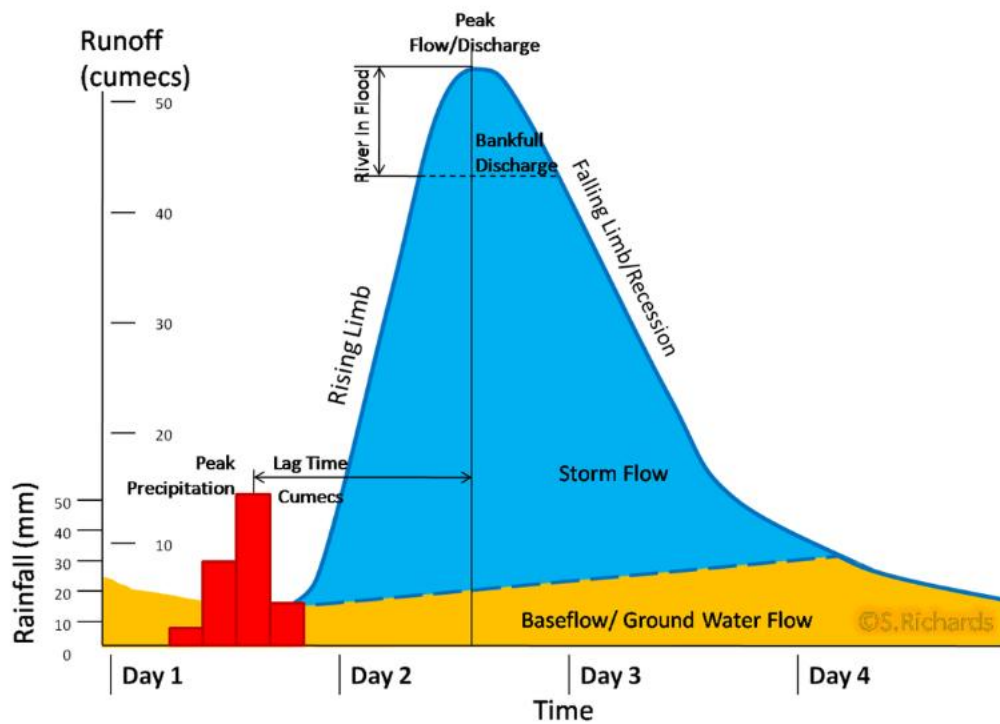


Figure 4: Hydrograph showing key characteristics of events (Source: Team Geography, N.D).

The hydrograph, as displayed in Figure 4, shows the relationship between changes to flow and precipitation at a set point in a river which is significantly influenced by watershed characteristics determining the hydrological response (Singh, 1998). As seen in Figure 3, catchment geology is significant in determining water pathways, with geology and landcover the most influential factors contributing to high flows, however, due to the complexity and heterogeneity of geomorphology between catchments it is difficult to predict and compare responses to precipitation events (Zhang et al., 2022). Factors influencing flood vulnerability include geomorphology, hydro-climatology, and social and economic variables (Pathak et al., 2020). Small catchments experience a greater sensitivity to storm events as precipitation is likely to cover the extent of the catchment, leading to soil saturation and increases to peak flows and discharge (Sharma et al., 2018). However, the main contributor to severe flooding is extreme precipitation events in an already saturated catchment (Sharma et al., 2018).

1.2 Flooding in the United Kingdom

Flooding is recognised as the most significant natural hazard in the UK, with a predicted increase in fluvial flooding of two to four times by 2080 (Thorne, 2014). Estimated economic damages in England and Wales, occurring in 2016 and 2019, range between 504 and 924 million pounds (Environment Agency, 2024).

In the UK, 6.4 million people live within flood prone areas, and it was estimated that with a 2°C rise in temperature by 2025, those exposed to significant flood risk was predicted to rise from 1.8 to 2.6 million people (Carvalho and Spataru, 2023). The UK has experienced numerous significant flood events, particularly those during the winters of 2013 and 2014, resulting from storm surges and heavy persistent rainfall, widespread flooding occurred (Thorne, 2014). These flooding extremes are linked to changes in atmospheric circulation patterns which increased storminess (Climate Change Committee, 2021). Precipitation over the last decade within the UK has increased, with summers 20% and winters 5% wetter than that recorded between 1990 - 2000 (Climate Change Committee, 2021).

1.3 Flood management

Flooding is a naturally occurring process, nevertheless management prioritises mitigation primarily through hard engineered solutions which have high installation and maintenance costs, however, flood events still occur leading to scrutiny on overall cost effectiveness (Wang et al., 2022). Hard engineering techniques include structural alterations to move water away from populations, and non-structural techniques such as policies to prevent

populations living in flood vulnerable areas with the main aims of protecting, reducing or eliminating the impacts of a flood event (Wang et al., 2022). Within the UK, hard engineering techniques adopted include the mechanical dredging and channelisation of approximately 8,500km of rivers (Newson et al., 2021).

Flood perception is significant within management and is derived from the probability of the event occurring, and the subsequent consequences and impacts to society subdivided into awareness, behaviour and preparedness (Lechowska, 2018). The main hydrological approaches to reducing flood risk aim to increase infiltration, storage and groundwater recharge whilst delaying the flow and volume of water entering watercourses (Thaler et al, 2023). There is evidence that current water regulation and management have increased flood resilience, but it does not eliminate extreme flooding events (Seneviratne et al., 2021). Hard engineering and channelisation approaches are reported as being inadequate to respond to future climatic challenges whilst sustainable NFM approaches are proposed as being both economically and environmentally viable (Waylen et al., 2017).

1.4 Natural flood management

A greater understanding of river science specifically sediment transport, sources and sinks has resulted in policy shifts towards holistic, catchment-based interventions, with a focus on enhancing natural processes (Dadson et al., 2017). Working with natural processes incorporates restoring or enhancing natural functions and processes within catchments such as woodlands, floodplains and river morphology (Dadson et al., 2017). The UK Government's 25 year environmental plan for England includes increasing the adoption of NFM providing funding of 15 million pounds to further develop evidence and solutions to enable effective implementation within differing catchments, and rewilding 4,000km of river channels (HM, Government, 2018).

NFM functions by increasing flow attenuation and infiltration resulting in a reduction in peak flow and event discharge (Vann et al., 2025). This is achieved by reducing the rate and volume of surface runoff, increasing available storage during high precipitation events, and reducing the connectivity between runoff sources and areas of high flood risk and inundation (Lane, 2017). NFM changes hydrological and morphological processes with methods including wood debris within the river channel, re-meandering and catchment scale interventions such as reed beds and reforestation. (Waylen et al., 2017).

NFM provides additional benefits including improving water quality and biodiversity, however, its implementation presents challenges as it requires support from numerous

stakeholders including private landowners (Thaler et al, 2023). Also, the involvement of local community groups utilises local knowledge to develop the best solution for a specific location (Short et al., 2018).

1.5 Effectiveness of NFM

The efficiency of NFM between specific catchments is poorly documented with no quantitative approach to assess the effectiveness (Connelly et al., 2023). Research into the effectiveness of NFM is predominantly within small catchments (<20km²) as there is greater spatial and temporal heterogeneity to rainfall events, and these benefits observed may not be representative to that implemented within larger scale catchments (Zhu et al., 2024). However, there is little evidence of the viability with large catchments to extreme flood events due to land use changes and uncertainty within modelling (Hankin et al., 2021).

Table 1: Descriptions, evidence of effectiveness and limitations of the main NFM measures implemented within the Isbourne catchment. Synthesised from: (Ellis et al., 2021), (Metcalf et al., 2017), (Lockwood et al., 2022), (Leeuwen et al., 2023).

NFM intervention	Function	Evidence	Limitations
Floodplain afforestation	Interception of overland flow, increased infiltration and soil holding capacity	Hydraulic modelling shows a 5 times greater surface roughness in comparison to grass. Study site in Wales had a reduction in surface runoff of 78%. 94 studies averaged water yield reduction between 10 and 40 mm for every additional 10% of catchment reforested.	Weak relationship between flood frequency and natural forest cover. A significant reduction in peak flows only seen within small flood events.
Storage ponds	Increase surface water storage attenuating flow	Peak flow attenuation, upper limit reduction of 7% for large events whereas, for smaller events, where pond filling occurs directly from rainfall or runoff display a peak flow reduction of 3%	Lack of evidence for efficiency at differing flow rates.
Leaky dams	Decrease water velocity, increased upstream water storage enabling reconnection to the floodplain	Modelling shows potential to decrease flood peaks within high gradient streams on average by 10%.	Few empirical studies quantifying addition of leaky dams in upland of catchment on flood peak magnitude.

Table 2: Table showing gauging stations with quantified evidence of reducing peak flows with NFM measures and potential peak flow reduction for a 50 year return period. Synthesised from (Kay et al., 2019).

River	Location	NRFA ID	Catchment area (km ²)	Estimated flood response type	Estimated potential peak flow reduction for 50 year return period peak flow
Lymington	Brokenhurst	42003	99	Mixed	6 - 19
Pickering Beck	Ings Bridge	27056	68	Mixed	15 - 20
Laver	Ripon	27059	97	Enhanced	1 - 2
Enrick	Mill of Tore	6008	106	Neutral	0.8

Also, there is limited quantitative study-based evidence for the potential of NFM to reduce local and downstream flood events, particularly for major precipitation events (Dadson et al., 2017). Modelling empirical evidence suggests that NFM is effective in providing resilience within small catchments for low to medium probability flood events and provides a small reduction to peak flow of between 5 to 10% (Hankin et al., 2021). Modelled and quantitative evidence of the NFM methods utilised within the Isbourne catchment are described in Table 1 and successful implementation projects within Table 2. Modelling is indicative of higher estimated peak flows in comparison to field studies with reductions inputting at a national scale suggesting peak flow reductions between 5% and 20%, which is the upper limit to estimated potential of NFM (Kay et al., 2019). Contrastingly, it is estimated that within NFM schemes observed quantitative evidence of project effectiveness is less than 25% with variable results (Black et al., 2021).

Limitations to quantifying NFM effectiveness include difficulty in isolating the effect of individual measures, the magnitude of the flood event influences the effectiveness, and the small timeframe since implementation within studies, whereas greater evidence of the effectiveness may be apparent over the long term (Connelly et al., 2023). Precipitation patterns and preceding catchment conditions will affect the peak discharge, and the response will differ with expected variation between storm events (Zhu et al., 2024). The main factors stated as the challenges to implementation of NFM within England include: the need for stakeholders in projects to acknowledge and act; that engagement and partnership is critical for success; also quantifying economic benefits and long term performance (Vann et al., 2025). It is stated that in order to improve confidence of flood mitigation and NFM it is crucial to quantify the impacts on flood characteristics including impacts to peak flow and duration of the event (Zhu et al., 2024).

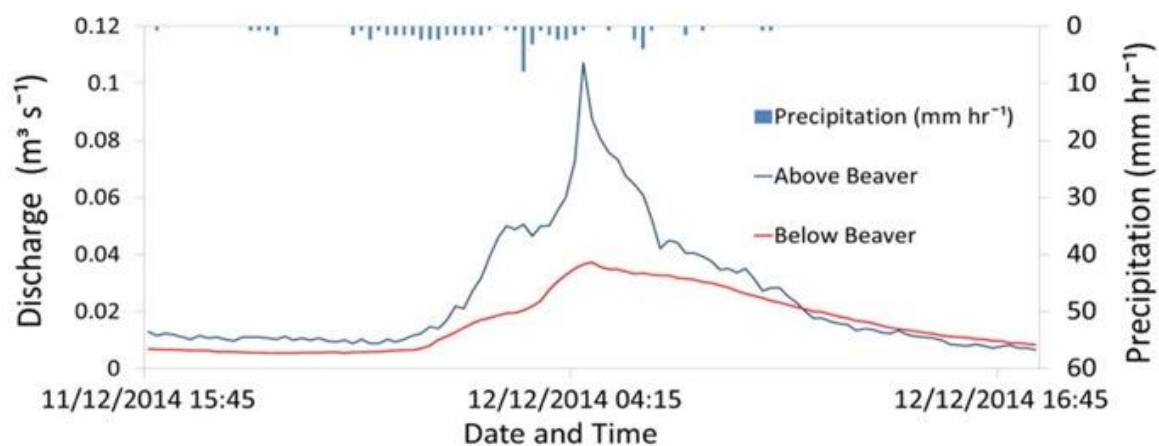


Figure 5: Discharge above and below beaver dams for a rainfall event. Source (Puttock et al., 2017).

There is a greater confidence in the evidence of the introduction of beavers and subsequent beaver dams on flood risk reduction. As seen in Figure 4, there is evidence of increased water storage within the site before the dam with peak mean discharges of $30\text{m}^3/\text{s} \pm 19\%$ reduction and mean Lag time of 29, a 21% increase during storm events (Puttock et al., 2016).

3. Site description

3.1: Study site

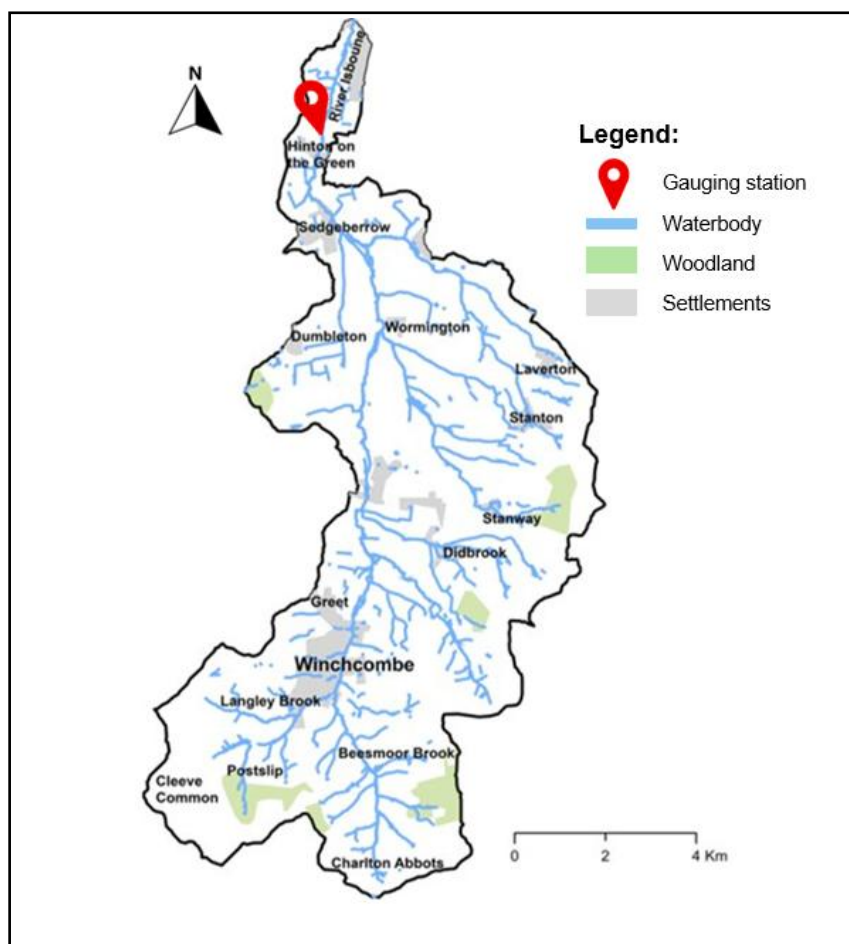


Figure 6: The Isbourne catchment extent showing waterbodies, settlements and woodland. © Crown copyright and database rights 2026 Ordnance Survey (100025252)

The Isbourne River has five main tributaries and flows in a northerly direction from the source at Postlip draining into the River Avon at Evesham, as seen in Figure 6. The river is defined as in “poor” ecological status, as classified by the Water Framework Directive, with physical modifications a key contributing factor (Environment Agency, N.D).

