To what extent can leaky dams alleviate flooding under current and future climate conditions? A case study of South Moor, County Durham.

A 3D scan of a leaky dam in Stanley Burn, South Moor captured using Scaniverse

Abstract

While existing research has demonstrated the potential of leaky dams to slow flow and increase storage, there is still a need to constrain how their effectiveness varies from reach-level processes to catchment-scale flood response under both present and future climate change conditions. This study integrates field-based measurements with modelling using Flood Modeller Pro to evaluate the influence of leaky dams on channel morphology, flow characteristics and flood dynamics within South Moor, County Durham.

Field measurements collected upstream and downstream of ten leaky dams show significant but spatially variable changes in channel morphology. Kruksal-Wallis results indicate that dam type and proximity exert a stronger control on morphological response than dam size, highlighting the importance of structural configuration and network effects. Velocity decreases downstream across all leaky dams ranging between -0.009 and -0.043 m/s, while discharge reductions remain smaller in comparison (-0.002 to -0.011 m^3/s), indicating limited attenuation under non-event conditions. These findings were used to inform subsequent modelling across a range of return periods (0.5%-50% AEP events) under baseline and UKCP18 future climate scenarios across lower, central and upper uncertainty bounds.

A calibrated and validated Flood Modeller Pro model achieved high performance (accuracy: 96% and precision: 90%), supporting its application for scenario testing. At the reach scale, leaky dams increase maximum flood depth and extent, while at the catchment scale they reduce downstream flood extent by up to 7,468m^2 and delay flood peak timing by ~4.8 hours under baseline conditions. These effects weaken with event magnitude. Under future climate scenarios, flood depth and extent increase most strongly in intermediate events (~3.33% AEP), with maximum depth increasing by ~15% and extent by ~18% by 2060-2080. However, attenuation effects diminish with increasing event magnitude, with flood extent reductions falling to <5% and peak delays to <1 hour in higher magnitude (1-0.5% AEP) events, indicating a threshold transition from storage- to conveyance-dominated behaviour as capacity is exceeded. Scenario testing shows that NFM measures are most effective under current and near-future conditions, providing the highest cost-benefit performance (0.51), whereas hard-engineered interventions become increasingly effective under larger and future events. Hybrid approaches achieve the greatest overall damage reduction but do not maximise cost efficiency.Therefore, this study recommends a phased, catchment-scale flood management approach rather than reliance on leaky dams as a stand-alone solution.

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List of Abbreviations

1D One-dimensional

2D Two-dimensional

AEP Annual Exceedance Probability

AR5 / AR6 Assessment Report 5 / 6

CBA Cost-benefit analysis

CBR Cost-benefit ratio

CC Climate change

CEDA Centre for Environmental Data Analysis

CSA Cross-sectional area

DCC Durham County Council

DTM Digital Terrain Model

EA Environment Agency

EAD Expected Annual Damages

FCERM Flood and Coastal Erosion Risk Management

FEH Flood Estimation Handbook

FCRIP Flood and Coastal Resilience Innovation Programme

FMP Flood Modeller Pro

FRM Flood risk management

GAD Geotextile-assisted dams

HM His Majesty's

IPCC Intergovernmental Panel on Climate Change

LD Leaky dam

LiDAR Light Detection and Ranging

MIDAS Met Office Integrated Data Archive System

NAO North Atlantic Oscillation

NFM Natural flood management

NWDD Natural woody debris dams

RCPs Representative Concentration Pathways

RQ Research question

SSPs Shared Socioeconomic Pathways

SuDS Sustainable Drainage Systems

UK United Kingdom

UKCP18 UK Climate Projections 2018

1 Introduction

Flooding is the most common weather-related natural disaster with profound and escalating socioeconomic and environmental consequences (NOAA, 2020). Around 23% of the global population is exposed to significant flood risk, expected to rise by 5-13% by 2050 (Rentschler et al., 2022; UNDRR, 2025). Flood magnitude has increased over the last five decades, with annual damages estimated at £2.4 billion (UKCEH, 2019; Laville, 2025). Beyond direct economic losses, flooding causes water pollution, infrastructure disruption, societal displacement and in severe cases, loss of life (HM Government, 2021). Climate change, combined with urbanisation and land-use change, is amplifying these risks (UK Government, 2025). 6.3 million properties in the UK are at risk of flooding, a number projected to rise to 8 million (1-in-4 properties) by 2050 (EA, 2025). In North East England, projections indicate substantial increases in the frequency and intensity of extreme rainfall events (Sanderson, 2010). South Moor, located in the upper Twizell Burn catchment in County Durham, has experienced repeated fluvial flooding, including notable events in 2012, 2015 and 2019. These trends underscore the urgent need for effective and adaptive flood-risk management strategies.

Nationally, investment in flood defences is increasing, with £830 million allocated for 2026-27 flood schemes as part of a wider £10.5 billion programme between 2024-2036, where every £1 invested is estimated to prevent £8 of damage (HM Government, 2026). Increasingly, nature-based solutions (NbS) are being adopted to enhance flood risk resilience; the European Open Rivers Programme has implemented its 100th targeted dam and weir removal to enhance flood management by restoring natural river processes (WPM, 2025). Natural flood management (NFM) is a nature-based solution, involving measures to protect, restore, and emulate the natural functions of catchments to reduce flood risk (Connelly et al., 2020). The introduction of the national Natural Flood Management Programme in 2023 marks a significant policy shift towards integrating NbS into mainstream flood-risk management (HM Government, 2023). Leaky dams (LD's) represent a widely adopted NFM measure, designed to attenuate peak flows by slowing channel velocities and promoting temporary upstream storage (Alzabari et al., 2024). However, their effectiveness remains uncertain, particularly under high-magnitude events and future climate conditions (Rubinato et al., 2019).

This uncertainty reflects a broader evidence gap identified in the Pitt Review, highlighting the need for improved understanding of local flood processes to support resilient catchment management (Pitt, 2008). In South Moor, flood management efforts have increasingly focused on NFM approaches (including LD’s) through the SuDS+ programme, one of 25 pilot projects across England funded by the Flood and Coastal Resilience Innovation Programme (FCRIP) (DEFRA, 2021). Therefore, this study aims to evaluate the ability of LD’s to attenuate flooding under current and projected climate conditions in the South Moor catchment. It contributes to national efforts to strengthen evidence-based flood-risk management and supports the wider objectives of the FCRIP by advancing understanding of how NFM measures perform under future hydrological extremes.

2 Literature review

2.1 Flooding

2.1.1 Fluvial flooding

The IPCC conceptualises floods as the ‘overflowing of the normal confines of a stream or other body of water or the accumulation of water over areas not normally submerged’ (IPCC, 2012). In the UK, flooding is categorised as fluvial, pluvial, coastal and groundwater (EA, 2025), alongside anthropogenic sources such as sewer failure or reservoir failure (HM Government, 2025). Although often treated as discreet types, flood mechanisms frequently interact. Evidence from urban floodplains in Leeds shows that fluvial and pluvial flooding occur simultaneously or consecutively, producing greater impacts than in isolation (Sertyeşilışık, 2021). Fluvial flooding occurs when river discharge exceeds channel capacity and water spills onto adjacent banks and floodplains (Perrini et al., 2024). Rainfall–runoff relationships are often conceptualised using methods such as convolution and unit hydrographs (Guang et al., 2023).

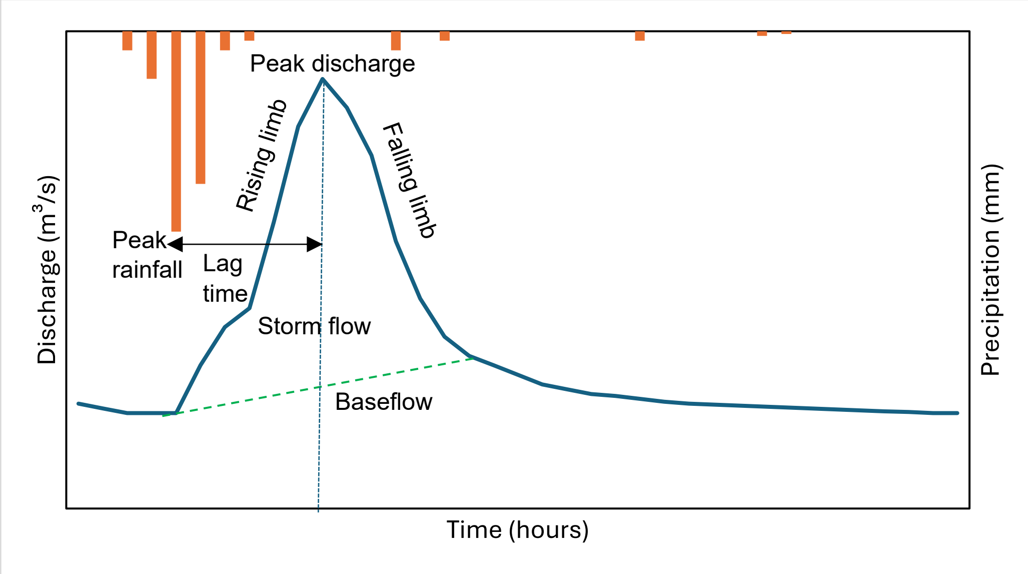


Figure 1 - Annotated model hydrograph for a given flood event. The rising limb shows runoff following rainfall, leading to peak discharge where channel capacity may be exceeded. Lag time reflects catchment controls, while the falling limb shows flow recession and baseflow maintains discharge between events (Knighton, 1998).

Hydrograph form varies between catchments: steep rising limbs and short lag times indicate flashy systems, while attenuated hydrographs reflect greater storage (Fischer et al., 2025). However, such methods have been criticised for reducing non-linear, complex catchment behaviour to overly simplified relationships (Guang et al., 2023; Fenton, 2024). Flood response is controlled by interacting factors including slope, roughness and land-use (Kundzewicz and Pińskwar, 2021). Antecedent wetness can amplify flood response by reducing infiltration capacity, but dry or compacted soils may also promote rapid overland flow, particularly in small catchments with short response times (DEFRA, 2024). Flooding should therefore be understood as the integrated outcome of complex, interacting catchment-scale processes, with implications for flood risk assessment and mitigation.

2.1.2 Flood events in the UK

Event	Location and Scale	Key Characteristics	Impacts	Key Insight
Summer floods (2007)	UK-wide	~415mm rainfall (May-July); prolonged rainfall	>55,000 properties flooded	Demonstrates impact of sustained rainfall on widespread flooding (EA, 2007)
Storm Desmond (2015/16)	Northern England	>300mm in 24 hrs; peak flows ~1,700 m^3/s	~£1.6 billion damages	Highlights role of extreme short-duration rainfall and high peak discharge (EA, 2018)

Storm Claudia (2025)	UK regions	River levels up to 18× normal	Severe hydrological response (reported)	Indicates increasing variability and extremity of river response (Williams, 2026)
Storm Desmond (local)	North East England (Wear, Tyne, Tees)	Extreme rainfall; rapid runoff	294 properties flooded	Demonstrates regional vulnerability to extreme events (EA, 2016)
Chester-le-Street flooding	River Wear (local)	Stage >3.0m (bankfull = 2.7m)	Floodplain inundation	Shows exceedance of channel capacity and local flood thresholds (Barker et al., 2016; NRFA, 2026)
Stanley Burn events (2012, 2015, 2019)	Twizell Burn catchment (local)	Repeated events; rapid runoff response	Road flooding, infrastructure disruption, school closures	Highlights vulnerability of small tributary catchments and rapid flood propagation (SuDS+, 2023; EA, 2024)

Table 1 - Summary of UK and local flood events and associated impacts.

Extreme flood events in the UK have significant environmental and socioeconomic impacts, with local examples from South Moor highlighting these effects (Figure 2).

A

B

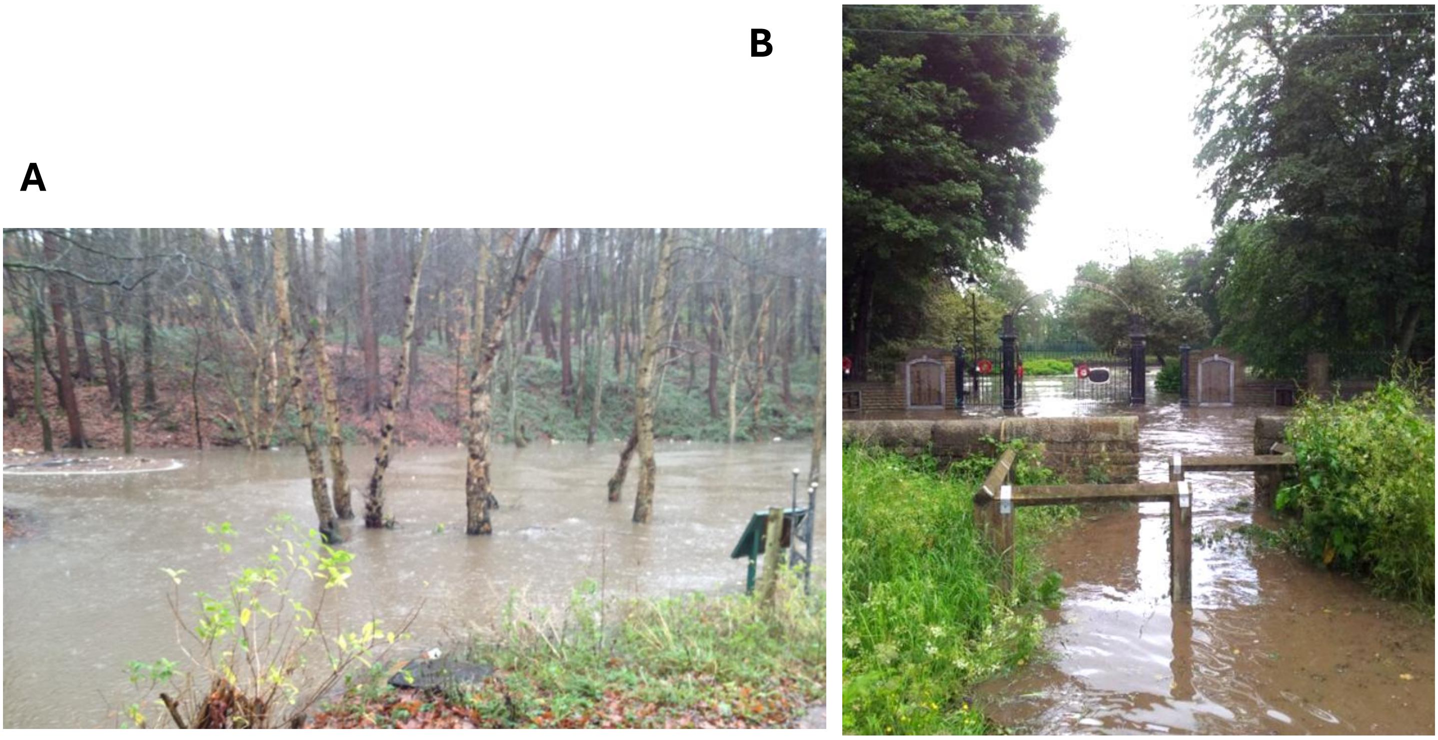


Figure 2 - A). Exceedance of bankfull capacity as water inundates surrounding vegetation, increasing flood risk to adjacent pathways and downstream residential areas and B). Flooded road, pedestrian pathway and entrance to the South Moor Memorial Park, highlighting the disruption to mobility and accessibility (Imagery taken from community flood observations - SuDS+, 2023).

2.1.3 Climate change

Rising greenhouse gas concentrations increase atmospheric moisture-holding capacity, enhancing the intensity of extreme precipitation (7% per 1°C of warming) (IPCC, 2021). By 2070, UK winters are projected to be 30% wetter and summers 60% drier (Met Office, 2025) with winter precipitation particularly receptive to fluvial flooding due to prolonged antecedent saturation (Bouet, 2026). Climate change has also increased the likelihood of extreme events such as Storm Desmond by ~40% (Otto et al., 2018). Attributing changes in flood frequency and magnitude solely to anthropogenic climate change remains contested. While some studies identify trends consistent with climatic warming (Blenkinsop et al., 2021), others emphasise the role of internal climate variability and catchment-scale controls, suggesting flood records may not clearly reflect a climate change signal (Deser, 2020). Extreme rainfall events in the UK are linked to diverse atmospheric circulation regimes rather than a single dominant driver, with North East England showing particular sensitivity to the North Atlantic Oscillation (Cotterill et al., 2024) (see figure 3). This aligns with findings that internal atmospheric variability was a key driver of observed summer rainfall trends between 1981-2010 (Chan et al., 2025).

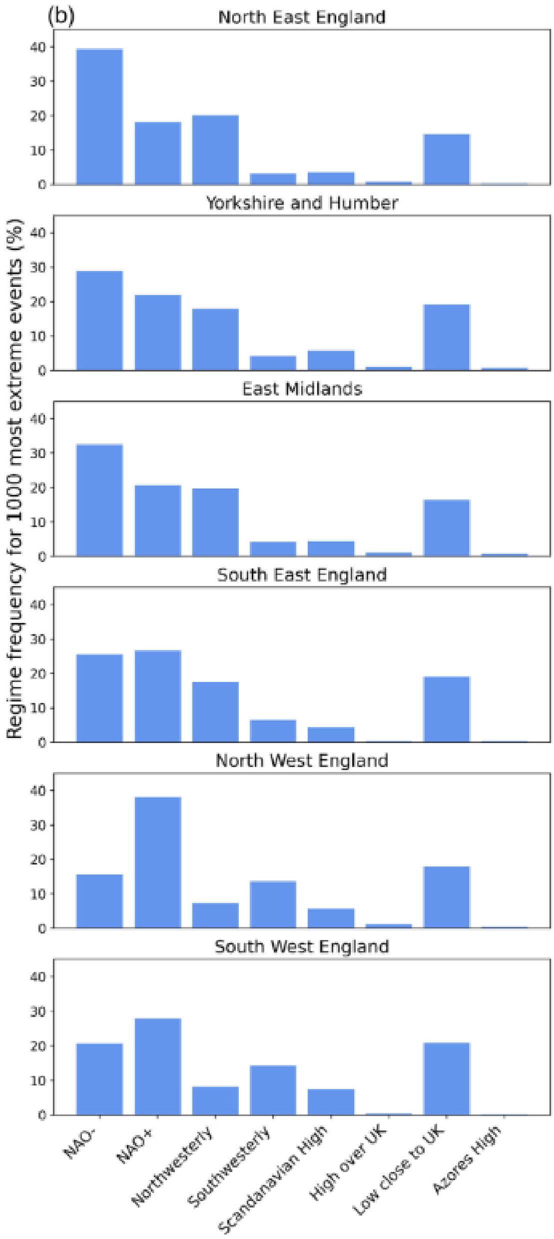


Figure 3 - Analysis of the 1,000 most extreme UK rainfall events for each region and the corresponding % related to each of the eight Met Office specified climatic regimes (Cotterill et al., 2024).

Consequently, natural variability may mask or modulate climate change signals, increasing uncertainty in attributing and projecting future flood risk.

2.1.4 Climate projections

Climate projections are used to assess how changing atmospheric conditions may alter hydrological regimes (Mourot et al., 2025). Global Climate Models simulate large-scale processes but their coarse resolution limits representation of catchment-scale hydrology, necessitating downscaling, which introduces uncertainty in translating climate signals to local conditions (Hannah, 2022; Hadjipetrou, 2026). UKCP18 improves upon UKCP09 through higher-resolution simulations (up to 2.2km), enhancing representation of convective, high-intensity rainfall (Met Office, 2019). Projections indicate increased winter precipitation and extreme rainfall across northern England (Kay et al., 2021). Table 2 highlights the key sources of uncertainty of UKCP18 projections and their implications.

Component	Description	Limitation / Critique	Implication for flood risk assessment
Bias correction	Applied to reduce systematic model errors	Assumes climatic stationarity and may distort extreme values (Zhang et al., 2024)	May misrepresent magnitude and frequency of extreme rainfall events
Emission scenarios (RCPs)	UKCP18 uses RCP2.6-RCP8.5 from IPCC AR5 (Met Office, 2019)	Based on older scenario framework compared to SSPs (AR6) (Gidden et al., 2019)	May not fully capture current climate–society interactions
Use of RCP8.5 in high-resolution models	12 km and 2.2 km simulations driven by RCP8.5	Criticised for overestimating extreme future outcomes (Hausfather, 2019)	Useful for stress-testing worst-case flood risk (Orr et al., 2021)
Scenario divergence	Different emission scenarios produce a divergence in outcomes; higher return period events often show greater sensitivity to climatic forcing (Chan et al., 2025)	Flood response not uniform across return periods	Requires analysis across multiple return periods and scenarios
Representation of extremes	UKCP18 projections used for rainfall extremes	Does not capture full probabilistic range of UKCP09 (ONR, 2022)	May underestimate uncertainty in extreme event projections
Model framework	Based on AR5 RCP's rather than AR6 Shared Socioeconomic Pathways (SSP's) (Gidden et al., 2019)	Reflects lag in climate modelling frameworks	Projections remain widely used due to high spatial resolution and UK applicability. As modelling capabilities evolve, projections are likely to be refined.

Table 2 - Key limitations and uncertainties associated with UKCP18 climate projections, and their implications for flood risk assessment across different event magnitudes and scenarios.

2.2 UK Flood Management Approach

2.2.1 Risk-based approach

Flood impacts are shaped not only by physical hazard but also by socioeconomic factors such as exposure and vulnerability. Flood management can be conceptualised as:

prevention, protection, mitigation, preparation and recovery (Wesselink et al., 2015), while Wang et al., 2022, distinguish between flood control (hazard reduction) and resilience-based approaches to cope and recover. These frameworks highlight that effective flood management requires integration of hazard reduction with adaptive capacity. This is increasingly important as the UK aims to build 1.5 million additional homes by 2029 placing growing pressure on flood-prone areas (HM Government, 2024). Flood management has thus shifted towards a risk-based approach.

$$Flood\ risk = hazard \times exposure \times vulnerability$$

Equation 1 – Flood risk function (Kron, 2002), whereby: hazard is the likelihood and magnitude (depth and extent) of a given flood event occurring, exposure is the value of assets subject to flooding and vulnerability may be defined as the capacity of a society to respond to the event. (Koks et al., 2015).

This framework highlights that flood risk evolves across space and time, requiring approaches that consider not only hazard reduction but also changes in exposure and vulnerability. In the UK, this is operationalised through tools such as the EA Flood Map for Planning, which delineates Flood Zones based on annual exceedance probabilities and is used for both model validation and spatial planning (DEFRA, 2026).

2.2.2 Flood control

Flood management in the UK has traditionally relied on engineered interventions, such as flood walls, designed using return periods expressed as annual exceedance probability (AEP), where a 1% AEP represents a 1-in-100 chance of occurring in any given year for example (MCM, 2026). However, fixed design standards are increasingly criticised under climate change, as non-stationarity challenges their reliability, prompting calls to assess flood risk across multiple return periods and scenarios rather than a single threshold (Ward et al., 2011). Engineered defences are also criticised for lacking a catchment-based perspective; by increasing channel conveyance, they can actually transfer or amplify downstream flood risk (Ellis et al., 2021) and are often only economically viable in high-value urban areas (Azhar et al., 2025). Their effectiveness is further limited during extreme events, where overtopping can lead to uncontrollable, rapid failure as seen during Storm Bert in 2024 (FT, 2024). As a result, UK flood management is shifting away from 'hold-the-line' approaches towards more adaptive strategies, including set-back defences and controlled inundation, reflecting a broader transition from flood control to flood risk management (FRM) (HM Government, 2025).

2.2.3 Natural Flood Management

Following the 2007 UK floods, the Pitt Review questioned the long-term viability of existing flood control measures and promoted more catchment-based strategies (Pitt, 2008). Well-designed NFM schemes aim to reduce flood risk by working with natural catchment processes to slow, store and filter water, while also increasing the resilience of ecosystems (SEPA, 2015). Figure 4 represents the increase of NFM focus in UK policy in recent decades.

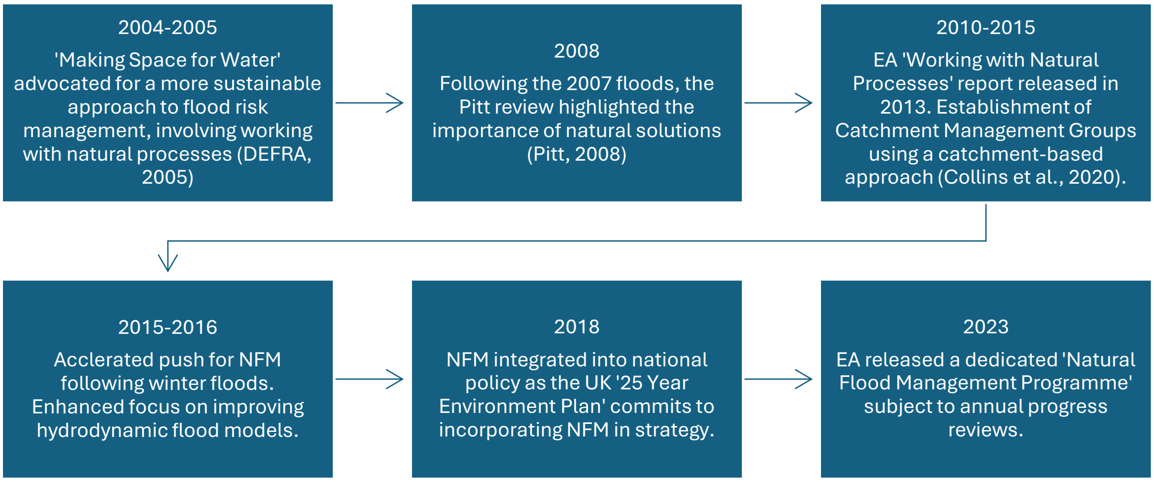


Figure 4 - A diagram to show the increased presence of NFM in UK 21st century policy

NFM interventions for fluvial systems may be categorised into 3 main types: river and floodplain management, woodland management and runoff management (EA, 2026):

<u>NFM Type</u>	<u>How it works</u>	<u>Quantified effectiveness</u>	<u>Opportunities and limitations</u>
Leaky dams	Increase channel roughness and temporarily store flow, delaying and attenuating hydrograph peaks (Addy et al., 2025).	UK studies indicate ~2-10% peak flow reduction for small-moderate events (van Leeuwen, et al., 2024). Muhawenimana et al., 2023 estimate that 102m^3 additional water storage can be provided by one barrier during 4 yr return period storm using field data.	Can improve sediment retention and ecological diversity but effectiveness is highly variable and often limited to small catchments (ERT, 2026). Performance declines during extreme events (van Leeuwen et al., 2024)
Offline storage	Diverts and stores excess flow away from the main channel, reducing downstream discharge and flood extent (The Flood Hub, 2023).	7% reduction in peak flow achieved for a maximum event AEP of 83% (Lockwood et al., 2022). Environment Agency NFM Programme delivered >1.6 million m^3 storage (EA, 2021).	More predictable, larger scale performance due to controlled design but requires significant land take and may conflict with stakeholders (like agriculture or development) (Bark, 2021).

River restoration (re-meandering, embankment removal)	Slows flow velocity and increases channel-floodplain interaction, desynchronising peak flows (SEPA, 2015).	In a 25 km^2 catchment in the New Forest, a monitoring study found river restoration led to a 21% reduction in flood peak and a 33% increase in peak travel for a 50% AEP event (EA, 2025).	Increases channel-floodplain connectivity and can enhance geomorphological stability but difficult to quantify benefits, particularly at larger catchment scales and long implementation timescales required (Schwendel et al., 2024).
Woodland creation (cross-slope, floodplain or riparian)	Enhances interception, evapotranspiration and infiltration, reducing runoff generation and slowing flow pathways. Increases roughness and stabilises soils (Forestry Commission, 2025).	Riparian forest restoration at the sub-catchment scale, representing 20-40% of the total catchment area can result in peak flow reduction of 19% and floodplain forest restoration over 10-15% of total catchment area can lead to reductions in peak magnitude of 6% (Dixon et al., 2016)	Can provide short and long-term co-benefits (such as carbon sequestration and biodiversity) (Willis et al., 2025). However, effectiveness declines during saturated conditions and extreme rainfall, limiting impact for larger return periods and there is often a time lag before benefits are realised (≥25 years in some reported cases) (Dixon et al., 2016)
Buffer strips (riparian, vegetated zones)	Increase surface roughness and infiltration, slowing overland flow and reducing sediment and runoff delivery to channels (Eden Rivers Trust, 2026).	Studies show runoff reductions of ~10-30% at plot scale, with modest influence on peak flows at catchment scale (Pattison, 2010).	Relatively low-cost and compatible with agricultural systems and reduce eutrophication but effectiveness is highly dependent on width, slope, and soil conditions (Gilley, 2005).
Retention ponds (permanent storage)	Provide continuous water storage with additional attenuation capacity during storm events, reducing runoff volume and peak discharge (Staccione et al., 2021).	Evidence finds that retention ponds reduced peak runoff by 77% and they are particularly effective when integrated into wider SuDS networks within urbanised catchments (Garcia et al., 2025).	Effective for volume control and water quality improvements through sedimentation but require lots of space which may create land conflicts and maintenance to avoid failure (Gulliver et al., 2010).
Detention basins (dry storage)	Temporarily store stormwater and release it gradually, reducing peak discharge and downstream flood depth (Griffiths, 2017).	Studies show rural flood detention basins can achieve 30-60% reductions in peak discharge across multiple storm events depending on design (Asadzadeh et al., 2026).	Beneficial for biodiversity but performance declines if storage capacity is exceeded in prolonged, extreme events (Cavadini et al., 2026). Blue-green SuDS usually work best as a combination of features working together as a network (EA, 2026).

Table 3 - Examples of UK Natural Flood Management interventions, their function, effectiveness and limitations. Rows are categorised as river and floodplain management (blue), woodland management (brown), and runoff management (green). Other NFM classifications and intervention types exist, as per EA guidance, but are not relevant to this study.

The effectiveness of NFM remains debated. While some studies report substantial peak flow reductions where interventions are strategically distributed (up to ~50%) (Ahmadisharaf et al., 2021), others highlight significant uncertainty, particularly under extreme events and future climate conditions. A key limitation is the consideration of NFM and hard-engineered approaches separately, restricting assessment of their combined catchment-scale effectiveness (Lashford et al., 2022). Hybrid approaches are increasingly recognised as a more resilient strategy (Hill et al., 2023), yet significant gaps remain in understanding their combined effectiveness, particularly under future climate, raising questions whether current policy, funding and implementation are keeping pace with increasing flood risk (HM Government, 2025). Implementation is further constrained by funding and difficulties in quantifying benefits. Despite £25 million investment through the UK NFM Programme (HM Government, 2023), only ~1% of flood risk funding is allocated to NFM (Flood Hub, 2025). Community-led and partnership approaches may help address this, as stakeholder involvement improves adaptive capacity through awareness and preparedness regarding long-term flood risk (Msongole et al., 2026).

2.2.4 Leaky dams

LD's are widely used NFM interventions designed to mimic natural, permeable flow obstructions (Zhuang et al., 2024). As in-channel structures, they temporarily store water during high flows, increasing roughness, reducing velocity and delaying downstream peak discharge (Wolstenholme et al., 2025; Tankard, 2021). They are reportedly most effective when installed in upstream catchments and tributaries, where they disperse concentrated flows and reduce downstream flood risk (Hansamali et al., 2025). Beyond hydrological benefits, LD's are relatively low-cost and scalable, while also enhancing biodiversity through habitat creation and promoting sediment deposition, with downstream sediment loads in one study reduced by 40–60% (Müller et al., 2021). These interactions reflect the dynamic feedbacks between flow, sediment and morphology described by the fluvial trinity (Leopold et al., 1964). However, the effectiveness of LD's is highly variable, influenced by interacting controls as summarised in table 4:

Factor	Key findings	Implication
Event magnitude	Peak flow reductions range from 15-20% in the Pickering scheme (Forest Research, 2017) while other studies show ~10% for frequent events and	Effectiveness declines with increasing event magnitude, requiring assessment across

and return period	<5% for higher return periods (van Leeuwen et al., 2024)	multiple return periods under non-stationary conditions (EA, 2022)
Catchment scale	Peak delays of up to ~5 hours reported at reach scale, but diminish at larger scales due to routing and land surface controls (Villamizar et al., 2024)	Localised attenuation does not necessarily translate to catchment-scale flood reduction.
Dam configuration and network effects	Distributed networks of LD's can generate a "network effect", whereby cumulative storage and delayed routing produce peak flow reductions of 30-60% during storm events, exceeding individual structures (Hansamali et al., 2025)	Performance is highly sensitive to spacing, positioning and connectivity, with poorly configured systems yielding limited benefits.
Dam characteristics and site conditions	Performance varies by permeability, size, material and slope; runoff reductions up to 57% reported for brushwood dams (Hansamali et al., 2025) and most effective on 5-12% slopes (Frankl et al., 2020)	Strong site and design dependency limits transferability and comparability across studies (Addy and Wilkinson, 2019)
Research limitations and knowledge gaps	~80% of studies focus on downstream response, with limited consideration of geomorphological and upstream processes (Wolstenholme et al., 2020; Khaleghi and Nosrati, 2025). Flume experiments are common but often isolate hydraulic processes but oversimplify flow-sediment-morphology interactions (Leakey et al., 2022).	Highlights need for integrated, multi-scale approaches combining field data and modelling (Muhawenimana et al., 2023)

Table 4 - Key factors influencing the effectiveness of leaky dams, highlighting variability in performance, controlling processes and associated research limitations.

2.2.5 Cost-benefit analysis

Flood management is underpinned by economic appraisal, particularly cost-benefit analysis (CBA), which evaluates interventions based on risk reduction relative to cost (van der Pol et al., 2015). Hydrological outputs (including depth, extent and probability) are converted into economic terms using depth-damage relationships to estimate Expected Annual Damages (EAD), with UK guidance requiring comparison of whole-life costs against avoided damages (Merz and Thieken, 2009; EA, 2021). Assessing interventions across multiple return periods and land-use types can reduce uncertainty and improve robustness (Egorova et al., 2008; Chan et al., 2025). However, CBA is criticised for underrepresenting intangible impacts such as social disruption and environmental change, often undervaluing NFM benefits including biodiversity and water quality (EA, 2025). UK guidance is therefore evolving beyond purely ratio-based approaches; The Green Book emphasises that decision-making should not rely solely on fixed cost-benefit thresholds but must also consider non-monetised social and environmental impacts alongside explicit treatment of uncertainty and future climate change (HM Government, 2026).

2.3 Flood Modelling

2.3.1 Flood Modeller Pro

Evaluating UK flood management schemes against future climate change increasingly relies on spatial-focused modelling methods (Sayers et al., 2024). Hydraulic modelling software such as Flood Modeller Pro (FMP) can spatially resolve channel flows, floodplain behaviour and defence performance and is widely used in UK appraisals (such as the Thames Estuary 2100 programme), linking inundation depth and extent with associated economic damage (Jacobs, 2025). Linked 1D–2D models are particularly effective for flood hazard mapping and planning, combining efficient channel representation with more realistic, spatially-distributed inundation (DEFRA, 2023), with 2D approaches better capturing multidirectional flow pathways (Cea and Costabile, 2022). The 2D component is governed by the shallow water equations:

A $$\frac{\partial h}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0$$

B $$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial (h+z)}{\partial x} + \frac{gn^2 u\sqrt{u^2+v^2}}{h^{4/3}} - \frac{\nu}{h}\left(2\frac{\partial^2 hu}{\partial x^2} + \frac{\partial^2 hu}{\partial x^2} + \frac{\partial^2 hv}{\partial x \partial y}\right) = 0$$

C $$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial (h+z)}{\partial y} + \frac{gn^2 v\sqrt{u^2+v^2}}{h^{4/3}} - \frac{\nu}{h}\left(\frac{\partial^2 hv}{\partial x^2} + 2\frac{\partial^2 hv}{\partial y^2} + \frac{\partial^2 hu}{\partial x \partial y}\right) = 0$$

Equation 2A, B and C – The shallow water equations used to describe depth-averaged flow, where u and v : two components of the horizontal velocity, h : flow depth, z : bed elevation, x and y : horizontal distances, t : time, g : acceleration due to gravity, n : Manning's coefficient of roughness and ν : the kinematic eddy viscosity (Flood Modeller, 2022).