Since 2016, the project of NFM has been jointly delivered by the Environment Agency and Worcestershire County Council with support from the Isbourne Catchment Group. As of November 2025, 171 interventions are in place, engagement established with 14 landowners, funds of £96,165 used on interventions including leaky dams and afforestation (Isbourne Catchment Group, 2025).

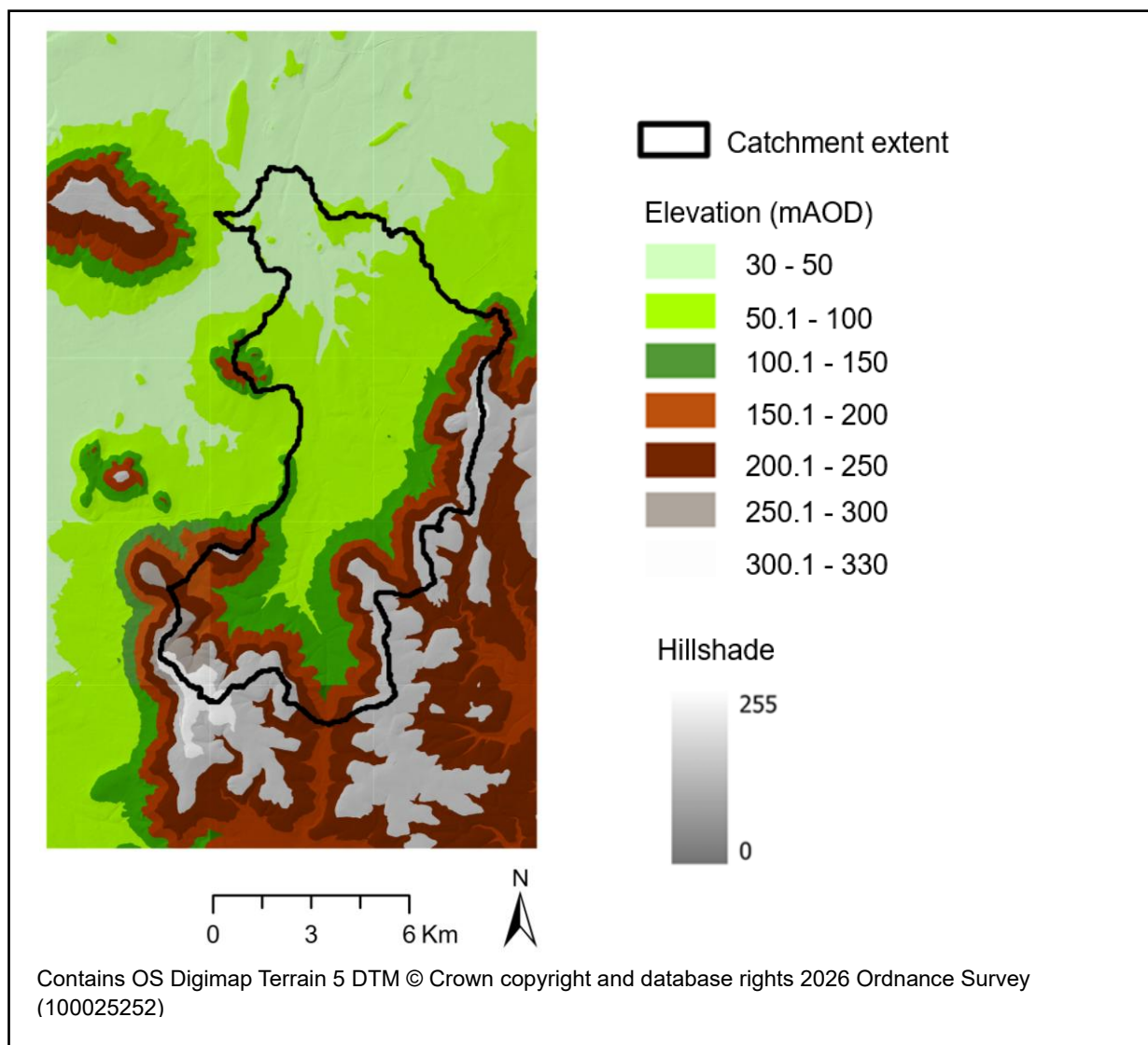


Figure 7: Elevation map of the Isbourne catchment extent and surrounding area.

Topography is varied, as seen in Figure 7, with elevation ranging from 30 to 330 mAOD, and the highest elevations located to the east and south edges of the catchment. The elevation is significant in relation to flood risk, with the upland areas and river valleys low risk, whilst the floodplains are a high risk (Clarke et al., 2016).

Land Cover

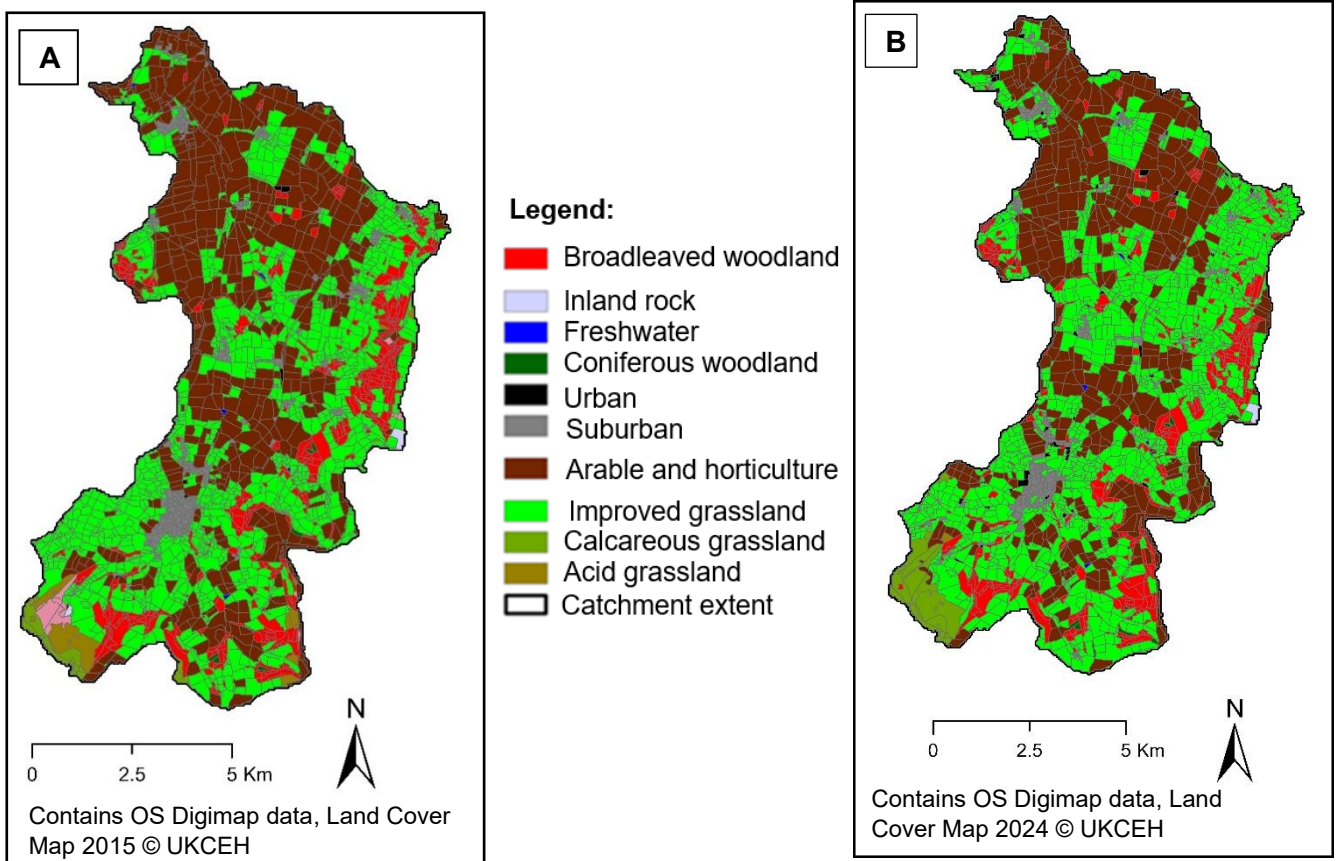


Figure 8: Land cover within the Isbourne catchment (A) 2015 (B) 2024

Table 3: Comparison of the percentage land cover types within the Isbourne catchment between 2015 and 2024.

Landcover type	2015 (%)	2024 (%)
Broadleaved woodland	11.21	9.96
Inland rock	0.16	0.16
Freshwater	0.06	0.07
Coniferous woodland	0.22	0.18
Urban	0.11	0.51
Suburban	3.42	2.82
Arable & horticulture	41.02	37.52
Improved grassland	41.42	45.51
Calcareous grassland	0.89	3.04
Acid grassland	1.5	0.05

The predominant land cover types within the Isbourne catchment are improved grassland, and arable and horticulture, accompanied by urban and sub-urban accounting for 3.3%, as shown in Figure 8. The main changes to landcover since the addition of NFM, between 2015

and 2024, is an increase to improved and calcareous grassland, and decrease to arable and horticulture, and broadleaved woodland, as indicated in Table 3.

Geology

The Isbourne catchment bedrock geology is composed of predominantly impermeable Charmouth Mudstone to the south, and in combination with Blue-Lias formation, a sequence of limestone and shale layers, to the north, forming an interbedded sequence (British Geological Survey, 2026).

The river valleys consist of loamy and clayey soils, which are free draining through chalk and limestone, groundwater has slightly impeded drainage with rapid flows to streams characterised by slow permeability and seasonally waterlogged soil (UK Soil Observatory, N.D). The floodplains also have a loamy and clayey texture with local groundwater feeding into the river (UK Soil Observatory, N.D). The Isbourne percentage of sand silt and clay is: 28, 30.59 and 41.41, dominant land cover grass and pasture with an aridity ratio of 0.71 and runoff ratio of 0.32 (Wang et al., 2023). The impermeable nature of the catchment results in a flashy response to storm events with fluvial flows from upstream (Clarke et al., 2016).

3.2: Control site

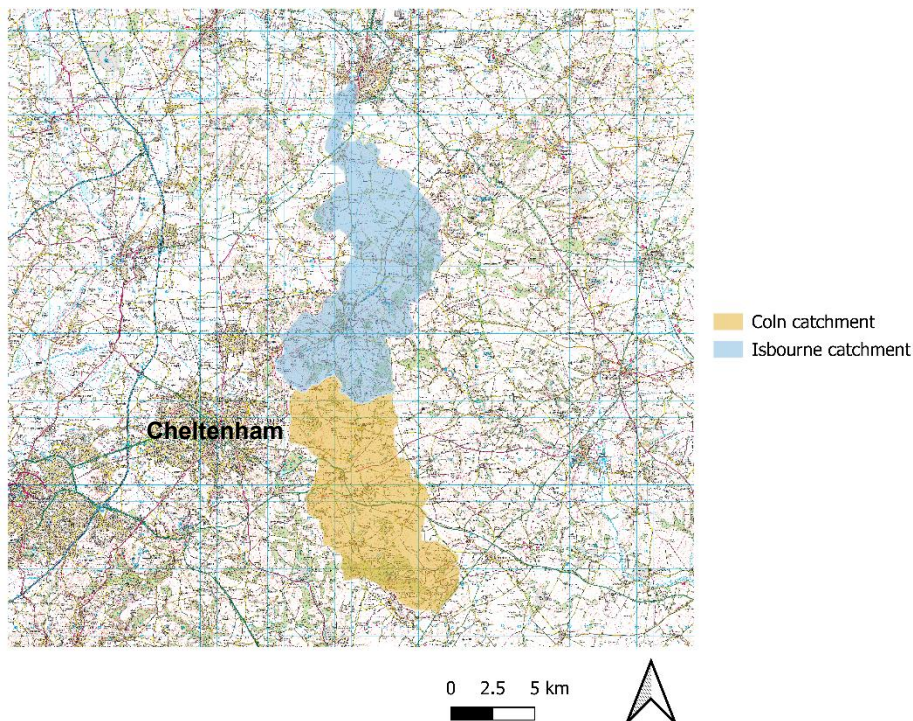


Figure 9: Map showing proximity of the control Coln catchment in comparison to the Isbourne catchment.

Table 4: Isbourne and Coln catchment summary table. Synthesised from (Environment Agency, N.D).

Water body	Extent	Water body ID	Hydromorphological designation	Area (Km ²)	Length
Isbourne	Source to confluence River Avon	GB109054039631	Not designated artificial or heavily modified	88	30.05
Coln	Source to Coln Rogers	GB106039029991	Not designated artificial or heavily modified	90	27.14

The control catchment, named the Coln catchment, is located to the south of the Isbourne catchment, as seen in Figure 9, however, the catchment is positioned within the neighbouring Thames River basin district. As displayed in Table 4, the catchments are similar in relation to catchment area and length, with the Coln catchment 2% larger in area but 9% shorter in waterbody length. The Coln catchment features no interventions including hard engineering and NFM. The decision to include a control site was made as it enables a greater confidence in the observed findings between the two catchments, if significant, it can be attributed to the addition of NFM interventions.

Table 5: Elevation summary statistics for the Isbourne and Coln catchment. Synthesised from (NRFA, N.D).

Statistics	Elevation (mAOD)	
	Isbourne Catchment	Coln Catchment
Minimum	28.8	116.3
Maximum	330.2	330.2
Average	98.9	211.5
90 percentile	256.3	161.0
10 percentile	48.2	267.5

Table 6: Landcover type statistics from 2023 comparing the Isbourne and Coln catchments. Synthesised from (NRFA, N.D).

Landcover type	Percentage cover (%)	
	Isbourne	Coln
Deciduous woodland	10.16	14.69
Evergreen woodland	0.16	1.01
Cropland	33.98	36.34
Grassland/pasture	52.1	46.03
Bare soil/rock	0.13	0.06
Inland water	0.07	0.05
Built up areas	3.41	1.82

Both catchments possess a similar elevation and landcover types, as indicated in Tables 5 and 6, with the dominant land type of grassland/pasture, succeeded by cropland and deciduous woodland. The main difference between the catchments is the hydrogeology, with the Isbourne catchment 89.9% very low permeability bedrock whilst the control site has 82.9% very high permeability bedrock (NRFA, N.D).

Table 7: Hydrological statistics summary table for the Isbourne and Coln catchment. Synthesised from (NRFA, N.D).