Alternating Direction Implicit (ADI) methods are implemented to address alternating spatial directions, allowing larger time steps without loss of stability (Li et al., 2021). However, their depth-averaged formulation limits representation of complex flow behaviour, particularly supercritical flow regimes that generate hydraulic jumps; advanced solvers like Total Variation Diminishing solvers address this, improving stability by limiting spurious oscillations near sharp gradients, making them well suited to capturing discontinuities such as hydraulic jumps (Kvočka et al., 2017).

2.3.2 Modelling challenges and opportunities

Modelling LD's presents several methodological challenges, but also opportunities to improve model reliability, as summarised below:

Limitation	Challenge	Opportunity
LD representation	Absence of standardised modelling approaches introduces uncertainty (Furnues et al., 2024). LD's are typically represented using barriers/weirs (blockage), culverts (flow pathways) and increased roughness (drag), simplifying their heterogeneous and dynamic structure (Senior et al., 2022). Model outputs are highly sensitive to culvert size, number, positioning and roughness values (Wolstenholme et al., 2025).	Enables flexible, scenario-based testing of LD configurations. Varying structure and placement allows evaluation of how design influences flow attenuation, supporting optimisation of NFM interventions.
Roughness parameterisation	Typically represented using Manning's *n* (0.05-0.2 commonly applied based on published datasets (Addy and Wilkinson, 2019; Furnues et al., 2024)). However, Manning's equation assumes uniform flow and constant roughness, limiting representation of variable resistance from blockage, depth and pooling. Alternative laws (Chezy, Darcy-Weisbach) are possible but less suitable for complex open-channel systems (Smith, 2009).	Justifies calibration and sensitivity testing of roughness values. Incorporating field-derived parameters improves representation of site-specific behaviour and reduces reliance on fixed, generalised assumptions (Xing et al., 2021).
Model selection and scale	Hydrological models (like HBV-Light) improve catchment parameterisation but lack floodplain dynamics, while hydraulic models (such as LISFLOOD-FP) provide detailed flow representation but are computationally intensive (Tibangayuka et al., 2022; Bao et al., 2025).	Supports integrated or hybrid modelling approaches that balance efficiency and physical realism, enabling multi-scale assessment from reach to catchment scale.

Uncertainty and non-stationarity	Model outputs are sensitive to parameters such as roughness, boundary conditions, outflow gradients and resolution (Mishra, 2009). Deterministic simulations fail to capture variability under changing climatic conditions.	Sensitivity testing and probabilistic scenarios (P5, P50, P95) improve robustness under non-stationary conditions (EA, 2022; Webber et al., 2025). Emerging approaches, including improved NFM representation in Flood Modeller Pro and machine learning calibration, offer potential to reduce uncertainty (Kumar et al., 2023).

Table 5 - Modelling challenges and opportunities in representing leaky dams, highlighting key sources of uncertainty and approaches to improve model robustness and applicability.

These challenges highlight the importance of combining sensitivity testing and probabilistic approaches to improve confidence in modelling LD performance under current and future conditions.

3 Study area

3.1 Overview

South Moor is a village within the parish of Stanley, County Durham, located in the upper reach of the Twizell Burn catchment (DCC, 2021). Stanley Burn is the source of the Twizell Burn, originating near Annfield Plain and flowing eastwards to South Moor. The Twizell Burn is a tributary of the Cong Burn, which joins the River Wear east of Chester-Le-Street. South Moor has experienced repeated flood events (notable events: 28th June 2012, winter 2015, and 5th November 2019), causing road inundation and disruption to infrastructure including school closures (Stanley SuDS, 2022). Stanley SuDS+ is one of 25 pilot projects funded through the FCRIP. The scheme is delivered through a Partnership under the Catchment Based Approach and has invested over £90,000 in NFM interventions within the Twizell catchment (EA, 2017). Delivered in collaboration with the Wear Rivers Trust, DCC, EA and local community, the scheme integrates LD's, wetland creation and SuDS measures to reduce flood risk, enhance in-stream habitat and improve access (Stanley SuDS, 2022). Figure 5 shows the 12 LD's in the upper catchment that this study focuses on (see figure 5).

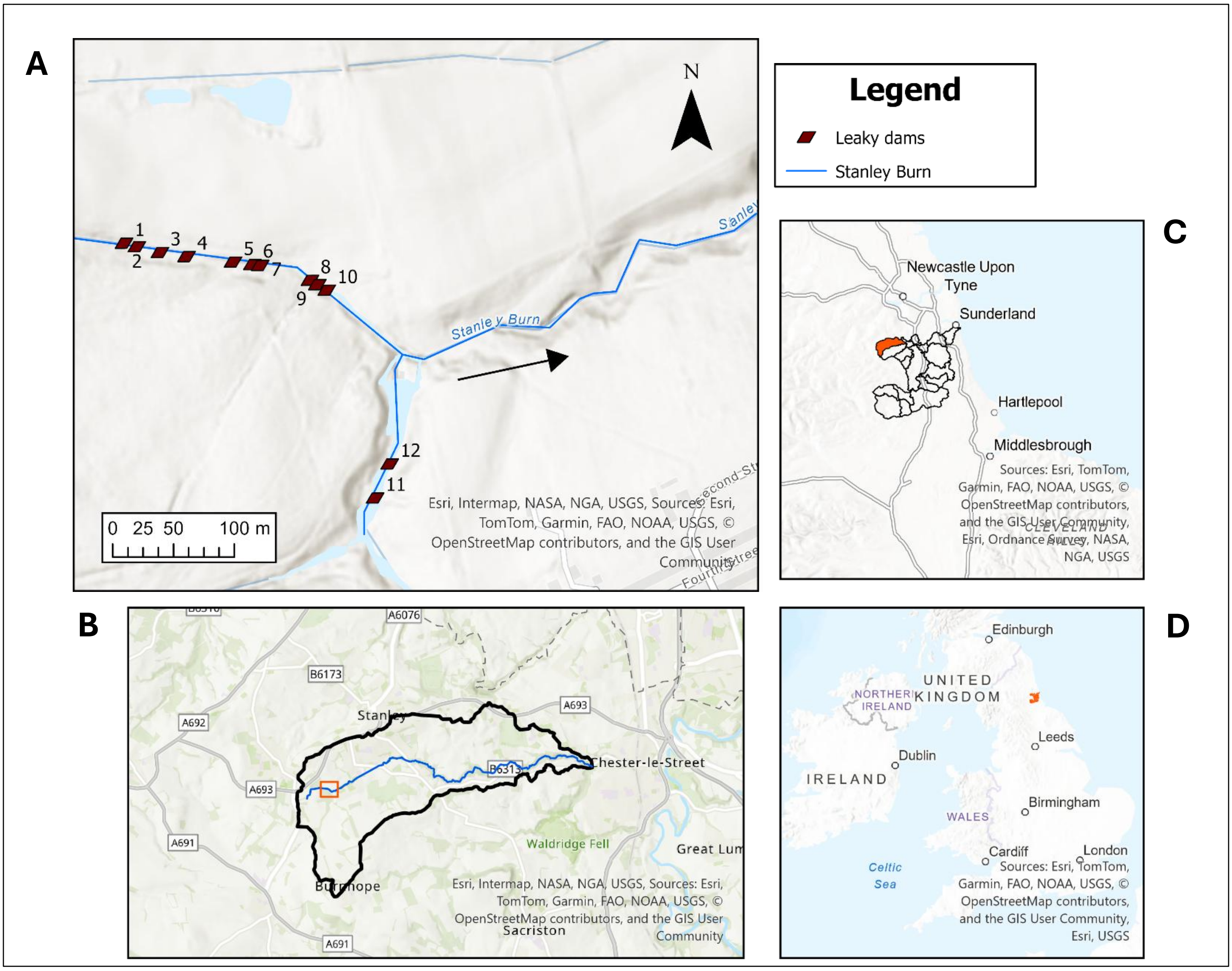


Figure 5 -A). The study area showing the placement of the 12 leaky dams and the flow direction of Stanley Burn B). The location of the leaky dams study area within the Twizell Burn from Source to Cong Burn Water Body which makes up 1 of 22 water bodies within C). the Wear Lower and Estuary Operational Catchment and D). the UK as a whole.

3.2 Catchment characteristics

The catchment exhibits a steep topographic gradient as elevation decreases from ~262m in the headwaters to 27m downstream, promoting rapid runoff generation and increasing flood risk (figure 6).

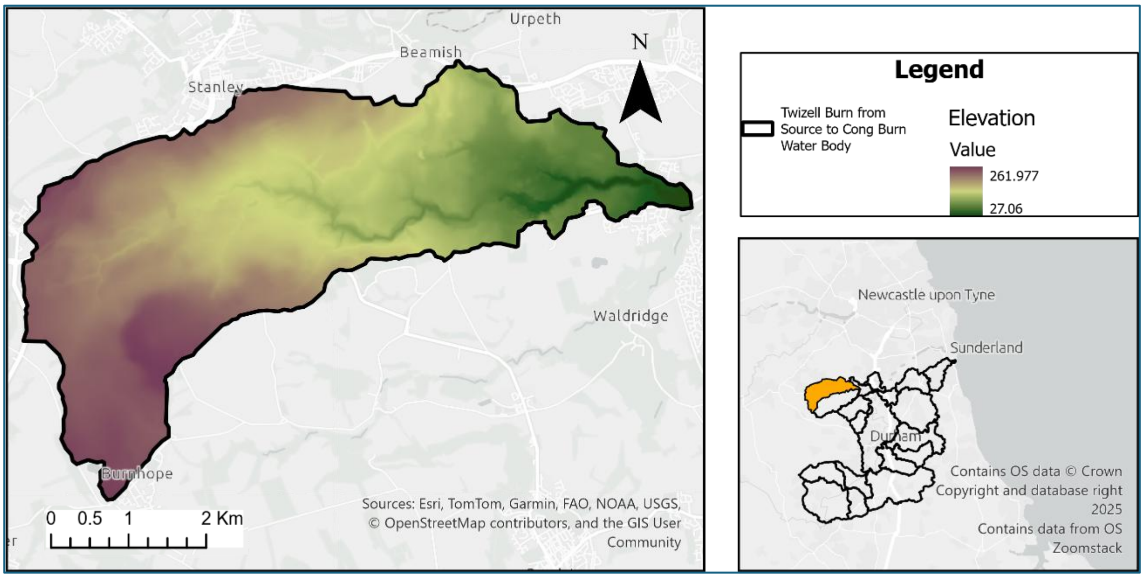


Figure 6 - Topography of the Twizell Burn from Source to Cong Burn Water Body. Produced using the EDINA Digimap 1m Composite DTM (Ordnance Survey, 2022). The box highlights the location of South Moor in the upper catchment.

This is exacerbated by underlying geology, dominated by diamicton (71%) which has low-permeability, limiting infiltration capacity and enhancing overland flow pathways (Weedon et al., 2023).) (see figure 7A).

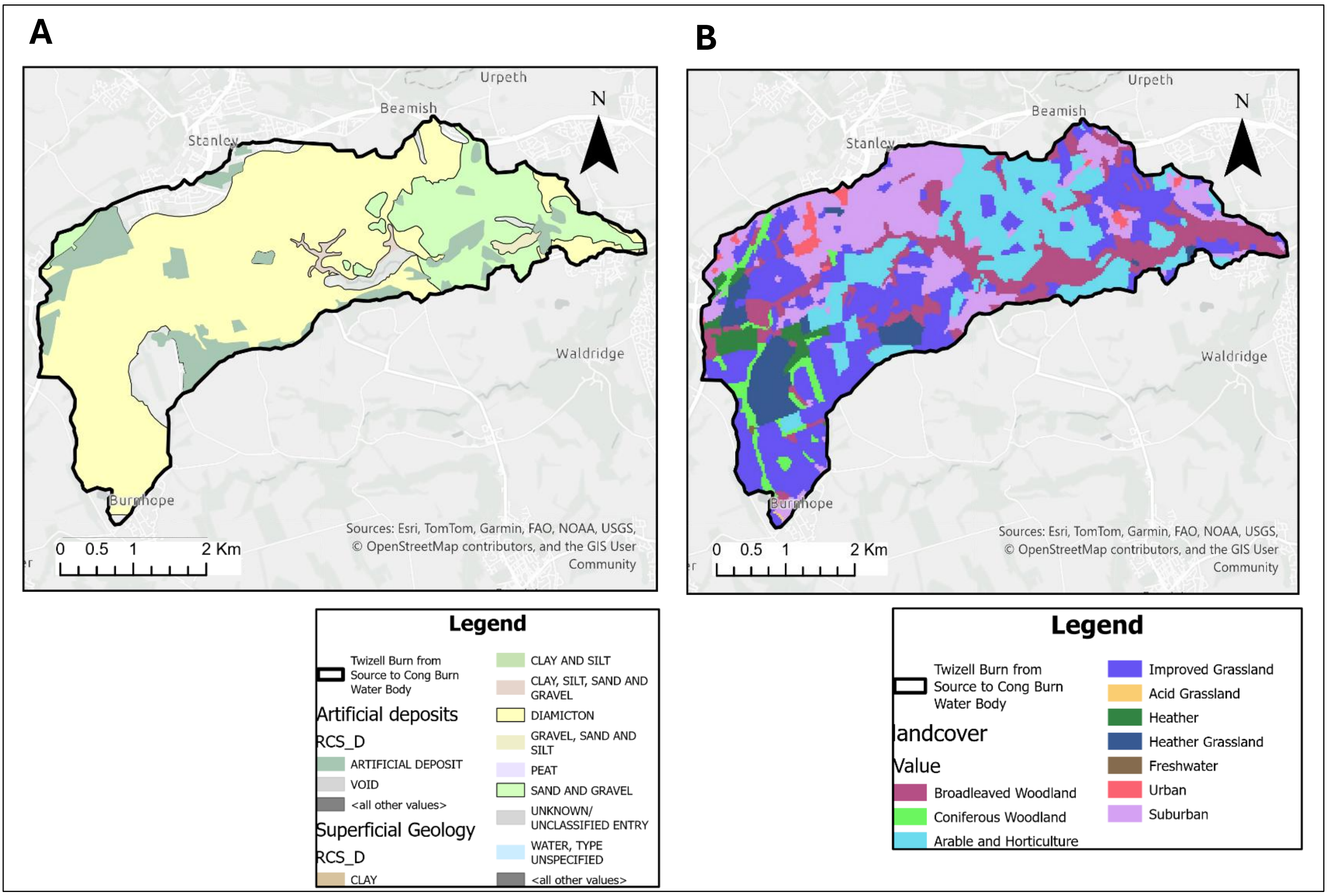


Figure 7 – A). Geological composition of the Twizell Burn from Source to Cong Burn Water Body. Produced using the 1:50,000 2016 onshore geology shapefile (Ordnance Survey, 2016). B). Land use of the Twizell Burn from Source to Cong Burn Water Body. Produced using GB environment land cover map 10m raster TIFF file (Ordnance Survey, 2024).

Land use (figure 7B) is mixed, comprising of grassland (33%), urban and suburban cover (29%), agricultural land (28%) and woodland (10%); rapid runoff production occurs in developed areas, combined with partial attenuation in vegetated zones, resulting in a complex and potentially flashy flood response (Gao, 2013). Impervious surfaces which accelerate runoff and can increase peak flows (Sohn et al., 2020). Planned development of ~24,800 homes by 2035 is likely to further increase flood risk (DCC, 2020). Even a 1% increase in urbanisation is associated with measurable increases across low, median, and high flows (Han et al., 2022). This effect is often amplified in low-permeability catchments like South Moor where infiltration is already constrained. Additionally, the Twizell Burn is classified as a heavily modified water body with moderate ecological status, reflecting historic mining activity (DEFRA, 2026). Uncertainty remains over how effective the LD's are at increasing resilience to climate-related flooding in South Moor.

4 Aims and Research Questions

The Environment Agency assigns only medium confidence in the effectiveness of LD's for reducing flood risk, particularly under extreme events and spatial scales (EA, 2025). This highlights a key gap in understanding their performance across varying climatic conditions, underpinning the aim of this study:

To examine the effectiveness of leaky dams for flood alleviation under current and projected climate conditions.

Responding to the growing need for sustainable flood management as flood risk intensifies, this study adopts a multi-scale approach to evaluate LD performance in the South Moor catchment through four research questions:

<u>RQ1: How do leaky dams alter channel morphology and flow characteristics under current conditions?</u>

Despite increasing implementation, high-resolution evidence of morphological and hydraulic impacts at localised scales remains limited (Wolstenholme et al., 2025). RQ1 addresses this through reach-scale field measurements upstream and downstream of ten LD's installed as part of the SuDS+ project, providing insight into channel morphology and flow attenuation under non-event conditions.

<u>RQ2: How do leaky dams change the magnitude and timing of peak discharge events under baseline conditions?</u>

Existing studies show uncertainty across event magnitude (depth and extent) and limited integration between spatial scales (Hill et al., 2026). RQ2 models multiple flood events across a range of AEP's and uncertainty bounds, linking reach-scale processes to catchment-scale flood response, enabling robust assessment of LD's.

RQ3: How do leaky dams change the magnitude and timing of a range of peak flow events under future conditions?

A key limitation in NFM research is understanding LD performance under future climate scenarios. Simplified or single hydrograph inputs prevent studies from capturing how event-magnitude variability shapes distributed dam network behaviour and cumulative impacts on storage and flow synchronisation (Hankin et al., 2020). RQ3 applies climate-driven discharge projections within FMP to simulate future events, assessing LD robustness under projected conditions.

RQ4: How can flood management strategies be optimised to improve flood risk mitigation?

Significant uncertainty remains regarding LD long-term performance and economic viability at catchment scale, particularly relative to engineered approaches (Hansamali et al., 2025). RQ4 models a series of flood management schemes in FMP and integrates outputs with cost-benefit analysis to identify optimised strategies to reduce future flood risk in South Moor.

5 Methodology

5.1 RQ1

5.1.1 Fieldwork

Data was collected between January and July 2024 at monthly intervals to capture temporal variability in channel morphology and flow conditions. Repeated measurements improve reliability and reduce short-term variability, consistent with hydrological practice (NRFA, 2026). April data were omitted due to time constraints and not interpolated, as methods such as K-Nearest Neighbours may obscure variability (Ebrahimi and Shourian, 2021). Measurements were conducted under non-storm conditions, representing routine flow regimes and aligning with previous field-based LD studies for safety purposes (Jones et al., 2025). Detailed measurements were undertaken at dams 1-10 over a 175m reach in the upper catchment (Figure 5), where NFM measures are most effective. Dams 11 and 12 were excluded from field sampling but included in catchment-scale modelling, (Chen et al., 2021). LD dimensions and channel slope were measured using a clinometer and converted to m/m (Appendix 1). Channel morphology was characterised using ten evenly spaced depth measurements per cross-section to calculate cross-sectional area (CSA), following Satchithanantham et al., 2019. Measurements were taken 2m upstream and downstream of each dam to capture local effects (Muhawenimana et al., 2023). Flow velocity was measured at 0.4 depth using a Valeport electromagnetic flow meter, approximating depth-averaged velocity (Linsley et al., 1982).

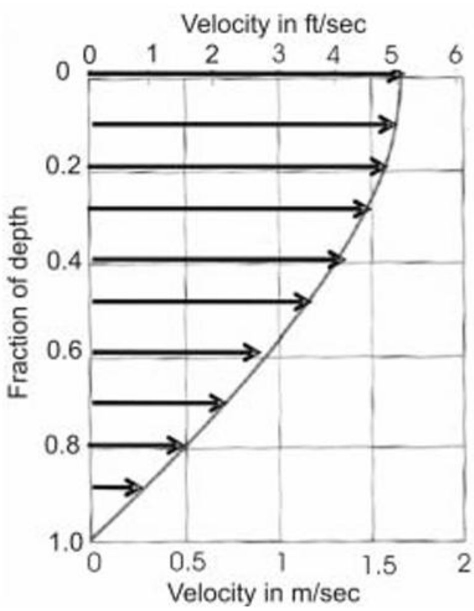


Figure 8 - Schematic vertical velocity profile for open channel flow, illustrating the non-linear increase in velocity from the channel bed to the water surface. The 0.4d position is indicated, where point velocity provides a close approximation of depth-averaged flow velocity (Graph taken from Vacher, 2005).

This approach is based on the logarithmic velocity profile and provides a robust approximation of depth-averaged velocity (Wilcock, 1996). However, it assumes ideal flow conditions and uncertainty arises under turbulence and backwater effects, particularly near LD's (Liu et al., 2021). To reduce this, velocity was recorded over 30 seconds at 3-second intervals to capture variability. Alternative methods such as salt dilution gauging were not used, as restricted mixing in low-velocity, obstructed flows can reduce measurement accuracy and pose ecological risks (Hudson and Gilman, 1996; Hauet et al., 2020). Baseline data is provided in Appendices 2 and 3.

LD's were classified into four structural types following Hansamali et al., 2025, supported by field observations and consultation with Wear Rivers Trust members responsible for implementation.

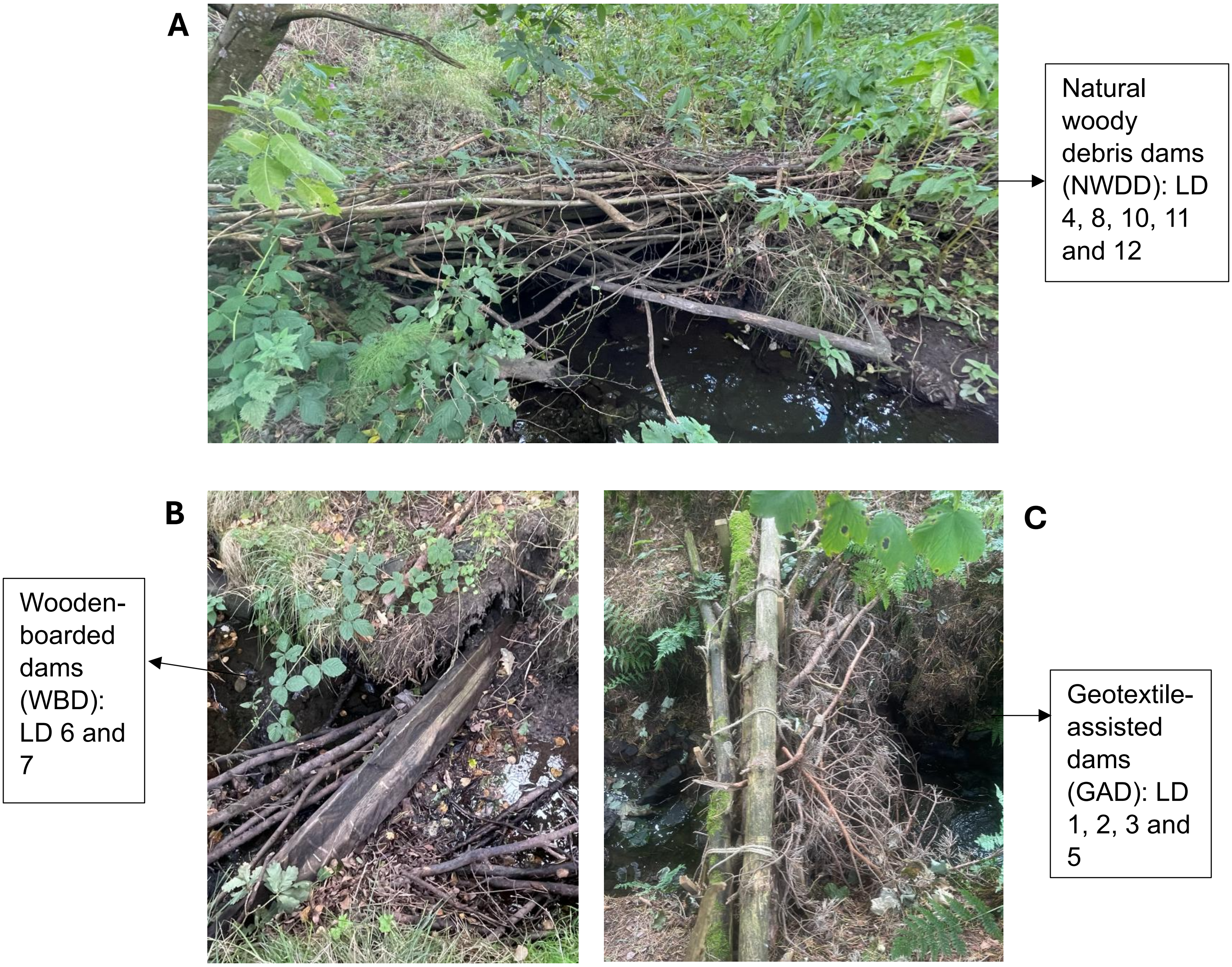


Figure 9 – Photographs to capture the different types of dam. A). Natural woody debris dam, with loosely placed long branches and other fallen material across the channel B). Wooden-Boarded Dam, created by cutting a groove into either bank side and using several plank-like pieces of wood C). Geotextile-assisted dam using rope and wooden pegs to hold it in place (Classifications adapted from Hansamali et al., 2025).

Rainfall data were obtained from a local tipping-bucket gauge (2-minute resolution) provided by the Wear Rivers Trust, with 99% accuracy up to 120mm/hr and a 0.197mm per tip calibration (EML, 2025) (see Appendix 4). Although tipping-bucket gauges may underestimate high-intensity rainfall, this is unlikely to significantly affect analysis of non-extreme conditions (Molini et al., 2005).

5.1.2 Data analysis

CSA was used to interpret how the LD's are impacting channel morphology and calculated using the trapezoidal rule, widely applied in fluvial geomorphology due to its suitability for irregular channel profiles (equation 3). This approach was selected in preference to simpler rectangular approximations, which assume uniform depth and would therefore underestimate variability in bed morphology (Oye et al., 2021).

$$A = \sum_{i=1}^{n-1} \frac{(d_i + d_{i+1})}{2} \times (x_{i+1} - x_i)$$

Equation 3 – Trapezoidal rule formula, where: A=cross-sectional area (m^2), d_i, d_{i+1}= water depths at consecutive measurement points (m), x_i, x_{i+1}= horizontal positions across the channel (m) and n= total number of measurement points.

Mean CSA values were compared upstream and downstream and uncertainty was expressed as the standard error of the mean, representing ~68% confidence interval:

Step 1	Uncertainty in depth	$\epsilon depth = Error\ in\ depth\ (\frac{Standard\ deviation}{\sqrt{number\ of\ samples}})$
Step 2	Uncertainty in width	$\epsilon width = Error\ in\ width\ (\frac{Standard\ deviation}{\sqrt{number\ of\ samples}})$
Step 3	Relative Uncertainty	$\epsilon_{CSA} = \sqrt{(\epsilon_{depth})^2 + (\epsilon_{width})^2}$
Step 4	Absolute Uncertainty	$\Delta CSA = \epsilon_{CSA}$ x CSA

Table 6 – A table to show the steps taken for multiplicative error propagation of CSA.

A paired two-tailed t-test was used to assess differences in CSA between upstream and downstream LD's without assuming a directional response (Huang et al., 2022). While an increase in upstream CSA may be expected due to pooling and storage effects (Khalegi and Nosrati, 2025), downstream scour and erosion can also increase CSA due to accelerated flow through the structures (Wolstenholme et al., 2025).

A

$$t = \frac{(\bar{x}_1 - \bar{x}_2)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

B

H_0 (null hypothesis): upstream CSA = downstream CSA

H_1 (alternate hypothesis): upstream CSA ≠ downstream CSA.

Equation 4 – A). A two-sampled t-test, where: t = test statistic, $\bar{x}_1$ = observed mean of first sample, $\bar{x}_2$ = observed mean of second sample , s_1= standard deviation of first sample, s_2 = standard deviation of second sample, n_1= sample size of first sample and n_2 = sample size of second sample (Xu et al., 2017). B). The null and alternate hypothesis; if the test statistic exceeds the critical value, the null hypothesis is rejected. The critical value for 69 degrees of freedom and at a 5% significance level is 1.999; the significance level (α) will be: 0.05 (5%), as conventional and most used amongst wider literature, in order to find the critical value (Loftus, 2022).

To assess the influence of dam characteristics on CSA (type, size, grouping), Kruskal–Wallis tests were applied due to small sample sizes and non-normal data distributions commonly associated with field-based measurements (Cox et al., 2025).

$$H = \frac{12}{n\,(n+1)} \Sigma \frac{r_{i^2}}{n_i} - 3(n+1)$$

Equation 5 - The Kruksal-Wallis test where: H = Kruksal-Wallis test statistic, n = sample size, r_i =mean ranking, n_i= rank variance (Lomuscio, 2021).

Kruksal-Wallis Test number	Null hypothesis (H_0)	Alternate hypothesis (H_1)	Approach and justification for grouping
1	There is no statistically significant difference in median ΔCSA between dam types	There is a statistically significant difference in median ΔCSA between dam	Dam types were previously classified into three types considering the types of wood used, the structural integrity, placement in channel (see figure 9). Based on existing studies, this influences morphology through differences to flow attenuation, sediment transport and localised scour or deposition, which in turn can affect CSA; higher density such as the wooden boarded dams encourage upstream storage and greater CSA whereas more permeable dams may increase turbulence and scour downstream (Ronnquist and Westbrook, 2021). As three groups were defined; the degrees of freedom was equal to 2 and the critical chi-square value at a 5% significant level was 5.99.
2	There is no statistically significant difference in median ΔCSA between dam sizes	There is a statistically significant difference in median ΔCSA between dam sizes	Based on dam measurements, they were classified into two size types: those with width, height and thickness > 1m (LD 1, 2, 3, 8, 9, 10) and those with width, height and thickness < 1m (LD 4, 5, 6 and 7). Based on existing studies, larger dams influence morphology by increasing flow resistance and enhancing backwater effects (Lo et al., 2022). As two groups were defined; the degrees of freedom was equal to 1 and the critical chi-square value at a 5% significant level was 3.84.
3	There is no statistically significant difference in median ΔCSA between clustered and isolated dams	There is a statistically significant difference in median ΔCSA between clustered and isolated dams	Based on existing studies documenting a potential 'network effect' whereby dams located in close succession (in this study: ≤10m apart) may act cumulatively and compound any morphological effects as opposed to dams in isolation, dams were classified (Hankin et al., 2020). LD 2, 7, 9 and 10 are positioned closely after the previous dam (less than 10m downstream) whereas LD 1 is the uppermost dam in the reach scale network and LD 3, 4, 5 and 6 are >10m apart from the previous dam. As two groups were defined; the degrees of freedom was equal to 1 and the critical chi-square value at a 5% significant level was 3.84.

Table 7– The three Kruksal-Wallis tests performed to understand how leaky dam characteristics influence CSA and thus morphology. The null and alternative hypothesis and rejection of the null hypothesis works in the same way as that of the two-sample, paired t-test with a 0.05 significance level used.

Discharge was calculated as the product of velocity and CSA, enabling analysis of the interaction between channel morphology and flow dynamics (Adams, 2021). Stage-discharge relationships were developed with polynomial functions fitted to investigate how LD's altered flow conveyance, attenuation or discharge sensitivity, similar to van Leeuwen et al., 2024, and evaluated using R^2 values to identify best-fit models (Maydeu-Olivares et al., 2023). The coefficient of determination (R^2) was used to assess the strength of fitted stage–discharge relationships, with higher values indicating a better fit. The best-fitting curves were selected to represent LD hydraulic behaviour as this provided the most robust fit to the observed data (Maydeu-Olivares et al., 2023). Monthly curves were retained to preserve temporal variability, as averaging would obscure hydrological differences and reduce the sensitivity of the analysis (Guerrero et al., 2012). To determine whether observed differences between upstream and downstream stage-discharge relationships are statistically significant, a paired one-tailed t-test was applied to the linear coefficients (b) of the fitted relationships, based on expected downstream increases in discharge for a given stage (Furnues, 2023). However, a limitation of rating curves is that they do not cover a range of flows, as they only use observed data; therefore, CSA and slope data will be integrated to calculate potential channel conveyance and discharge capacity at bankfull conditions (EA, 2003).

Manning's equation (see equation 7) was rearranged to estimate roughness; however, values were often unrealistically high (>1), reflecting sensitivity under shallow, low-velocity conditions where vegetation, obstructions and channel irregularity increase resistance (Arcement and Schneider, 1989). As the equation assumes steady, uniform flow at higher stages, its application to low-flow conditions introduces uncertainty (Limerinos, 1970). A representative roughness value (n = 0.045) was thus selected using Chow's classifications based on observed channel characteristics (Chow, 1959) (see Appendix 5). Estimated discharge capacity was calculated using Manning-based formulations to assess channel conveyance under bankfull conditions, supporting FRM assessment guidance (Rantz, 1982; DEFRA, 2019).

$$K = \frac{AR^{2/3}}{n}$$

Equation 7 – The channel conveyance capacity equation derived from Manning's, where: K is conveyance (m^3/s), A is cross-sectional area, R is hydraulic radius (m), and n is Manning's roughness coefficient (unitless in SI form). Comparing upstream and downstream conveyance enabled evaluation of how leaky dams influence flow efficiency and attenuation potential (Zhuang et al., 2025).

Conveyance is influenced by vegetation and sediment deposition, channel irregularity, and in-channel obstructions, highlighting the importance of both channel form and roughness in determining flow capacity (equation 8) (DEFRA, 2019).

$$Q_{est} = KS^{1/2}$$

Equation 8 - where Q_{est} is estimated discharge capacity (m^3/s) and S is channel slope (m/m) (DEFRA, 2019).

Measured discharge reflects observed low-flow conditions, while estimated discharge represents potential channel capacity derived from conveyance and slope. Upstream and downstream comparisons were used to assess how LD's influence flow capacity and attenuation downstream (Zhuang et al., 2025).

5.2 RQ2

5.2.1 Catchment delineation

Catchment delineation was undertaken using a LiDAR Composite Digital Terrain Model (DTM) (1m resolution) and processed in ArcGIS Pro (DEFRA, 2023). High-resolution data was used to capture fine-scale topographic controls on flow routing, critical for representing headwater systems and NFM features (Hill et al., 2026).

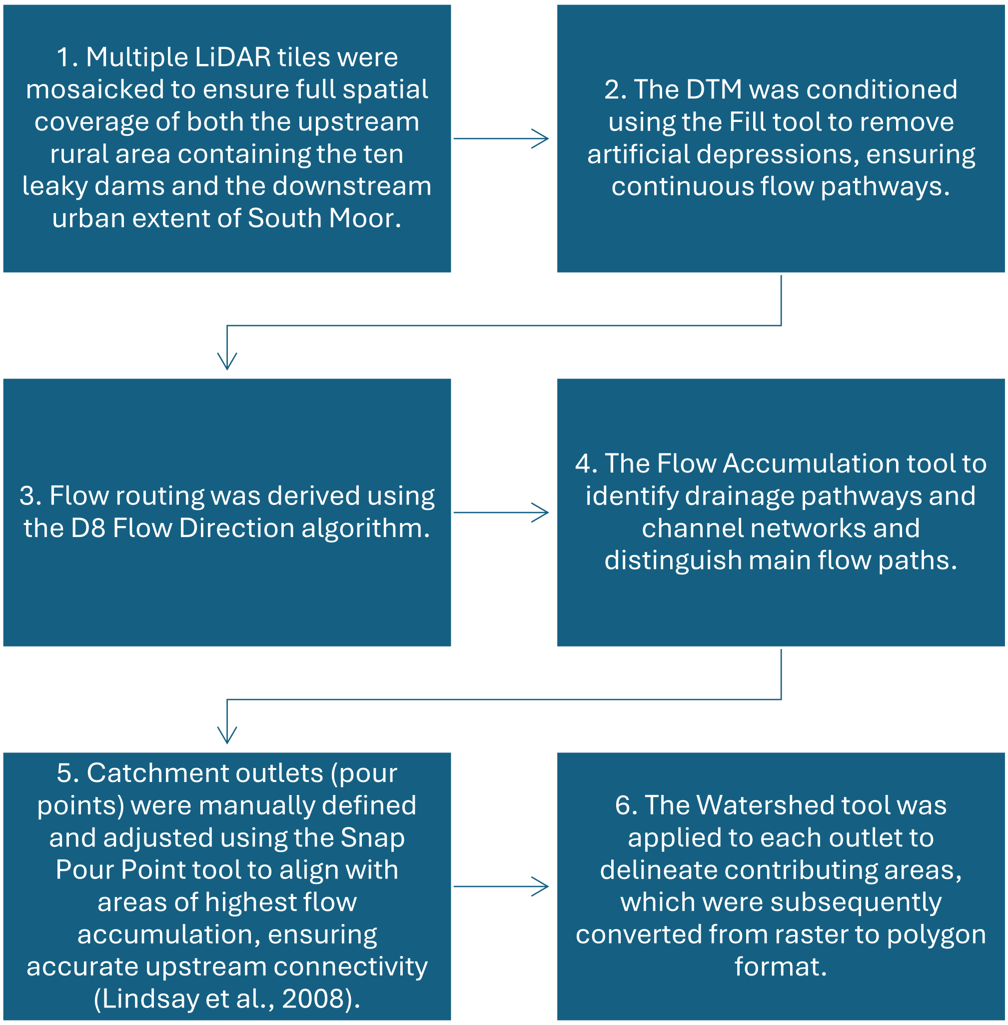


Figure 10 - Catchment delineation workflow in ArcGIS Pro, enabling multi-scale assessment of leaky dam impacts from reach to catchment scale (Lindsay et al., 2008).

Two nested catchments were produced: a small upstream sub-catchment containing the LD network (354,077m^2) and a larger catchment (1,908,837m^2) encompassing South Moor; this nested delineation approach enables comparison between localised hydrological responses and cumulative downstream impacts (Betterle and Botter, 2021). Delineated boundaries informed model extent and runoff scaling (see appendix 6).

5.2.2 Rainfall-discharge translation

Hourly rainfall data was obtained from the UK Met Office MIDAS dataset (CEDA, 2025) using three gauges in proximity to the catchment: Chopwell Wood, Durham and Newcastle. Thiessen polygon analysis using ArcGISPro was used to determine the proportional area of the catchment associated with each gauge as outlined by Hwang et al., 2020. Although Chopwell Wood represented ~58% of the catchment, its short record (4 years) the minimum record length recommended for robust extreme value analysis (typically ~30 years) and so was excluded (Institute of Hydrology, 1999). This decision was supported through comparison of overlapping periods, where summary statistics of rainfall characteristics were found to be broadly consistent with Durham (1997-2024) and Newcastle (1974-2005), indicating that exclusion did not introduce high levels of systematic bias in rainfall magnitude estimation.

Time of concentration (Tc) was derived to estimate flow travel time for both catchment scales, to identify the critical storm duration that maximises peak flow (Bruce et al., 2016). While multiple empirical methods exist, the Watt and Chow (1985) equation was selected due to its applicability across a range of catchment sizes and slopes, enabling consistent comparison between reach- and catchment-scale responses (Perdikaris et al., 2018).

$$Tc = 0.0014\left(\frac{L_c}{\sqrt{S_c}}\right)^{0.79}$$

Equation 9 – Watt and Chow (1985) formula for Time of Concentration, whereby. $L_c$represents the longest flow path length (m), derived from GIS delineation of the catchment. $S_c$is the average channel slope (m/m), calculated as the elevation difference between the catchment headwater and outlet divided by L_c. Time of concentration (T_c) is expressed in hours. See appendix 7 for calculations.

This provides a physically based estimate of catchment response time, avoiding reliance on fixed empirical constants used in simplified unit hydrograph approaches (Gericke and Smithers, 2014). The upstream sub-catchment showed a rapid response (~1 hour), while the larger catchment responded over longer durations (~3 hours), reflecting scale-dependent lag effects including urban drainage, storage and routing (Black et al., 2021). Rainfall extremes were analysed using an Annual Maxima Series (AMS) approach following FEH guidance (SEPA, 2022). Rolling rainfall totals (1- and 3-hour) were calculated, from which AMS datasets were extracted, yielding 28 years of data for Durham and 32 years for Newcastle, sufficient for robust frequency analysis (Institute of Hydrology, 1999) (see Appendix 8). The steps taken to transform rainfall to discharge hydrographs are summarised below:

Step	Key Equations	Description and justification	Limitations/ Assumptions
Step 1: Ranking of extremes		Largest rainfall event per year extracted for 1-hour and 3-hour durations, ensuring independence of extremes and reducing clustering bias; AMS values ranked in ascending order to enable probability-based analysis and L-moment estimation (Institute of Hydrology, 1999)	Sensitive to record length and ignores secondary extreme events within a year potentially underrepresenting variability (SEPA, 2022).

Step 2: L-moment estimation	$b_r = \frac{1}{n}\sum_{i=1}^{n} x_{(i)} \left(\frac{i-1}{n-1}\right)^r$ $t = \frac{L_2}{L_1}, t_3 = \frac{L_3}{L_2}$	$x_{(i)}$: ordered rainfall values; n: sample size; r: moment order. L-moments: L_1(mean), L_2(scale), L_3(skewness). Ratios: $t = L_2/L_1$, $t_3 = L_3/L_2$, used to describe variability and asymmetry (Namitha and Ravikumar, 2018)	Assumes stationarity and can be sensitive to small sample sizes (Hosking, 1990).
Step 3: GEV parameter estimation and extreme rainfall calculation	$X_T = \mu + \frac{\sigma}{\xi}\left[(-\ln(-p))^{-\xi} - 1\right]$	X_T : rainfall depth for AEP p; μ: location (L_1); σ: scale (L_2); ξ: shape (from t_3 and controls tail behaviour). Provides rainfall estimates across a range of AEPs using L-moment-derived parameters (Hosking and Wallis, 1997)	Assumes GEV distribution adequately represents extremes; shape parameter highly sensitive to skewness and sample variability (Syafrina et al., 2019).
Step 4: Uncertainty estimation and propagation	Mean uncertainty (t-distribution): $\mu \pm t_{\alpha/2,n-1}\frac{s}{\sqrt{n}}$ Standard deviation uncertainty (chi-square): $\sigma^2 = \frac{(n-1)s^2}{\chi^2}$	(s): sample standard deviation; (n): sample size. Uncertainty incorporated to account for skewed hydrological extremes, defining bounds for GEV parameters (Montgomery and Runger, 2018)	Assumes approximate normality for mean estimation; uncertainty increases with small sample sizes (UKCEH, 2025).
Step 5: Design events (AEP)		Rainfall estimated for 50%, 10%, 3.33%, 1% and 0.5% AEP events, reflecting both NFM operational ranges and UK flood risk practice (EA, 2022)	Higher magnitude (low AEP) events are associated with greater uncertainty (Villamizar et al., 2024).
Step 6: Spatial rainfall weighting	$w_i' = \frac{w_i}{\sum w_i}$ $R_{combined} = \sum w_i' R_i$	Rainfall estimates combined using renormalised Thiessen weights after excluding short-record gauges, maintaining spatial representativeness (Lee et al., 2018).	Assumes spatially uniform rainfall within each polygon and introduces sharp, non-physical boundaries between gauges, limiting its ability to represent spatial rainfall variability. Spare or uneven networks increase uncertainty (Han and Bray, 2006).

Step 7: Hyetograph construction	∑P=1	Observed rainfall events (2-minute data) normalised and scaled using GEV depths, preserving realistic temporal structure instead of synthetic storms	Limited number of observed events may restrict variability.
Step 8: Effective rainfall	Pe(t)=Cr × P(t)	(C_r): runoff coefficient; (P(t)): rainfall at time (t). Represents catchment losses; sensitivity testing applied (Son and Kwon, 2022)	Sensitive to runoff coefficient selection and antecedent conditions (Son and Kwon, 2022).
Step 9: Runoff timing	$t_{cm} = \frac{\sum P_e(t) \times t}{\sum P_e(t)}$ $T_p = T_c + t_{cm}$ $T_b = T_p + T_c$	Temporal centroid defines rainfall timing; time to peak combines rainfall timing and travel time; base time represents total hydrograph duration (Black et al., 2021).	Assumes simplified, linear response behaviour.
Step 10: Unit hydrograph	$Q_p = \frac{2V}{T_b}, V = A \times 0.001$	(Q_p): peak discharge; (V): runoff volume; (A): catchment area.	Simplifies real hydrograph shape and routing processes (Boorman and Reed, 1981).
Step 11: Flow routing (convolution)	$(Q(t) = \sum P_e(i) \times UH(t-i)$	Effective rainfall routed through time using convolution, producing discharge hydrographs for Flood Modeller Pro, consistent with FEH methods (Institute of Hydrology, 1999)	Assumes linear system response; does not capture turbulence, sediment or dynamic channel feedbacks (Boorman and Reed, 1981)

Table 8 - Transformation of observed rainfall into discharge hydrographs, in line with the Flood Estimation Handbook (Institute of Hydrology, 1999).

The result is a continuous discharge hydrograph for each return period and uncertainty bound as input to FMP (see appendix 9).

5.2.3 Model setup

Model simulations were undertaken in FMP using a 1m resolution LiDAR DTM clipped to delineated catchment boundaries. Upstream inflow points were defined at the highest point of channel connectivity to capture all contributing flow paths, with a downstream free outfall (slope: 0.001) applied to minimise artificial backwater effects while maintaining numerical stability (DEFRA, 2023). A timestep of 60 seconds was selected following Wolstenholme et al., 2025), balancing computational efficiency with accurate representation of short-duration flow routing, as longer timesteps may smooth peak flows and underestimate attenuation. LD's were represented by modifying the DTM (raised topography) and embedding 1D culvert elements within the 2D domain, a commonly adopted approach in wider modelling studies (Senior et al., 2022). Two culverts per dam were used to reflect distributed flow pathways rather than idealised single openings (Senior and Willis, 2022). Gap dimensions were derived from field measurements using Scaniverse and converted to equivalent circular diameters (Appendix 10). While practical, this simplification introduces uncertainty as natural gaps are irregular (Miranzadeh et al., 2022). A uniform Manning's roughness (n = 0.045) was applied across the reach, with higher values (0.16) assigned to culverts to represent additional resistance of LD's based on existing studies (Wolstenholme et al., 2025). Assumptions including uniform roughness, culvert representation, grid resolution and boundary conditions introduce uncertainty and were therefore evaluated through sensitivity testing (Dakhlalla and Parajuli, 2019).

Simulations were run for 50%, 10%, 3.33%, 1% and 0.5% AEP events under baseline and LD scenarios, including lower, central and upper rainfall bounds. Inflow hydrographs were applied, with runtimes extended to capture the full hydrograph response (Wolstenholme et al., 2025). Identical inflows were used at both upstream points for the larger catchment due to similar CSA and velocity (Appendix 3); however, these were based on a single survey (July), introducing uncertainty in representing wider flow variability. Model setup is shown in Appendix 11. Outputs were analysed in ArcGIS Pro to quantify flood depth, extent and time to peak magnitude at the outlet, defined here as the point of maximum depth and extent before the onset of hydrograph recession. Model validation was undertaken by comparing simulated 200-year flood extents (no dams) with EA flood zones and local observations.

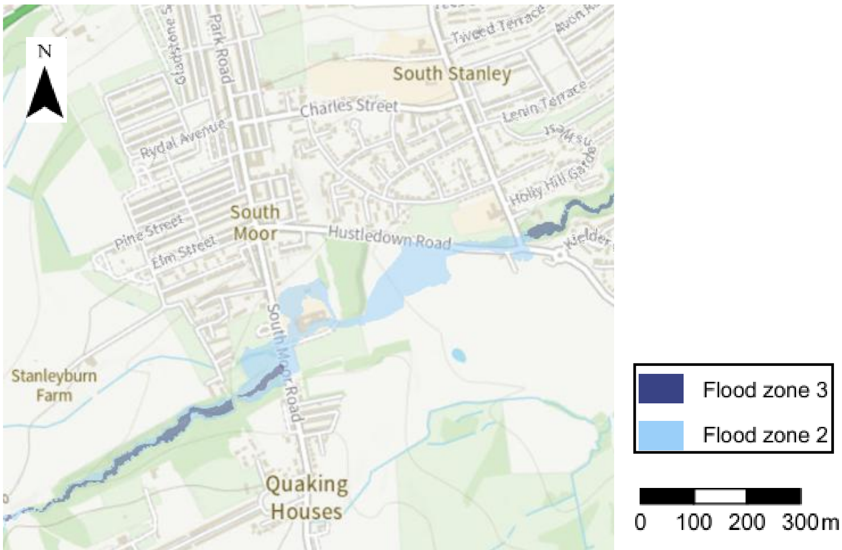


Figure 11 - EA Flood Map for Planning showing Flood Zone 3 (≥1% annual probability) and Flood Zone 2 (0.1-1% AEP) under present-day conditions. The modelled 1-in-200-year flood extent (0.5% AEP) falls within the probability range represented by Flood Zone 2 and is therefore used as a representative event for validation against this zone.

5.3 RQ3

5.3.1 Future Rainfall projections

Future rainfall projections were derived from UKCP18 convection-permitting regional climate model outputs (2.2 km resolution), using three ensemble members to represent projection uncertainty (Met Office, 2018) (see Appendix 12). Ensemble use captures uncertainty through spread rather than reliance on a single projection (Du, 2007). Hourly precipitation was extracted for five time periods (1981-2000 to 2061-2080) to capture short-duration rainfall driving peak runoff in small catchments. Although regridded to 5km, introducing some smoothing, this resolution remains widely used in hydrological studies, due to its ability to resolve convective extremes, despite all projections being driven by RCP8.5, representing a high-end scenario ((Asher et al., 2025). Extreme rainfall was estimated using a Gumbel-based frequency factor approach (Svensson and Jones, 2010).

A $$y_T = -\ln\left(-\ln\left(1 - \frac{1}{T}\right)\right)$$

B $$K_T = 0.7797 y_T - 0.45$$

C $$R_T = \bar{x} + K_T s$$

Equation 10A, B and C - Gumbel (Extreme Value Type I) frequency factor method used to estimate return period rainfall, where y_T is the reduced variate, K_T is the frequency factor, and R_T is the design rainfall from the sample mean $\bar{x}$ and standard deviation s of maximum hourly precipitation derived from UKCP18 data. The constants used in the frequency factor formulation (0.7797 and −0.45) are derived from the statistical properties of the Gumbel (Extreme Value Type I) distribution, which relates the mean and standard deviation of a dataset to its extreme value behaviour (Kite, 1977).

This method, widely used in hydrological frequency analysis, enables consistent estimation of extremes without direct parameter fitting from climate model outputs where only summary statistics are available (Kite, 1977; Betül, 2006). Change factors were derived by comparing future and baseline conditions and applied multiplicatively to observed rainfall from AMS L-moment analysis (Appendix 13). Projection uncertainty was incorporated using the 5th, 50th and 95th percentiles to define lower, central and upper bounds. Scaled rainfall was converted to discharge using the rainfall-discharge translation process used in RQ2 with hydrographs used as inputs to the FMP model (Appendix 14). Simulations were run across all AEPs, time periods and uncertainty bounds, with and without LD's. Outputs were analysed in terms of maximum flood depth, extent and time to peak magnitude to assess how climate change influences flood behaviour and LD effectiveness.

5.4 RQ4

5.4.1 Flood risk management scheme design

High-risk areas identified from model outputs were used to inform the design and costing of mitigation strategies combining NFM and hard-engineered measures. Simulations were undertaken for all climate scenarios, with analysis focused on the 3.33% and 1% AEP events, reflecting standard UK design thresholds for urban drainage and fluvial flood defence assessments (EA, 2022; DEFRA, 2025). Model outputs were exported to ArcGIS Pro, where flood depths and extents were intersected with OS OpenMap Local infrastructure datasets to estimate damage (OS, 2025).

5.4.2 Depth-damage estimation

Depth-damage relationships were applied to estimate economic flood damages across the South Moor study area using the European Commission dataset developed by Huizinga et al., 2017. Polynomial depth-damage functions were fitted to UK-specific curves for each asset class, describing the relationship between flood depth (m) and economic damage per unit area (*D*, £/m^2). The resulting functions are:

A $$D_{road}(flood\ depth) = -1.259h^2 + 13.251h + 2.134$$

B $$D_{residential}(flood\ depth) = -35.60h^2 + 409.34h + 85.29$$

C $$D_{commerical}(flood\ depth) = -38.98h^2 + 448.22h + 93.40$$

Equation 11 - Depth-damage equations for input in ArcGIS Pro. A). Roads, B). Residential buildings and C). Commercial (non-residential buildings). Values were converted from euros (2010 prices) to pounds and adjusted to 2026 using an *average annual inflation rate of 2.82%, resulting in maximum damages of £14.99/m² (roads), £2010/m² (residential), and £2201/m² (commercial/non-residential) infrastructure such as the local school or playing fields.*

This approach assumes uniform vulnerability within each land-use class and does not account for variation in building characteristics like internal property resilience or changing depth-damage functions and inflation in the future (Huizinga et al., 2017).

5.4.3 Cost calculation

Cost-benefit ratios (CBR's) were calculated by comparing scheme costs with estimated damage reduction, enabling evaluation of NFM, hard and hybrid approaches under present and future conditions.

Measure	Basis	Unit cost (2026)
Leaky dams	per dam	£194/dam
Detention basin 1	per m^3	£25/m^3
Detention basin 2	per m^3	£25/m^3
Offline storage basin	per m^3 (power-law cost function)	$15{,}370V^{-0.628}$
Retention pond	per m^3	£22/m^3
Flood wall	per metre	£4,000/m

Table 9 - Estimated capital costs of flood mitigation measures under 2026 price conditions for the South Moor catchment. Costs are presented for individual components (leaky dams, types of storage and flood wall) and aggregated for the hard, NFM, and hybrid schemes. Unit rates are derived from 2015 literature values and adjusted to 2026 using inflation, with offline storage costs calculated using an inflation-adjusted power-law relationship (DEFRA, 2015).

While EA guidance includes whole-life costing, maintenance and decommissioning were excluded to ensure consistency, as NFM costs remain highly variable and lack standardised unit rates compared to engineered defences (EA, 2015). Only capital costs were therefore used for direct comparison. This introduces uncertainty, as whole-life costs may be underestimated and wider ecosystem benefits are not captured, potentially undervaluing NFM benefits. Using the results, recommendations for FRM for decision-makers going forward including the Wear Rivers Trust SuDS+ scheme to boost resilience of the local community and South Moor in the future.

6 Results

6.1 RQ1

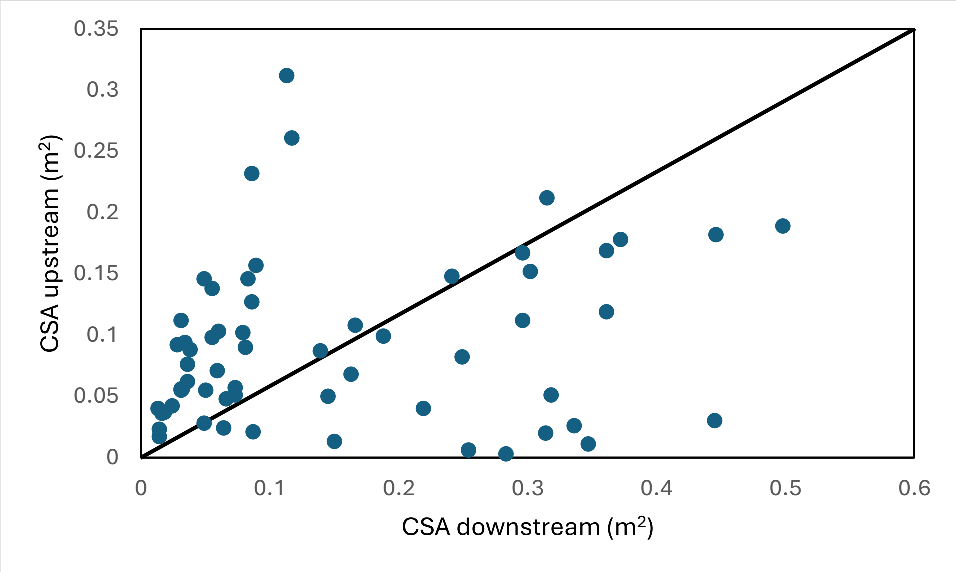


Figure 12 – Scatter plot of upstream and downstream cross-sectional area (CSA) across all sites and sampling periods. The 1:1 line denotes equal values, allowing visual assessment of differences in channel morphology between upstream and downstream locations. Each point represents a paired observation from the same site and sampling period.

Figure 13 shows variability in upstream and downstream CSA across the reach, with points distributed around the 1:1 line. Smaller cross sections (<0.1 m^2) are generally larger upstream, while larger sections (>0.2 m^2) are more often greater downstream. A paired two-tailed t-test indicates a significant difference between upstream and downstream CSA ($t = 3.70 > t_{crit} = 1.999, p = 0.001 < 0.05$). Mean CSA was 0.091 ± 0.010m^2 upstream and 0.151 ± 0.016m^2 downstream, although variability between sites remains. However, site-level results in table 3 show this pattern is not uniform.

LD	Upstream CSA (m^2)	Downstream CSA (m^2)	Δ CSA (m^2)
1	0.057 ± 0.009	0.069 ± 0.003	-0.011
2	0.065 ± 0.013	0.027 ± 0.004	+0.037
3	0.057 ± 0.014	0.025 ± 0.003	+0.029
4	0.105 ± 0.020	0.067 ± 0.012	+0.036
5	0.156 ± 0.050	0.129 ± 0.011	+0.034
6	0.100 ± 0.015	0.048 ± 0.005	+0.050
7	0.016 ± 0.004	0.330 ± 0.027	-0.312
8	0.082 ± 0.018	0.145 ± 0.028	-0.065
9	0.148 ± 0.021	0.393 ± 0.027	-0.241
10	0.128 ± 0.025	0.280 ± 0.014	-0.152

Table 10 – Mean upstream and downstream CSA for each leaky dam site. Values represent mean CSA (m^2) ± standard error based on repeated measurements across all sampling periods (January-July).

Dams 2-6 generally show greater upstream CSA, whereas Dams 7-10 show substantially greater downstream CSA. For example, Dam 6 has greater upstream CSA (+0.050m^2), while Dam 7 shows much larger downstream CSA (-0.312m^2).

Grouping classification	Number of groups (k)	Degrees of freedom (df)	H statistic	X^2 critical value (α=0.05)	p-value	Significant?
Dam type (LD 4, 8, 9 and 10: natural woody debris dams, LD 6 and 7 = wooden boarded dams and LD 1, 2, 3 and 5: geotextile-assisted dams)	3	2	12.70	5.99	0.002	Yes
Dam size (>1m : LD 1, 2, 3, 8, 9, 10 and <1m: LD 4, 5, 6 and 7)	2	1	3.00	3.84	0.083	No
Proximity (LD 2, 7, 9 <10m after previous dam and LD 1, 3, 4, 5 and 6 are >10m apart from the previous dam	2	1	22.5	3.84	<0.001	Yes

Table 11 – Kruskal-Wallis test results to assess whether dam characteristics exert a control on observed changes in cross-sectional area (ΔCSA) upstream and downstream of leaky dams over the sampling period.

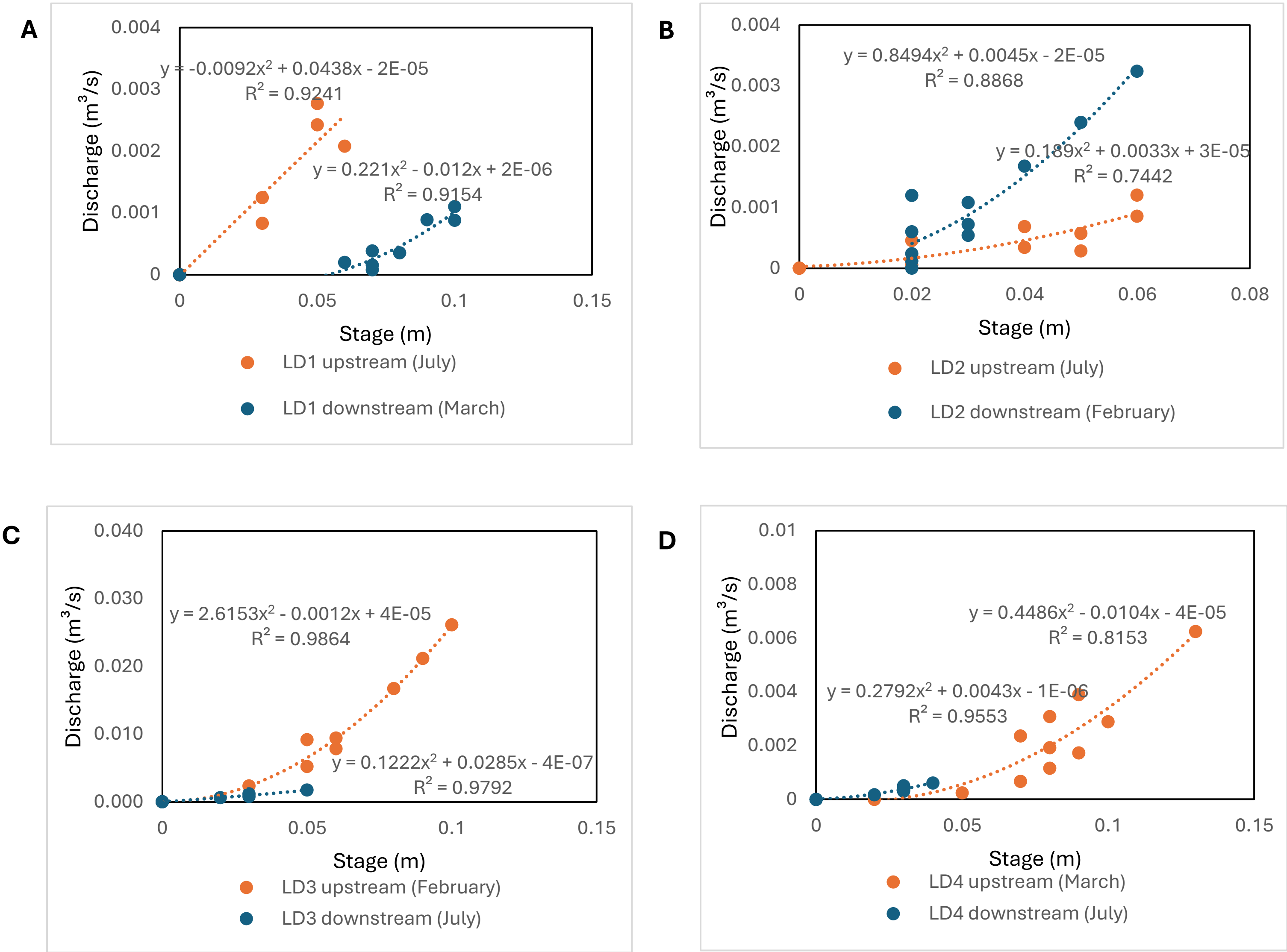
Dam type shows a significant effect (H = 12.70 which exceeds the critical threshold value of 5.99, p = 0.002 < 0.05), while dam proximity produces the strongest statistical signal ($H = 22.5 > t_{crit} = 3.84, p < 0.001$. In contrast, dam size is not statistically significant (H = 3.00 < 3.84 and p = 0.083 > 0.05), meaning the null hypothesis cannot be rejected. While

CSA provides a measure of morphological adjustment, changes in velocity reflect flow characteristic variability and discharge acts as a link between the two, allowing assessment of how channel form and flow interact.

Dam	Δ Velocity (m/s)	Δ Discharge (m^3/s)	Slope
1	-0.009	-0.002	0.006
2	-0.032	-0.010	0.009
3	-0.036	-0.010	0.013
4	-0.028	-0.006	0.008
5	-0.029	-0.006	0.011
6	-0.043	-0.011	0.006
7	-0.023	-0.007	0.015
8	-0.028	-0.007	0.003
9	-0.030	-0.009	0.006
10	-0.030	-0.008	0.006

Table 12 - Mean absolute differences (Δ: upstream − downstream) in CSA, velocity, and discharge for each leaky dam site averaged over the sampling periods is summarised here. Positive values indicate greater upstream values, while negative values indicate greater downstream values.

Table 12 indicates velocity consistently decreases downstream of all LD's (negative values). Discharge also shows a consistent downstream decrease, but less than velocity. Average slope was 0.0086 ± 0.0037m/m. Channel slope varies across sites (0.003-0.015 m/m) but does not show a proportional relationship with changes in velocity or discharge.



A
0.004
0.003
0.002
0.001
0
Discharge (m3/s)
y = -0.0092x² + 0.0438x - 2E-05
R² = 0.9241
y = 0.221x² - 0.012x + 2E-06
R² = 0.9154
0
0.05
0.1
0.15
Stage (m)
LD1 upstream (July)
LD1 downstream (March)
B
0.004
0.003
0.002
0.001
0
Discharge (m3/s)
y = 0.8494x² + 0.0045x - 2E-05
R² = 0.8868
y = 0.189x² + 0.0033x + 3E-05
R² = 0.7442
0
0.02
0.04
0.06
0.08
Stage (m)
LD2 upstream (July)
LD2 downstream (February)
C
0.040
0.030
0.020
0.010
0.000
Discharge (m3/s)
y = 2.6153x² - 0.0012x + 4E-05
R² = 0.9864
y = 0.1222x² + 0.0285x - 4E-07
R² = 0.9792
0
0.05
0.1
0.15
Stage (m)
LD3 upstream (February)
LD3 downstream (July)
D
0.01
0.008
0.006
0.004
0.002
0
Discharge (m3/s)
y = 0.4486x² - 0.0104x - 4E-05
R² = 0.8153
y = 0.2792x² + 0.0043x - 1E-06
R² = 0.9553
0
0.05
0.1
0.15
Stage (m)
LD4 upstream (March)
LD4 downstream (July)

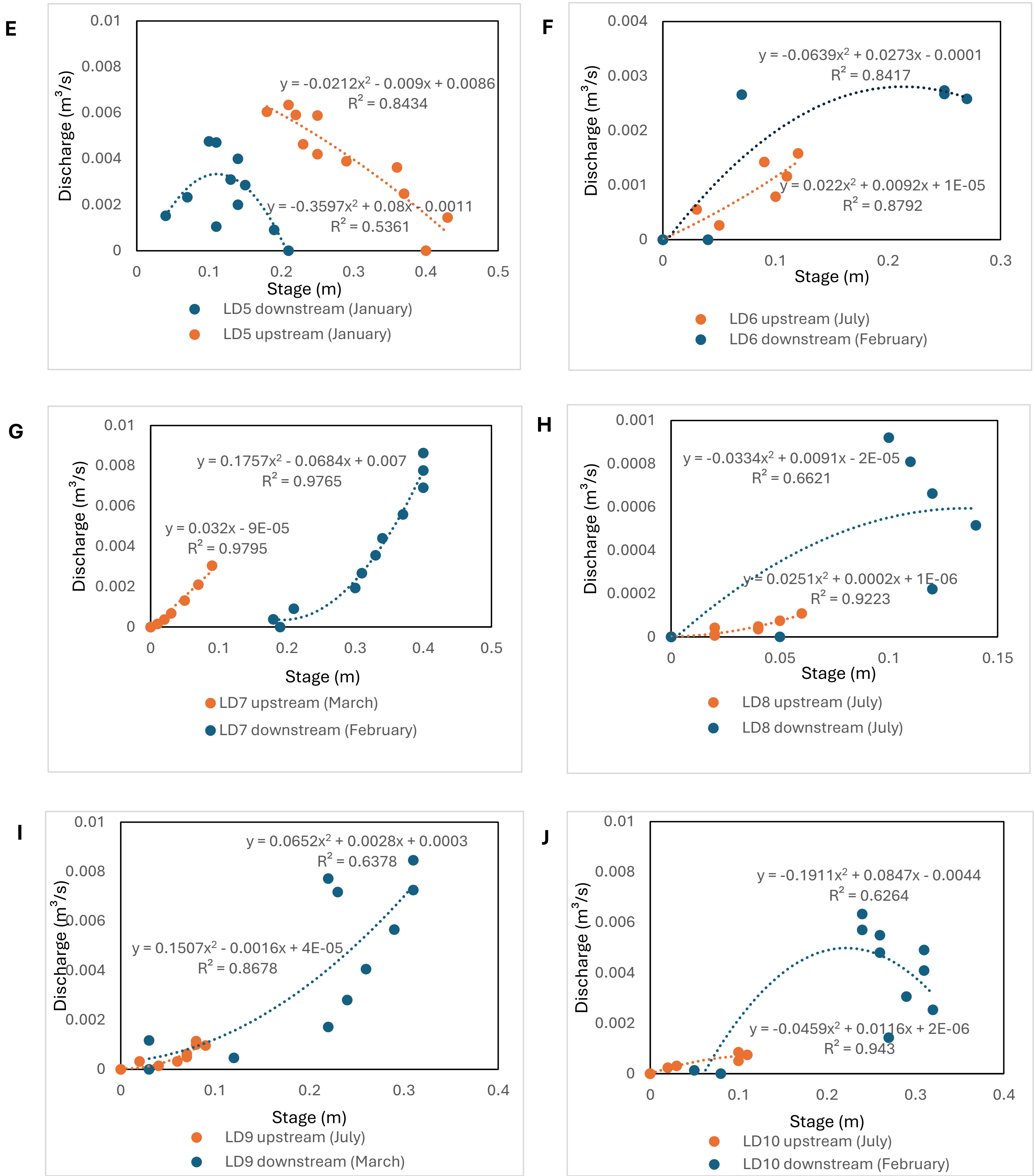


Figure 13 – Stage-discharge scatter graphs for upstream and downstream reaches at each leaky dam site. (A-J) represent leaky damns 1-10 respectively. Polynomial curves are fitted to measured data, with equations and coefficients of determination (R^2) shown for each relationship. See appendix 15 for complete results.

Stage-discharge relationships vary between sites, with no consistent upstream-downstream pattern. Some dams show steeper downstream responses, like LD2, while others are steeper upstream, like LD3. At several sites, including LD5 and LD6, relationships are irregular despite moderate R² values (~0.54-0.84), indicating instability. Winter-derived relationships are generally steeper and more coherent.