Variable	Catchment	
	Isbourne	Coln
Base flow	0.53	0.9
Mean flow	0.701 m ³ /s	0.597 m ³ /s
Q95	0.098 m ³ /s	0.042 m ³ /s
Q70	0.205 m ³ /s	0.15 m ³ /s
Q50	0.373 m ³ /s	0.337 m ³ /s
Q10	1.52 m ³ /s	1.52 m ³ /s
Q5	2.343 m ³ /s	1.98 m ³ /s
Record period	1972 - 2024	1990-2024

The Isbourne's flow regime is described as spring fed, with a flashy response to storms, whereas the Coln has a baseflow dominated regime (NRFA, N.D). As seen in Table 7, the Coln has a slightly higher baseflow and slightly lower mean flow. The control site is suitable for comparison due to its similar size and location therefore experiences similar climatic conditions and land use.

4. Methodology

4.1: Data acquisition

This study utilises secondary quantitative data to characterise hydrological response and flow regime through the collation of precipitation and flow data for the Isbourne and control catchments. Average gauged river flow data was sourced from the National River Flow Archive (NRFA), which is the official and largest database for rivers in the UK (NRFA, N.D).

There is one active gauge station within the Isbourne catchment located at Hinton on the Green, station ID 54036, which is positioned at the downstream section of the catchment, grid reference SP023406. This station has a 52 year record of flow data ranging between 1972 and 2024, with a record completeness of >99%. The gauge station is a crump profile weir with high flows measured by cableway until 2014, and after by rope or radio controlled boat, however, the river discharge often exceeds bank height and bypasses the gauge station, and the detection of low flows is insensitive (NRFA, N.D).

The control catchment gauge station, named Coln at Fossebridge, station ID 39109, is located in the upper section of the River Coln, grid reference SP080112. The flow data record ranged between 1990 and 2024, with a record completeness of >99%.

Precipitation data was required in order to collate precipitation intensity to individual flow events, thus the use of one gauge for rainfall can reduce certainty as it is a spatially variable process (Graham et al.,2022). However, the rainfall events were collected from the same gauging stations within each catchment so were viable for this study and are representative with the flow records. The rainfall data for both catchments spanned between January 1961 and 2023 therefore aligning with the flow data in 2024.

This is a limitation of secondary data, with the most recent data missing, with the last interval consisting of two years of data, with the winter data for 2023 only representative for December however, as this is the most recent available data is important as most reflective of the potential for established NFM.

4.2: Data filtration

Initially, the data sets were checked for missing data which were then removed and excluded from further analysis. Discharge data for the Isbourne catchment was divided into two time intervals: 2000-2015 (interval 1), 2017-2023 (interval 2) representative of before and after the addition of NFM for two areas: the Isbourne and Coln catchments.

A systematic approach to data filtration was conducted to identify the ten largest precipitation events and corresponding peak flows covering a timeframe of two days before and one week after the event to enable the pairing of data. The ten largest precipitation events were selected as larger storm events are the most advantageous for analysing catchment response and determining flood risk (Puttock et al., 2020).

Table 8: Months corresponding to seasons within the Northern Hemisphere

Season	Corresponding months
Spring	March, April, May
Summer	June, July, August
Autumn	September, October, November
Winter	December, January, February

Table 9: Decade precipitation intervals

	Intervals
1	1961-1970
2	1971-1980
3	1981-1990
4	1991-2000
5	2001-2010
6	2011-2020
7	2021-2023

Variation in precipitation intensity is expected seasonally due to regular and periodic changes in climatic conditions, influencing the distribution and magnitude of events (Hajek and Knapp, 2021). Seasonality is recognised as being the greatest influence on rainfall magnitude and return period, specifically within the western parts of the UK (Jones et al., 2012). Therefore, precipitation and flow data was subdivided into seasons per water year, as stated in Table 8. Furthermore, data was subdivided into 10 year intervals, with the exception of the final interval reflective from 2021 to 2023, shown in Table 9, and annual intervals.

4.3: Hydrograph creation

This methodology adopts an approach using hydrographs, which is typical for studies investigating the effectiveness of NFM before and after interventions, to investigate flows and stream response (Black et al., 2021). Single peaked hydrographs were adopted within this study, as described by Grayson et al. (2010), with the exclusion of multi-peaked hydrographs, in order to measure the return to baseflow conditions and LAG time to a specific event, therefore, numerous storm events were excluded from analysis.

The variables calculated from these events included peak precipitation, peak flow (defined as the highest discharge), the Lag time (determined as the time between peak precipitation),

return to baseflow and peak discharge, as reported by Puttock et al (2017). For each peak precipitation event the peak and total event precipitation, which is noted by Graham et al. (2022) as the rainfall metric with the strongest correlation to peak flow, was recorded. Discharge was calculated utilising the hydrographs created by establishing the area underneath the hydrograph multiplied by the peak flow, then divided by two, until baseflow conditions were met, as described by (Adeyi et al., 2020). These metrics were selected as NFM aims to decrease flood magnitude and slow the flow of water through the catchment; therefore, this would be reflected within these statistics.

4.4: Statistical analysis

The statistical analytical approach adopted for this study focuses on before and after the intervention of NFM within the Isbourne catchment, and in comparison, to these timeframes at the control site.

Hydrological response to storm events produces abnormally distributed data with unbalanced comparable factors, therefore, the selection of statistical analysis methodology should be suitable to interpret unbalanced datasets without excluding extremes within the data introducing bias and decreasing precision (Puttock et al., 2020). The median was calculated as the measure of central tendency for the top 10 events for peak flow, precipitation, LAG time, event discharge and return to baseflow conditions. The IQR was calculated to measure data variability using the standard formula and is representative of the upper 0.75 and lower 0.25 quartile to establish the variability of data around the median. This measure was chosen over standard deviation due to positively skewed data sets as this method focuses on 50% of the data, so is less affected by outliers within the data (Willcox, 2013).

Confidence intervals using the T test were calculated for the top 10 events to establish if the data is statistically significant and conducted at 95% confidence levels ($p < 0.05$) using the T value of 1.812. This was used for the variables including: peak discharge, Lag time, total event discharge and time to return to baseflow. The difference between Q5:Q95 intervals is a method to describe range in flow with low values and range reflective of increased lag time and less flashy response (Graham et al., 2022). Results therefore would be indicative of likely discharge rates for a set precipitation event. Also, the median and interquartile range was established for these variables to analyse the spread between the middle 50% of the data.

The mean was calculated for seasonal and annual levels to establish average precipitation. The standard deviation for seasonal precipitation means for each interval was calculated to determine the variation of average precipitation within the data. Low standard deviation suggests stable precipitation patterns – high reflects greater climatic variability and irregular rainfall events. This quantifies the degree of variability of mean seasonal precipitation within the timeframe. Running averages were calculated to smooth out short term disturbances and highlight long term trends within the long-term precipitation and flow data.

5. Results

5.1: Rainfall

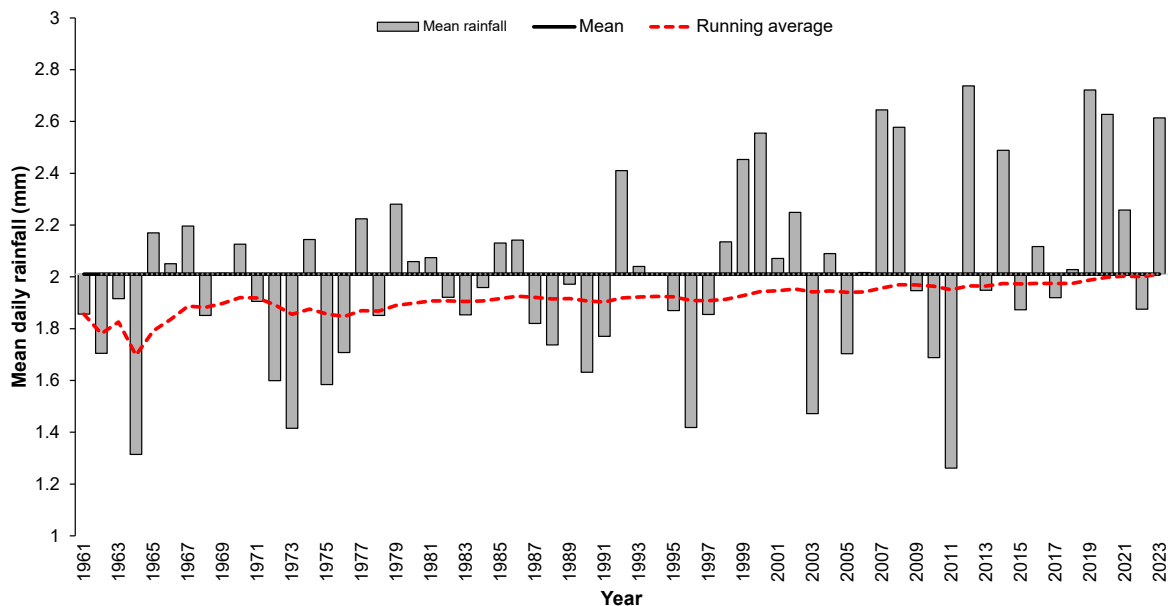


Figure 10: Bar chart showing average daily rainfall annually and the running average from the Hinton on the Green gauging station between 1961 and 2023 recorded above and below the mean.

The rainfall events were recorded between the years 1961 and 2023, with a range in average daily accumulative precipitation annually of between 1.26 and 2.73mm, and a mean daily rainfall of 2.01mm (± 0.34). Overall, rainfall fluctuates, predominantly drier before 1990 followed by wetter periods and increased variation around the mean. The driest rainfall average occurred in 2011 whilst the wettest average in 2012. The running average indicates that the UK is experiencing more rainfall.

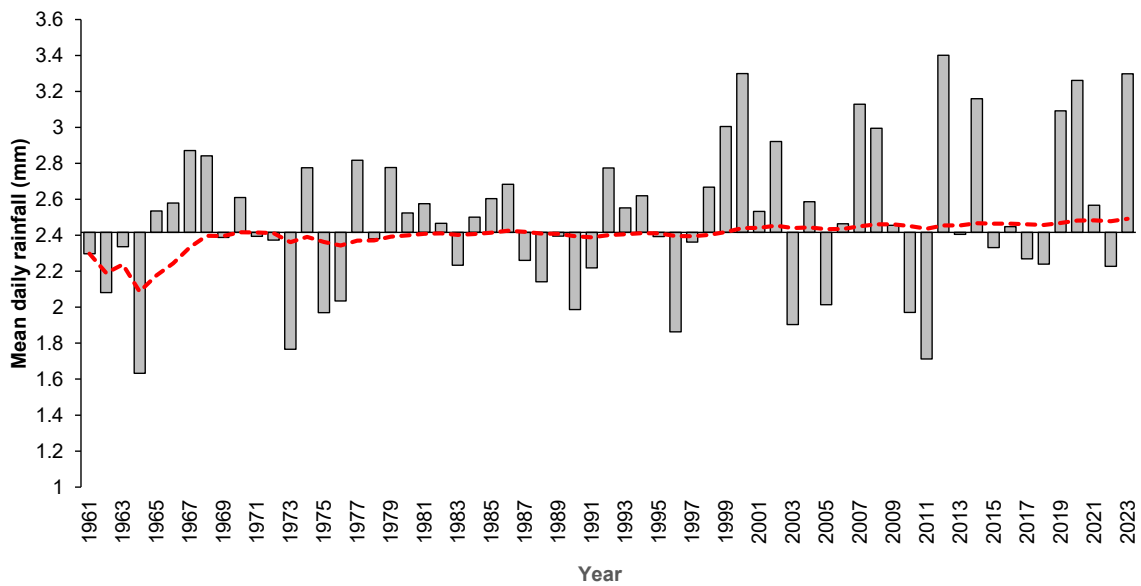


Figure 11: Coln catchment annual daily precipitation plotted against mean with running average.

Mean daily precipitation between 1961 and 2023 within the Coln catchment was 2.50mm (± 0.40) following the trend in Figure 11, and an overall increasing trend shown by the running average.

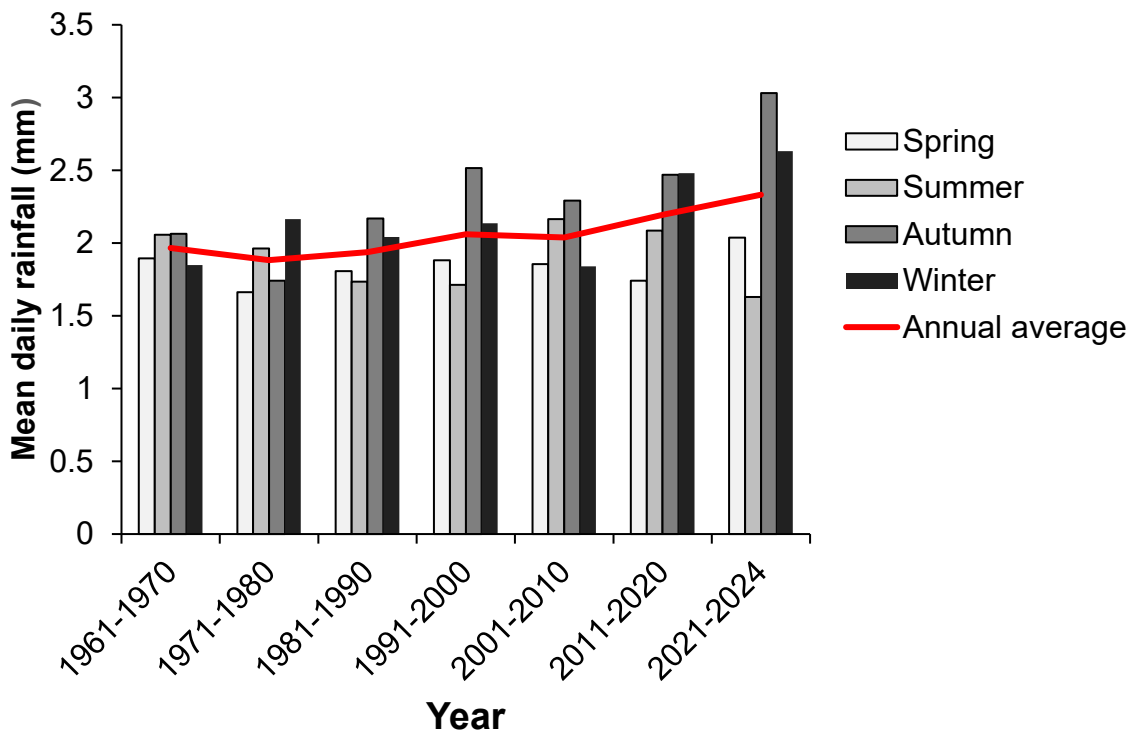


Figure 12: Mean daily precipitation subdivided into intervals and seasons plotted against annual average precipitation for the Isbourne catchment. Data source (NRFA, N.D)

As seen in Figure 12, within the timeframe investigated, the most significant increases in precipitation were within the autumn and winter months, consistently above the annual average and a percentage increase of 47 and 21%.