Dam	Upstream best predictor	R^2	Downstream best predictor	R^2
1	7-day	0.2615	3-day	0.6321
2	3-day	0.5993	1-day	0.6727
3	1-day	0.4046	1-day	0.6296
4	1-day	0.6228	3-day	0.5127
5	3-day	0.4135	1-day	0.0902
6	1-day	0.5458	7-day	0.799
7	1-day	0.4851	7-day	0.2447
8	3-day	0.8393	7-day	0.7486
9	1-day	0.2443	7-day	0.5894
10	7-day	0.1729	3-day	0.2182

Table 13 - Summary of the strongest relationships between antecedent rainfall and discharge response for each site. The rainfall period (1-day, 3-day, 7-day or 1 month) producing the highest coefficient of determination (R^2) is shown for upstream and downstream reaches, indicating differences in the temporal controls on flow behaviour. Appendix 16 shows antecedent rainfall.

However, relationships between antecedent rainfall and discharge response are generally weak to moderate (R^2 = 0.0005-0.799). Upstream responses are more strongly associated with short-term rainfall (1-3 day), whereas downstream responses more frequently correspond to longer antecedent periods (7-day rainfall).

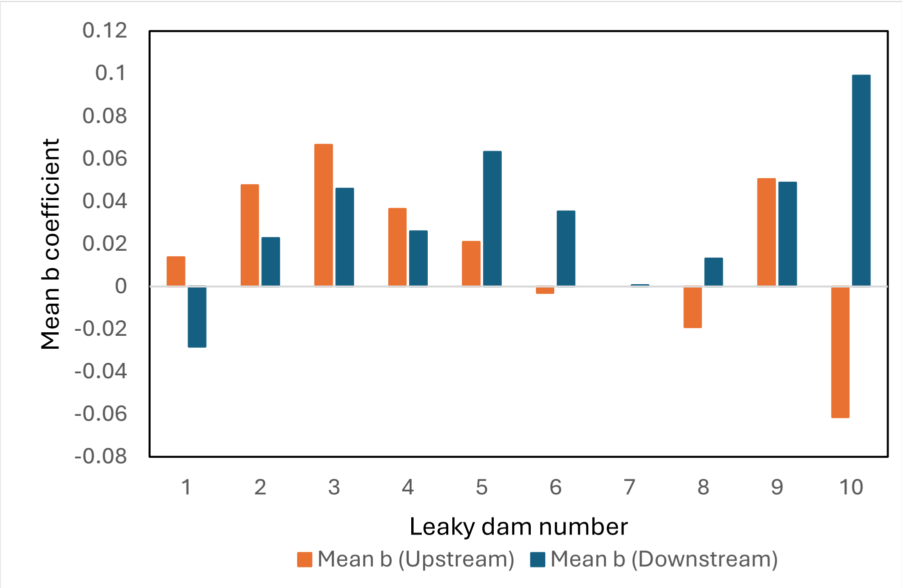


Figure 14 - Mean b coefficients for upstream and downstream reaches at each leaky dam, derived by averaging monthly polynomial stage-discharge relationships across the six sampling months. Higher b values indicate a steeper increase in discharge with stage.

Downstream b values are slightly greater on average (mean difference: 0.0174), but this difference is not statistically significant $(t(59) = 1.12 < t_{crit} = 1.671,\ p = 0.133 > 0.05)$, so the null hypothesis cannot be rejected, indicating that LD's do not produce a consistent downstream increase in stage-discharge sensitivity under current conditions, highlighting the need to further examine channel conveyance.

Dam	Mean upstream conveyance capacity (m^3/s)	Mean downstream conveyance capacity (m^3/s)	Δ in conveyance capacity (upstream - downstream) (m^3/s)	Mean upstream estimated discharge capacity (m^3/s)	Mean downstream estimated discharge capacity (m^3/s)	Δ in estimated discharge capacity (upstream - downstream) (m^3/s)
1	0.208	0.242	-0.034	0.016	0.019	-0.003
2	0.244	0.053	0.191	0.019	0.005	0.014
3	0.209	0.044	0.166	0.020	0.005	0.015
4	0.458	0.263	0.195	0.052	0.023	0.029
5	1.349	0.783	0.566	0.120	0.081	0.039
6	0.579	0.146	0.433	0.061	0.011	0.049
7	0.041	3.009	-2.967	0.003	0.368	-0.365
8	0.380	0.971	-0.591	0.047	0.053	-0.007
9	0.921	3.369	-2.448	0.080	0.290	-0.211
10	0.601	2.224	-1.623	0.047	0.173	-0.126

Table 14 - Mean upstream and downstream channel conveyance capacity (K, m^3/s) calculated using Manning's equation with a fixed roughness value ($n = 0.045$). Differences (ΔK) are calculated as upstream minus downstream, where positive values indicate greater upstream conveyance capacity and negative values indicate greater downstream capacity. Estimated discharge incorporates channel slope and provides an indication of potential flow transmission under higher-stage or near-bankfull conditions.

In the upper reach, Dams 2-6 generally show greater upstream conveyance capacity, indicating downstream flow restriction, while Dams 7-10 show higher downstream capacity. For example, Dam 6 decreases from $0.061 m^3/s$ upstream to $0.011 m^3/s$ downstream, whereas Dam 7 increases from $0.003 m^3/s$ to $0.368 m^3/s$. Dam 1 shows minimal difference ($\Delta Q_{est} = -0.003 m^3/s$).

6.2 RQ2

Fifteen sensitivity trials were conducted to assess the influence of key parameters and identify an optimal set for model validation against observed flood extents.

Trial	Manning's roughness	Outflow coefficient	Grid size (m)	Loss coefficient	Measure of fit (%)
1	0.035	0.001	1	0.5	93.3
2	**0.045**	**0.001**	**1**	**0.5**	**96.0**
3	0.055	0.001	1	0.5	92.7
4	0.075	0.001	1	0.5	90.1
5	0.045	0.002	1	0.5	94.9
6	0.045	0.003	1	0.5	93.7
7	0.045	0.004	1	0.5	92.1
8	0.045	0.001	3	0.5	93.9
9	0.045	0.001	5	0.5	91.5
10	0.045	0.001	10	0.5	89.5
11	0.045	0.001	1	0.3	79.3
12	0.045	0.001	1	0.4	87.9
13	0.045	0.001	1	0.6	89.0
14	0.045	0.001	1	0.7	80.4
15	0.045	0.001	1	0.8	74.2

Table 15 - Sensitivity of model validation performance to changes in key parameters. Parameters include Manning's roughness (n), representing channel resistance to flow; the loss coefficient, applied to discharge hydrographs to scale inflow magnitude; the outflow coefficient, controlling the gradient and conveyance of flow across the floodplain and grid resolution, which determines the spatial representation of topography within the model.

Table 15 indicates model performance is most strongly influenced by the loss coefficient, followed by Manning's roughness and grid resolution. The optimal parameter set highlighted in bold produces the closest spatial correspondence with the EA flood extent, as shown in figure 15.

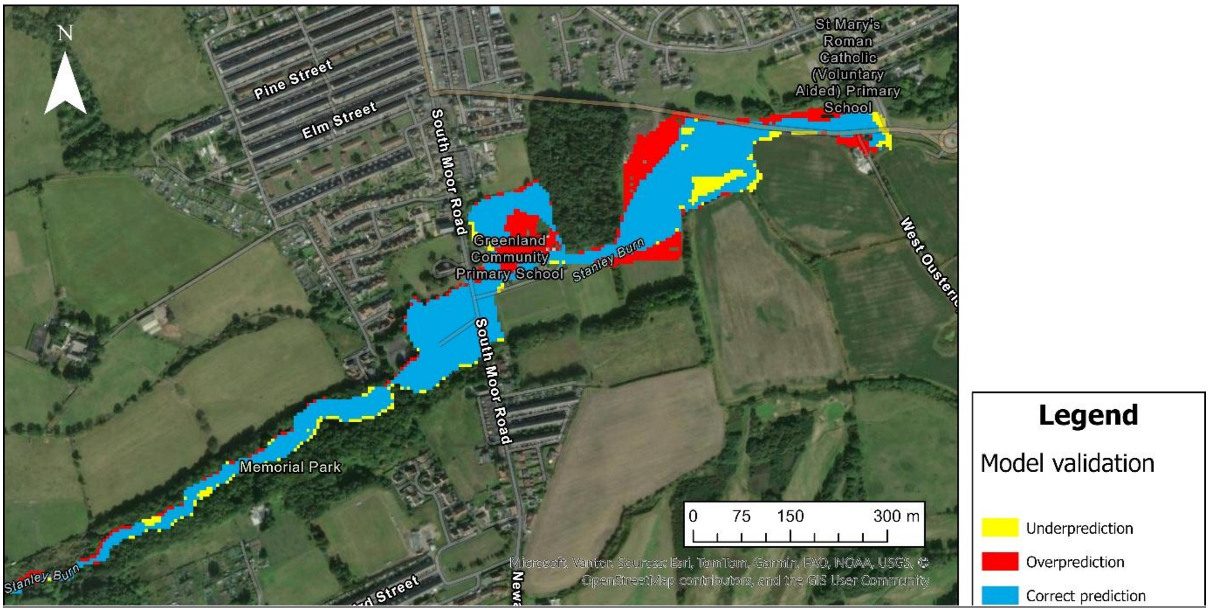


Figure 15 - Model validation comparing the central estimate of simulated flood extent for a 0.5% AEP event under baseline conditions with the Environment Agency Flood Risk Zone mapping. Areas of correct prediction (blue), overprediction (red), and underprediction (yellow) are shown.

Model validation demonstrates a strong agreement between modelled and observed flood extents under baseline conditions. The modelled extent is supported by the observations of local residents with reports of inundation of roads and playing fields nearby the primary school.

TN (0)	23046
FP (1)	297
FN (2)	787
TP (3)	2709
Accuracy	0.96
Precision	0.90

Table 16 - Results from the model validation. True positives (TP) represent areas correctly predicted as flooded, true negatives (TN) represent areas correctly predicted as not flooded, false positives (FP) indicate areas incorrectly predicted as flooded (overprediction) and false negatives (FN) indicate areas where flooding occurred but was not predicted (underprediction).

Table 16 shows the optimised model achieved 96% accuracy and 90% precision, indicating strong agreement between modelled and observed flood extent. The model can therefore be applied with confidence to assess flood depth and extent under baseline scenarios with and without LD's.

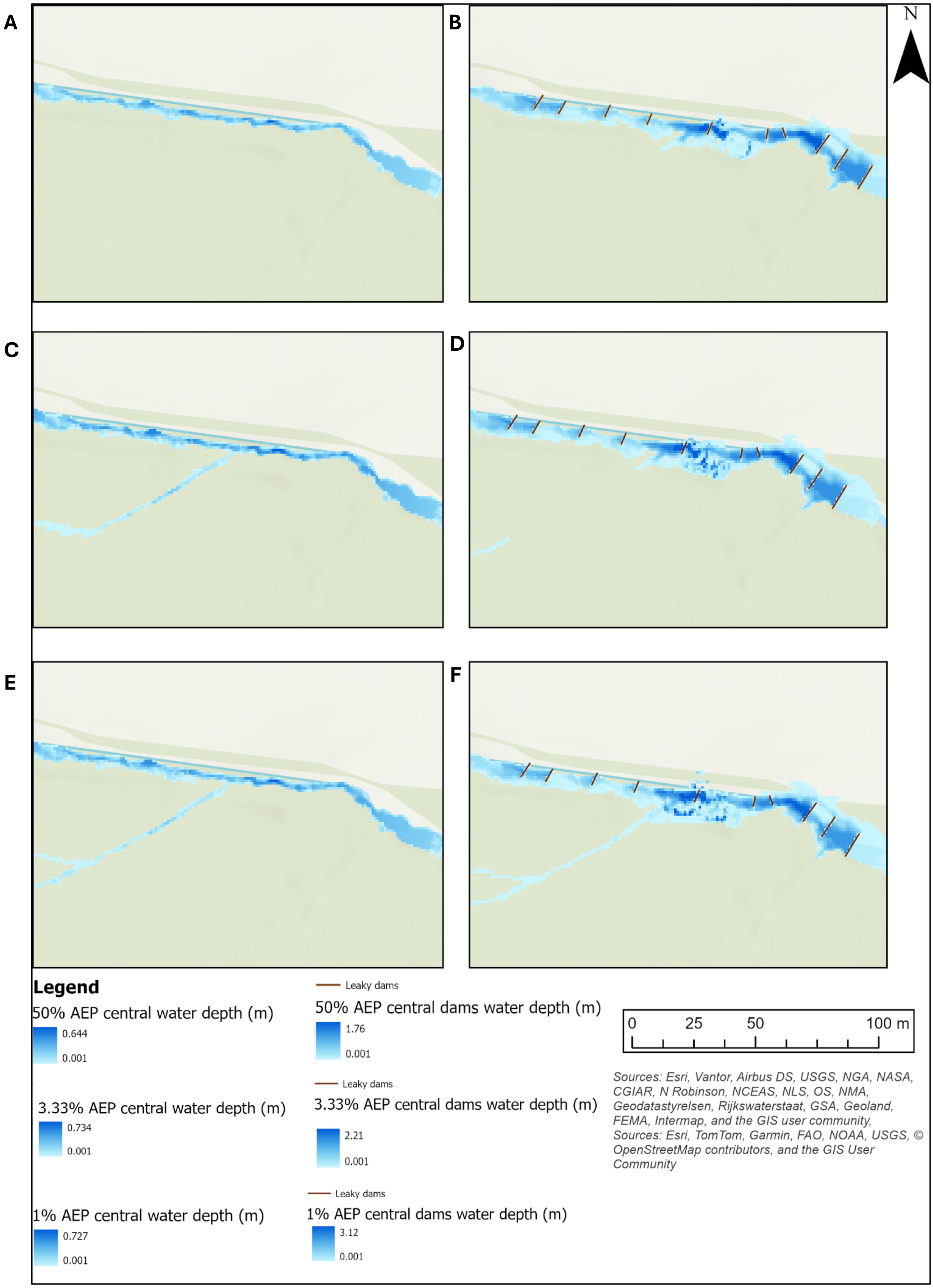


Figure 16 - Modelled maximum flood depth under baseline conditions with no leaky dams (left panels) and leaky dam scenarios (right panels) for 50% AEP (A and B), 3.33% AEP (C and D) and 1% AEP (E and F) events.

Figure 16 shows that without LD’s, floodwater remains largely confined to the channel with shallow depths and limited inundation. With LD’s, deeper upstream ponding occurs, indicating backwater storage, which becomes more extensive with increasing event magnitude. The greatest depth increases occur towards the downstream end of the reach, with expanded inundation and channel connectivity during the 1% AEP event.

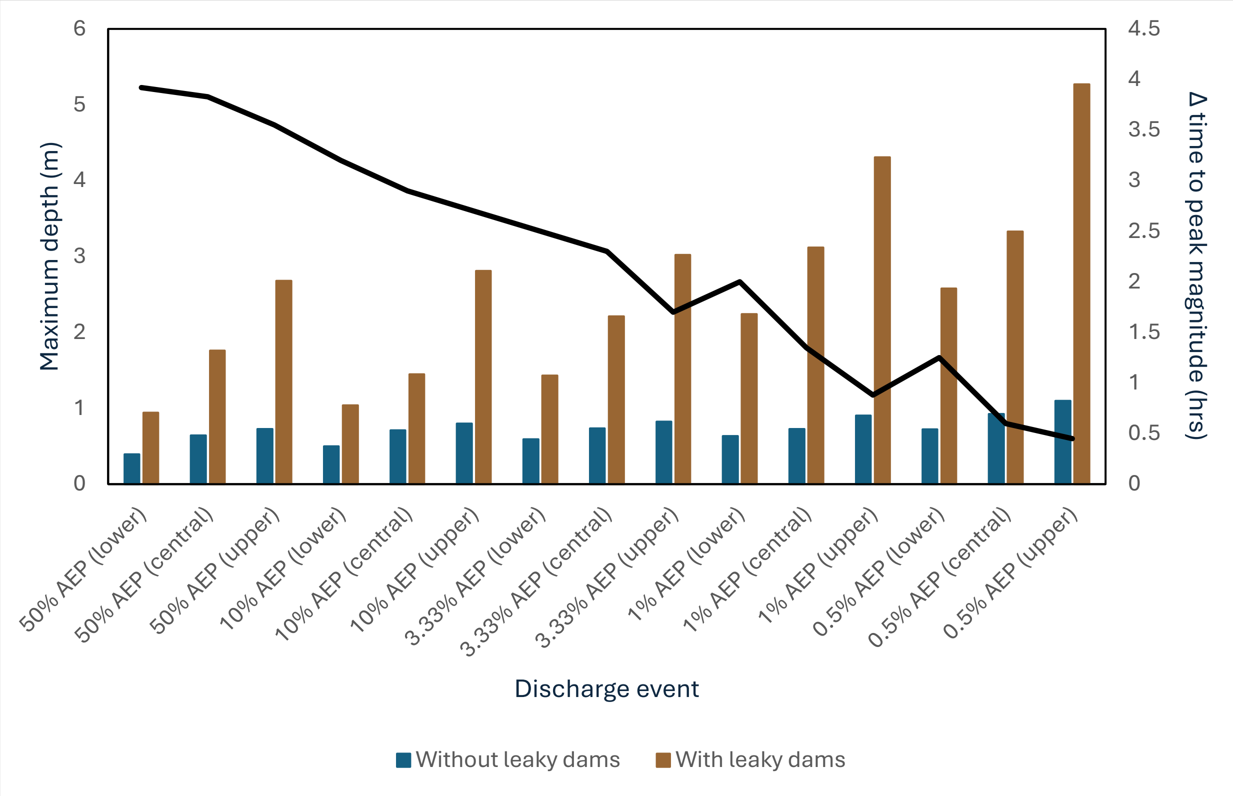


Figure 17 - Maximum flood depth under baseline without leaky dams and with leaky dam scenarios across all return periods and uncertainty bounds at the reach scale. The black line represents the change in time to peak magnitude (maximum depth and extent for the event), calculated as the difference between leaky dam and baseline conditions.

Figure 17 shows maximum depth is consistently higher with LD’s across all events. For example, for 50% AEP events, depths increase from 0.393-0.728 m (no dams) to 0.940-3.15 m (with dams), rising further at 1% AEP from 0.633-0.903 m to 2.24-4.31 m. Time to peak magnitude reduces from ~3.9 hours (50% AEP lower) to 0.45 hours (0.5% AEP upper), indicating diminishing attenuation with increasing event size and remains consistently higher with LD’s (see appendix 17 for all results).

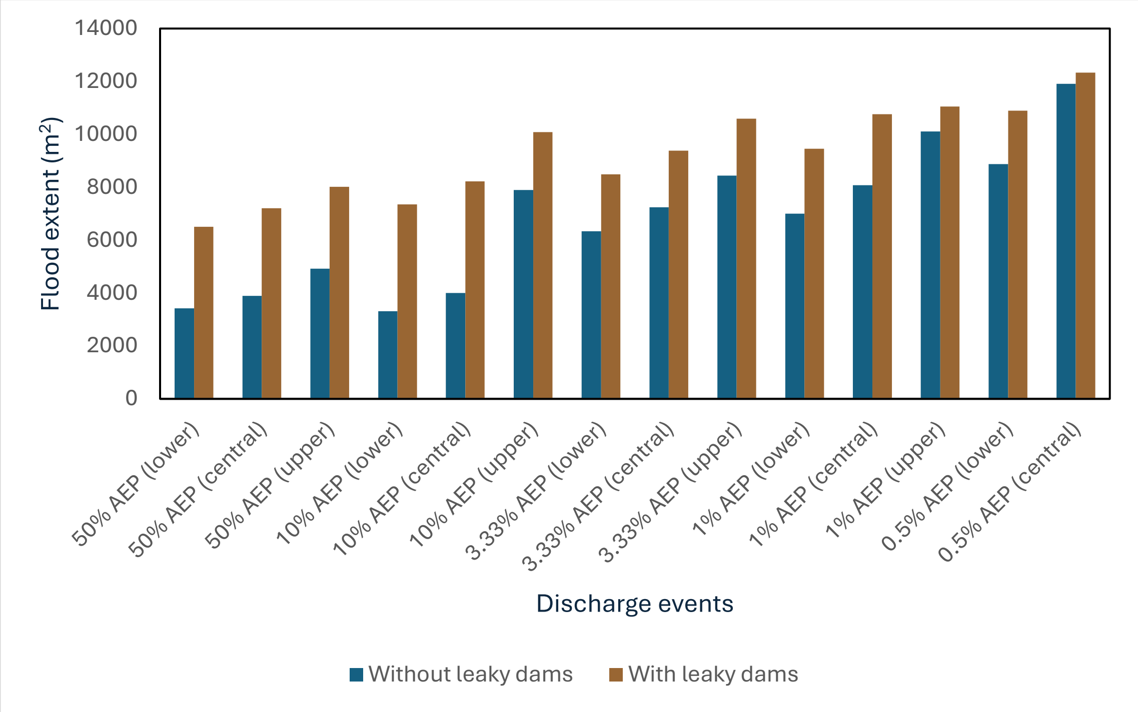


Figure 18 –Flood extent (m^2) under baseline without leaky dams and with leaky dam scenarios across all return periods and uncertainty bounds at the reach scale.

Figure 18 shows that flood extent is greater with LD's at the reach scale, but differences reduce with increasing magnitude (3,086m^2 in the 50% AEP lower event to 432m^2 at 0.5% AEP upper). This convergence indicates that storage capacity is exceeded at higher flows, so the model is extended to the larger catchment scale to assess downstream translation.

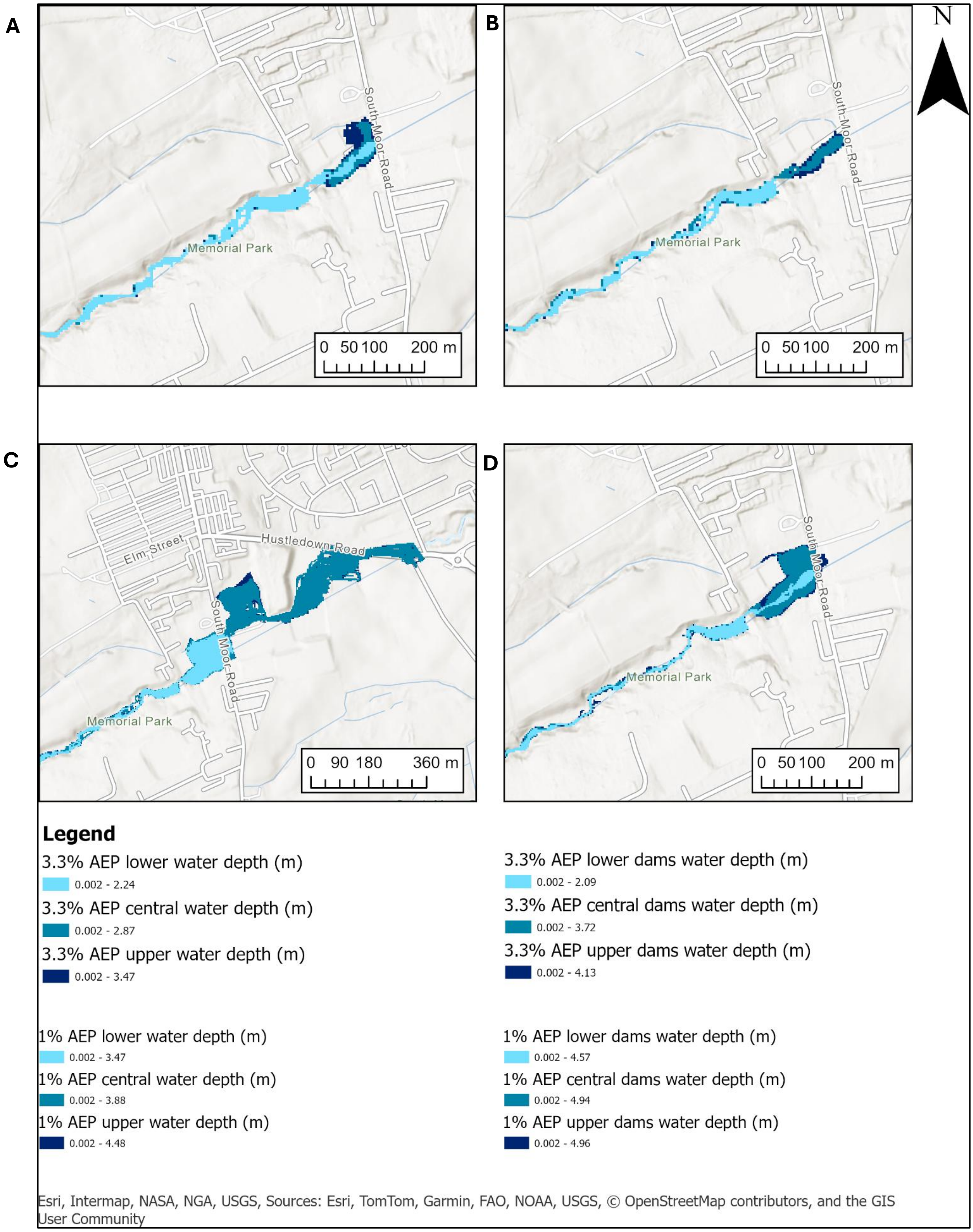
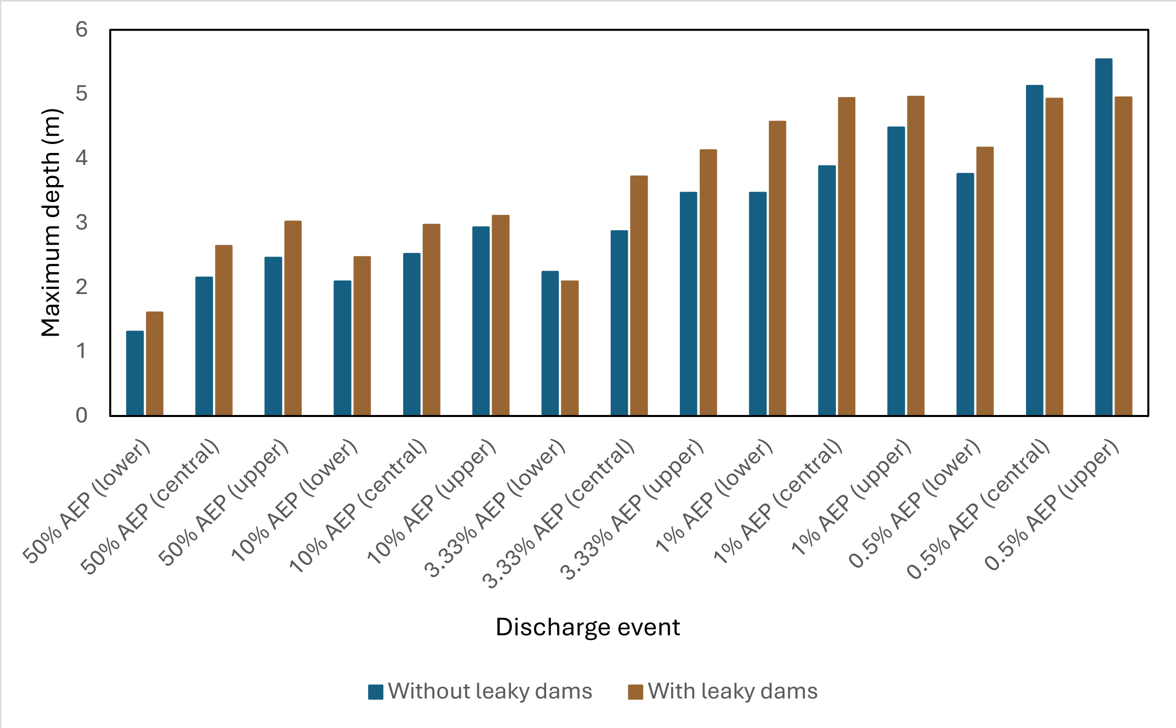


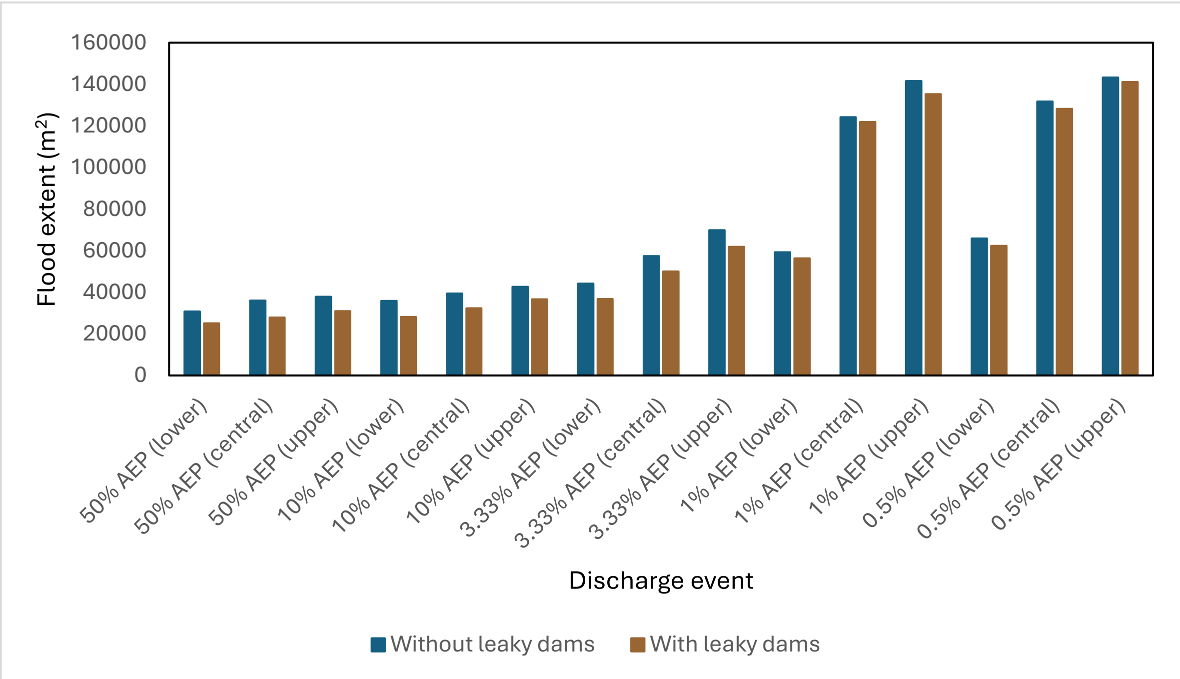
Figure 19 - Spatial distribution of maximum flood extent for 3.3% AEP (A and B) and 1% AEP (C and D) events under baseline conditions without leaky dams (left panels) and with leaky dams (right panels), illustrating differences in downstream flood propagation across the catchment.

For the 3.33% AEP event, LD's reduce flood extent in the Memorial Park and increase local depths in the central and upper scenarios. Under 1% AEP, LD's constrain widespread floodplain inundation, limiting impacts on infrastructure such as South Moor Road and the Greenland Community Primary School. Compared to reach-scale results, effects at the catchment scale show clearer reductions in downstream flood extent.

A



B



C

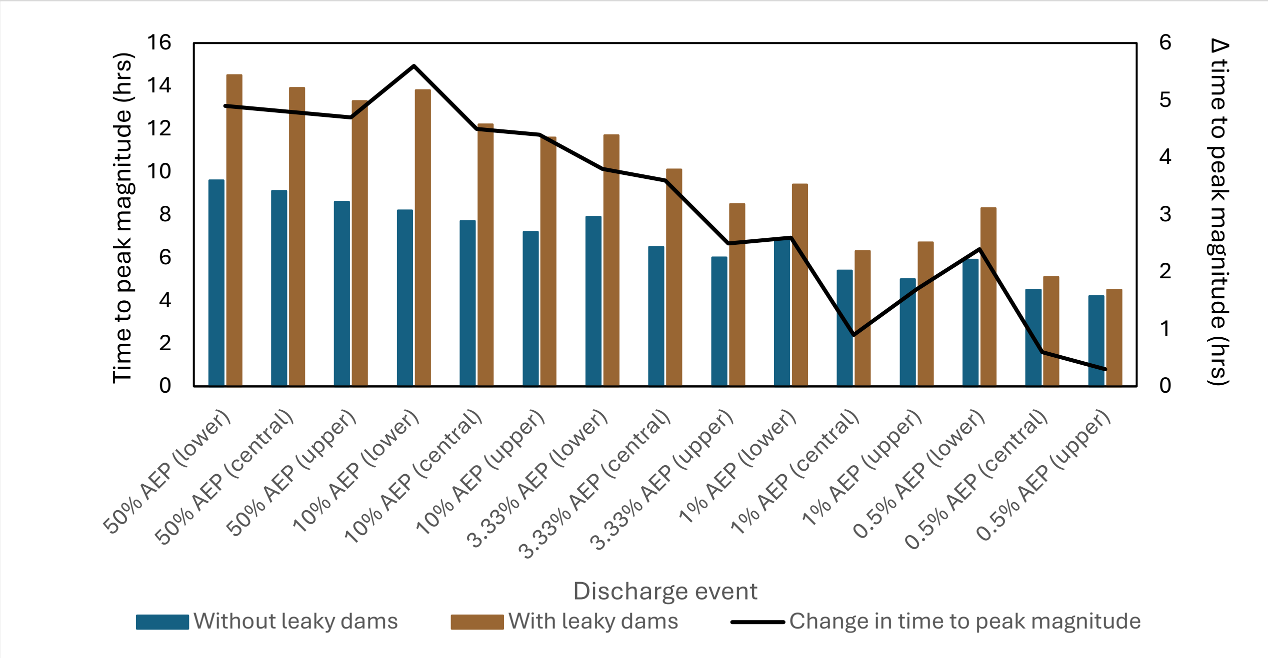


Figure 20 – A). Changes in maximum flood depth, B). flood extent, and C). time to peak magnitude at the outlet across all return periods under scenarios without leaky dams (blue) and with leaky dams (brown). The line shows the difference in time to peak magnitude between scenarios.

In figure 20A, maximum flood depth generally increases under LD's at lower and intermediate events (50% AEP: 2.15 to 2.64m; 3.33% AEP: 2.87 to 3.72m), but differences reduce at higher magnitudes, with slight decreases in extreme events (0.5% AEP: 5.54 to 4.95m). In figure 20B, flood extent generally decreases with LD's with greatest reduction in the 3.33% AEP central event (-7,468m^2) and relative reduction declines at higher magnitude events. Figure 20C shows LD's delay peak timing across all events, with the largest delays in smaller events (approximately 4.8-4.9hrs for 50% AEP events) reducing to negligible delays (~0.3hrs) at higher magnitudes, reflecting reduced influence as flows exceed storage capacity (see appendix 18 for all results).