Table 3: Mean daily precipitation between 1961 and 2024 recorded at Hinton on the Green gauging station.

Season	Mean daily precipitation (mm)
Spring	1.84
Summer	1.91
Autumn	2.36
Winter	2.16

The wettest season was autumn followed by winter, summer and spring, as shown in in Table 10, with the difference between the highest and lowest mean precipitation equating to 21%.

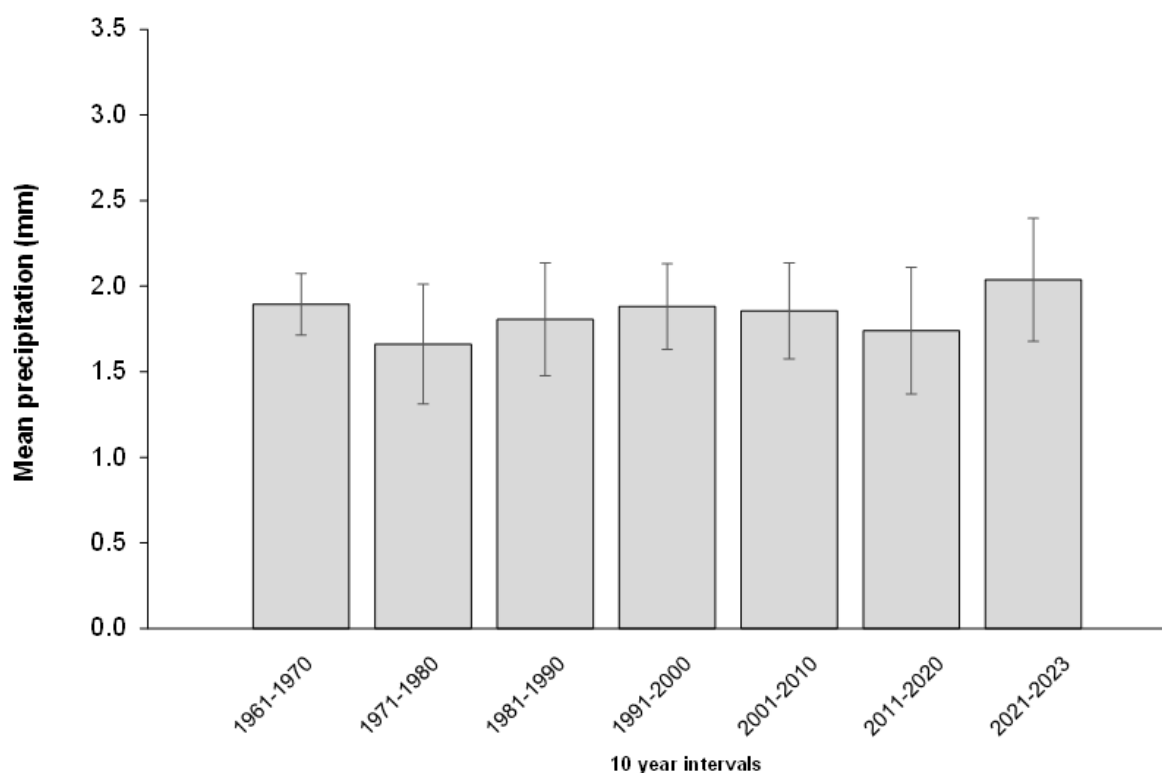


Figure 13: Spring mean precipitation recorded at the Hinton on the Green gauging station with standard deviation error bars at intervals between 1961 and 2023.

As seen in Figure 13, during spring, precipitation remained relatively consistent with a mean of 1.84 mm (± 0.12) and a R^2 value of 0.16, indicating a weak relationship suggesting little change. However, the standard deviation of mean precipitation between intervals has significantly increased, as illustrated in Figure 13, rising by 50% between 1961-1970 and 2011-2020 from ± 0.36 to ± 0.7 .

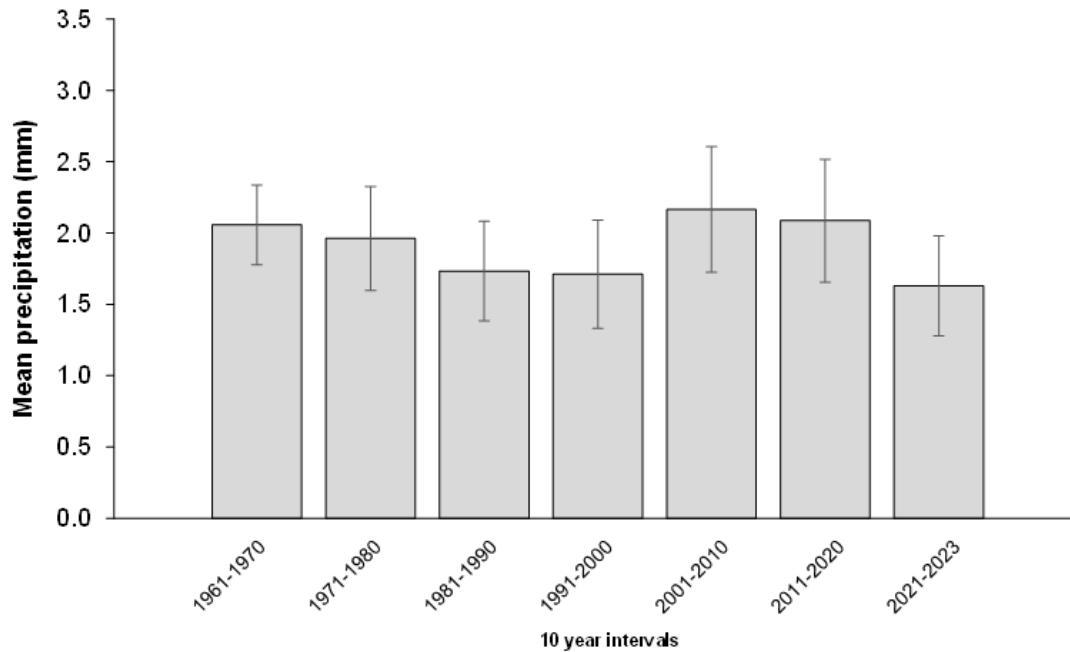


Figure 14: Summer mean precipitation recorded at the Hinton on the Green gauging station with standard deviation error bars at intervals between 1961 and 2023.

Figure 14 demonstrated summer precipitation had minimal variation with no apparent trend, indicated by a R^2 value of 0.01, but annual variation. The mean summer daily precipitation of 1.91mm (± 0.75) with an interval range of between 1.6 and 2.2mm and the greatest standard deviation was between 2001 and 2020 at ± 0.9 .

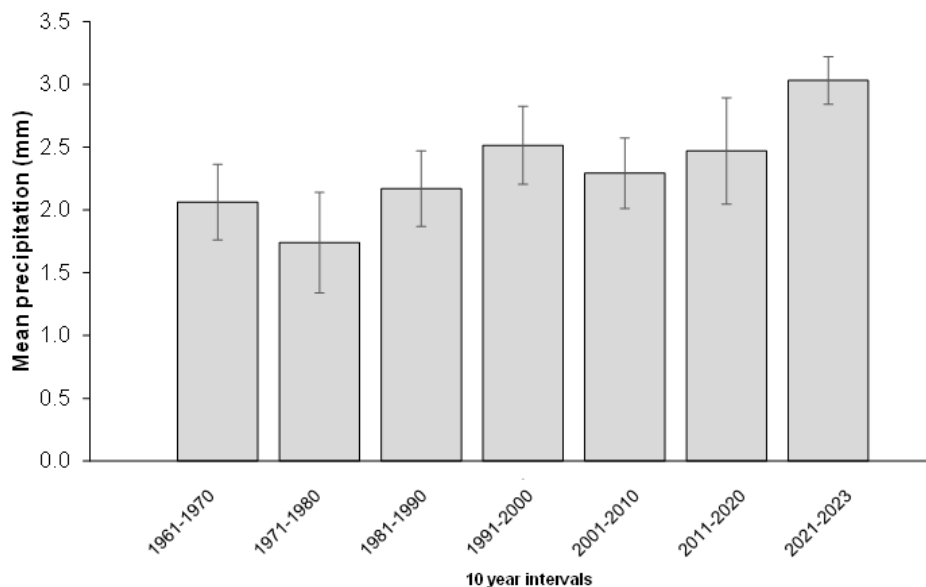


Figure 15: Autumn mean precipitation recorded at the Hinton on the Green gauging station with standard deviation error bars at intervals between 1961 and 2023.

The mean autumn precipitation, shown in Figure 15, was 2.3mm (± 0.41), with an increasing trend supported by the R^2 value of 0.73. The range in mean precipitation between intervals equalled a 56% increase from 1.7 to 3.0mm.

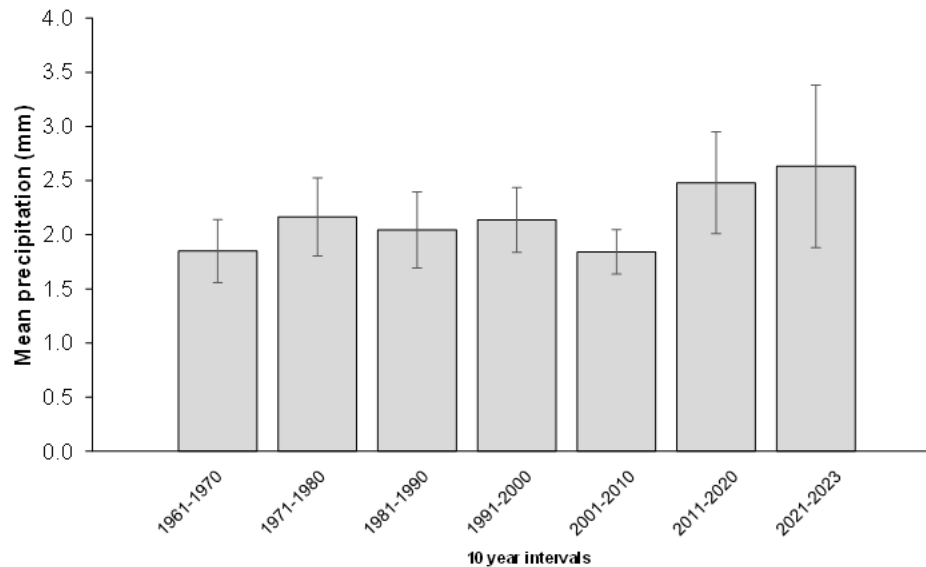


Figure 16: Winter mean precipitation recorded at the Hinton on the Green station with standard deviation error bars at intervals between 1961 and 2023.

The mean winter daily precipitation was 2.2mm (± 0.30), with a range between 1.8 and 2.6mm. As illustrated in Figure 16, there was a 38% increase in mean precipitation between 1961-1970 and 2021-2023, with the increasing trend supported by the R^2 value of 0.51. The greatest standard deviations were within the last two intervals (2011-2020 and 2021-2023) at ± 0.94 and ± 1.5 .

5.2: River flow

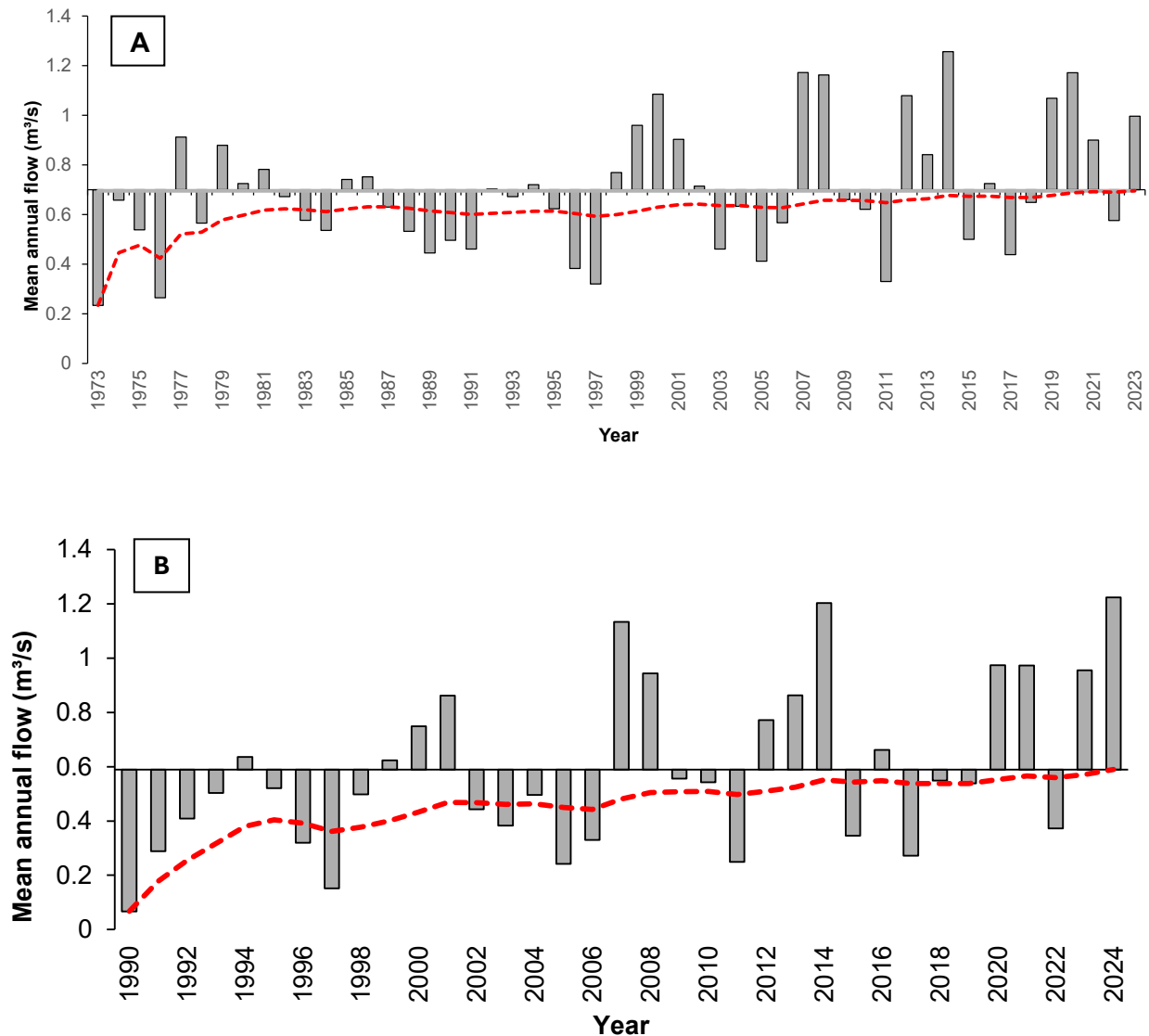


Figure 17: Mean annual flow presented above and below the mean with running average indicated by dashed line (A) the Isbourne catchment recorded at the Hinton on the Green gauge 10973-2023, (B) Coln catchment recorded at Coln at Fossebridge gauge between 1990-2024.

As seen in Figure 17, there was an upward trend in mean annual flow with a mean between 1973 and 2023 of $0.70\text{m}^3/\text{s}$ (± 0.25) but significant inter-annual variations. This trend is also observed within the control, Coln catchment with mean flow of $0.59\text{m}^3/\text{s}$ (± 0.30).