6.3 RQ3

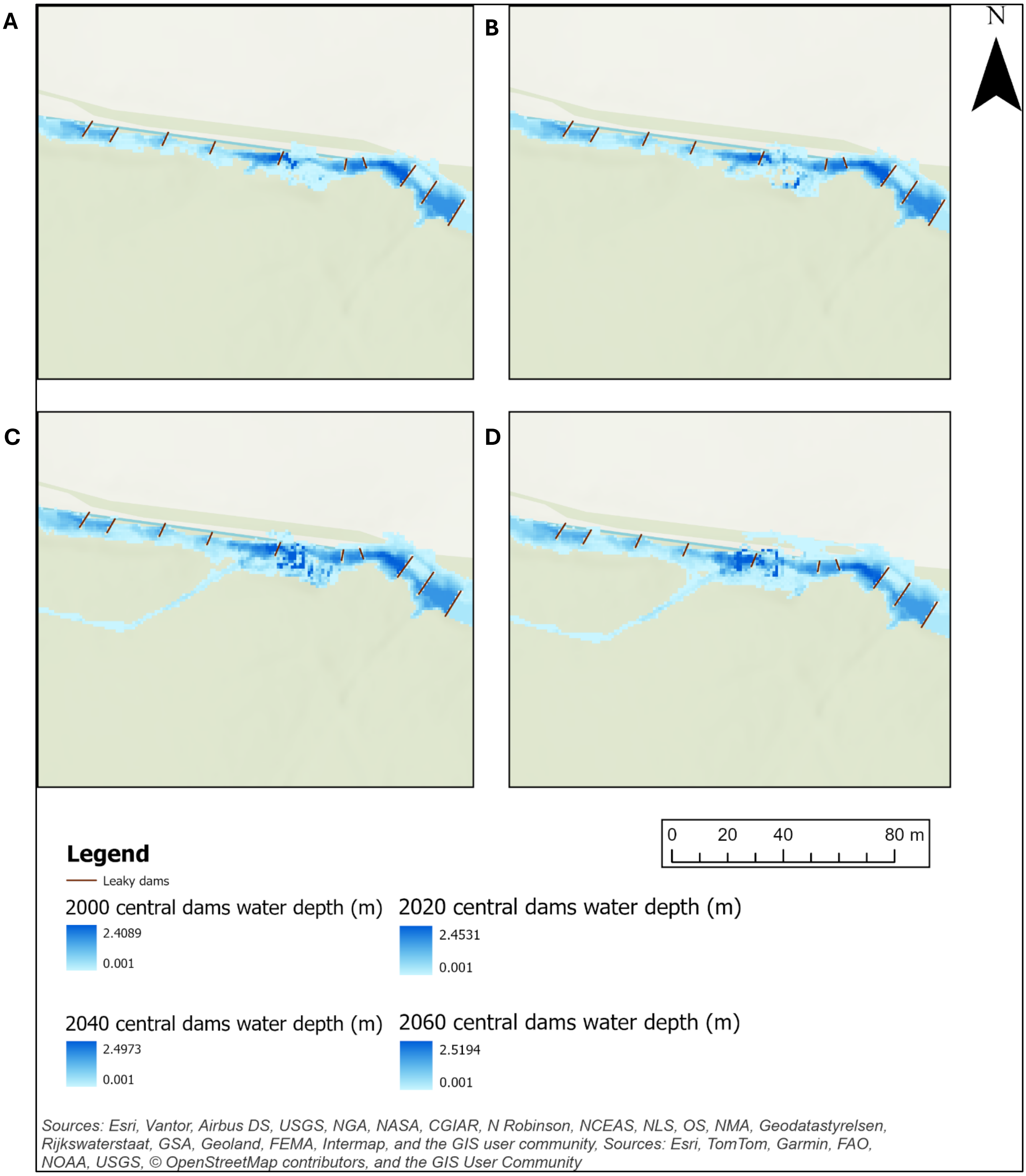


Figure 21 – Maps to show the spatial distribution of maximum flood depth for the 3.33% AEP event under future climate scenarios (RCP8.5) at the reach-scale, showing leaky dam influence on flow storage and routing across four time slices: A). 2000-2020, B). 2020-2040, C). 2040-2060, and D). 2060-2080. The 3.33% AEP is presented as it represents a critical threshold where leaky dams remain functional under baseline conditions but begin to show reduced effectiveness under future scenarios, making it suitable for assessing changes in performance over time.

Figure 21 shows at the reach scale, flood depth patterns at 3.33% AEP show a progression from discrete upstream ponding in earlier periods (2000-2020) to more connected and extensive inundation with greater depths by 2060-2080.

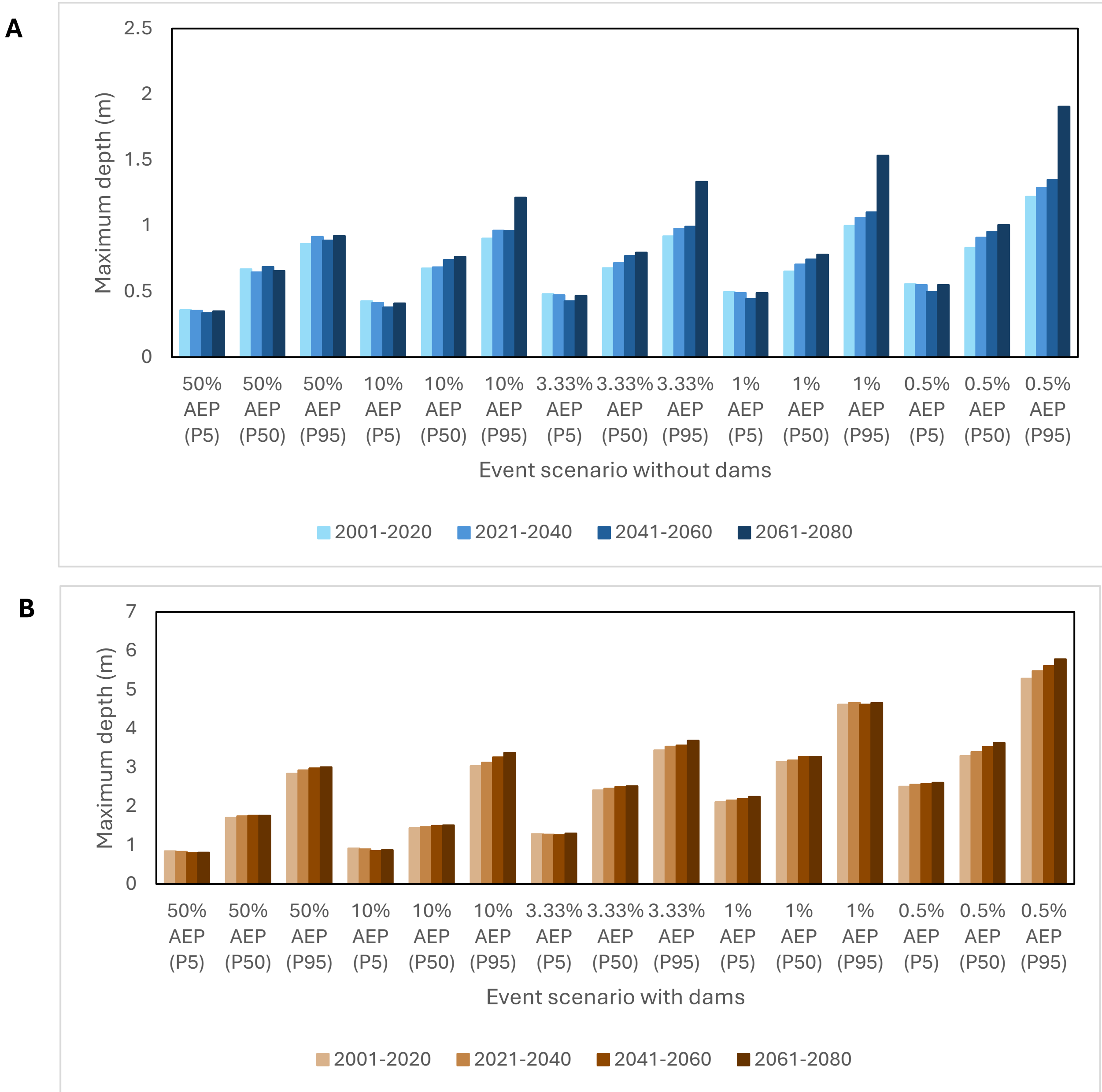
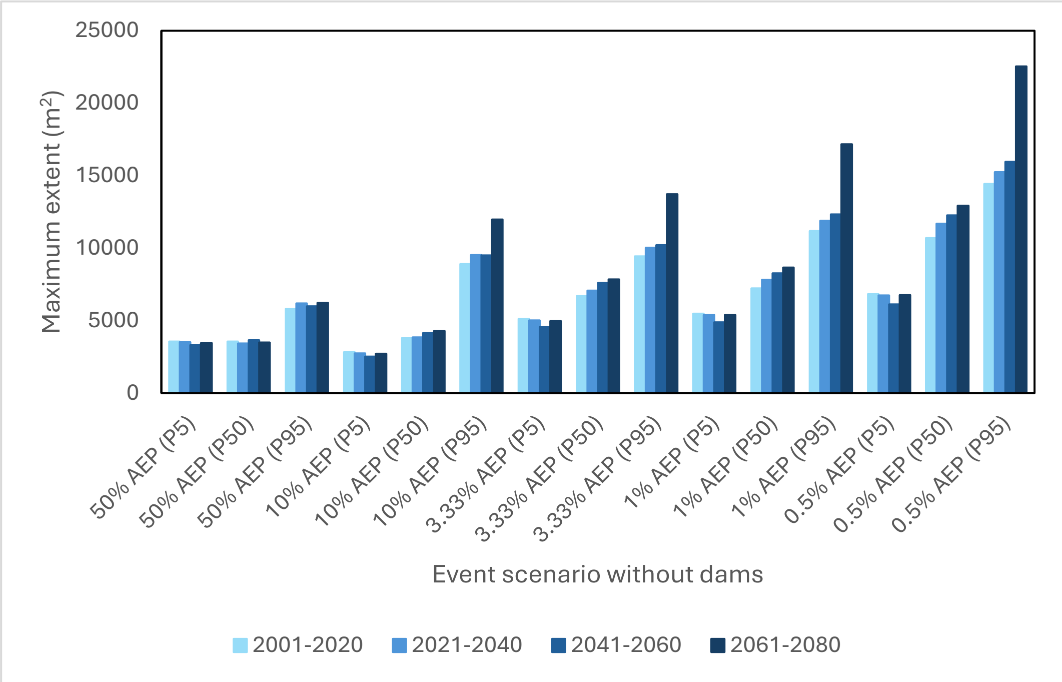


Figure 22 – Comparative bar charts to show changes in maximum flood depth across the dam network at the reach-scale simulations under future climate scenarios (RCP8.5), comparing A). conditions without leaky dams and B). conditions with leaky dams across all return periods and uncertainty bounds. Results are shown for four time slices (2000-2020, 2020-2040, 2040-2060, and 2060-2080).

Figure 22 shows that maximum depth remains higher with LD's across all return periods and climate scenarios, consistent with baseline trends. Without LD's, depths remain low (<1m), increasing slightly over time (3.33% AEP: 0.68m to 0.80m), whereas with LD's depths are substantially greater (3.33% AEP: 2.41m to 2.52m; 1% AEP: 4.61m to 4.65m). Increases are largest in P95 scenarios (up to 5.78m for the 0.5% AEP event by 2060-

2080), although relative differences reduce at higher return periods. Results are summarised in appendix 19.

A



B

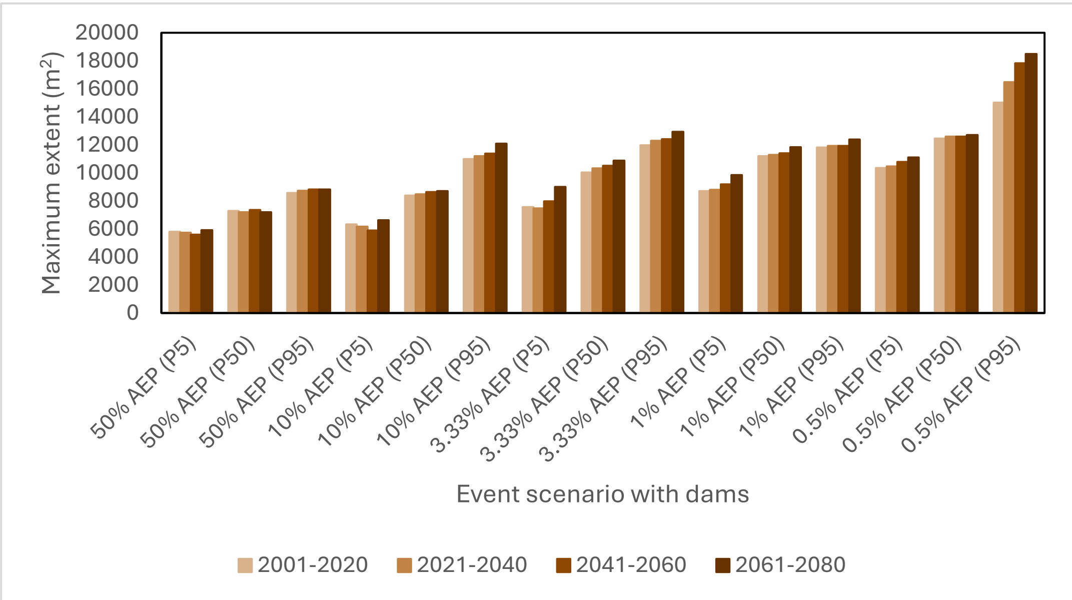


Figure 23 – Comparative bar charts to show changes in maximum flood depth across the dam network at the reach-scale simulations under future climate scenarios (RCP8.5), comparing A). conditions without leaky dams and B). conditions with leaky dams across all return periods and uncertainty bounds. Results are shown for four time slices (2000-2020, 2020-2040, 2040-2060, and 2060-2080).

Figure 23 shows that flood extent is generally higher with LD’s, consistent with baseline patterns (for example, 3.33% AEP P50: 6,692m^2 without dams and 10,038m^2 with LD’s in 2000-2020). However, extent increases more rapidly without LD’s at higher magnitudes over time, with differences reducing by 2060-2080 (for example, 3.33% AEP P95: 13,713m^2 without LD’s and 12,927m^2 with LD’s; 0.5% AEP P95: 22,549m^2 and 18,480m^2 respectively).

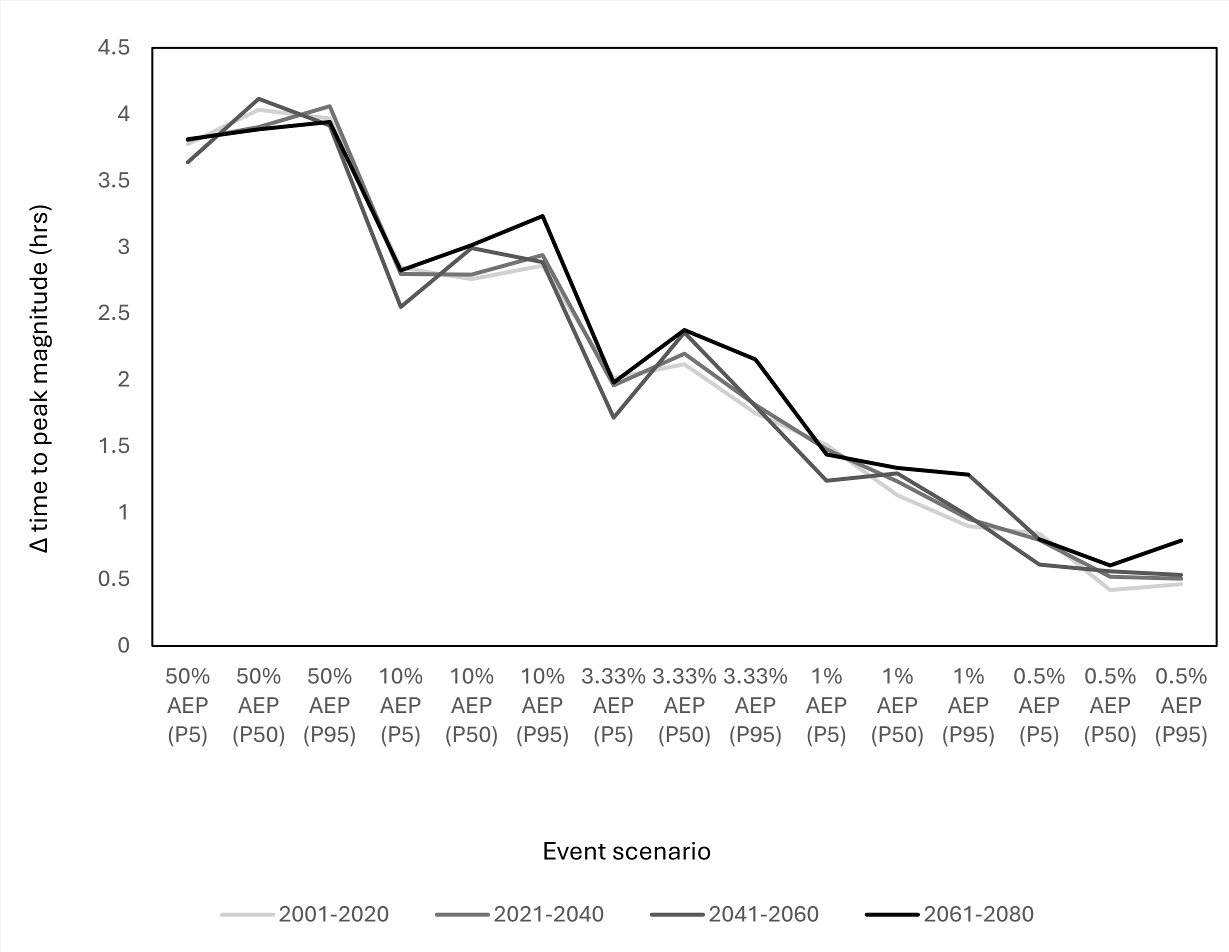


Figure 24 – A line graph to show changes in time to peak magnitude across the dam network at the reach-scale simulations under future climate scenarios (RCP8.5), across all return periods and uncertainty bounds. Results are shown for four time slices (2000-2020, 2020-2040, 2040-2060, and 2060-2080).

Figure 24 shows that time to peak decreases with increasing event magnitude under both scenarios (approximately 4.3 hours in the 50% AEP event to ~1.04 hours in the 0.5% AEP event for 2000-2020), consistent with baseline patterns. LD's increase time to peak, with the largest delays at lower magnitudes (for example, 50% AEP P50: 3.37 to 7.40 hours), but this reduces to ~0.79 hours at higher magnitudes, indicating limited influence under extreme events.

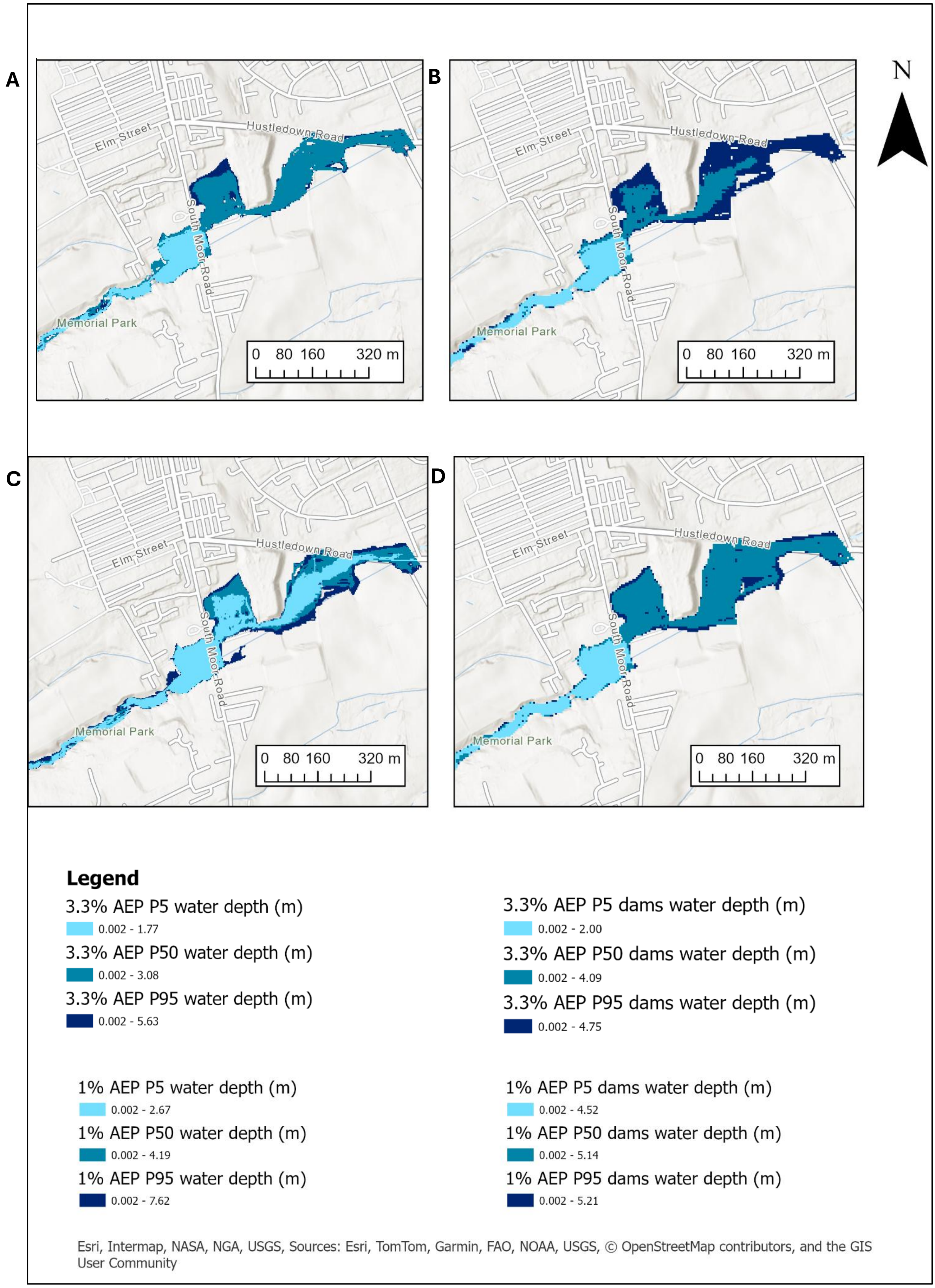
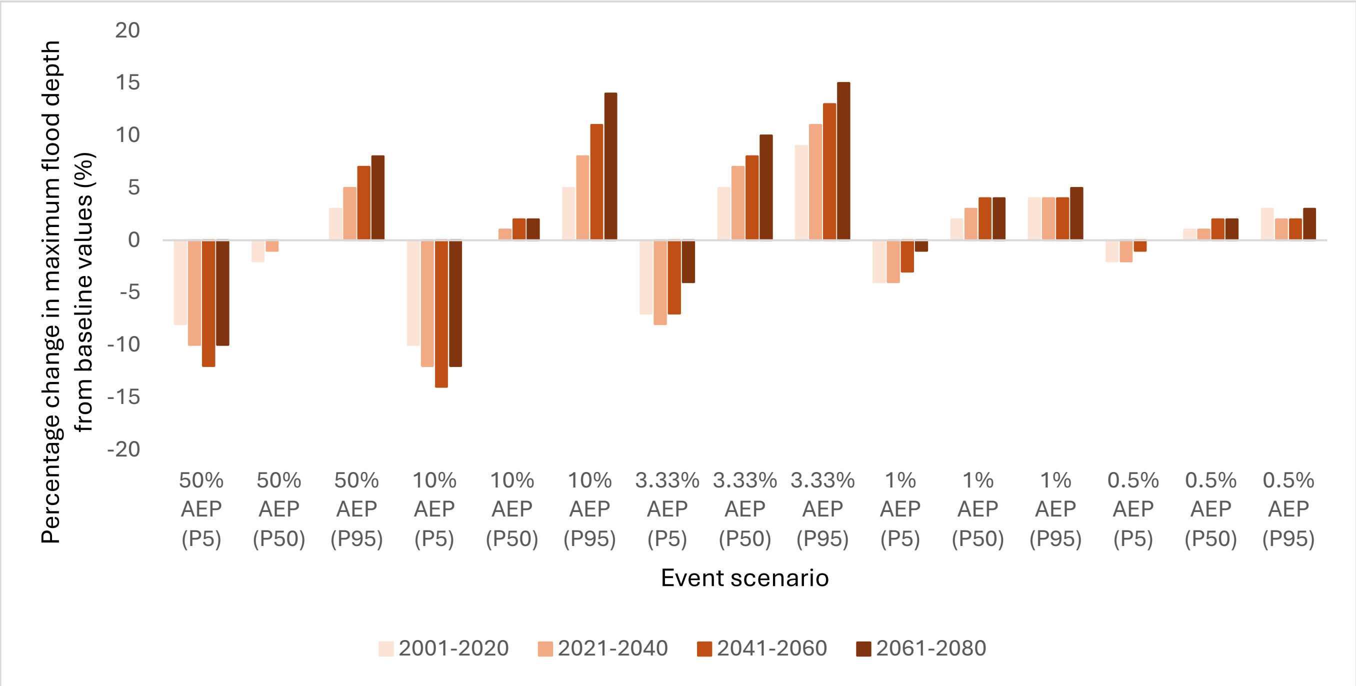


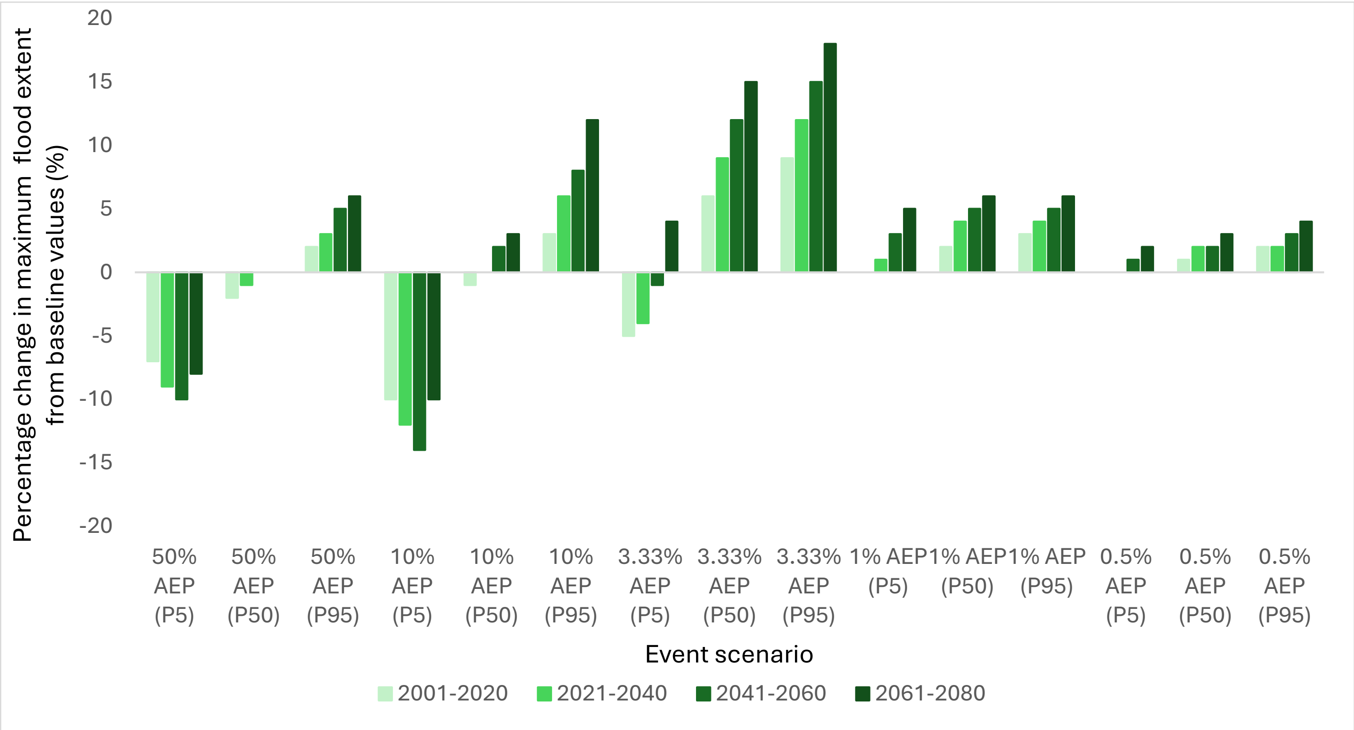
Figure 25 - Spatial distribution of maximum flood depth and associated depth damage for the 30-year (A and B) and 100-year (C and D) events under the 2060-2080 climate scenario at the larger catchment scale, comparing simulations without leaky dams (A and C) and with leaky dams (B and D).

At the catchment scale (2060-2080), LD's slightly reduce flood extent in the 3.33% AEP event under P50 conditions, although key areas such as Memorial Park and Greenland Community Primary School remain inundated under P50 and P95 scenarios. In the 1% AEP event, widespread floodplain inundation persists across P5, P50 and P95, with only minor upstream confinement under P5, while continuous flow and overtopping indicate limited effectiveness of LD's alone.

A



B



C

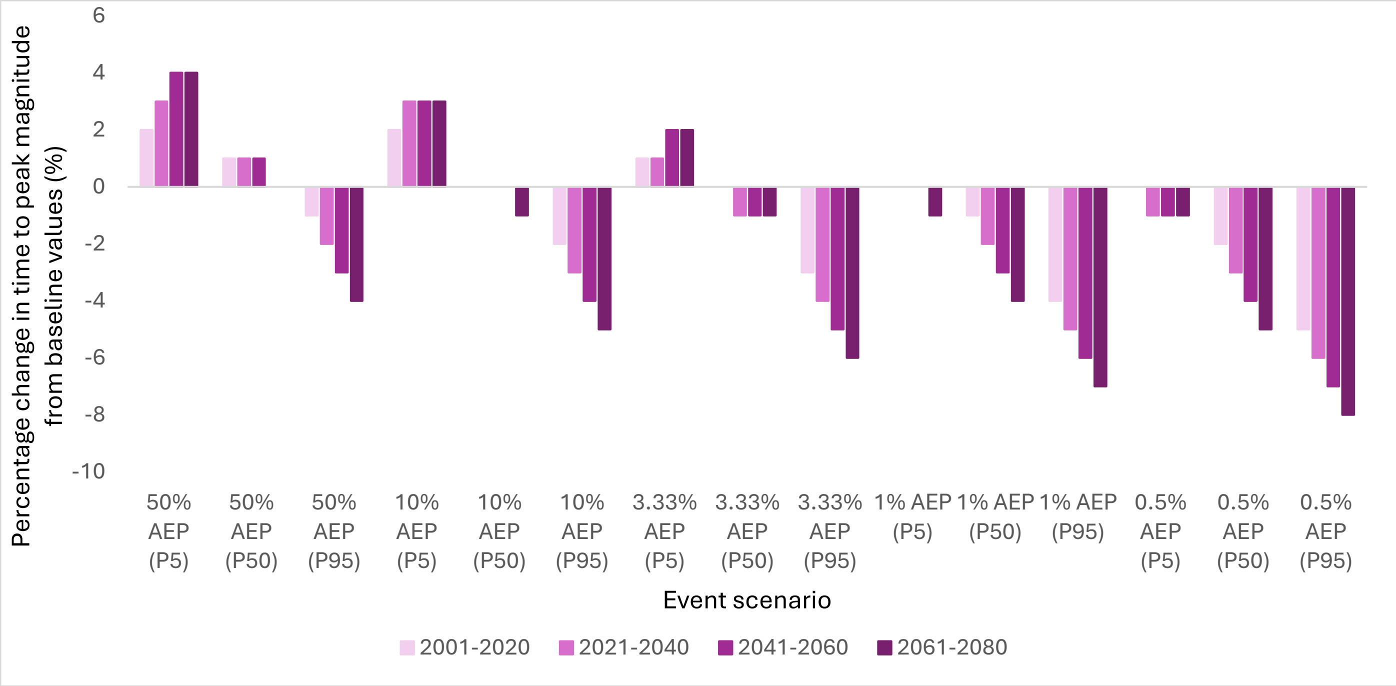


Figure 26 - percentage change in maximum depth (A), flood extent (B), and time to peak magnitude (C) across all return periods, uncertainty bounds and future climate scenarios from the baseline for the large catchment scale. % change calculated as: future with dams – baseline with dams) / baseline with dams × 100. See appendix 20 for raw results.

Maximum depth decreases under P5 scenarios (−14% in the 10% AEP event), but increases under P50 and P95, peaking at 15% in 3.33% AEP P95 events, with smaller proportional changes (~+2-4%) at higher return periods. Flood extent follows a similar trend, decreasing under P5 (−12% in the 10% AEP event), but increases for P50 and P95, reaching 18% in 3.33% AEP P95 events, with less change at higher magnitudes. Time to peak magnitude increases for lower and intermediate events (50-60% under 10% AEP), but changes are smaller at higher magnitudes (~0-10%), with decreases of ~−6% to −8% observed in 1 and 0.5% AEP P95 events under 2060-2080 conditions.

6.4 RQ4

Based on the trends in flood depth and extent identified in RQ2 and RQ3, three flood mitigation schemes were developed, including optimisation of upstream LD’s as part of a wider NFM scheme and a hard engineered scheme and a catchment-based hybrid approach.

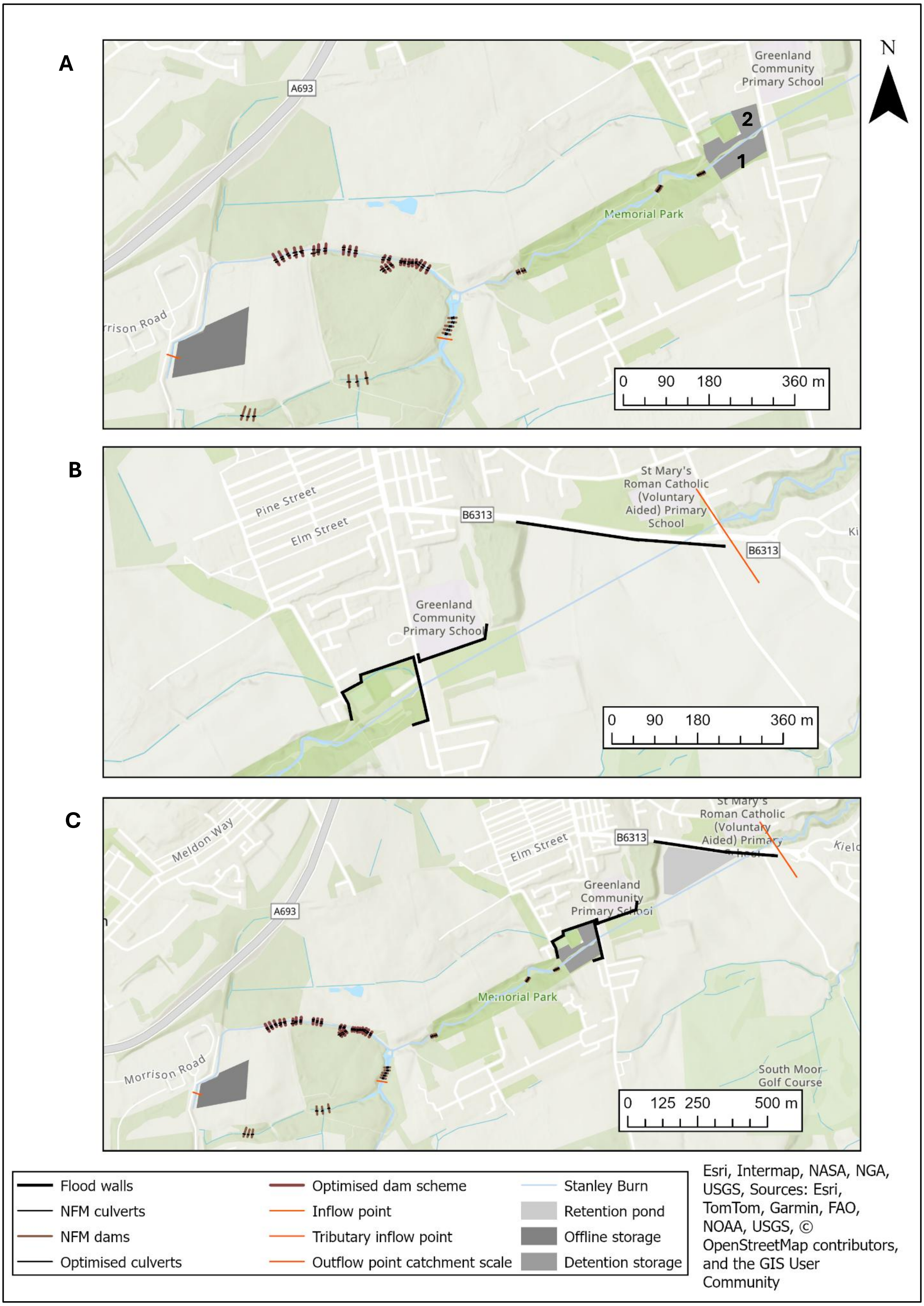


Figure 27 – The three flood management schemes modelled. A). NFM scheme including an optimised leaky dam configuration which is subsequently modelled and offline and detention storage, B. a hard-engineered scheme including flood walls and C). A hybrid approach combining the NFM and hard-engineered measures with an additional retention pond based on the flood modelling outcomes.

Justification for scheme design is detailed with relevant assumptions:

<u>Scheme</u>	<u>Design justification</u>	<u>Design assumptions</u>
NFM	The NFM scheme reflects the preferred approach within the existing SuDS+ pilot project in Stanley, emphasising attenuation through natural processes. The design builds upon the existing LD network, with dams increased in size, grouped in clusters of at least 3, and spaced approximately 5-7 times the channel width, based on RQ1 findings and following Environment Agency guidance (EA, 2019). Improved dam performance was tested at the reach scale using 1-hour discharge events to capture localised hydraulic responses. Additional upstream attenuation was introduced through an offline storage basin near the catchment inflow (3.5 m depth), where limited public access allows for greater storage capacity Two detention basins within the memorial park (maximum depth 2m), consistent with wider guidance for maintaining a safer depth in urban areas (CIRIA, 2015). These were positioned upstream of key flood receptors identified in RQ2 and RQ3 modelling, including the main road and school.	The basins were placed where the existing car park and playground are assuming that the benefits of flood hazard reduction will outweigh the social costs of relocation in the long run; this trade-off might make the scheme unpopular with the local community. Storage basins are assumed to be low-complexity earthworks with no structural lining or graded sides, reflecting typical rural SuDS design (EA, 2012). The storage basins assume agreement between stakeholders for land excavation and basins also need increasing maintenance over time as sediment accumulates and repeated excavation is required.
Hard-engineered	The hard engineering scheme was developed as a comparative benchmark to assess the performance of traditional defences relative to NFM approaches. A “set-back” flood defence strategy was adopted, consisting of 2m high flood walls positioned within the park but offset from the channel to allow controlled floodplain storage and reduce overtopping risk. Additional protection is provided by a secondary flood wall surrounding the primary school to protect critical infrastructure A downstream wall is placed near the outlet to safeguard the road network and	Flood wall height is assumed to be 2m based on typical design practice although site-specific freeboard requirements are unaccounted for meaning the adopted height represents a simplified design assumption rather than a fully optimised engineering specification (Rickard, 2009). The scheme assumes reinforced concrete flood walls with sheet-piled foundations, constructed along the existing channel alignment, with no allowance made for land acquisition, legal agreements or planning approval. The hard-engineered approach may be socially unpopular, as it contrasts with the

	adjacent developed areas identified as high-risk in RQ2 and RQ3. This scheme prioritises protection of assets rather than upstream flow attenuation.	Stanley SuDS+ emphasis on community-led, nature-based solutions. It also assumes local community acceptance; visual intrusion and possible access restriction may pose challenges. The decision to implement a set-back defence, which allows flooding of lower-value areas such as the memorial park and playing fields, represents a trade-off that may reduce public acceptability.
Hybrid	The retention pond provides additional storage capacity within the floodplain with the aim to complementing upstream attenuation and reducing downstream flood propagation. This scheme represents the most intervention-intensive option, designed to maximise flood risk reduction across a range of event magnitudes by combining upstream storage, in-channel flow reduction, and downstream protection.	Implementation assumes sufficient stakeholder cooperation across the catchment, including landowner agreement and that distributed interventions function effectively as a connected system. Scheme costs are based on simplified design representations and standard unit rates, assuming comparable construction conditions across the study area. Inflation and annual maintenance costs are not included, with capital costs assumed constant over time to enable consistent comparison between scenarios. This introduces uncertainty, as long-term costs are likely to increase and vary between scheme types. It is assumed that NFM and hard-engineered components operate effectively in combination, with no loss of efficiency due to overlap or interaction.

Table 17 - justification for flood management measures as part of the schemes and any assumptions made in the design process.

Table 18 indicates total costing of the schemes:

Measure	Basis	Unit cost (2026)	Quantity	Total cost (£)
Leaky dams	per dam	£194/dam	45	£8,730
Detention basin 1	per m³	£25/m³	13,200 m³	£330,000
Detention basin 2	per m³	£25/m³	13,600 m³	£340,000
Offline storage basin	per m³ (power-law cost function)	$15{,}370V^{-0.628}$	67,000 m³	£959,440
Retention pond	per m³	£22/m³	60,000 m³	£1,320,000
Flood wall	per metre	£4,000/m	1,000 m	£4,000,000
Scheme	Components included		Total cost (£, 2026)	
NFM scheme	45 LD's + 2 detention basins + offline storage basin		£1,638,170	
Hard scheme	1 km flood wall		£4,000,000	
Hybrid scheme	NFM scheme + retention pond + 1 km flood wall		£6,958,170	

Table 18 – Estimated costs of flood management measures and schemes modelled in this study. Inflation is not accounted for, assuming defence costs stay constant with time in future extreme events and does not account for annual maintenance costs, recognising the uncertainty in predicting costs, under future economic and climatic conditions.

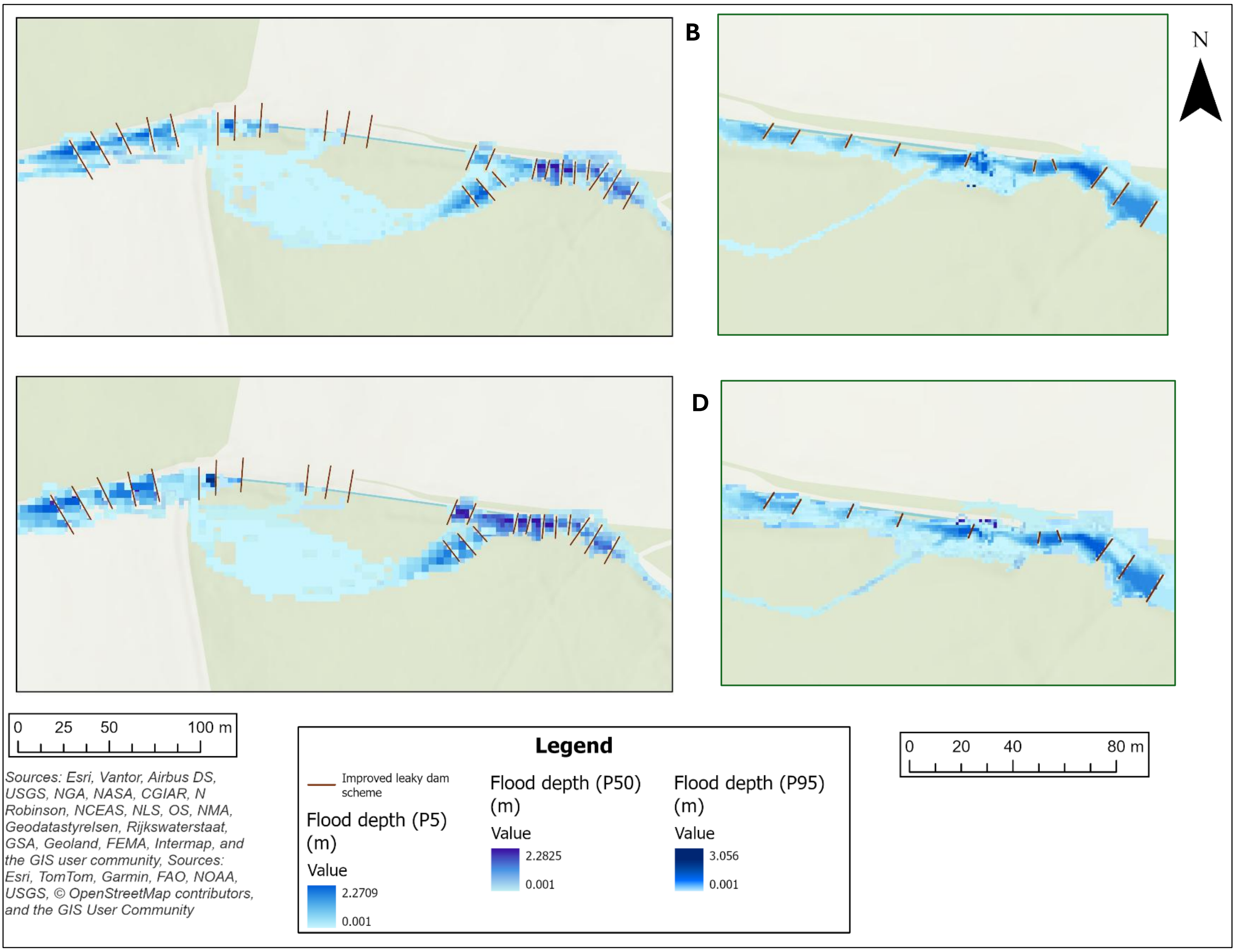


Figure 28 – Spatial comparison of flood depth and extent under optimised and existing leaky dam configurations for the 30-year event. Top row: baseline conditions with A). Improved dams and B). existing dams. Bottom row: future conditions (2060-2080), with (C) improved dams and (D) existing dams.

Figure 28 shows that the improved dam configuration creates greater upstream ponding and reduced downstream connectivity compared to the existing LD's, which exhibits more continuous flow. This pattern is consistent in both baseline and 2060-2080 scenarios, with more extensive and deeper storage under future conditions due to higher inflows.

1-in-30-year baseline			
Scenario	Δ Max depth (m)	Δ Extent (m²)	Δ Time to peak (hrs)
Lower	0.76	2,609	6.35
Central	0.51	5,956	5.73
Upper	-0.75	9,553	5.77
1-in-30-year 2060–2080			
Scenario	Δ Max depth (m)	Δ Extent (m²)	Δ Time to peak (hrs)
Lower	0.97	7,975	5.26
Central	-0.24	8,923	5.02
Upper	-0.74	9,575	4.52

Table 19- Absolute change in maximum depth, flood extent and time to peak between existing and improved leaky dam configurations for the 30-year event under baseline and future (2060–2080) conditions. Positive values indicate increases under the improved dam scenario. See appendix 21 for raw results.

For the baseline 30-year event, maximum depth increases in the lower (P5) and central (P50) scenarios (+0.76 m, +0.51 m) but decreases in the upper (P95) (−0.75 m), while flood extent increases across all scenarios (+2,609 to +9,553 m²) and time to peak is delayed (~5.7–6.4 hours). Under 2060–2080 conditions, depth increases only in P5 (+0.97 m) but decreases in P50 and P95, with larger extent increases (+7,975 to +9,575 m²) and peak delays of ~4.5–5.3 hours. This is investigated further by testing how the improved LD scheme operates with upstream offline storage and downstream detention basins as part of the wider NFM scheme.

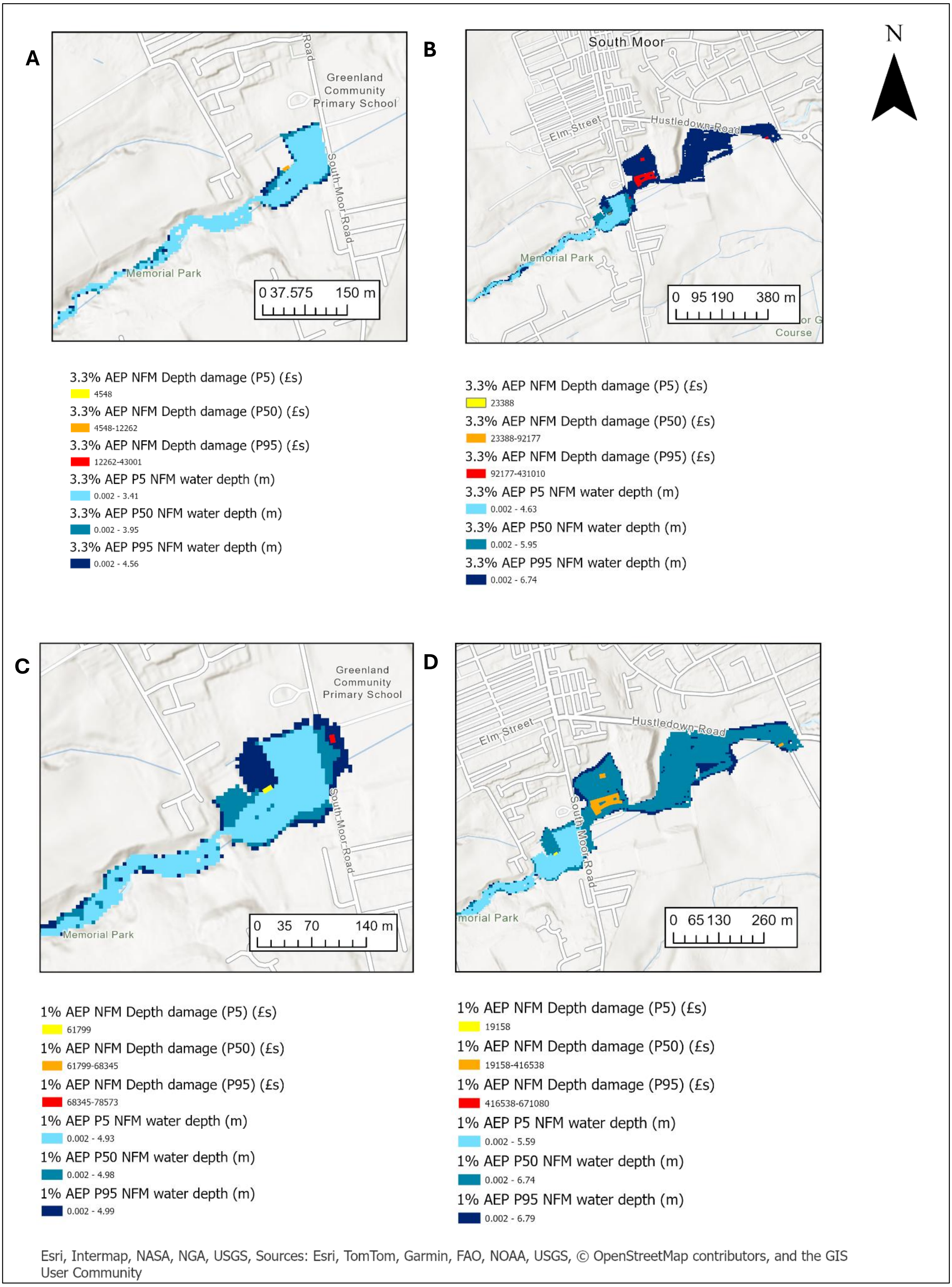


Figure 29 – Spatial comparison of flood depth and extent under the NFM scheme for the 3.33% AEP and 1% AEP events. A). NFM scheme under baseline conditions for the 3.33% event. B). NFM scheme under 2061-2080 climate scenario for the 3.33% AEP event. C). NFM scheme under baseline conditions for the 1% AEP event. D). NFM scheme under 2061-2080 climate scenario for the 1% AEP event.

Figure 29 shows that under baseline conditions, NFM largely contains flooding within offline and detention basins for the 3.33% AEP event, with only minor impacts under P50 and P95. By 2060-2080, flood extent increases, particularly under P95 for the 3.33% AEP event and under both P50 and P95 for the 1% AEP event, where basin capacity is exceeded and inundation extends across roads and infrastructure including Greenfield Community School and adjacent playing fields. Appendix 22 summarises modelled flood depth, extent, depth-damage and CBR's for the NFM scheme.

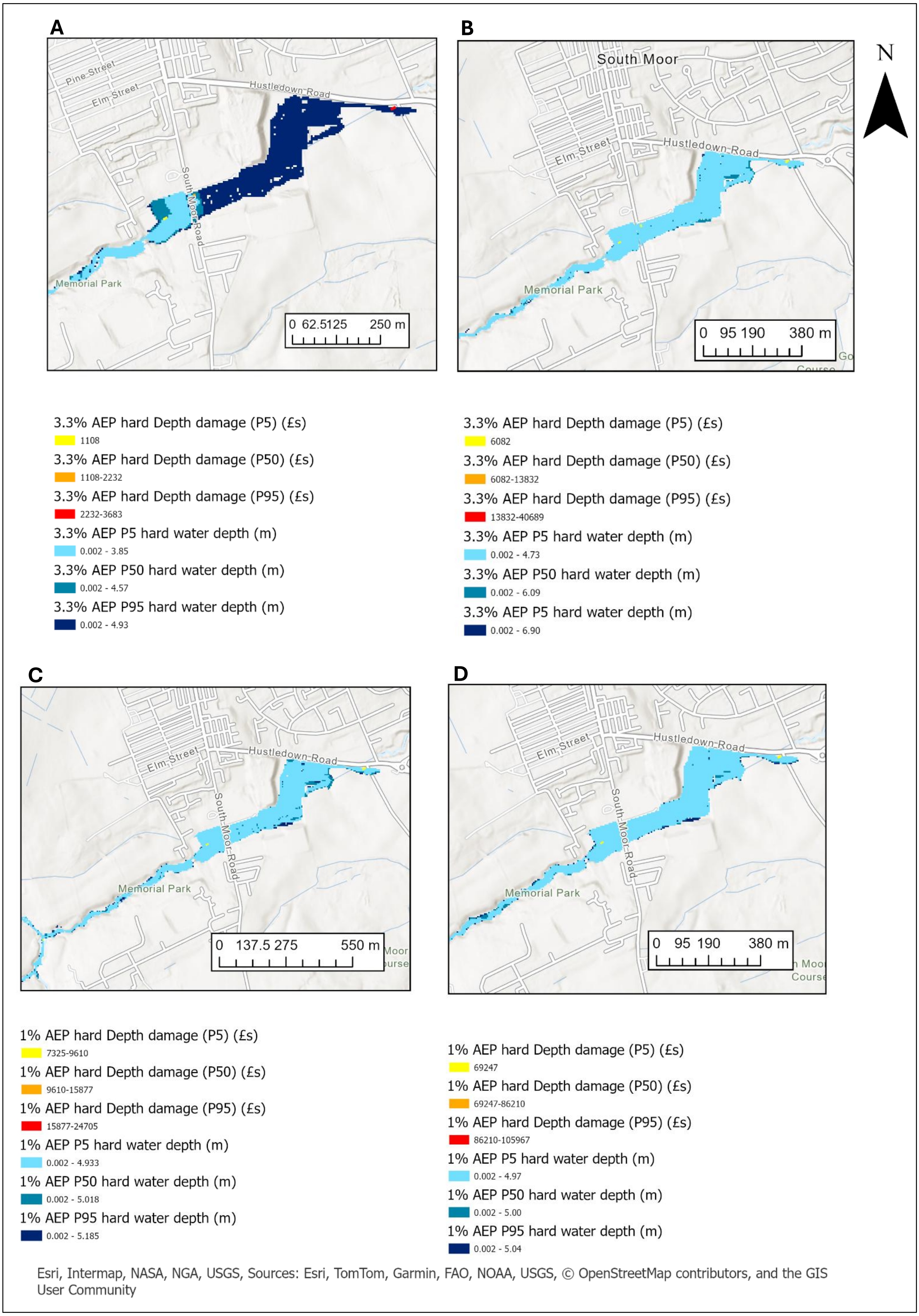


Figure 30 – Spatial comparison of flood depth and extent under the hard engineered scheme for the 3.33% AEP and 1% AEP events. A). Hard engineered scheme under baseline conditions for the 3.33% AEP event. B). Hard engineered scheme under 2061-2080 climate scenario for the 3.33% AEP event. C). Hard engineered scheme under baseline conditions for the 1% AEP event. D). Hard engineered scheme under 2061-2080 climate scenario for the 1% AEP event.

Figure 30 shows that under baseline conditions, the 3.33% AEP event results in overtopping of the 2m flood wall under P5 and P50, causing minor road inundation, with greater floodplain expansion under P95. However, flooding is largely contained by the set-back walls, protecting key assets such as the school and downstream road, although the Memorial Park and playing fields remain inundated. Under 2060-2080 conditions, this pattern shifts to lower percentiles (P5 included), indicating reduced protection, with similar trends observed for the 1% AEP event where overtopping occurs in all scenarios, depth increases but high-value assets remain protected. Compared to NFM, the hard scheme produces greater flood extent at lower magnitude events but lower overall damage to critical infrastructure. Appendix 23 summarises modelled flood depth, extent, depth-damage and CBR's for the hard-engineered scheme.

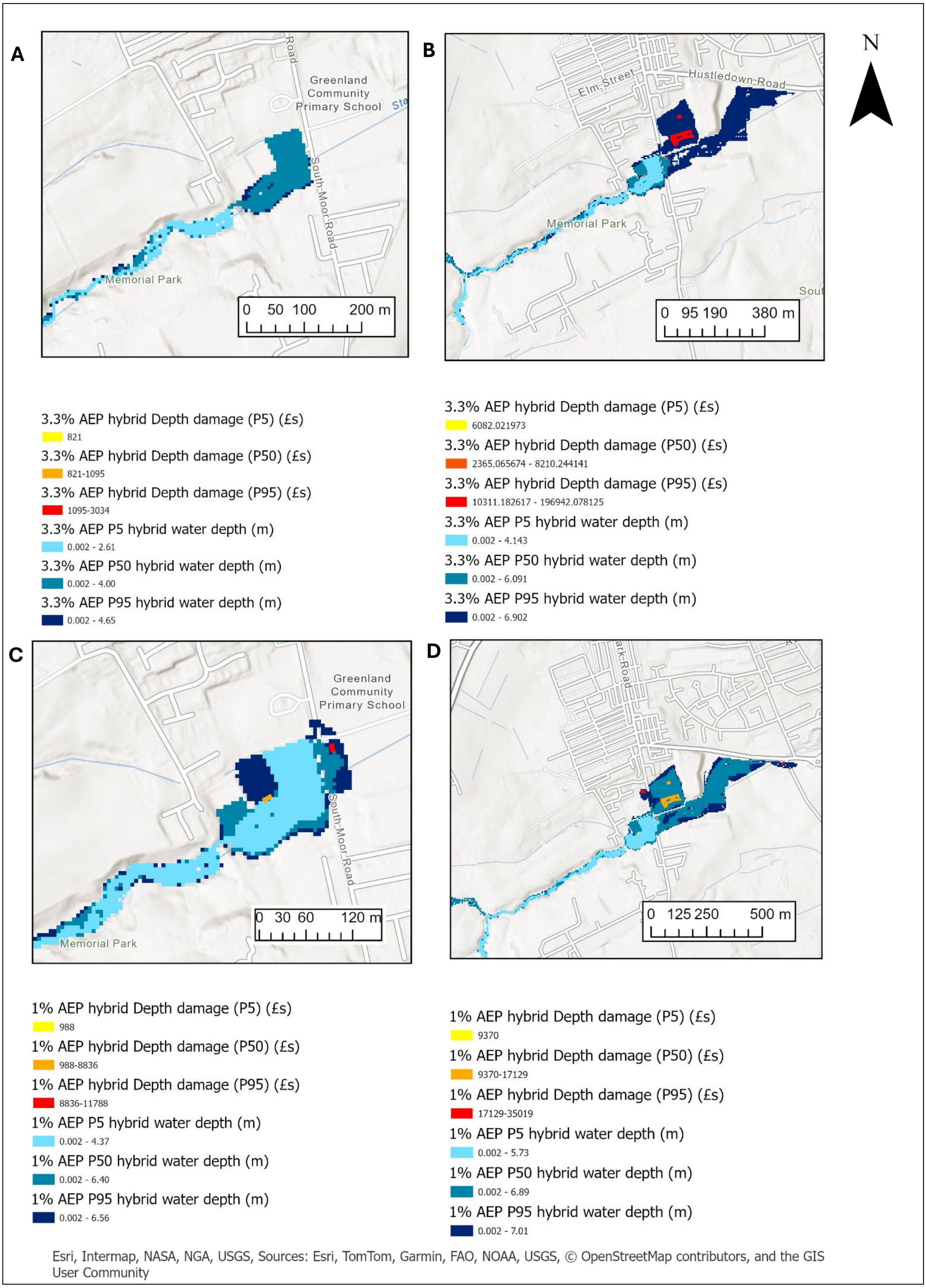


Figure 31 – Spatial comparison of flood depth and extent under the hybrid scheme for the 3.33% AEP and 1% AEP events. A). Hybrid scheme under baseline conditions for the 3.33% AEP event. B). Hybrid scheme under 2061-2080 climate scenario for the 3.33% AEP event. C). Hybrid scheme under baseline conditions for the 1% AEP event. D). Hybrid scheme under 2061-2080 climate scenario for the 1% AEP event.

Figure 31 shows that under baseline conditions, the 3.33% AEP event remains contained within the Memorial Park, while 1% AEP causes minor overtopping of South Moor Road under P50 and P95 but does not affect the school. By 2060-2080, the 3.33% AEP event inundates South Moor Road under P50 and extends across the floodplain under P95, while 1% AEP produces widespread floodplain inundation under P50 and P95, including impacts to roads and the school, with minor road flooding also occurring under P5. Appendix 24 summarises modelled flood depth, extent, depth-damage and CBR's for the hard-engineered scheme.

Scheme	Peak CBR	When peak CBR occurs	Maximum damage reduction (£)	Maximum depth range (m)	Maximum extent (m^2)
NFM	**0.51**	2000–2020 (1% AEP P95)	£838,613	2.61- 7.80	159,775
Hard	**0.29**	2060–2080 (1% AEP P95)	£1,163,071	3.85- 5.04	162,325
Hybrid	**0.18**	2060–2080 (1% AEP P95)	£1,234,019	2.61- 7.01	152,400

Table 20 - Summary of flood management scheme performance, showing peak cost–benefit ratios (CBR), timing of peak performance, maximum damage reduction (£), and associated flood depth and extent ranges. Values represent the highest observed outcomes across modelled event scenarios and illustrate differences in economic efficiency and flood characteristics between NFM, hard-engineered and hybrid approaches.

The NFM scheme achieves the highest economic efficiency (CBR = 0.51; £838,613 reduction) but is associated with greater depth and extent, while the hard-engineered scheme delivers larger damage reduction (£1,163,071) with lower efficiency (CBR = 0.29) and consistently large extents. The hybrid scheme achieves the greatest reduction (£1,234,019) but lowest efficiency (CBR ≤ 0.18), highlighting trade-offs between cost, damage reduction and flood characteristics. Figure 32 further explores temporal variation in CBR's.

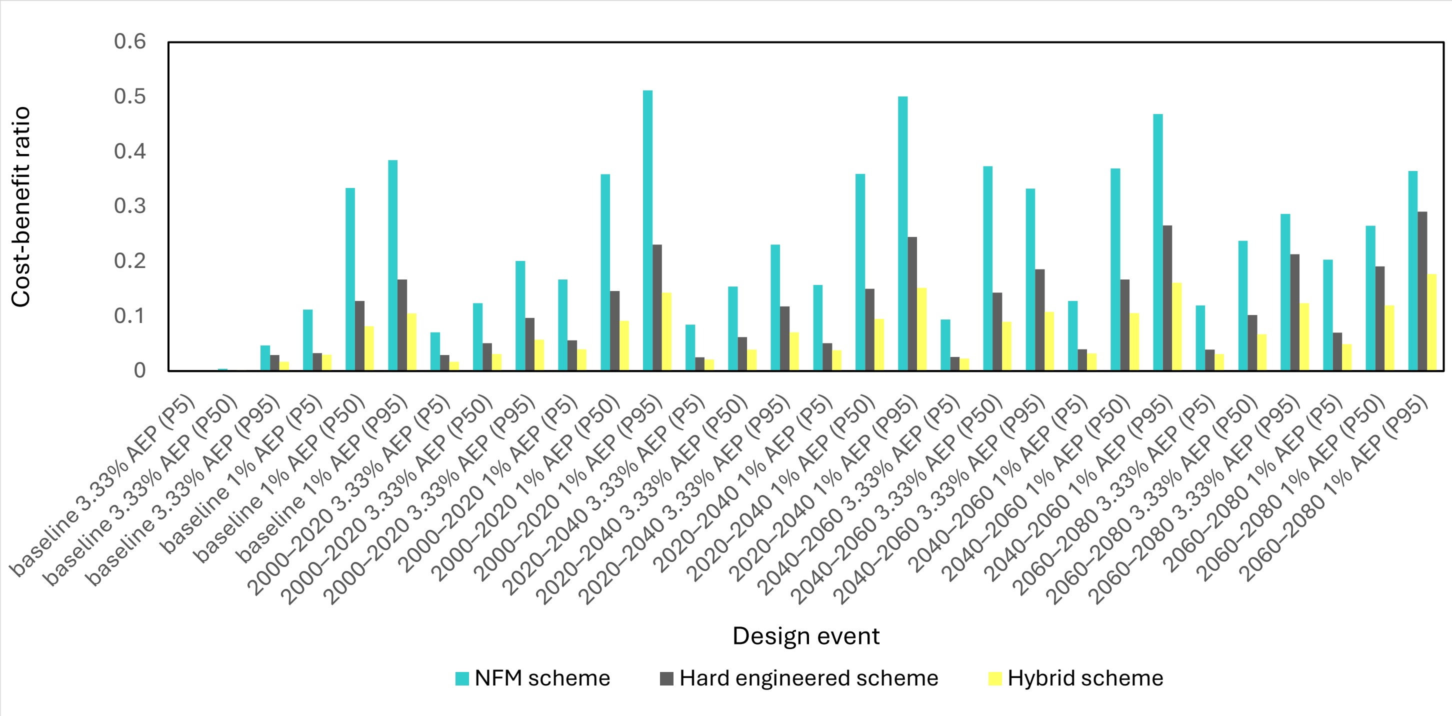


Figure 32 - Cost–benefit ratio (CBR) variation across climate periods and event scenarios for the NFM, hard-engineered and hybrid flood management schemes. Results are presented for 3.33% AEP and 1% AEP events (P5, P50 and P95 scenarios), demonstrating temporal trends in economic performance and differences in scheme effectiveness under increasing flood magnitude and projected climate conditions.

Figure 32 shows contrasting temporal trends, with the NFM scheme achieving the highest CBR (0.512 in 2000-2020) but declining to 0.365 by 2060-2080. In contrast, the hard-engineered scheme increases from 0.167 to 0.291. The hybrid scheme follows a similar but weaker upward trend, increasing from 0.105 to 0.177 over the same period. Across all scenarios, it does not exceed the CBR of either NFM or hard engineering, despite combining both approaches, contrary to expectations from the design stage.

7 Discussion

7.1. RQ1

The paired two-tailed t-test confirms a significant difference between upstream and downstream CSA, demonstrating that LD's alter channel morphology. In the upper reach (LD2–6), greater upstream CSA reflects backwater effects, where flow is impounded, increasing depth and reducing velocity. This promotes sediment deposition and lateral flow expansion, increasing wetted perimeter and CSA (Liro et al., 2022), consistent with reported backwater rises in wider studies (Muhawenimana et al., 2023). From a flood perspective, this supports local storage and lag, aligning with wider NFM literature. However, this pattern is inconsistent. Downstream sites (LD7–10) show greater CSA downstream, indicating scour-dominated processes. While upstream deceleration promotes deposition, downstream turbulence enhances erosion (Schwindt et al., 2018), reflecting the “hungry water” concept where sediment-depleted flows increase transport capacity and channel incision (Kondolf, 1997). Stronger downstream responses suggest cumulative effects of sequential structures, consistent with network-based redistribution of energy and sediment (Hankin et al., 2020). Kruskal-Wallis results identify dam proximity as the dominant control, with spacing <10 m producing the strongest CSA response, supporting grouped installation guidance (Natural England, 2025). In contrast, dam size is not significant, aligning with Fencl et al., 2015, who show geomorphic impact is more strongly controlled by density and spatial arrangement. Dam type plays an influential role for channel adjustment: GAD promote upstream impoundment, whereas NWWD increase downstream scour. These differences reflect permeability, where less porous structures retain water, while more permeable dams allow throughflow and concentration downstream (Zhuang et al., 2025).

Velocity decreases downstream are consistent while discharge changes are minimal in comparison indicating resistance from the LD’s is offset by increased channel CSA (Bisson et al., 1987). This reflects channel re-equilibration, where systems adjust morphology to maintain flow efficiency following disturbance (Petts, 1978). In the upper reach, reduced downstream conveyance reflects storage and deposition, suggesting attenuation under flows below entrainment thresholds, whereas the lower reach shows increased conveyance and more efficient downstream transmission (Olsen et al., 2007). This supports the fluvial trinity concept, where flow, sediment and morphology interact to control channel response (Leopold et al., 1964). Short monitoring period can underestimate alleviation potential, so event-based, continuous monitoring using automated approaches like pressure transducers could be a useful extension (Tankard, 2021). In answer to RQ1, LD’s alter channel morphology and flow, but under observed non-event conditions their alleviation effect is limited and highly context dependent.

7.2 RQ2 and RQ3

7.2.1 Model application

Sensitivity analysis indicates model performance is most strongly controlled by the loss coefficient, meaning predicted flood alleviation is highly dependent on inflow magnitude, reflecting wider hydrological modelling uncertainty where rainfall–runoff estimation strongly influences flood predictions (Hu, 1987). Uncertainty is further introduced through roughness parameterisation. A single Manning’s n (0.045) was applied across the reach, despite evidence that spatial variability in roughness can alter predicted flood depth and extent by up to 20% (Feldmann et al., 2026). Although roughness influence may decline at higher flows, its simplification may overestimate attenuation under low flows and underrepresent resistance during larger events (Ye et al., 2018). Incorporating a spatially distributed roughness grid would better represent localised resistance and storage (Ozdemir et al., 2013).

7.2.2 Flood magnitude

At the reach scale under baseline conditions, LD's increase maximum flood depth and local inundation, particularly upstream of structures. For example, depth increases from 0.73m to 2.21m in the 3.33% AEP event and to 3.12m under 1% AEP, with extent increasing by ~30%. This reflects in-channel storage and backwater effects, consistent with RQ1 and wider evidence that attenuation is most effective in headwater systems (Thompson, 2026). However, this storage effect is threshold-dependent. Under future conditions, depth remains higher with dams, but differences in flood extent between scenarios reduce with increasing return period and climate forcing, becoming minimal or reversed by 2060–2080. This indicates a transition from storage-dominated to conveyance-dominated behaviour, where storage capacity is exceeded and overtopping occurs. Similar threshold responses have been observed experimentally, where leaky barriers shift to combined orifice-weir flow, increasing discharge non-linearly and reducing alleviation (Martín-Moreta et al., 2025). This threshold behaviour also introduces the potential for cascading impacts, where overtopping or instability in upstream dams may trigger downstream flow pulses (IMA, 2022). Dam permeability needs to also be considered as more permeable woody debris dams allow gradual throughflow, reducing pressure build-up, whereas less permeable structures enhance storage but may produce more abrupt flow release once thresholds are exceeded (Furnues et al., 2026). This highlights a trade-off in NFM design between maximising storage and maintaining controlled release.

At the catchment scale, LD's reduce downstream flood extent for lower to intermediate events. Under baseline conditions, reductions of ~11-18% are observed for 50% to 3.33% AEP events, declining to <5% for 1% AEP events and becoming negligible by 0.5% AEP. This reflects how upstream storage and delayed release reduce downstream flood propagation, consistent with wider empirical evidence that NFM is most effective during smaller to moderate events (typically ≤10% AEP), with diminishing influence under larger events (Taylor and Clarke, 2021). Under future conditions, this trend persists but weakens, with convergence between scenarios occurring at lower return periods by 2060-2080. This suggests that the effective operating range of LD's narrows under increased climate forcing. Uncertainty also increases with lower AEP, as higher-magnitude events rely on extrapolation beyond observed data (Willems et al., 2012). Additionally, extreme flows introduce complex floodplain interactions and 3D turbulence that 2D shallow-water models may not fully capture (Dewals et al., 2023). The model also assumes consistent dam performance, whereas RQ1 demonstrates structural variability, suggesting real-world attenuation may be less uniform.