Table 114: Exceedance of flows of 2.65m and 3.60 metres in days at Hinton on the Green between 2007 and 2024.

Before NFM			After NFM		
Year	Flows greater than 2.65 m	Flows greater than 3.60 m	Year	Flows greater than 2.65 m	Flows greater than 3.60 m
2007	27	14	2016	16	11
2008	26	17	2017	8	4
2009	21	13	2018	17	6
2010	10	6	2019	41	21
2011	3	2	2020	40	25
2012	32	18	2021	25	13
2013	17	13	2022	14	10
2014	47	27	2023	26	16
2015	8	5	2024	33	22
Median	21	13	Median	25	13

As stated by GOV.UK (2025), it is estimated that water levels of the River Isbourne at Hinton on Green of above 2.65m result in the possibility of low lying land flooding, and over 3.60m there is a possibility of property flooding. Shown in Table 11, the median number of days greater than 2.65m before NFM was 21 and after 25, a 14% increase. Furthermore, flows greater than 3.60m both had the median of 13 days.

Table 12: Flow summary table of seasonal mean daily discharge and standard deviations of the Isbourne catchment: gauging station Hinton on the Green, and Coln catchment: gauging station Coln at Fossebridge.

Season	Isbourne mean discharge (m ³ /s)		Coln mean discharge (m ³ /s)	
	2007-2015	2016-2024	2007-2015	2016-2024
Spring	0.75 (± 0.30)	0.89 (±0.46)	0.81 (± 0.42)	1.03 (± 0.53)
Summer	0.52 (± 0.48)	0.27 (±0.12)	0.41 (± 0.41)	0.27 (± 0.14)
Autumn	0.69 (± 0.57)	0.82 (± 0.75)	0.40 (± 0.40)	0.29 (± 0.26)
Winter	1.46 (± 0.72)	1.50 (± 0.83)	1.32 (± 0.84)	1.18 (± 0.80)

Table 12 demonstrates that seasonal dominance in discharge is consistent between catchments with peak flow significantly highest in winter, followed by autumn, spring and summer. The difference between highest (winter) and lowest (summer) mean daily discharge within the Isbourne catchment is 1.23m³/s.

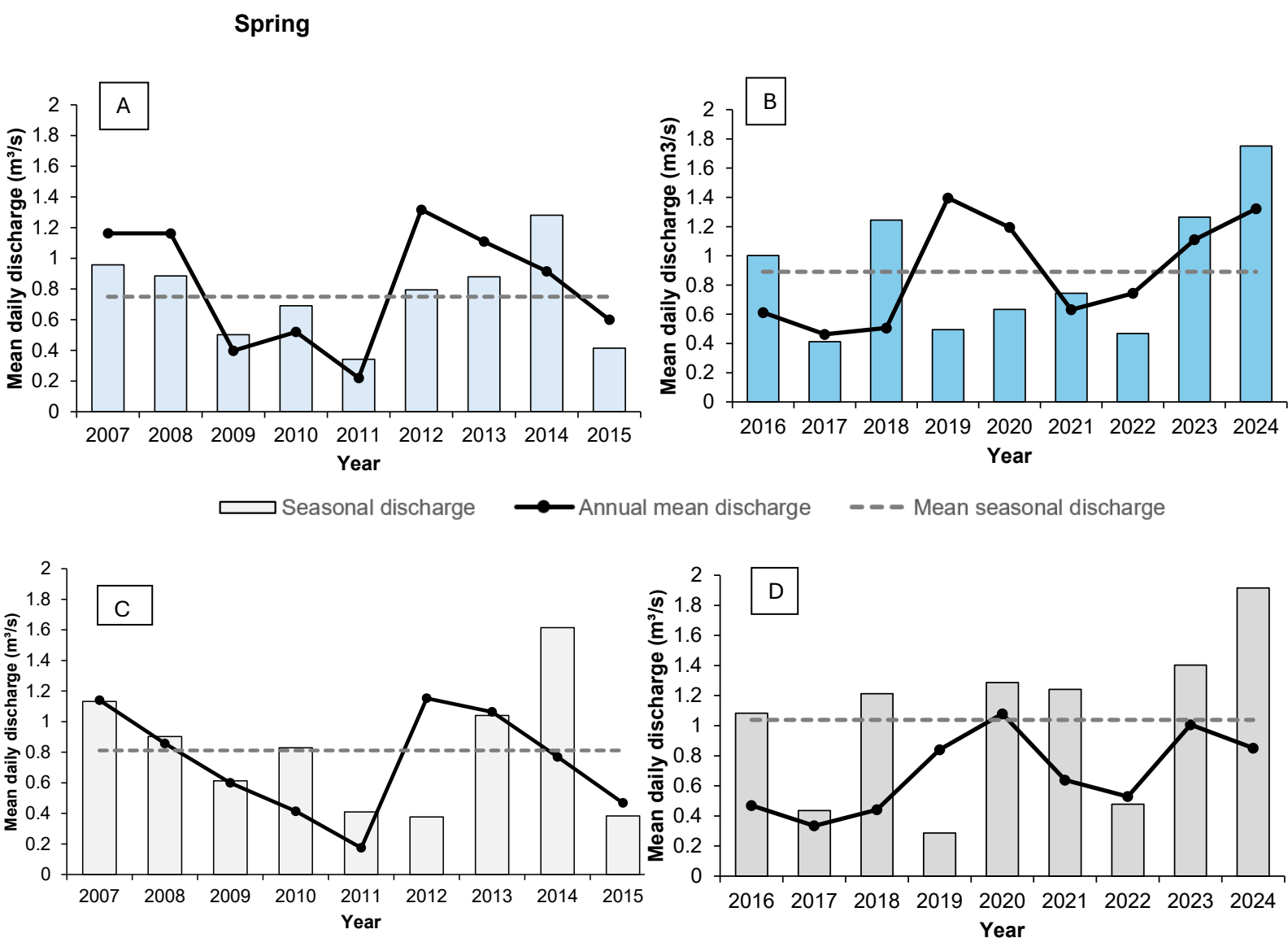


Figure 18: Spring seasonal mean daily discharge plotted against mean spring and annual discharge (A) Isbourne catchment: 2007-2015, (B) Isbourne catchment: 2016-2024, (C) Coln catchment 2007 – 2015, (D) Coln catchment 2016-2024. Data source (NRFA, N.D)

Table 12 indicates that spring mean discharge had increased between 2007 - 2015 and 2016 - 2024, with an observed increase in mean flow of 18% within the Isbourne catchment and 27% in the Coln catchment. The number of years exceeding both annual and seasonal averages during spring since 2016 has fluctuated, with three years exceeding in the Isbourne catchment: 2018, 2023 and 2024. In contrast, the Coln catchment had 6 years exceeding the seasonal and annual mean. As illustrated in Figures 18 B and D, noticeable differences in peak flow are seen between the years 2020 and 2021 with higher mean discharge in the Coln catchment of 103% and 67%.

Summer

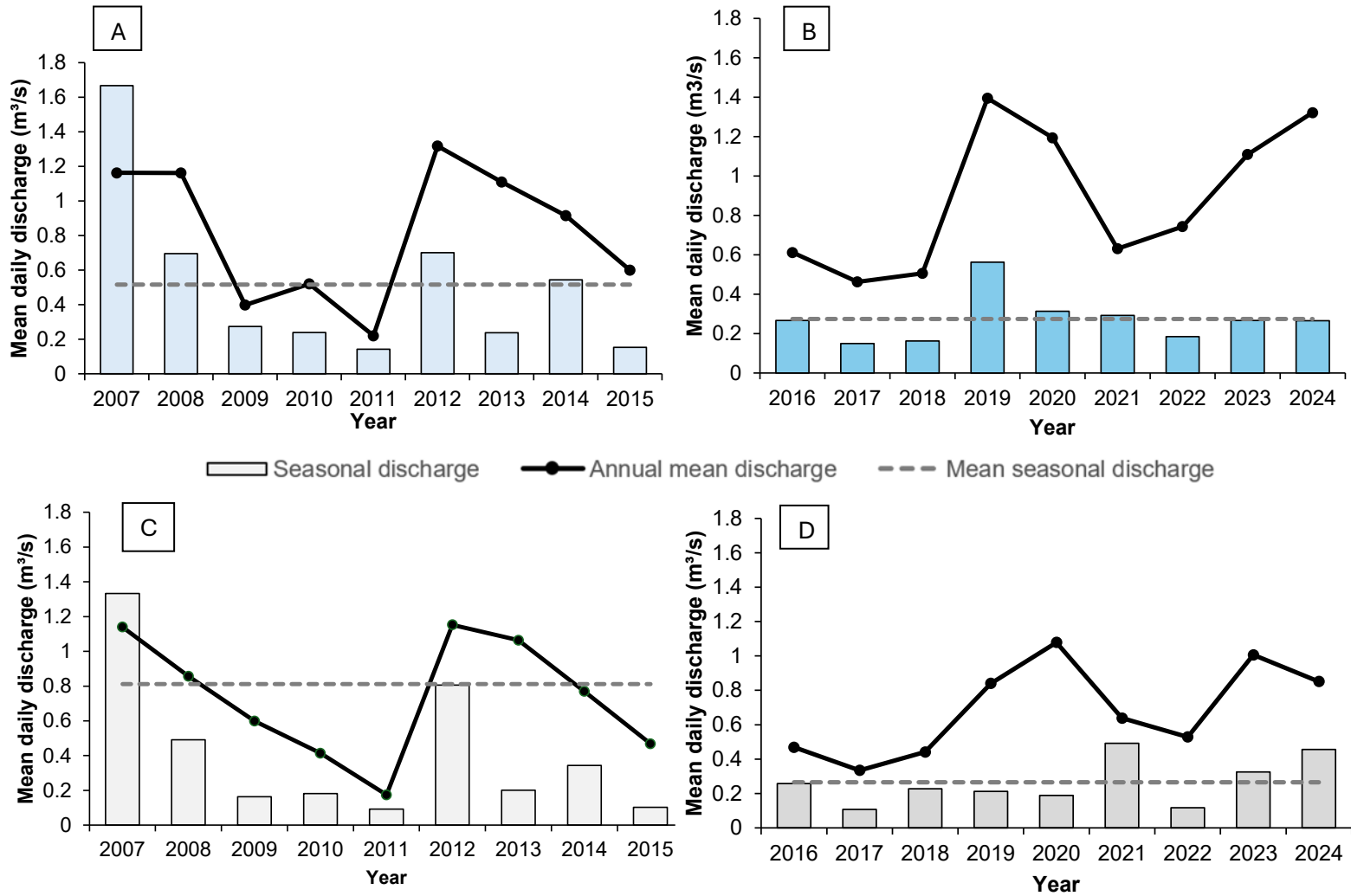


Figure 19: Summer seasonal mean daily discharge plotted against mean summer and annual discharge (A) Isbourne catchment 2007-2015, (B) Isbourne catchment 2016-2024, (C) Coln catchment 2007-2015, (D) Coln catchment 2016-2024. Data source (NRFA, N.D)

Summer mean discharge has decreased, indicated in table 11, by 48% within the Isbourne catchment and 34% within the Coln catchment. Mean discharge within the Isbourne catchment since 2016 is $0.27\text{m}^3/\text{s}$ (± 0.12), with two years exceeding this, most significantly 2019 with a mean of $0.56\text{m}^3/\text{s}$ (± 1.4). Contrastingly, between 2007 – 2015, in the year 2007 discharge was significant and above the annual average at $1.6\text{m}^3/\text{s}$, an increase of $0.4\text{m}^3/\text{s}$ in comparison to this timeframe within the Coln catchment.

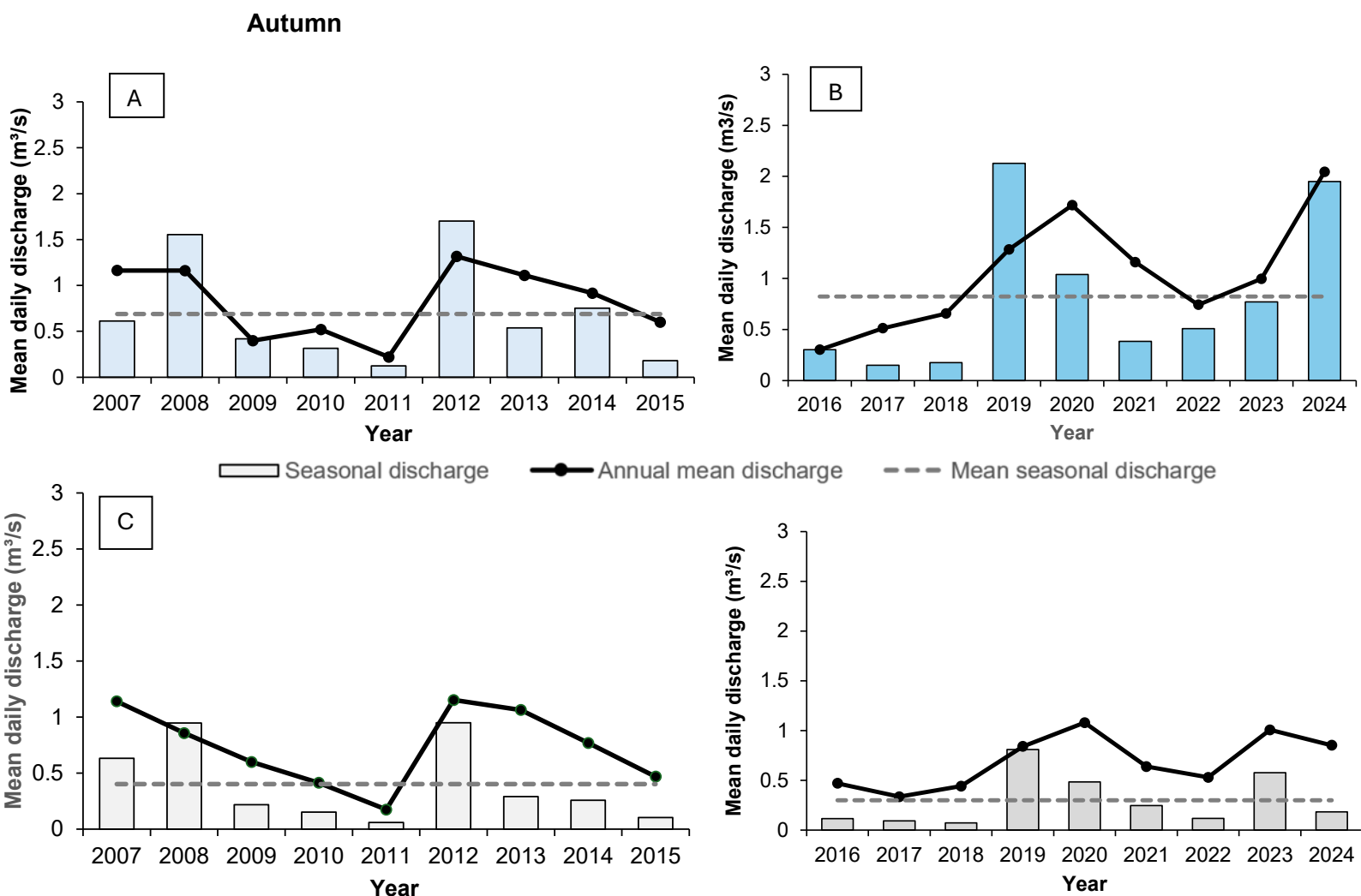


Figure 20: Autumn seasonal mean daily discharge plotted against mean autumn and annual discharge (A) Isbourne catchment 2007-2015, (B) Isbourne catchment 2016-2024, (C) Coln catchment 2007-2015, (D) Coln catchment 2016-2024. Data source (NRFA, N.D)

Autumn had significant variation around a mean of $0.82 \text{ m}^3/\text{s}$ (± 0.75). As seen in Figure 20, the wettest years of 2019 and 2024 were significantly above the mean at 2.1 and $2.0 \text{ m}^3/\text{s}$ showing great variability in this season. 2017 was the driest with a mean of $0.15 \text{ m}^3/\text{s}$. Between 2007-2015 and 2016-2024, during autumn, there was an increase in mean discharge within the Isbourne catchment by 19%, conversely, the Coln catchment experienced a 38% decrease.

Winter

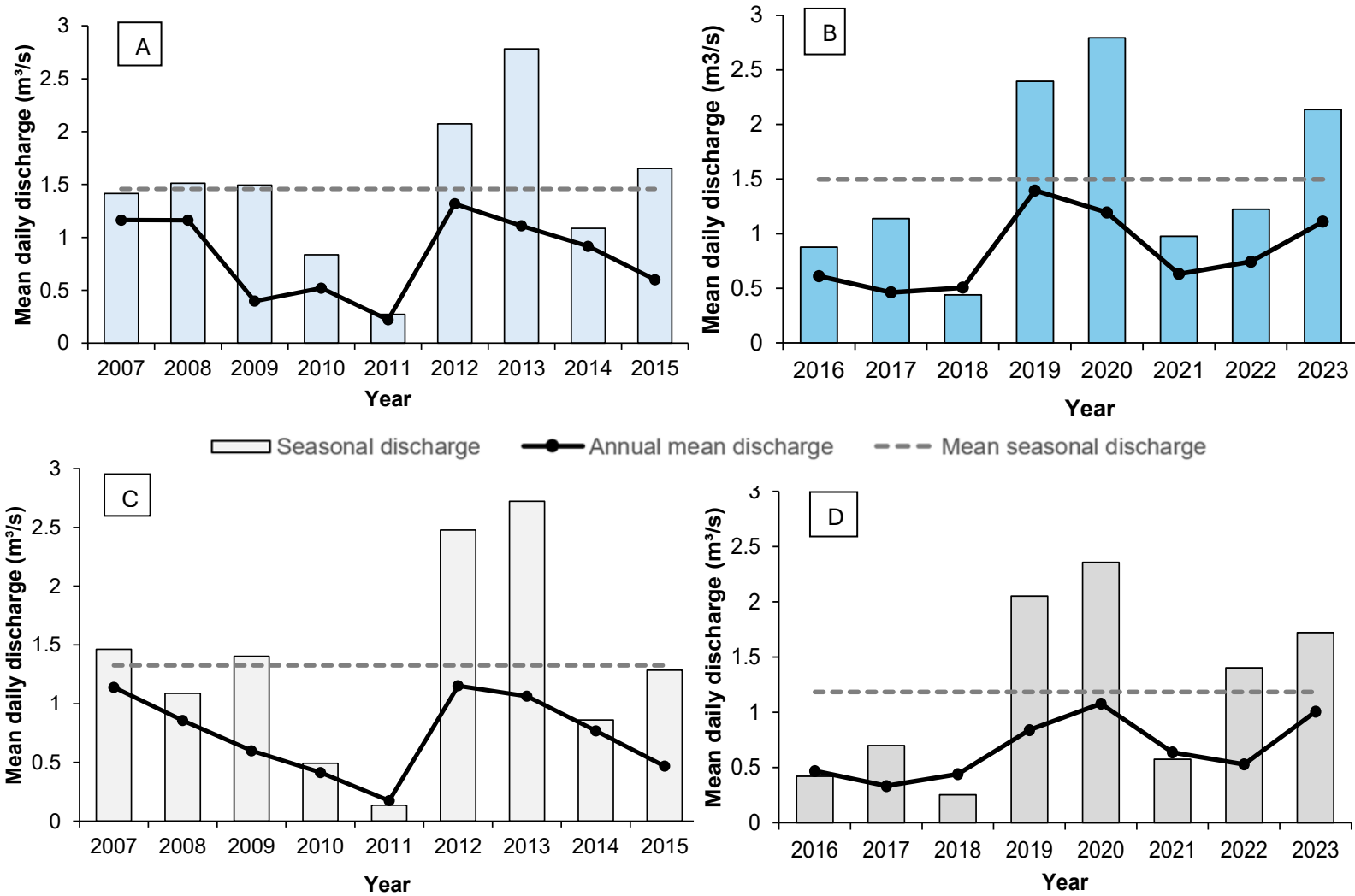


Figure 21: Winter seasonal mean daily discharge plotted against mean winter and mean annual discharge (A) Isbourne catchment 2007-2015, (B) Isbourne catchment 2016-2024, (C) Coln catchment 2007-2015, (D) Coln catchment 2016-2024. Data source (NRFA, N.D).

During winter, Figure 21 shows the highest mean discharge of 1.50m³/s and the highest recorded annual average in 2020 at 2.79m³/s. Fluctuations in discharge had three years exceeding the mean: 2019, 2020 and 2023, and low flows with the driest in 2018 at 0.44m³/s.

5.3 Hydrographs

Low intensity rainfall event

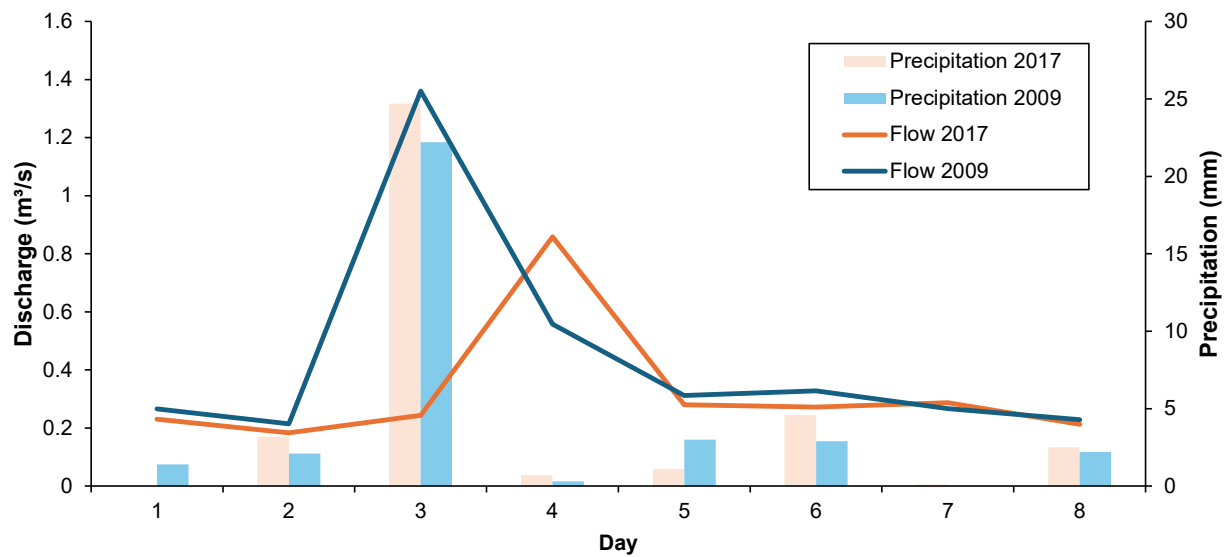


Figure 22: Hydrograph showing the peak precipitation events and subsequent discharge dated 5th June 2017 and 29th July 2009.

As illustrated in Figure 22, peak flow for the 2009 event was 1.4m³/s with a rainfall of 22.2mm, whilst in 2017, peak precipitation increased by 2.3mm with a subsequent peak flow of 0.9m³/s the following day. Total discharge decreased by 45% between the two events, 140,400m³ in 2009 and 77,760m³ in 2017.

High intensity rainfall events

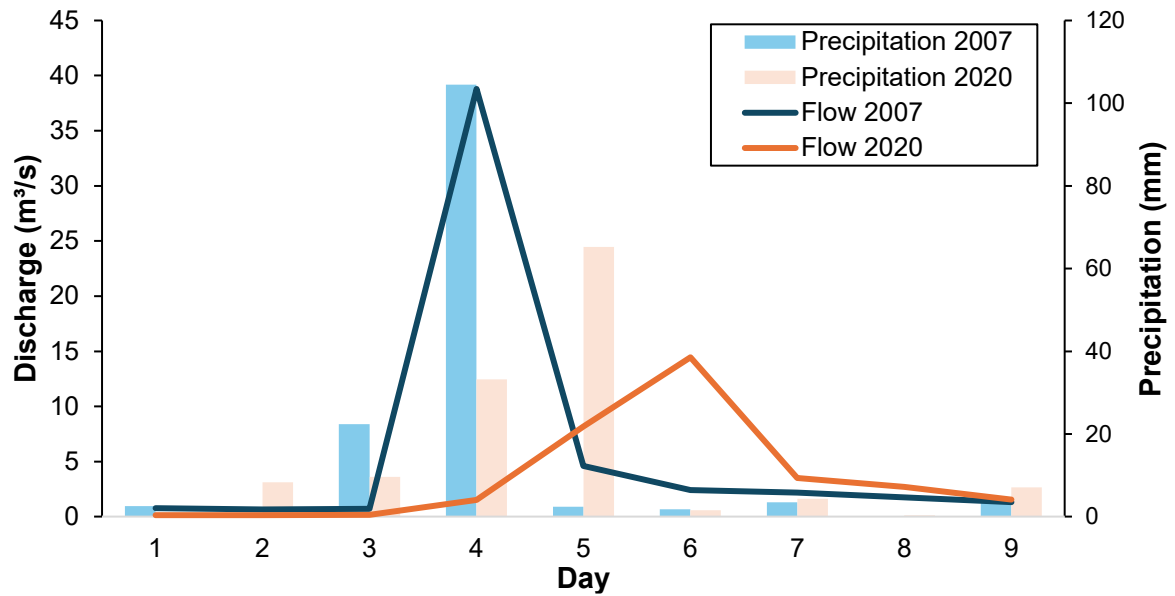


Figure 23: Hydrograph showing the largest precipitation event before NFM dated 20th July 2007 and after the intervention of NFM dated 3rd October 2020 at the Hinton on the Green gauging station.

As seen in Figure 23, the largest precipitation event before the addition of NFM was in 2007, with a peak rainfall of 104.5mm, peak flow of 38.8 m^3/s and event discharge of 3,456,864 m^3 . The largest precipitation event following NFM occurred in 2020, with peak rainfall of 65.2mm and peak flow of 14.46 m^3/s occurring 24 hours later with an event discharge of 1,482,624 m^3 . This equates to a difference in peak flow of 24.3 m^3/s and an increased Lag time of one day.

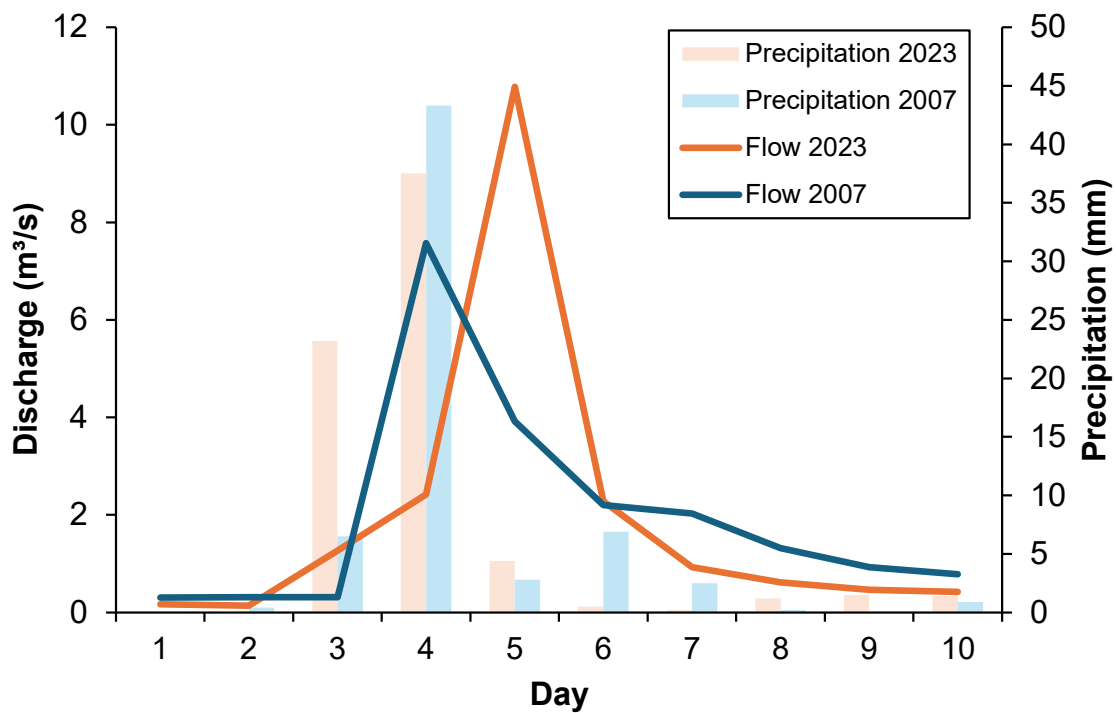


Figure 24: Hydrograph showing precipitation and average daily discharge on 18th October 2007 and 19th September 2023 at the Hinton on the Green gauging station during a significant rainfall event.

Total event precipitation leading up to peak discharge for the 2007 event equalled 49.8mm and 60.7mm in 2023. Peak flow discharge was highest for the 2023 event at $10.8\text{m}^3/\text{s}$ occurring the day after the peak precipitation, a 43% increase to the peak in 2007 which had a Lag time of 0 days. Total event discharge for 2007 was $1,075,440\text{m}^3$ whereas the 2023 event totalled $1,134,648\text{m}^3$, a 6% increase, but returned to baseflow quicker, as indicated in Figure 24.