7.2.3 Flood peak timing

LD's also modify flood timing, by delaying peak flows and increasing response time (WWT, 2017). At the reach scale under baseline conditions, peak timing is consistently delayed due to reduced velocity and increased residence time, but delays decrease with event magnitude, from ~3.9 hours in smaller events to <1 hour in extreme events. This reflects the same threshold behaviour observed in magnitude results, where storage becomes ineffective once capacity is exceeded. This is consistent with wider findings that desynchronisation effects are strongest under lower-magnitude events (van Leeuwen et al., 2024). At the catchment scale, this is expressed as desynchronisation of peak flows. Under baseline conditions, delays increase substantially for lower to intermediate events, from 9.6 to 14.5 hours in the 50% AEP event and from 7.7 to 12.2 hours in the 10% AEP event. These multi-hour delays reduce coincident tributary peaks, contributing to downstream attenuation. This aligns with modelling studies suggesting retention times of ~10 hours are required to maximise NFM effectiveness (Metcalfe et al., 2018; Follett et al., 2024) and with evidence that cumulative storage across dam networks is critical (Villamizar et al., 2024). Under future conditions, this desynchronisation effect weakens. While delays persist for smaller events, they decline rapidly with increasing return period and climate forcing, with reductions of ~−6% to −8% in higher-magnitude events by 2060–2080. This reflects overtopping and bypass flow, which reduce storage efficiency and accelerate downstream routing. The use of UKCP18 RCP8.5 represents a high-emissions scenario, meaning threshold exceedance may occur earlier than under lower-emission pathways (Chen et al., 2020). As noted by Pacchetti et al., 2021, such scenarios are useful for stress-testing system behaviour but may overestimate rainfall intensity, meaning the decline in effectiveness observed here may represent an upper-bound estimate. Under lower-emission scenarios, these threshold points may be exceeded less frequently, meaning that LD's could remain effective across a wider range of events than suggested in this study. Fragility-based approaches could address this by incorporating failure probabilities into modelling (van Leeuwen, 2021).

In response to RQ2 and RQ3, LD's reduce downstream flood magnitude and delay peak timing under baseline and lower-magnitude events, but their effectiveness declines with increasing event magnitude and climate forcing, making their flood alleviation role scale-dependent, threshold-limited and increasingly constrained under future conditions.

7.3 RQ4

The improved LD configuration increases peak delay by ~4.5–6.4 hours under baseline and 2060-2080 conditions (3.33% AEP) compared to the existing LD's, demonstrating enhanced storage and desynchronisation. This confirms optimisation is possible through LD configuration alone, supporting RQ1-RQ3 findings that permeability, spacing and cumulative network effects control performance. Increasing dam density (10 to 24 structures) and reducing spacing (<10 m) strengthens interacting backwater effects (Villamizar et al., 2024). However, as testing is limited to the 3.33% AEP, where alleviation is strongest, this likely represents near-optimal conditions, and performance may decline under larger events. A key challenge is identifying diminishing returns, where additional structures provide limited gains but increase cost and maintenance, particularly for small catchments like South Moor and schemes such as Stanley SuDS+. Increased density may also alter sediment dynamics (Zhuang et al., 2025), while ecological responses remain uncertain (Hansamali et al., 2025).

By combining the optimised LD network with upstream storage and downstream detention, the NFM scheme delivers distributed flood alleviation. Its strong economic performance (CBR: 0.51 in 2000-2020 1% AEP) reflects attenuation is greatest when runoff is intercepted early and storage capacity is not exceeded. However, storage efficiency is sensitive to basin geometry and sedimentation over time, requiring maintenance such as dredging not captured in the model (Ahilan et al., 2019). Land-use change, including repurposing areas of South Moor Memorial Park, may reduce societal acceptance, reinforcing the need for stakeholder engagement (King and Bark, 2024). The Green Book emphasises accounting for non-monetised impacts and wider studies report higher returns when co-benefits such as biodiversity and resilience are considered (HM Government, 2026; WWT, 2025). Declining CBR over time highlights reduced efficiency as storage thresholds are exceeded while the hard-engineered scheme shows a contrasting profile. CBR is initially lower but increases relative to the NFM scheme over time (~0.29 by 2060-

2080), reflecting greater robustness under higher-magnitude events. Although flood extent remains widespread, impacts on high-value assets such as Greenland Community School are reduced, demonstrating that optimisation involves managing exposure as well as hazard. However, effectiveness is threshold-dependent, as overtopping leads to more rapid, concentrated impacts, resulting in more damage (Azhar et al., 2025). Increasing structural loads also raise maintenance demands and may reduce lifespan (30-50 years), lowering long-term efficiency (Moreta et al., 2020). High capital costs (~£4 million/km) further constrain feasibility in small catchments (Wells et al., 2020). The hybrid scheme highlights a key finding: combining interventions does not necessarily improve performance. Although it achieves the greatest damage reduction (£1.23 million), it produces the lowest cost-benefit efficiency, indicating costs increase faster than benefits. This indicates that optimisation depends on how interventions interact, not simply their quantity (Barnes et al., 2023). This indicates for small UK catchments like South Moor, prioritising targeted, cost-effective measures is more viable than implementing multiple high-cost interventions simultaneously.

Overall, optimised alleviation is not achieved by maximising single interventions, but by balancing attenuation, protection, cost and long-term resilience. NFM is most efficient under current conditions, while hard engineering becomes more effective as thresholds are exceeded. In answer to RQ4, the optimal strategy is a phased, adaptive approach that prioritises NFM for frequent to moderate events, with targeted engineered interventions introduced as risk increases.

7.4 Further research

A key contribution of this study is the integration of field-based morphological and flow evidence (RQ1) with event-based modelling across reach and catchment scales (RQ2–RQ4). This is important, as much of the LD literature treats these scales separately; field data captures real process-based behaviour, whereas modelling simplifies structure and assumes consistent performance. Emerging work is beginning to bridge this gap through coupled hydrological–hydraulic and multi-scale frameworks. For example, Wolstenholme et al., 2025, demonstrate how models such as CAESAR-Lisflood can incorporate both hydrology and sediment transport, enabling local processes (like backwater effects) to propagate through the system. In contrast, the FMP approach used here does not explicitly represent sediment dynamics or vegetation, which may bias alleviation estimates and limit representation of flow–morphology feedbacks (McParland, 2020). Future research should therefore focus on integrating morphodynamic processes into coupled modelling frameworks to better capture these feedbacks and improve representation of long-term LD performance. Zhuang et al., 2025, highlight the need for standardised classification frameworks in how LD's are characterised to enhance comparability and transferability of studies. While this study differentiates between dam types, further research could focus on quantifying how structural characteristics control attenuation efficiency and threshold behaviour.

Conventional cost-benefit approaches prioritise direct damage reduction and often fail to capture peak delay, desynchronisation and ecosystem services, leading to systematic undervaluation of NFM (Connelly et al., 2020). This is reflected in funding patterns, where historically only ~1% of UK flood risk funding has supported NFM, although this is increasing (~3–4%) (EA, 2026). Strengthening feasibility may therefore require community-led schemes, partnerships, and incremental delivery within programmes such as Stanley SuDS+. The modelling also does not account for future land-use changes, which may significantly alter runoff pathways, roughness and infiltration (Black et al., 2020). Approaches such as Monte Carlo simulations could better represent parameter and structural uncertainty (Metcalfe et al., 2018).

These uncertainties also limit transferability: NFM effectiveness is highly context-dependent, varying with catchment characteristics, morphology, and intervention design (Zhuang et al., 2025). As such, results from South Moor cannot be directly generalised, reinforcing the need for site-specific optimisation. Advances in modelling, including machine learning and planned LD representation in Flood Modeller Pro 8, offer potential to better capture non-linear responses and improve reliability of NFM assessments under climate change (Kumar et al., 2023; Wang et al., 2025).

8 Conclusion

Field evidence (RQ1) shows that LD's generate upstream storage through increased CSA and reduced velocity, though these effects are not consistently propagated downstream due to changes in conveyance and local scour. Modelling results (RQ2–RQ3) indicate that LD's enhance reach-scale storage and delay hydrograph peaks, but alleviation potential diminishes as events exceed storage thresholds and behaviour becomes conveyance-dominated. The optimisation analysis (RQ4) confirms that no single intervention is effective across all conditions: LD's and NFM perform best under moderate flows, while hard-engineered defences become increasingly important under more extreme events. LD performance is therefore scale- and threshold-dependent, shaped by spatial and temporal interactions.

These findings address the aim by demonstrating that LD's provide measurable flood alleviation benefits, but their effectiveness is variable. They are most effective during smaller to moderate events, particularly within catchment-scale strategies, but decline under larger events and future conditions, limiting their suitability as a stand-alone measure. For South Moor, the results support a phased, catchment-scale approach aligned with the Stanley SuDS+ programme, prioritising NFM for frequent events, with hard-engineered measures introduced under more extreme events as thresholds are exceeded. This balances present-day efficiency with long-term resilience. More broadly, the findings support a shift from viewing LD's as a stand-alone solution to a layered, adaptive system, with LD's acting as a targeted, scalable component of UK FRM under climate change. A key contribution of this study is the integration of field-based evidence and hydraulic modelling to link reach-scale processes to catchment-scale flood response. Ultimately, designing flood mitigation measures with the goal of balancing complexities between both environmental and socioeconomic livelihoods involving multistakeholder collaboration will lead to the most cost-effective outcomes in the long run.

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Appendices

Appendix 1

Leaky dam	Height (m)	Width (m)	Thickness (m)	Coordinates	Distance (m)	Slope
1	1.2	2.2	1.2	54.8534579, -1.7194066		
2	1.2	2.2	1.2	54.8534318, -1.7192420	7.5	0.006
3	1.2	2.0	1.1	54.8533882, -1.7189466	17	0.009
4	1	0.6	0.9	54.8533570, -1.7186063	28.5	0.013
5	0.9	0.6	0.7	54.8533155, -1.7180102	38.5	0.008
6	0.6	0.7	0.4	54.8532962, -1.7177614	14.5	0.011
7	0.5	0.5	0.3	54.8532896, -1.7176615	5	0.006
8	1.2	2.2	1.1	54.8531784, -1.7170238	46	0.015
9	1.2	2.2	1.2	54.8531458, -1.7169299	8	0.003
10	1.2	2.2	1.2	54.8531049, -1.7168096	10	0.006
					175	
11	1.2	2.2	1.2	54.851472, -1.716278		
12	1.2	2.2	1.2	54.851694, -1.716139		0.002

Dimensions, location, and spacing characteristics of leaky dams within the study reach. Distance (m) and slope (m/m) represent the longitudinal spacing and channel gradient between each dam and the next downstream structure, calculated along the channel. Coordinates are provided here in decimal degrees (WGS84)

Appendix 2

Leaky dam 1 upstream																	
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**		
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)
0	9	0.069	0	8	0.023	0	9	0.024	0	7	0.043	0	11	0.02	0	9	0.019
12	28	0.056	12	5	0.022	12	27	0.023	11	24	0.046	12	28	0.012	11	20	0.021
24	32	0.047	24	27	0.023	24	34	0.025	22	26	0.043	24	32	0.01	22	21	0.025
36	31	0.043	36	32	0.025	36	34	0.023	33	30	0.042	36	32	0.01	33	25	0.021
48	31	0.038	48	29	0.021	48	31	0.025	44	28	0.041	48	30	0.015	44	24	0.022
60	28	0.035	60	31	0.023	60	29	0.024	55	26	0.042	60	28	0.017	55	24	0.018
72	26	0.034	72	31	0.024	72	26	0.019	66	25	0.042	72	26	0.016	66	23	0.018
84	22	0.03	84	26	0.023	84	25	0.027	77	23	0.045	84	26	0.015	77	22	0.016
96	23	0.031	96	26	0.021	96	23	0.023	88	20	0.039	96	18	0.02	88	20	0.022
108	21	0.024	108	24	0.021	108	23	0.025	99	16	0.043	108	14	0.021	99	11	0.021
120	10		120	24		120	12		110	9		120	14		110	9	
Leaky dam 1 downstream																	
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**		
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)
0	0	0.355	0	0	0.115	0	0	0.01	0	0	0.027	0	0	0.065	0	0	0.037
10	9	0.342	11	5	0.112	10	7	0.009	12	3	0.029	10	0	0.082	11	0	0.036

20	6	0.259	22	7	0.116	20	7	0.015	24	6	0.029	20	7	0.083	22	5	0.042
30	7	0.211	33	7	0.11	30	6	0.005	36	2	0.025	30	8	0.082	33	5	0.037
40	9	0.112	44	9	0.109	40	8	0.011	48	2	0.023	40	7	0.071	44	4	0.035
50	2	0.112	55	8	0.104	50	7	0.005	60	6	0.029	50	8	0.068	55	5	0.038
60	2	0.044	66	1	0.102	60	0	0.017	72	11	0.026	60	10	0.079	66	10	0.039
70	10	0.131	77	1	0.11	70	0	0.015	84	9	0.025	70	12	0.082	77	10	0.043
80	11	0.046	88	12	0.108	80	10	0.014	96	6	0.023	80	13	0.074	88	9	0.041
90	12	0.051	99	11	0.103	90	9	0.015	108	7	0.021	90	11	0.076	99	7	0.037
100	10		110	10		100	10		120	6		100	9		110	7	
Leaky dam 2 upstream																	
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**		
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)
0	5	0.079	0	7	0.082	0	5	0.091	0	2	0.053	0	7	0.061	0	0	0.027
12	6	0.069	10	9	0.088	9	5	0.09	11	2	0.054	11	8	0.065	11	2	0.025
24	7	0.067	20	10	0.086	18	5	0.098	22	2	0.064	22	9	0.068	22	5	0.03
36	5	0.077	30	11	0.085	27	7	0.102	33	3	0.061	33	8	0.073	33	4	0.023
48	6	0.078	40	12	0.086	36	9	0.101	44	5	0.061	44	12	0.065	44	5	0.027
60	12	0.074	50	12	0.089	45	8	0.096	55	4	0.058	55	9	0.066	55	6	0.026
72	10	0.082	60	10	0.088	54	6	0.097	66	2	0.06	66	10	0.06	66	4	0.028
84	10	0.062	70	7	0.085	63	7	0.098	77	0	0.058	77	9	0.058	77	6	0.024

96	9	0.073	80	6	0.081	72	6	0.099	88	2	0.058	88	10	0.067	88	2	0.026
108	8	0.08	90	6	0.082	81	5	0.016	99	0	0.054	99	4	0.074	99	0	0.023
120	6		100	3		90	3		110	0		110	2		110	0	
Leaky dam 2 downstream																	
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**		
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)
0	2	0.076	0	2	0.067	0	4	0.012	0	0	0.06	0	3	0.111	0	2	0.051
12	3	0.069	12	2	0.063	11	5	0.039	11	0	0.065	11	4	0.113	11	2	0.053
24	4	0.099	24	2	0.051	22	4	0.035	22	0	0.062	22	5	0.111	22	3	0.055
36	2	0.065	36	3	0.047	33	3	0.036	33	2	0.062	33	3	0.113	33	3	0.046
48	4	0.082	48	3	0.053	44	2	0.066	44	1	0.061	44	2	0.097	44	1	0.045
60	1	0.067	60	2	0.049	55	3	0.059	55	1	0.061	55	3	0.096	55	1	0.038
72	2	0.066	72	3	0.049	66	2	0.053	66	1	0.06	66	2	0.1	66	1	0.036
84	2	0.075	84	4	0.051	77	2	0.057	77	2	0.062	77	3	0.107	77	2	0.044
96	3	0.096	96	5	0.049	88	2	0.051	88	3	0.062	88	2	0.103	88	2	0.046
108	5	0.088	108	6	0.044	99	3	0.048	99	2	0.06	99	0	0.094	99	0	0.042
120	3		120	2		110	2		110	1		110	0		110	0	

Leaky dam 3 upstream																	
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**		
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)
0	4	0.032	0	0	0.22	0	3	0.19	0	1	0.169	0	1	0.063	0	0	0.035
9	5	0.086	12	0	0.211	7	3	0.193	11	5	0.172	11	3	0.068	12	4	0.03
18	6	0.089	24	0	0.214	14	3	0.192	22	4	0.171	22	7	0.072	24	6	0.037
27	7	0.084	36	3	0.225	21	4	0.192	33	2	0.172	33	11	0.074	36	5	0.041
36	7	0.076	48	5	0.212	28	4	0.197	44	1	0.17	44	12	0.074	48	4	0.037
45	7	0.045	60	6	0.213	35	5	0.189	55	2	0.166	55	12	0.071	60	4	0.032
54	9	0.041	72	6	0.221	42	6	0.195	66	1	0.166	66	13	0.071	72	3	0.035
63	11	0.075	84	5	0.218	49	8	0.197	77	0	0.167	77	12	0.074	84	4	0.032
72	9	0.085	96	8	0.213	56	11	0.195	88	0	0.167	88	14	0.071	96	0	0.036
81	14	0.092	108	9	0.22	63	10	0.193	99	0	0.169	99	12	0.069	108	0	0.039

90	14		120	10		70	8		110	0		110	11		120	0	
Leaky dam 3 downstream																	
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**		
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)
0	2	0.017	0	2	0.078	0	1	0.061	0	1	0.048	0	0	0.145	0	0	0.042
12	4	0.138	13	4	0.086	13	0	0.065	12	3	0.053	12	0	0.141	12	0	0.036
24	2	0.13	26	5	0.074	26	0	0.067	24	3	0.054	24	2	0.148	24	0	0.039
36	0	0.128	39	4	0.089	39	0	0.067	36	2	0.053	36	0	0.137	36	0	0.039
48	0	0.131	52	3	0.078	52	0	0.063	48	3	0.051	48	0	0.148	48	0	0.038
60	2	0.127	65	2	0.082	65	2	0.062	60	0	0.052	60	2	0.151	60	0	0.037
72	4	0.128	78	0	0.09	78	2	0.071	72	0	0.049	72	4	0.143	72	3	0.033
84	5	0.114	91	0	0.082	91	5	0.062	84	0	0.051	84	4	0.139	84	2	0.034
96	7	0.128	104	2	0.097	104	6	0.065	96	0	0.054	96	4	0.139	96	5	0.032
108	4	0.136	117	2	0.074	117	3	0.068	108	0	0.049	108	7	0.148	108	3	0.0

																	32	
120	2		130	1		130	0		120	0		120	5		120	0		
Leaky dam 4 upstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	2	0.06	0	2	0.049	0	2	0.038	0	0	0.039	0	4	0.079	0	0	0.017	
13	4	0.051	13	4	0.039	13	5	0.035	12	1	0.041	15	8	0.072	12	1	0.014	
26	9	0.069	26	10	0.036	26	7	0.032	24	2	0.038	30	4	0.064	24	4	0.018	
39	10	0.06	39	11	0.043	39	8	0.033	36	2	0.041	45	8	0.069	36	7	0.017	
52	13	0.073	52	11	0.046	52	9	0.038	48	8	0.039	60	11	0.074	48	8	0.015	
65	15	0.06	65	11	0.047	65	8	0.037	60	5	0.042	75	16	0.069	60	6	0.013	
78	13	0.069	78	12	0.049	78	10	0.039	72	6	0.038	90	16	0.074	72	4	0.011	
91	14	0.072	91	9	0.053	91	7	0.043	84	7	0.041	105	10	0.081	84	3	0.015	
104	13	0.066	104	12	0.048	104	8	0.041	96	7	0.034	120	12	0.089	96	0	0.012	

117	14	0.073	117	12	0.041	117	9	0.038	108	5	0.041	135	10	0.086	108	0	0.011	
130	13		130	9		130	13		120	5		150	15		120	0		
Leaky dam 4 downstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	4	0.039	0	6	0.062	0	3	0.017	0	4	0.028	0	6	0.021	0	0	0.023	
10	6	0.035	10	7	0.053	11	4	0.018	10	8	0.03	9	10	0.024	8	0	0.023	
20	6	0.034	20	8	0.058	22	8	0.021	20	9	0.032	18	4	0.025	16	0	0.019	
30	8	0.019	30	8	0.061	33	8	0.031	30	8	0.035	27	10	0.023	24	0	0.018	
40	8	0.025	40	6	0.058	44	7	0.025	40	4	0.034	36	8	0.026	32	0	0.02	
50	9	0.029	50	8	0.065	55	7	0.019	50	0	0.031	45	10	0.031	40	2	0.021	
60	7	0.009	60	8	0.053	66	7	0.025	60	6	0.032	54	10	0.022	48	3	0.017	
70	10	0.016	70	12	0.047	77	9	0.033	70	6	0.032	63	14	0.02	56	3	0.024	
80	11	0.051	80	12	0.054	88	10	0.046	80	2	0.034	72	15	0.019	64	3	0.0	

																	25	
90	10	0.039	90	10	0.057	99	9	0.04	90	4	0.03	81	11	0.019	72	4	0.02	
100	12		100	8		110	2		100	2		90	8		80	3		
Leaky Dam 5 upstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	40	0.043	0	41	0.035	0	38	0.018	0	14	0.042	0	17	0.042	0	3	0.028	
8	43	0.048	9	39	0.031	10	38	0.011	8	12	0.037	8	13	0.049	8	4	0.026	
16	37	0.046	18	32	0.031	20	38	0.015	16	15	0.04	16	14	0.041	16	3	0.033	
24	36	0.032	27	31	0.03	30	38	0.015	24	8	0.038	24	14	0.039	24	3	0.032	
32	29	0.053	36	29	0.03	40	36	0.014	32	9	0.038	32	9	0.049	32	3	0.036	
40	25	0.048	45	26	0.029	50	34	0.019	40	6	0.033	40	7	0.045	40	2	0.031	
48	23	0.043	54	27	0.03	60	29	0.02	48	2	0.043	48	4	0.048	48	0	0.031	
56	25	0.041	63	28	0.028	70	24	0.018	56	2	0.039	56	4	0.049	56	0	0.028	

64	22	0.044	72	27	0.029	80	26	0.019	64	2	0.035	64	5	0.044	64	0	0.023	
72	21	0.037	81	21	0.028	90	22	0.018	72	0	0.039	72	5	0.045	72	0	0.033	
80	18		90	19		100	15		80	0		80	2		80	0		
Leaky dam 5 downstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	21	0.085	0	20	0.037	0	17	0.149	0	22	0.05	0	9	0.085	0	17	0.035	
7	19	0.069	9	23	0.055	8	23	0.127	8	22	0.048	9	20	0.105	9	21	0.037	
14	11	0.051	18	22	0.09	16	22	0.135	16	23	0.057	18	25	0.113	18	21	0.041	
21	14	0.084	27	11	0.079	24	22	0.103	24	24	0.047	27	24	0.116	27	22	0.035	
28	15	0.069	36	14	0.07	32	15	0.102	32	22	0.055	36	25	0.104	36	18	0.038	
35	13	0.072	45	13	0.084	40	16	0.106	40	22	0.053	45	25	0.081	45	13	0.038	
42	14	0.082	54	10	0.099	48	13	0.137	48	19	0.056	54	20	0.107	54	11	0.039	
49	7	0.074	63	6	0.066	56	9	0.144	56	12	0.045	63	13	0.131	63	14	0.0	

																	35
56	4	0.073	72	9	0.072	64	6	0.146	64	8	0.038	72	11	0.116	72	14	0.038
63	11	0.068	81	10	0.058	72	2	0.156	72	11	0.042	81	10	0.112	81	19	0.03
70	10		90	4		80	9		80	14		90	8		90	11	
Leaky dam 6 upstream																	
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**		
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)
0	12	0.057	0	2	0.065	0	2	0.034	0	4	0.038	0	13	0.079	0	0	0.044
12	18	0.076	11	3	0.039	10	3	0.038	9	4	0.04	10	13	0.083	11	0	0.021
24	13	0.061	22	4	0.048	20	7	0.035	18	5	0.036	20	17	0.085	22	5	0.025
36	9	0.079	33	8	0.045	30	13	0.028	27	5	0.035	30	16	0.086	33	10	0.022
48	17	0.089	44	18	0.047	40	11	0.033	36	10	0.037	40	16	0.076	44	11	0.019
60	15	0.086	55	17	0.043	50	11	0.036	45	19	0.034	50	16	0.078	55	12	0.021
72	17	0.088	66	12	0.045	60	16	0.038	54	8	0.04	60	16	0.068	66	9	0.023
84	8	0.082	77	11	0.048	70	16	0.034	63	8	0.032	70	22	0.081	77	3	0.0

																	19	
96	6	0.076	88	8	0.046	80	10	0.038	72	4	0.037	80	12	0.09	88	0	0.019	
108	5	0.072	99	6	0.048	90	7	0.034	81	4	0.036	90	9	0.078	99	0	0.017	
120	2		110	12		100	5		90	0		100	5		110	0		
Leaky dam 6 downstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	0	0.117	0	0	0.023	0	0	0.025	0	0	0.033	0	0	0.073	0	0	0.015	
7	0	0.127	8	0	0.019	7	0	0.028	8	0	0.037	7	0	0.062	8	0	0.01	
14	0	0.135	16	0	0.023	14	0	0.037	16	0	0.033	14	0	0.054	16	0	0.011	
21	0	0.141	24	0	0.017	21	0	0.039	24	0	0.034	21	0	0.063	24	0	0.007	
28	0	0.15	32	0	0.027	28	0	0.034	32	0	0.044	28	0	0.087	32	0	0.006	
35	0	0.171	40	0	0.013	35	4	0.025	40	0	0.039	35	0	0.078	40	0	0.009	
42	5	0.145	48	0	0.03	42	4	0.03	48	14	0.037	42	4	0.054	48	9	0.01	
49	27	0.164	56	25	0.014	49	7	0.03	56	0	0.034	49	7	0.089	56	11	0.0	

																	04	
56	15	0.159	64	22	0.023	56	25	0.031	64	15	0.037	56	24	0.051	64	10	0.009	
63	26	0.149	72	20	0.015	63	25	0.025	72	13	0.035	63	26	0.068	72	7	0.007	
70	12		80	17		70	27		80	5		70	19		80	4		
Leaky dam 7 upstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	2	0.074	0	2	0.046	0	0	0.094	0	1	0.028	0	5	0.074	0	0	0.013	
5	4	0.072	4	2	0.049	4	0	0.064	3	2	0.029	5	5	0.079	5	0	0.036	
10	8	0.082	8	3	0.05	8	0	0.09	6	2	0.028	10	6	0.063	10	0	0.034	
15	9	0.072	12	5	0.057	12	0	0.101	9	2	0.03	15	9	0.067	15	2	0.038	
20	9	0.036	16	6	0.045	16	1	0.091	12	2	0.031	20	9	0.074	20	6	0.039	
25	6	0.027	20	7	0.039	20	2	0.089	15	0	0.03	25	11	0.08	25	3	0.037	
30	5	0.028	24	8	0.047	24	3	0.115	18	0	0.028	30	10	0.071	30	0	0.035	

35	3	0.053	28	8	0.048	28	5	0.105	21	0	0.03	35	0	0.074	35	0	0.038	
40	6	0.07	32	9	0.05	32	7	0.098	24	0	0.028	40	0	0.062	40	0	0.039	
45	4	0.105	36	0	0.053	36	9	0.089	27	0	0.023	45	0	0.071	45	0	0.041	
50	10		40	0		40	0		30	0		50	0		50	0		
Leaky dam 7 downstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	20	0.028	0	19	0.011	0	19	0.018	0	1	0.028	0	3	0.015	0	0	0.02	
14	28	0.024	9	18	0.022	11	18	0.019	14	1	0.03	13	4	0.023	13	3	0.012	
28	27	0.026	18	21	0.03	22	18	0.021	28	10	0.034	26	16	0.014	26	10	0.01	
42	29	0.023	27	30	0.027	33	25	0.018	42	16	0.032	39	8	0.023	39	21	0.024	
56	28	0.022	36	31	0.025	44	30	0.032	56	19	0.03	52	30	0.021	52	22	0.015	
70	30	0.026	45	33	0.027	55	31	0.021	70	26	0.034	65	33	0.019	65	27	0.017	
84	31	0.023	54	34	0.029	66	32	0.021	84	26	0.027	78	33	0.024	78	27	0.016	

98	32	0.037	63	37	0.022	77	24	0.018	98	27	0.034	91	32	0.025	91	27	0.015	
112	31	0.029	72	40	0.027	88	38	0.021	112	23	0.032	104	32	0.019	104	18	0.02	
126	26	0.027	81	40	0.025	99	39	0.02	126	25	0.035	117	31	0.023	117	14	0.021	
140	28		90	40		110	38		140	17		130	24		130	14		
Leaky dam 8 upstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	5	0.045	0	7	0.047	0	11	0.028	0	0	0.043	0	5	0.124	0	0	0.005	
11	6	0.053	10	11	0.051	9	12	0.029	6	0	0.041	11	8	0.124	10	2	0.003	
22	12	0.047	20	7	0.061	18	7	0.032	12	0	0.043	22	8	0.122	20	2	0.003	
33	13	0.043	30	8	0.058	27	8	0.028	18	3	0.046	33	10	0.124	30	4	0.008	
44	15	0.046	40	12	0.058	36	8	0.03	24	3	0.049	44	11	0.123	40	4	0.004	
55	14	0.041	50	15	0.062	45	7	0.031	30	5	0.039	55	13	0.125	50	5	0.001	
66	13	0.037	60	12	0.056	54	7	0.031	36	5	0.046	66	12	0.122	60	6	0.0	

																	02	
77	12	0.036	70	11	0.046	63	11	0.029	42	5	0.041	77	11	0.123	70	2	0.007	
88	15	0.038	80	8	0.057	72	10	0.027	48	5	0.042	88	8	0.121	80	0	0.004	
99	16	0.042	90	2	0.062	81	10	0.027	54	5	0.041	99	4	0.123	90	0	0.003	
110	5		100	0		90	3		60	0		110	1		100	0		
Leaky dam 8 downstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	13	0.062	0	30	0.028	0	24	0.026	0	11	0.033	0	5	0.046	0	5	0.028	
10	19	0.063	8	30	0.026	8	22	0.029	8	15	0.031	10	16	0.053	8	12	0.023	
20	18	0.07	16	33	0.028	16	23	0.026	16	18	0.032	20	17	0.057	16	14	0.022	
30	22	0.069	24	30	0.03	24	22	0.026	24	15	0.035	30	16	0.054	24	12	0.019	
40	31	0.068	32	27	0.029	32	19	0.027	32	11	0.031	40	16	0.049	32	11	0.023	
50	34	0.064	40	22	0.028	40	15	0.028	40	9	0.034	50	21	0.048	40	10	0.025	

60	31	0.065	48	18	0.027	48	17	0.027	48	9	0.03	60	25	0.049	48	0	0.021	
70	32	0.062	56	14	0.024	56	22	0.027	56	10	0.033	70	25	0.047	56	0	0.024	
80	22	0.07	64	14	0.026	64	15	0.027	64	7	0.03	80	17	0.056	64	0	0.025	
90	21	0.06	72	22	0.027	72	6	0.026	72	7	0.035	90	9	0.053	72	0	0.019	
100	8		80	19		80	2		80	5		100	3		80	0		
Leaky dam 9 upstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	6	0.049	0	5	0.038	0	3	0.036	0	7	0.037	0	7	0.033	0	0	0.019	
11	8	0.043	11	6	0.038	9	9	0.035	10	9	0.038	9	10	0.041	9	0	0.016	
22	10	0.042	22	9	0.037	18	22	0.038	20	24	0.035	18	17	0.043	18	4	0.02	
33	17	0.041	33	18	0.038	27	23	0.037	30	19	0.034	27	22	0.045	27	6	0.019	
44	20	0.04	44	25	0.041	36	20	0.04	40	12	0.036	36	23	0.039	36	7	0.016	
55	22	0.042	55	23	0.036	45	18	0.037	50	11	0.039	45	20	0.039	45	7	0.0	

																	21	
66	25	0.03	66	18	0.037	54	19	0.035	60	10	0.037	54	19	0.034	54	9	0.021	
77	18	0.034	77	12	0.036	63	21	0.042	70	12	0.037	63	23	0.028	63	8	0.026	
88	13	0.04	88	9	0.032	72	25	0.041	80	5	0.034	72	20	0.035	72	8	0.022	
99	13	0.041	99	9	0.038	81	16	0.031	90	2	0.036	81	16	0.027	81	2	0.019	
110	12		110	13		90	7		100	0		90	16		90	0		
Leaky dam 9 downstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	8	0.04	0	2	0.025	0	3	0.025	0	2	0.029	0	11	0.025	0	3	0.014	
16	9	0.051	15	8	0.03	15	12	0.023	14	15	0.03	15	17	0.022	14	7	0.021	
32	25	0.048	30	22	0.037	30	22	0.024	28	19	0.033	30	30	0.025	28	25	0.017	
48	38	0.041	45	22	0.038	45	24	0.021	42	23	0.031	45	33	0.023	42	29	0.016	
64	37	0.044	60	26	0.035	60	26	0.023	56	28	0.028	60	36	0.032	56	29	0.019	

80	39	0.049	75	29	0.034	75	29	0.025	70	31	0.03	75	32	0.045	70	29	0.023	
96	38	0.051	90	28	0.038	90	31	0.023	84	31	0.034	90	34	0.028	84	26	0.024	
112	31	0.046	105	32	0.039	105	31	0.027	98	31	0.032	105	30	0.025	98	22	0.02	
128	29	0.042	120	19	0.043	120	23	0.021	112	29	0.034	120	28	0.022	112	20	0.025	
144	25	0.043	135	25	0.035	135	22	0.026	126	19	0.036	135	20	0.025	126	12	0.024	
160	10		150	9		150	3		140	10		150	4		140	8		
Leaky dam 10 upstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**			**July 12th**			
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	2	0.074	0	1	0.07	0	10	0.056	0	2	0.078	0	8	0.036	0	0	0.013	
10	4	0.072	10	2	0.066	9	13	0.052	10	8	0.075	10	19	0.031	10	0	0.015	
20	9	0.072	20	3	0.068	18	11	0.06	20	14	0.075	20	25	0.035	20	0	0.02	
30	11	0.08	30	6	0.07	27	13	0.052	30	15	0.076	30	11	0.033	30	10	0.026	
40	13	0.081	40	10	0.062	36	14	0.056	40	10	0.074	40	22	0.038	40	11	0.019	

50	16	0.074	50	12	0.066	45	10	0.053	50	7	0.073	50	17	0.041	50	10	0.021	
60	19	0.071	60	17	0.063	54	9	0.054	60	7	0.072	60	15	0.038	60	3	0.018	
70	18	0.068	70	14	0.06	63	13	0.059	70	5	0.069	70	12	0.037	70	2	0.015	
80	17	0.076	80	14	0.074	72	14	0.048	80	5	0.072	80	10	0.035	80	0	0.018	
90	17	0.072	90	15	0.071	81	14	0.053	90	2	0.076	90	11	0.027	90	0	0.015	
100	23		100	14		90	11		100	0		100	8		100	0		
Leaky dam 10 downstream																		
January 11th			**February 8th**			**March 8th**			**May 10th**			**June 7th**				**July 12th**		
Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	Width (cm)	Depth (cm)	Flow (m/s)	
0	9	0.069	0	8	0.023	0	9	0.024	0	7	0.043	0	11	0.02	0	9	0.019	
12	28	0.056	12	5	0.022	12	27	0.023	11	24	0.046	12	28	0.012	11	20	0.021	
24	32	0.047	24	27	0.023	24	34	0.025	22	26	0.043	24	32	0.01	22	21	0.025	
36	31	0.043	36	32	0.025	36	34	0.023	33	30	0.042	36	32	0.01	33	25	0.021	
48	31	0.038	48	29	0.021	48	31	0.025	44	28	0.041	48	30	0.015	44	24	0.0	

																	22	
60	28	0.035	60	31	0.023	60	29	0.024	55	26	0.042	60	28	0.017	55	24	0.018	
72	26	0.034	72	31	0.024	72	26	0.019	66	25	0.042	72	26	0.016	66	23	0.018	
84	22	0.03	84	26	0.023	84	25	0.027	77	23	0.045	84	26	0.015	77	22	0.016	
96	23	0.031	96	26	0.021	96	23	0.023	88	20	0.039	96	18	0.02	88	20	0.022	
108	21	0.024	108	24	0.021	108	23	0.025	99	16	0.043	108	14	0.021	99	11	0.021	
120	10		120	24		120	12		110	9		120	14		110	9		

Baseline field measurements collected upstream and downstream of leaky dams 1-10 in the upstream Stanley Burn reach. Width and depth are presented in centimetres but were converted to metres for the purpose of the study. Flow velocity is reported in m/s.