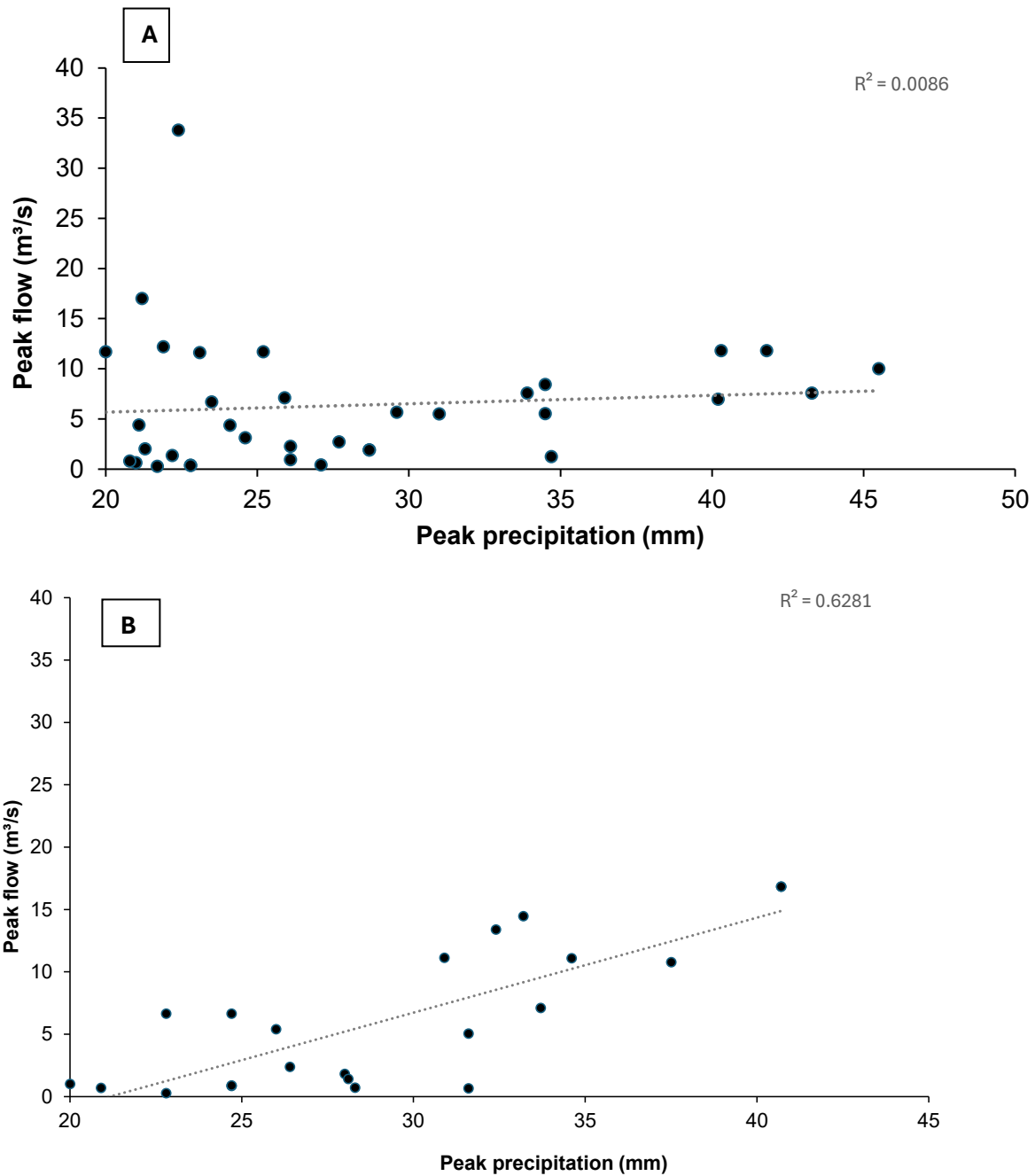


Figure 25: Peak flows for precipitation events between 20-50mm within the Isbourne catchment, Hinton on the Green Gauging station, (A) before NFM between 2000-2015, (B) after NFM between 2017-2023.

Low precipitation events (20-25mm) before NFM had a mean peak flow of $7.3\text{m}^3/\text{s}$ (± 8.7) with 5 events exceeding $10\text{m}^3/\text{s}$, whereas after NFM implementation mean peak flow reduced to $2.3\text{m}^3/\text{s}$ (± 2.9). Illustrated in figure 25, there is an increasing trend to peak flow value after NFM as indicated by the R^2 value of 0.6. For precipitation events between 25-45mm, the mean peak flow before NFM was $5.4\text{m}^3/\text{s}$ (± 3.8), whilst after NFM it increased to $7.9\text{m}^3/\text{s}$ (± 6.0) but with a higher variance.

Table 13: Summary statistics of the ten largest precipitation events between 2000 and 2015 within the Isbourne catchment.

	Peak rainfall (mm)	Peak flow (m ³ /s)	Lag time (days)	Event discharge (m ³)	Return to baseflow (days)
Before NFM	104.5	33.8	0	3,352,320	2
	45.5	10	1	864,000	2
	43.3	7.6	0	952,128	5
	41.8	11.8	1	1,529,280	3
	40.3	11.8	0	2,039,040	4
	40.2	7.0	1	602,208	2
	34.7	1.2	1	214,790	4
	34.5	10.2	0	1,662,336	5
	34.5	5.5	1	613,786	4
	33.9	2.1	0	170,208	2
Median	40.3	8.8	0.5	908,064	3.5
Interquartile range	8.3	5.5	-	1,023,971	2
Upper Interval (95%)	-	15.3	0.8	1,758,998	2.6
Lower Interval (95%)	-	4.9	0.2	641,021	4.0

Table 14: Summary statistics of the ten largest precipitation events between 2017 and 2023 within the Isbourne catchment after the addition of NFM.

	Peak rainfall (mm)	Peak flow (m ³ /s)	Lag time (days)	Event discharge (m ³)	Return to baseflow (days)
After NFM	65.2	14.5	1	23,514	5
	40.7	16.8	0	1,614,384	3
	37.5	10.8	1	2,109,024	3
	33.7	7.1	1	76,230	3
	31.6	5.1	1	57,110	2
	31.6	0.7	0	1,586,736	4
	30.9	11.1	0	2,045,606	3
	28.3	0.7	1	499,738	2
	28.1	1.4	1	2,538	2
	28	1.8	1	237,168	3
Median	31.6	6.1	1	368,453	3
Interquartile range	7.6	9.4	-	1,545,582	0.8
Upper Interval (95%)	-	10.4	1	1,339,933	2.5
Lower Interval (95%)	-	3.6	0.4	310,476	3.5

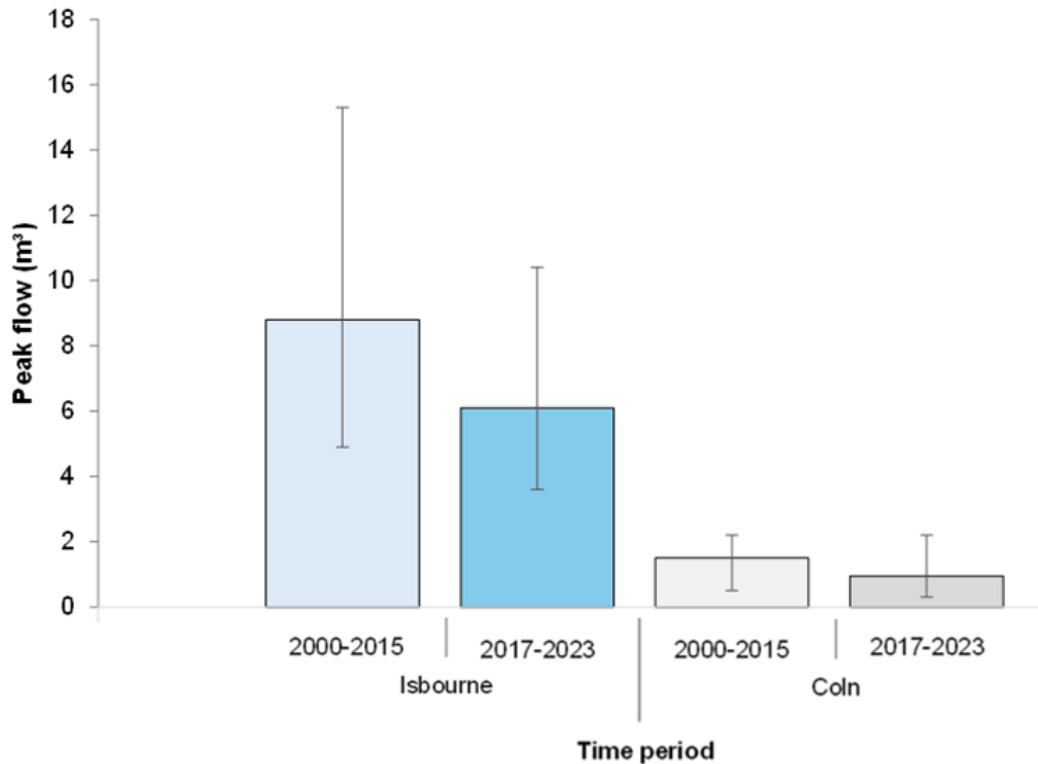


Figure 26: Peak flow for the periods between 2000 - 2015 and 2017 - 2023 representing the statistics for the corresponding peak flows and 95% confidence intervals for the ten largest precipitation events within the Isbourne and Coln catchment.

Table 14 presents the median peak rainfall for the ten largest precipitation events for the Isbourne catchment between 2000 and 2015 was 40.3mm (± 21.2) and median peak flow 8.8m³/s (± 9.1). There is a 95% confidence that for this precipitation event range peak flow will be between the intervals of 4.9 and 15.3 m³/s. Whereas since 2017 and the addition of NFM, the median peak rainfall was 31.6mm (± 11.2) and peak flow 6.1m³/s (± 6.0). There is a 95% confidence that for this rainfall event subsequent peak flows will range between 3.6 and 10.4 m³/s. The median rainfall event decreased between the two intervals to post 2017 by 21.6% and peak flow by 31%, and a subsequent smaller IQR after intervention by 3.9. As seen in Figure 26, the 95% confidence intervals were significantly higher before NFM intervention, with a range of 10.4m³/s, in comparison to 6.4m³/s after NFM intervention, which is a reduction in upper interval reduction of 48%. The difference in peak flows between the two values has a t-test value of 0.27 indicating the difference in data set is statistically significant and is unlikely to have occurred by chance.

Tables 13 and 14 demonstrate the Lag time increased since the addition, with a 95% confidence interval, where before NFM the Lag time ranged between 0.2 to 0.8 days, with half of the peak flow events occurring on the same day as the precipitation event. After the

addition of NFM, both the lower and upper confidence intervals increased to a median of 1 day ranging between 0.4 and 1 day. The median return to baseflow before NFM was 3.5 days and after NFM 3 days, with a larger IQR of 2 in comparison to 0.8.

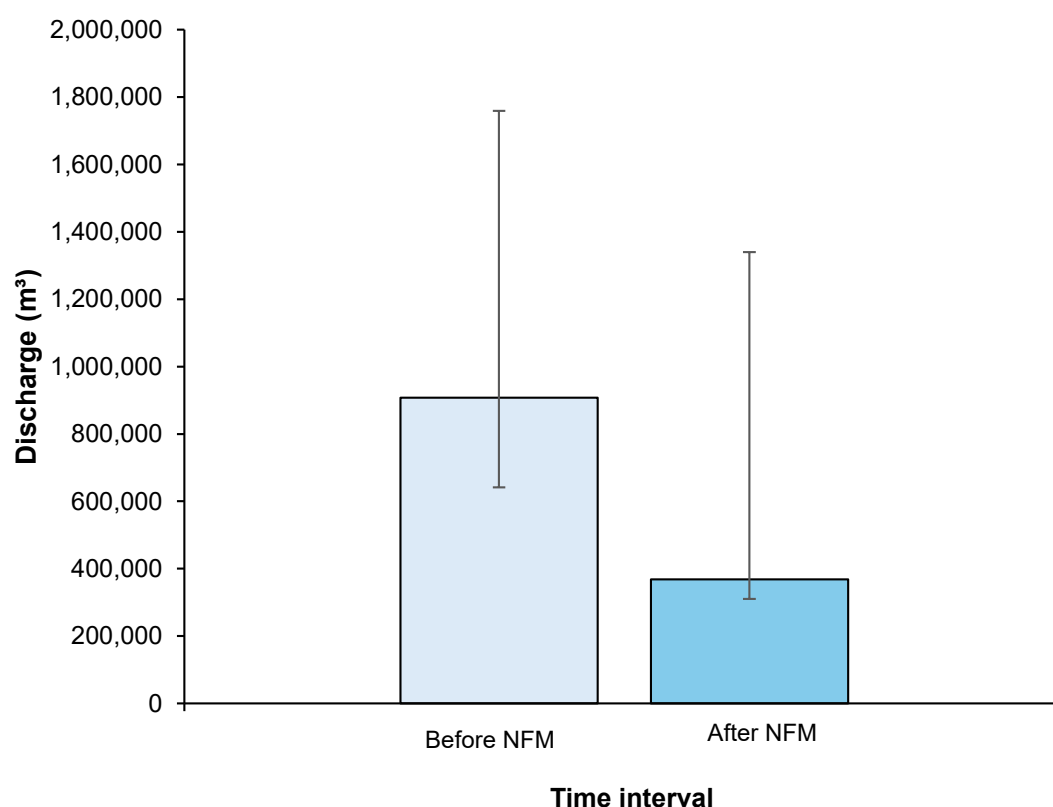


Figure 27: Total event discharge for the periods between 2000 - 2015 before NFM and 2017 - 2023 after the addition of NFM with 95% confidence intervals for the ten largest precipitation events within the Isbourne catchment.

The total event discharge, displayed in Figure 27, shows a significant decrease in median discharge after the addition of NFM from 908,064 to 368,453m³, a percentage decrease of 73.9%. However, the IQR after the addition of NFM increased by 51% in comparison to before. There is a 95% confidence that before NFM, discharge would range between 641,621 and 1,758,998m³ compared to after NFM the range is between 310,476 and 1,339,933m³, a percentage decrease in upper interval of 24% and lower interval of 52%. T-test value of 0.5 shows that results are statistically significant.

Table 15: Summary descriptions of the ten largest precipitation events between 2000 and 2015 within the Coln catchment.

	Peak rainfall (mm)	Peak flow (m ³ /s)	LAG time (days)
2000-2015	106.0	3.0	1
	64.6	2.6	0
	49.6	1.7	1
	48.7	0.7	2
	47	1.4	1
	46.5	0.1	0
	45.7	0.2	1
	43.6	0.6	1
	40.5	1.7	3
	39.1	3.4	1
Median	46.8	1.5	1
Interquartile range	1.8	1.1	-
Upper Interval (95%)	-	2.5	2.1
Lower Interval (95%)	-	0.5	0.6

Table 16: Summary descriptions of the ten largest precipitation events between 2017 and 2023 within the Coln catchment.

	Peak rainfall (mm)	Peak flow (m ³ /s)	LAG time (days)
2017-2023	66.4	0.2	0
	52.4	3.2	2
	46.4	2.5	3
	40.4	1.3	0
	39.5	0.3	1
	37.9	0.6	3
	36.7	2.3	3
	36	1.7	1
	34.3	0.4	1
	34.1	0.2	0
Median	38.7	0.95	1
Interquartile range	7.4	1.7	-
Upper Interval (95%)	-	2.2	2.4
Lower Interval (95%)	-	0.3	0.2

As seen in Table 15 and 16, the median peak rainfall within the control catchment was 46.8mm between 2000-2015 and 38.7mm between 2017 and 2023, a decrease of 20.9%. Subsequent median peak flows of these events decreased by 33%, at 1.5m³/s and 1.0m³/s, although, the 95% intervals overlap, with a percentage decrease between upper intervals of 12% and lower intervals of 40% equating to 0.3m³/s. Between both intervals the lag time has remained constant with a median in both of 1 day.

6. Discussion

6.1: Rainfall

An overall general increasing trend to mean annual precipitation was identified between 1961 and 2023 in the Isbourne and control catchments of approximately 11%, with significant annual variation. These findings align with previous research by Kendon et al. (2024) who report a 10% increase in precipitation within the UK, between 1961-1990 and 2014-2023. There is strong confidence that anthropogenically induced global warming will intensify the hydrological system at both a local to global scale, with predictions of enhanced mid-latitude precipitation intensity and increased frequency of extreme rainfall events (Osborn et al., 2000). Variations to annual rainfall is expected during consecutive years and over decades, however, the holding capacity of water vapour within the atmosphere increases by 7-8% for every 1°C increase in temperature, therefore influencing the volume, intensity, frequency and type of precipitation (Trenberth, 2005). Furthermore, critical observations in precipitation trends indicate the intensification of short-duration rainfall at a greater extent than that expected atmospheric moisture capacity, increasing the risks from flash flooding (Fowler et al., 2021).

However, the relationship between increases to precipitation and flood risk is non-linear, with external climatic phenomena driving annual variation (Islam, 2025). El Niño (warm phases) and La Niña (cold periods) occur every 2-7 years for approximately 8-12 months, leading to changes in weather patterns globally and can cause droughts and influence the intensity and frequency of flood events, also having a direct effect within the UK of colder winters (Islam, 2025). Additionally, annular and dipolar modes have a significant effect on UK climate, with a positive North Atlantic oscillation index resulting in stronger winds and wetter winter conditions (UK Government, N.D).

Within the Isbourne catchment, the highest mean precipitation is experienced in the seasons of autumn and winter, with increases of 47% and 42% between the intervals of 1961-1970

and 2021-2024 respectively. The UK experiences heavier winter extremes in the west, with the greatest variability to daily extremes in the summer for the west (Herrera et al., 2023). Osborn et al (2000) reports a change in the distribution of daily precipitation between 1961 and 1995 with increasing average precipitation in winter and the heaviest events, but a decrease is seen in summer, with notable complexities in spring and autumn depending on location within the United Kingdom. Observed patterns include increases to spring and autumn extreme rainfall, increases in seasonal maxima found in spring, autumn and winter suggesting wetter conditions. 2023 was the wettest year since 2012 and the 7th wettest year since 1976 therefore it is an important measure for assessing the effect of NFM (Kendon et al., 2024).

However, mean seasonal and annual rainfall statistics are not necessarily reflective of the years with extreme events, as seen in the flash flood in 2007, with a lower mean. Convective storms are a key threat during summer in the UK, resulting in increased intensity and frequency of rainfall events across small timescales, whilst with greater temperatures and evaporation in comparison to other seasons affecting soil moisture and infiltration at the onset of the events there is increasing flood risk, specifically with the concurrence of saturated catchments (Ledingham et al., 2019). Although summer mean precipitation is the second lowest seasonally, this season experiences the largest variability with a standard variation of ± 0.75 . This is significant as there is a threat of flooding, if high intensity rainfall is associated with prolonged dry conditions (Jones et al., 2012).

6.2 Flow

Mean annual river flow between 1973 and 2023 indicates an overall increasing trend with the greatest flows observed since 1979. Clarke et al. (2016) state the increase in flow between the 1970s and 2010 is a result of changes within catchment conditions specifically: land-use and agricultural changes, greater soil compaction and surface runoff increasing peak flows and not resulting from the increase in rainfall. Seasonally, the highest mean discharges are within winter, subsequently spring, autumn and lowest summer which has the greatest variation.

One of the key findings is the indication that peak flow has decreased since the implementation of NFM, specifically within low to medium rainfall events (20-35mm). Upstream attenuation and increases in catchment storage is significant in relation to the reduction in peak flows, with small decreases significant in reducing the risk of flooding (Asselman et al., 2022).

Analysis of the top ten precipitation events before and after the intervention of NFM has indicated changes to attenuation and hydrological response within the Isbourne catchment. Overall, median peak flow decreased by 31%, which is statistically significant, however, the median rainfall event after the addition of NFM saw a reduction of 22%. Comparatively, within the control catchment, the median peak flow decreased by 33%, however the 95% confidence intervals overlap suggesting no significant statistical significance between these intervals, notably also with a decrease in median peak rainfall of 20.9%. Therefore, the impacts observed within the Isbourne catchment are reflective of the NFM not annual climatic variation. Despite this, the comparison of similar magnitude events shows varying implications regarding peak flow, with observed increases and decreases after the addition of NFM for comparable rainfall events in terms of seasonality and intensity. This suggests the exceedance of storage capabilities and the ability to slow the flow in specific conditions. Kay et al. (2019) state low confidence in NFM to offset and effectively manage the consequences of predicted medium and higher emissions scenarios.

6.3 Hydrograph characteristics

A key observation since the implementation of NFM is the increase in Lag time. Factors shaping Lag time include preceding conditions to the event, the quantity of rainfall, land-use, storage and geomorphology (Black et al., 2021). For the ten highest precipitation events, the median Lag time increased from 0.5 to 1 day after the implementation of NFM, with 70% of events experiencing a delay in peak flow. In contrast, the control catchment for the same timeframe remained consistent with a median of 1 day. This is significant as it implies the changes to Lag time are consequential of the NFM, whose purpose is to slow the flow and increase storage, indicating success. The increase in Lag time of approximately one day is significant in comparison to results reported by Black et al. (2021) who stated scarce evidence of increase to LAG time as a result of NFM with evidence accounting to a 30 minute delay. Black et al (2021) suggest greater increases to Lag time, particularly in relation to the addition of leaky dams, with the system not becoming overwhelmed at higher flow events due to expandable field storage, however, the maximum threshold before the system is overwhelmed is not quantified.

As stated by the NRFA (N.D), the Isbourne catchment is characterised by a flashy response to storm events, so the expected hydrograph for this catchment would be a steep rising and falling limb. There is an evident change to hydrograph shape after the implementation of NFM, specifically a more gradual rising limb. This provides insight into changes within the hydrological processes within the catchment since the introduction of NFM suggestive of

more infiltration and temporary water storage rather than rapid surface runoff associated with a flashy hydrograph. In contrast, there is evidence of a slight increase to the steepness of the recession limb, with a decrease in median of 0.5 days, after the intervention of NFM, for the top 10 rainfall events. However, for the largest precipitation event (>65mm) after the addition of NFM, there was a much more gradual return period to baseflow of 5 days. This suggests a prolonged release of water throughout the catchment with greater infiltration and storage.

There is evidence that the application of NFM has reduced the total event discharge experienced. This is observed in comparison between low rainfall events and the top ten precipitation events, with a decrease in median discharge of 59%. However, the IQR and range between 95% confidence intervals increased after the introduction of NFM, with a decrease in peak rainfall. This suggests the event size or preceding conditions led to saturation within certain events exceeding the capabilities/capacity of the NFM. There is evidence that during days of consecutive rainfall, the discharge has decreased. Most noticeably, the highest rainfall event (65.2mm) since the addition of NFM resulted in an event discharge of 25,514m³, considerably less than that for lower rainfall events before NFM. Nevertheless, only two significant intense daily rainfall events (greater than 40mm), significant as flash flooding highest risk, have been experienced within the timeframe since the introduction of NFM, limiting the ability to reliably conclude the effectiveness of NFM during extreme events and limits.

6.4 Study limitations

The limitation to this study is the short baseline monitoring duration equating to 8 years, recorded from one gauging station. However, as stated by Black et al. (2021), although it is expected to lack multiple extreme events in these monitoring periods due to timescales, there is a significant benefit from the study using empirical data and it is not reliant on modelling assumptions. This study is also of a greater catchment magnitude to most studies at an area of <20km so there is limited comparative data. The lack of extreme precipitation events since the implementation of NFM means there is insufficient data to state with confidence that the currently installed NFM is adequate to cope with these events. Furthermore, the flow and precipitation data is recorded daily means, therefore it is an estimate in regard to peak flow and Lag time.

6.5 Future research considerations

To further enhance this study, it would be recommended to install further gauging stations at various locations along the river to enable the collection of greater flow measurements, and to establish the direct quantitative impacts of specific NFM features. Flow data is limited with the most recent data of September 2024, therefore data is missing, a future study including this and for the next 5 years would be beneficial for data reliability and understanding extreme weather events on NFM capabilities. Also, higher resolution data would be advantageous with hourly measurements in order to curate hydrographs with higher precision regarding true peak flow and LAG times quantified by hours rather than days. This study processes methods to analyse general impacts of NFM within differing catchments of different scales and characteristics.

7. Conclusion

This study aimed to assess the effectiveness of NFM within the Isbourne catchment in regard to flood risk reduction. From quantitative analysis, it can be concluded that the addition of NFM has had a significant impact on hydrological response to precipitation events specifically event discharge and Lag time.

Rainfall within the catchment has increased since 1960, with further predicted change. Nevertheless, flood risk within the Isbourne catchment is not necessarily increasing as a direct result of this, but it is the capability of the NFM to cope with the increase in extreme, short term rainfall events.

There is evidence that peak flow has decreased by a statistically significant amount since the addition of NFM. However, there is significant variation, and effectiveness is dependent on the preceding conditions, with evidence of overloading of the system during intervals of extreme precipitation and consecutive days of rainfall. The highest precipitation events observed after the implementation of NFM were lower than that before NFM and significant below that of the 2007 flash flood. Overall, the Lag time has increased from occurring on the day of the peak rainfall event to one day after. Total event discharge decreased overall, with direct comparison between events of a similar magnitude, and a statistically significant decrease in the top ten rainfall events. Conversely, the interquartile range and 95% confidence intervals for total discharge had substantially increased in spread. This suggests a decrease in the speed of water movement within the catchment, but the system exceeds capacity in specific high rainfall events. The control catchment between the intervals of 2000-2015 and 2017-2023, shows minor changes to peak flow and Lag time which are not

statistically significant. Therefore, the observed findings in the Isbourne catchment are a direct result of the NFM not external variation in atmospheric conditions. The overall shape change in hydrographs suggests a less flashy response with a more gradual rising limb, however, the falling limb has remained consistent to that observed before the addition of NFM.

Overall, the data implies significant reductions to flood risk within small to medium precipitation events. This study further contributes to the quantitative studies for methodology to assess the effectiveness of NFM in different catchments. However, as in agreement with past research, there is evidence that NFM measures may be insufficient under high intensity rainfall events.

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9. Appendices

9.1 Meta data tables

Table 1. Original datasets:

Dataset / file name	Description	Where it is used	Raster or Vector	File type	Data source	Organisation	Date/Year	Original projection
Isbourne gauged flow	Mean gauged daily flow (m ³ /s) recorded at Hinton on the Green station between 01/03/1972 and 30/09/2024.	Fig. 2,17,18,19,20, 21,22,23,24,25. Tables 11, 13,14.	N/A	.xlsx	<u>NRFA station mean flow data for 54036 - Isbourne at Hinton on the Green</u>	National River Flow Archive	24 October 2025	N/A
Isbourne rainfall	Mean accumulative daily rainfall (mm) recorded at Hinton on the Green Station between 01/01/1961 and 31/12/2023.	Fig. 2,10,12,13,14, 15,16, 22,23,24. Tables 13,14.	N/A	.xlsx	<u>NRFA station mean flow data for 54036 - Isbourne at Hinton on the Green</u>	National River Flow Archive	24 October 2025	N/A
Coln gauged flow	Mean gauged daily flow (m ³ /s) recorded at Coln at Fossebridge station between 01/10/1990 and 30/09/2024.	Fig. 17,18,19,20,21, 28. Tables 15, 16.	N/A	.xlsx	<u>NRFA station mean flow data for 39109 - Coln at Fossebridge</u>	National River Flow Archive	29 January 2026	N/A
Coln rainfall	Mean accumulative daily rainfall (mm) recorded at Coln at Fossebridge between 01/01/1961 and 31/12/2023.	Fig. 11. Tables 15, 16.	N/A	.xlsx	<u>NRFA station mean flow data for 39109 - Coln at Fossebridge</u>	National River Flow Archive	29 January 2026	N/A
Isbourne land cover 2015	Land cover map of Great Britain for the year 2015 scale	Fig.8	Vector	File Geodatabase	<u>Digimap</u>	Edina	26 May 2017	OSGB36

	1:25,000 subdivided into 21 broad-habitat based classes.							
Isbourne land cover 2024	Land cover map of Great Britain for the year 2015 scale 1:25,000 subdivided into 21 broad-habitat based classes.	Fig.8	Vector	File Geodatabase	Digimap	Edina	11 August 2025	OSGB36
Terrain 5 DTM	OS Terrain 5 image scale 1:10,000	Fig. 7	Raster	.asc	Digimap	Edina	1 July 2025	OSGB36
Isbourne extent	Extent of the Isbourne Catchment	Fig. 1, 7, 8, 9	Vector	.shp	Isbourne - source to conf R Avon Catchment Data Explorer Catchment Data Explorer	Environment Agency		OSGB36
Isbourne waterbody	Waterbodies within the Isbourne catchment.	Fig. 6	Vector	.shp	Isbourne - source to conf R Avon Catchment Data Explorer Catchment Data Explorer	National River Flow Archive	N.D	OSGB36
England river basin districts	Extent of the ten river districts within England.	Fig 1	Vector	.shp	England Catchment Data Explorer	Environment Agency	2026	OSGB36
Severn River districts	Extent of the Severn River district including the 11 management catchments	Fig 1	Vector	.shp	Severn River Basin District Catchment Data Explorer	Environment Agency	2026	OSGB36
Coln extent	Extent of the Coln catchment	Fig. 9	Vector	.shp	NRFA station catchment information for 39109 - Coln at Fossebridge	National River Flow Archive	N.D	OSGB36

Vector map local	Detailed urban map showing woodland and urban extent.	Fig. 6	Vector	.shp	<u>OS</u>	Edina	2025	OSGB36
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Table 2. Generated Layers:

File name	Description / Creation process	Where it is used	Raster or Vector	File type	Projection	Data set used to create this file (if applicable)
DTM Merge	Set symbology classified defined intervals of 50 mAOD.	Fig. 7	Raster	.tif	OSGB36	Terrain 5 DTM
Hill shade	Application of hill shade tool to DTM with a set transparency of 45%	Fig. 7	Raster	.tif	OSGB36	DTM Merge
Landcover15 clip	Isbourne land cover 2015 clipped to the extent of the Isbourne catchment.	Fig. 8	Vector	.shp	OSGB36	Isbourne extent, Isbourne land cover 2015
Landcover24 clip	Isbourne land cover 2024 clipped to the extent of the Isbourne catchment.	Fig. 8	Vector	.shp	OSGB36	Isbourne extent, Isbourne land cover 2024