Appendix 3

Leaky dam 11 downstream		
July 12th		
Width (cm)	Depth (cm)	Flow (m/s)
0	0	0.027
8	0	0.028
16	0	0.031
24	0	0.03
32	0	0.035
40	1	0.026
48	6	0.032
56	11	0.026
64	21	0.03
72	19	0.025
Leaky dam 11 upstream		
July 12th		

Width (cm)	Depth (cm)	Flow (m/s)
0	13	0.019
11	12	0.024
22	16	0.028
33	24	0.026
44	27	0.029
55	30	0.027
66	31	0.026
77	29	0.025
88	34	0.027
99	35	0.027
Leaky dam 12 downstream		
July 12th		
Width (cm)	Depth (cm)	Flow (m/s)
0	5	0.026
15	17	0.028
30	20	0.031
45	26	0.03
60	27	0.029
75	30	0.03
90	29	0.032
105	28	0.033
120	25	0.033
135	16	0.032
Leaky dam 12 upstream		
July 12th		
Width (cm)	Depth (cm)	Flow (m/s)
0	8	0.03
11	19	0.03
22	29	0.03
33	32	0.03
44	29	0.029
55	29	0.03
66	27	0.028
77	25	0.032
88	23	0.028
99	21	0.03

Baseline field measurements collected upstream and downstream of leaky dams 11 and 12 in the other tributary of Stanley Burn taken on the final data collection period. Width and depth are presented in centimetres but were converted to metres for the purpose of the study. Flow velocity is reported in m/s.

Appendix 4

05/01/2025 13:00:23	0
05/01/2025 13:02:23	0

05/01/2025 13:04:23	0
05/01/2025 13:06:23	0
05/01/2025 13:08:23	0
05/01/2025 13:10:23	0
05/01/2025 13:12:23	0
05/01/2025 13:14:23	0
05/01/2025 13:16:23	0
05/01/2025 13:18:23	0
05/01/2025 13:20:23	0
05/01/2025 13:22:23	0
05/01/2025 13:24:23	0
05/01/2025 13:26:23	0
05/01/2025 13:28:23	0
05/01/2025 13:30:23	0
05/01/2025 13:32:23	0
05/01/2025 13:34:23	0
05/01/2025 13:36:23	0
05/01/2025 13:38:23	0
05/01/2025 13:40:23	0
05/01/2025 13:42:23	0
05/01/2025 13:44:23	2.364
05/01/2025 13:46:23	0.197
05/01/2025 13:48:23	0.197
05/01/2025 13:50:23	0
05/01/2025 13:52:23	0.197
05/01/2025 13:54:23	0.197
05/01/2025 13:56:23	0
05/01/2025 13:58:23	0.197

05/01/2025 14:00:23	0
05/01/2025 14:02:23	0.197
05/01/2025 14:04:23	0
05/01/2025 14:06:23	0.197
05/01/2025 14:08:23	0.197
05/01/2025 14:10:23	0
05/01/2025 14:12:23	0.197
05/01/2025 14:14:23	0
05/01/2025 14:16:23	0.197
05/01/2025 14:18:23	0
05/01/2025 14:20:23	0.197
05/01/2025 14:22:23	0.197
05/01/2025 14:24:23	0
05/01/2025 14:26:23	0.197
05/01/2025 14:28:23	0
05/01/2025 14:30:23	0.197
05/01/2025 14:32:23	0
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06/01/2025 09:54:23	0
06/01/2025 09:56:23	0.197
06/01/2025 09:58:23	0
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06/01/2025 10:08:23	0
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06/01/2025 11:02:23	0
06/01/2025 11:04:23	0.197
06/01/2025 11:06:23	0
06/01/2025 11:08:23	0
06/01/2025 11:10:23	0.197
06/01/2025 11:12:23	0
06/01/2025 11:14:23	0
06/01/2025 11:16:23	0.197
06/01/2025 11:18:23	0
06/01/2025 11:20:23	0
06/01/2025 11:22:23	0
06/01/2025 11:24:23	0
06/01/2025 11:26:23	0.197

06/01/2025 11:28:23	0
06/01/2025 11:30:23	0
06/01/2025 11:32:23	0
06/01/2025 11:34:23	0.197
06/01/2025 11:36:23	0
06/01/2025 11:38:23	0
06/01/2025 11:40:23	0
06/01/2025 11:42:23	0.197
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06/01/2025 11:50:23	0
06/01/2025 11:52:23	0
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06/01/2025 11:56:23	0
06/01/2025 11:58:23	0
06/01/2025 12:00:23	0
06/01/2025 12:02:23	0
06/01/2025 12:04:23	0
06/01/2025 12:06:23	0
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06/01/2025 12:12:23	0
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06/01/2025 12:22:23	0

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06/01/2025 12:30:23	0
06/01/2025 12:32:23	0
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06/01/2025 12:42:23	0
06/01/2025 12:44:23	0
06/01/2025 12:46:23	0
06/01/2025 12:48:23	0
06/01/2025 12:50:23	0
06/01/2025 12:52:23	0
06/01/2025 12:54:23	0.197
06/01/2025 12:56:23	0
06/01/2025 12:58:23	0
06/01/2025 13:00:23	0

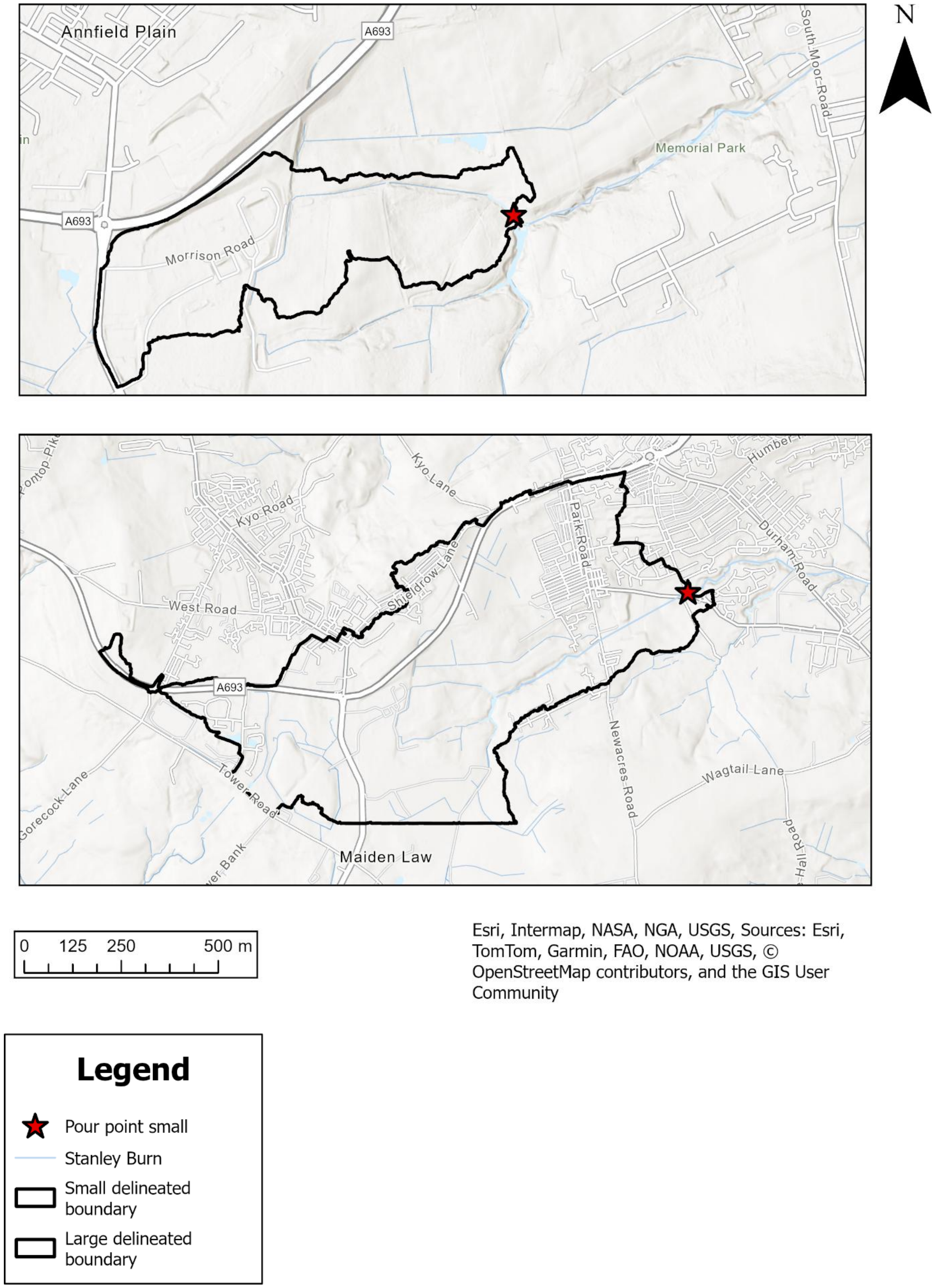
Example of high-resolution rainfall data recorded at 2-minute intervals for a 24 hour period, used to characterise event structure and temporal variability in precipitation. Collected from Stanley Burn farm rain gauge in the Upper Twizell-South Moor catchment area.

Appendix 5

Type of Channel and Description	Minimum	Normal	Maximum
Natural streams - minor streams (top width at floodstage < 100 ft)			
1. Main Channels			
a. clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. same as above, but more stones and weeds	0.030	0.035	0.040
c. clean, winding, some pools and shoals	0.033	0.040	0.045
d. same as above, but some weeds and stones	0.035	0.045	0.050
e. same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
f. same as "d" with more stones	0.045	0.050	0.060
g. sluggish reaches, weedy, deep pools	0.050	0.070	0.080
h. very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150

Manning's roughness coefficient (n = 0.045) adopted following Chow, 1959, representing a moderately rough natural channel with vegetation and channel irregularity. This value was chosen to reflect field-observed conditions, including bed material variability, vegetation presence and flow obstructions associated with leaky dam structures, with pools, weeds and stones present.

Appendix 6



Multi-scale delineation of the study area, showing both the A). smaller reach-scale boundary (354077m^2) and B). wider catchment boundary (1908837m^2) and used for subsequent analysis, enabling comparison between localised response and catchment-scale processes.

Appendix 7

	Channel length (L_c) (m)	Upstream elevation (m)	Downstream elevation (m)	Elevation change (m)	Slope (S_c) (m/m)	$\sqrt{S_c}$	$\frac{L_c}{\sqrt{S_c}}$	**(**T_c) (hours)
Small catchment	895.06	236.25	194.585	41.665	0.0465	0.216	4143.8	**0.96**
Large catchment	2864.47	274.623	155.086	119.537	0.0417	0.204	14041.5	**2.74**

Time of concentration (T_c) calculated using the Watt and Chow (1985) equation. Channel length (L_c) was derived from GIS as the longest flow path. Elevation change represents the difference between upstream and downstream elevations. Channel slope (S_c) was calculated as $\Delta H/L_c$(m/m). The coefficient (0.0014) and exponent (0.79) are empirically derived constants. $T_c$is expressed in hours. 0.96 was rounded to 1 hour and 2.74 was rounded to 3 hours for subsequent analysis.

Appendix 8

Newcastle Weather Station	Max of 1hr	Max of 3hr	Durham	Max of 1hr	Max of 3hr
1974	19.7	26.7	1997	15.8	16.2
1975	50.2	50.2	1998	52.6	58
1976	91.4	119.4	1999	65	95
1977	26.8	35.4	2000	95	95
1978	49.2	63.7	2001	145	145
1979	40.4	41.1	2002	52.5	52.5
1980	44.9	49.2	2003	42.4	45.1
1981	46.4	54.5	2004	53.2	54
1982	34.4	39	2005	64	64
1983	27.4	32.9	2006	77.4	77.4
1984	31.7	40.2	2007	77.4	77.4
1985	22.2	25.1	2008	41.4	42.2
1986	66.7	67.7	2009	35.2	39.6
1987	35	35.6	2010	33.2	36.6
1988	34.7	44	2011	35.2	35.8
1989	23.3	23.8	2012	38.4	40.8
1990	39	40.9	2013	57	67.4
1991	18.6	23.1	2014	19.4	24.4
1992	36.8	40.4	2015	27.2	31.8
1993	42	45.4	2016	35.8	40
1994	18	24.2	2017	35.4	42.6
1995	40.2	41	2018	23.5	23.7
1996	35.4	39.2	2019	26.8	29.6
1997	20.6	23.4	2020	27.8	30.2

1998	30.2	33	2021	26.6	28.6
1999	33.4	38.2	2022	23.4	24.8
2000	29.2	29.6	2023	37.8	40
2001	34.8	38.8	2024	27	29
2002	23.6	26.6			
2003	17.4	18			
2004	31.6	37.6			
2005	24	40.4			

Rolling rainfall totals (1 and 3hr) were calculated and Annual Maxima Series (AMS) extracted for Newcastle and Durham rain gauges.

Appendix 9

50% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.051	0.084	0.113
	0.17	0.054	0.090	0.121
	0.33	0.053	0.087	0.118
	0.5	0.051	0.084	0.114
	0.67	0.054	0.090	0.121
	0.83	0.049	0.082	0.110
	1	0.047	0.078	0.105
10% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.093	0.127	0.156
	0.17	0.100	0.136	0.168
	0.33	0.097	0.132	0.162
	0.5	0.094	0.128	0.157
	0.67	0.100	0.136	0.167
	0.83	0.091	0.124	0.152
	1	0.087	0.118	0.145
3.33% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.111	0.143	0.173
	0.17	0.120	0.154	0.186
	0.33	0.116	0.149	0.180
	0.5	0.112	0.144	0.174
	0.67	0.119	0.153	0.185
	0.83	0.109	0.140	0.169
	1	0.104	0.133	0.161
1% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.125	0.159	0.187
	0.17	0.134	0.171	0.201
	0.33	0.130	0.166	0.195
	0.5	0.126	0.160	0.189
	0.67	0.134	0.170	0.200
	0.83	0.122	0.155	0.183
	1	0.116	0.148	0.174

0.5% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.131	0.164	0.194
	0.17	0.141	0.176	0.208
	0.33	0.136	0.171	0.202
	0.5	0.132	0.165	0.195
	0.67	0.140	0.175	0.207
	0.83	0.128	0.160	0.189
	1	0.122	0.152	0.180
50% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.311	0.500	0.659
	0.17	0.327	0.526	0.692
	0.33	0.335	0.540	0.711
	0.5	0.329	0.530	0.698
	0.67	0.324	0.521	0.686
	0.83	0.318	0.513	0.675
	1	0.314	0.506	0.666
	1.17	0.317	0.511	0.673
	1.33	0.310	0.499	0.657
	1.5	0.303	0.487	0.642
	1.67	0.292	0.469	0.618
	1.83	0.255	0.410	0.540
	2	0.208	0.335	0.442
	2.17	0.144	0.232	0.306
	2.33	0.099	0.160	0.211
	2.5	0.068	0.109	0.143
	2.67	0.049	0.078	0.103
	2.83	0.034	0.056	0.073
	3	0.026	0.042	0.055
10% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.54	0.76	0.89
	0.17	0.57	0.79	0.94
	0.33	0.58	0.82	0.96
	0.5	0.57	0.80	0.94
	0.67	0.56	0.79	0.93
	0.83	0.55	0.77	0.91
	1	0.55	0.76	0.90
	1.17	0.55	0.77	0.91
	1.33	0.54	0.75	0.89
	1.5	0.53	0.74	0.87
	1.67	0.51	0.71	0.84
	1.83	0.44	0.62	0.73
	2	0.36	0.51	0.60
	2.17	0.25	0.35	0.41
	2.33	0.17	0.24	0.29
	2.5	0.12	0.16	0.19

	2.67	0.08	0.12	0.14
	2.83	0.06	0.08	0.10
	3	0.05	0.06	0.07
3.3% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.67	0.86	1.03
	0.17	0.71	0.91	1.08
	0.33	0.73	0.93	1.11
	0.5	0.71	0.91	1.09
	0.67	0.70	0.90	1.07
	0.83	0.69	0.88	1.05
	1	0.68	0.87	1.04
	1.17	0.69	0.88	1.05
	1.33	0.67	0.86	1.02
	1.5	0.65	0.84	1.00
	1.67	0.63	0.81	0.96
	1.83	0.55	0.71	0.84
	2	0.45	0.58	0.69
	2.17	0.31	0.40	0.48
	2.33	0.22	0.28	0.33
	2.5	0.15	0.19	0.22
	2.67	0.11	0.13	0.16
	2.83	0.07	0.10	0.11
	3	0.06	0.07	0.09
1% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.76	0.95	1.11
	0.17	0.80	1.00	1.17
	0.33	0.82	1.02	1.20
	0.5	0.80	1.00	1.18
	0.67	0.79	0.99	1.16
	0.83	0.78	0.97	1.14
	1	0.77	0.96	1.12
	1.17	0.77	0.97	1.13
	1.33	0.76	0.94	1.11
	1.5	0.74	0.92	1.08
	1.67	0.71	0.89	1.04
	1.83	0.62	0.78	0.91
	2	0.51	0.63	0.74
	2.17	0.35	0.44	0.52
	2.33	0.24	0.30	0.36
	2.5	0.16	0.21	0.24
	2.67	0.12	0.15	0.17
	2.83	0.08	0.10	0.12
	3	0.06	0.08	0.09
0.5% AEP	**Time (hours)**	Baseline lower	Baseline central	Baseline upper
	0	0.80	0.98	1.15

	0.17	0.84	1.04	1.21
	0.33	0.86	1.06	1.24
	0.5	0.84	1.04	1.22
	0.67	0.83	1.03	1.20
	0.83	0.82	1.01	1.18
	1	0.81	1.00	1.16
	1.17	0.81	1.01	1.17
	1.33	0.79	0.98	1.15
	1.5	0.78	0.96	1.12
	1.67	0.75	0.92	1.08
	1.83	0.65	0.81	0.94
	2	0.53	0.66	0.77
	2.17	0.37	0.46	0.53
	2.33	0.25	0.32	0.37
	2.5	0.17	0.21	0.25
	2.67	0.12	0.15	0.18
	2.83	0.09	0.11	0.13
	3	0.07	0.08	0.10

Catchment- and reach-scale discharge hydrographs generated at 10-minute temporal resolution for baseline peak discharge events.

Appendix 10

$$A_{total} = \sum(h \times w)$$

Where h = height of each individual gap and w = width of each individual gap

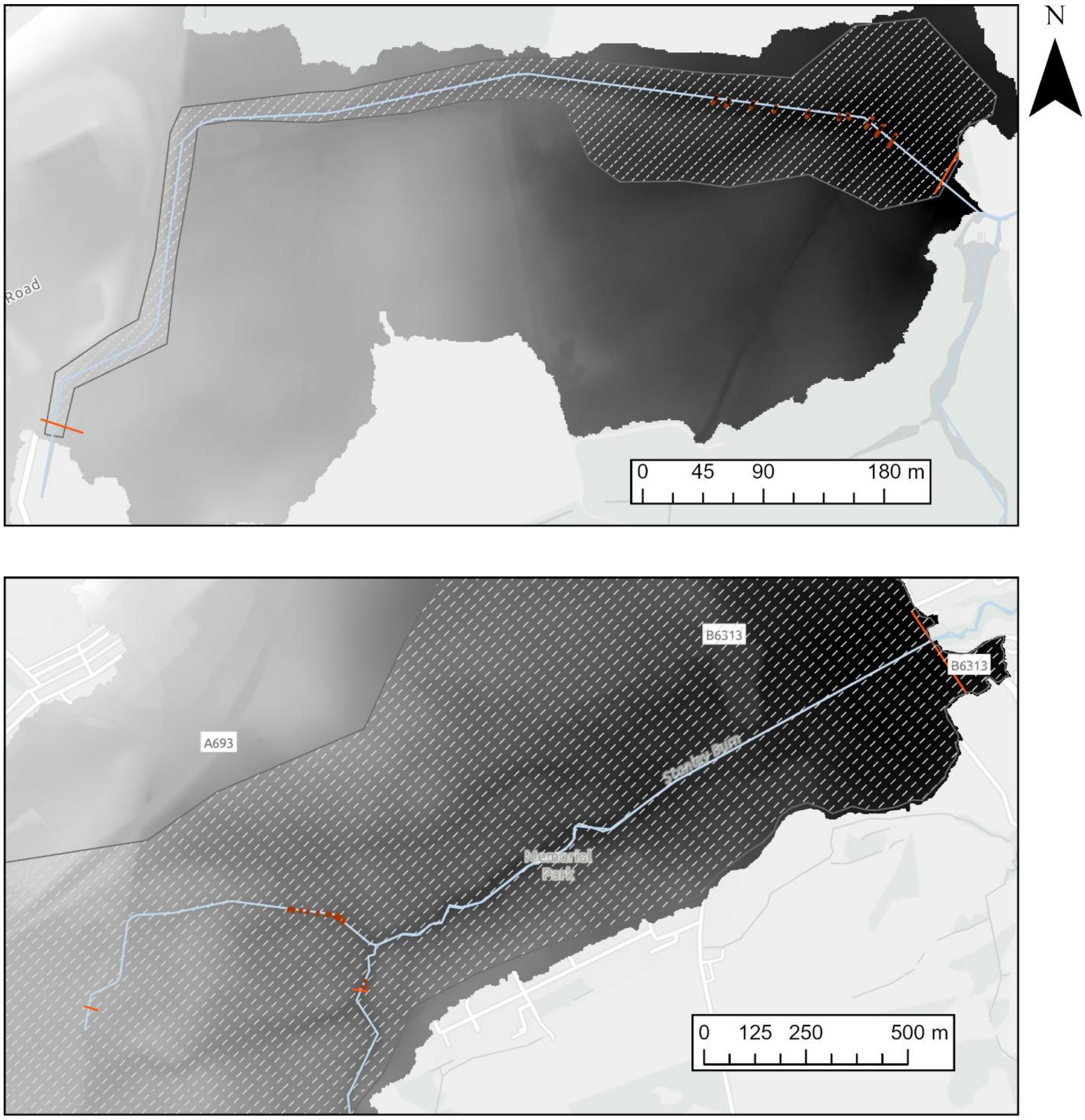
$$D = \sqrt{\frac{4(A_{total}/2)}{\pi}}$$

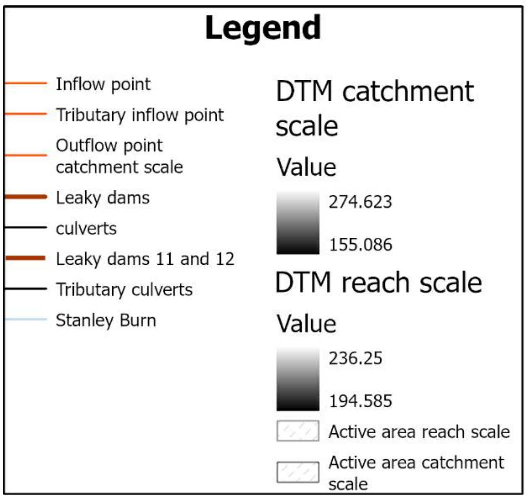
Where A_{total}= total estimated open area (m²) and D= diameter of each culvert (m)

Leaky dam	Culvert 1 diameter	Culvert 2 diameter
1	0.37	0.25
2	0.37	0.25
3	0.36	0.23
4	0.17	0.11
5	0.22	0.14
6	0.15	0.04
7	0.12	0.03
8	0.32	0.21
9	0.37	0.25
10	0.32	0.21
11	0.32	0.21
12	0.32	0.21

Estimation process of equivalent culvert sizes for dam leakiness representation. A). Scaniverse 3D imagery software was used to estimate leaky dam gap dimensions (height and width). The basal gap height can also be observed (18cm in height and is the width of the dam shown in appendix 1), representing the dominant flow route through the leaky dam, B). The formula used for estimating total combined effective flow area through the gaps of each leaky dam and C). the total estimated flow area was converted into two equivalent circular culverts, allowing representation of distributed flow through the structure. D). The final diameter values whereby culvert 1 represents basal gap through flow and culvert 2 represents secondary gap estimates. The wooden boarded dams (LD6 and LD7) have fewer gaps and lower permeability than other dam types. The conversion of irregular, multi-gap flow into a uniform equivalent opening introduces uncertainty, as gap variability, blockage and turbulence are not fully represented in the modelling stage (Senior et al., 2022).

Appendix 11





Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Model setup for catchment scale and reach scale in Flood Modeller Pro.

Appendix 12

	Member 1	Member 10	Member 29
2.2km	1980-2000		
2	11.80417	12.06224	10.37029
5	16.069	16.07628	19.27583
10	18.89269	18.73392	25.17207
20	21.60124	21.2832	30.82788
30	23.15941	22.74973	34.08154
50	25.10719	24.58297	38.14876
80	26.89001	26.26096	41.87153
100	27.7344	27.05569	43.63472
200	30.35202	29.51939	49.10067
	1	10	29
	2001-2021		
2	12.36021	14.06355	9.519979
5	16.14749	21.73217	16.74703
10	18.655	26.80946	21.53197
20	21.06026	31.67973	26.1218
30	22.44394	34.48147	28.76221
50	24.17362	37.98378	32.06286
80	25.75681	41.18949	35.08398
100	26.50665	42.70779	36.51485
200	28.83116	47.41455	40.9506
	1	10	29
	2021-2040		
2	13.05226	14.48034	7.564519
5	17.81262	20.152	9.801658
10	20.96439	23.90712	11.28284
20	23.98764	27.50913	12.70362
30	25.72684	29.58128	13.52096
50	27.90093	32.17156	14.54268
80	29.89089	34.54247	15.47787
100	30.83339	35.6654	15.9208
200	33.75515	39.14648	17.29389
	1	10	29
	2041-2060		
2	15.24119	16.28299	8.607367
5	20.35066	24.44695	15.08236
10	23.73358	29.8522	19.36937
20	26.97855	35.03705	23.48158
30	28.84531	38.01977	25.84722
50	31.17884	41.74831	28.8044
80	33.31475	45.16108	31.51114
100	34.32637	46.77745	32.79311
200	37.4624	51.78823	36.76726
	1	10	29
	2061-2080		

2	13.00447	14.30771	10.11131
5	19.45722	21.15837	15.65089
10	23.72951	25.69411	19.31858
20	27.82759	30.0449	22.83672
30	30.18511	32.5478	24.86062
50	33.13213	35.67655	27.39058
80	35.82957	38.54033	29.70629
100	37.10714	39.89668	30.80307
200	41.06764	44.10141	34.2031

UKCP18-derived design rainfall depths (mm) for the 2.2km² hourly, localised scale across return periods (2–200 years) and climate scenarios (1980–2080), using ensemble members 1, 10 and 29.

Appendix 13

2.2km			
2001-2020	5	50	90
2	0.930915	1.047106	1.154034
5	0.882418	1.004885	1.317123
10	0.868594	0.987419	1.3867
20	0.860104	0.974956	1.437132
30	0.856442	0.969107	1.461029
50	0.852704	0.962817	1.486895
80	0.849892	0.957858	1.507408
100	0.84872	0.955732	1.516236
200	0.845601	0.949893	1.540585
2021-2040			
2	0.767071	1.105734	1.190995
5	0.568496	1.108508	1.239022
10	0.514371	1.109656	1.259492
20	0.481921	1.110475	1.274323
30	0.468138	1.110859	1.281348
50	0.454216	1.111273	1.288951
80	0.443846	1.111599	1.294979
100	0.439553	1.111738	1.297573
200	0.428204	1.112122	1.304727
2041-2060			
2	0.876119	1.29117	1.34404
5	0.83085	1.266455	1.495262
10	0.818154	1.256231	1.559759
20	0.810423	1.248935	1.606501
30	0.807106	1.245512	1.628647
50	0.803732	1.241829	1.652618
80	0.801203	1.238927	1.671626
100	0.800152	1.237682	1.679807
200	0.797359	1.234264	1.702369
2061-2080			

2	0.987692	1.101685	1.177709
5	0.851835	1.210855	1.305597
10	0.816317	1.256015	1.359977
20	0.795527	1.28824	1.399329
30	0.786837	1.303363	1.417957
50	0.778157	1.319627	1.438106
80	0.771761	1.332449	1.454076
100	0.769132	1.337946	1.460947
200	0.762237	1.353045	1.479888

Climate change uplift factors for design rainfall depths from the hourly 2.2km² projectiles across return periods (2–200 years) and future time slices (2001–2080), based on UKCP18 percentiles (5th, 50th, and 90th).

Appendix 14

50% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.046	0.067	0.134	0.037	0.087	0.111	0.043	0.085	0.138	0.045	0.089	0.143
	0.17	0.050	0.072	0.144	0.039	0.094	0.119	0.046	0.092	0.148	0.048	0.096	0.154
	0.33	0.048	0.070	0.139	0.038	0.091	0.115	0.045	0.089	0.144	0.047	0.093	0.149
	0.5	0.047	0.068	0.134	0.037	0.088	0.111	0.044	0.086	0.139	0.045	0.090	0.144
	0.67	0.049	0.072	0.143	0.039	0.093	0.119	0.046	0.091	0.147	0.048	0.096	0.153
	0.83	0.045	0.065	0.130	0.036	0.085	0.108	0.042	0.083	0.134	0.044	0.087	0.139
	1	0.043	0.062	0.124	0.034	0.081	0.103	0.040	0.079	0.128	0.042	0.083	0.133
10% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.080	0.120	0.176	0.077	0.122	0.188	0.071	0.132	0.188	0.076	0.136	0.237
	0.17	0.086	0.129	0.189	0.083	0.131	0.202	0.076	0.142	0.202	0.082	0.146	0.254

	0.33	0.083	0.125	0.183	0.080	0.127	0.196	0.074	0.137	0.195	0.080	0.142	0.247
	0.5	0.080	0.121	0.177	0.078	0.123	0.189	0.071	0.133	0.189	0.077	0.137	0.238
	0.67	0.085	0.129	0.188	0.083	0.130	0.201	0.076	0.141	0.201	0.082	0.145	0.253
	0.83	0.078	0.117	0.172	0.075	0.119	0.183	0.069	0.128	0.183	0.075	0.133	0.231
	1	0.074	0.112	0.164	0.072	0.113	0.175	0.066	0.123	0.175	0.071	0.127	0.220
3.33% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.090	0.132	0.194	0.088	0.140	0.206	0.080	0.150	0.209	0.088	0.155	0.281
	0.17	0.097	0.142	0.208	0.095	0.150	0.221	0.086	0.162	0.225	0.094	0.167	0.302
	0.33	0.094	0.138	0.202	0.092	0.146	0.215	0.083	0.157	0.218	0.091	0.162	0.293
	0.5	0.091	0.133	0.195	0.089	0.141	0.207	0.081	0.151	0.211	0.088	0.156	0.283
	0.67	0.096	0.141	0.207	0.094	0.149	0.220	0.086	0.161	0.224	0.094	0.166	0.301
	0.83	0.088	0.129	0.189	0.086	0.136	0.201	0.078	0.147	0.204	0.085	0.151	0.274
	1	0.084	0.123	0.180	0.082	0.130	0.192	0.075	0.140	0.195	0.082	0.144	0.262
1% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.098	0.143	0.207	0.096	0.154	0.220	0.087	0.163	0.229	0.096	0.171	0.318
	0.17	0.105	0.153	0.223	0.103	0.166	0.237	0.094	0.175	0.246	0.103	0.183	0.342
	0.33	0.102	0.148	0.216	0.100	0.161	0.230	0.091	0.170	0.238	0.100	0.178	0.331
	0.5	0.098	0.143	0.208	0.097	0.155	0.222	0.088	0.164	0.230	0.097	0.172	0.320

	0.67	0.104	0.152	0.222	0.103	0.165	0.236	0.093	0.174	0.244	0.103	0.183	0.340
	0.83	0.095	0.139	0.202	0.094	0.150	0.215	0.085	0.159	0.223	0.094	0.166	0.310
	1	0.091	0.133	0.193	0.090	0.143	0.205	0.081	0.152	0.213	0.089	0.159	0.296
0.5% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.101	0.147	0.214	0.100	0.161	0.227	0.090	0.169	0.237	0.100	0.178	0.335
	0.17	0.108	0.158	0.231	0.107	0.173	0.244	0.097	0.181	0.255	0.107	0.191	0.360
	0.33	0.105	0.153	0.223	0.104	0.167	0.236	0.094	0.176	0.247	0.104	0.185	0.349
	0.5	0.101	0.148	0.216	0.100	0.162	0.228	0.091	0.170	0.239	0.100	0.179	0.337
	0.67	0.108	0.157	0.229	0.107	0.172	0.242	0.096	0.180	0.254	0.107	0.190	0.359
	0.83	0.098	0.143	0.209	0.097	0.157	0.221	0.088	0.164	0.231	0.097	0.173	0.327
	1	0.094	0.137	0.200	0.093	0.150	0.211	0.084	0.157	0.221	0.093	0.165	0.312
50% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.284	0.499	0.779	0.281	0.519	0.829	0.266	0.532	0.803	0.276	0.508	0.834
	0.17	0.299	0.525	0.819	0.167	0.546	0.871	0.280	0.559	0.845	0.291	0.534	0.877
	0.33	0.307	0.539	0.841	0.179	0.560	0.894	0.287	0.574	0.867	0.298	0.548	0.900
	0.5	0.301	0.529	0.825	0.178	0.549	0.878	0.282	0.563	0.851	0.293	0.538	0.883
	0.67	0.296	0.520	0.811	0.163	0.540	0.863	0.277	0.554	0.837	0.288	0.529	0.868
	0.83	0.291	0.512	0.798	0.169	0.531	0.849	0.273	0.545	0.823	0.283	0.520	0.854

	1	0.287	0.505	0.788	0.167	0.524	0.838	0.269	0.538	0.812	0.280	0.513	0.843
	1.17	0.290	0.510	0.795	0.206	0.530	0.846	0.272	0.543	0.820	0.282	0.518	0.851
	1.33	0.284	0.498	0.777	0.223	0.518	0.827	0.265	0.531	0.802	0.276	0.507	0.832
	1.5	0.277	0.486	0.759	0.237	0.505	0.807	0.259	0.518	0.782	0.269	0.495	0.812
	1.67	0.267	0.469	0.731	0.236	0.487	0.777	0.250	0.499	0.754	0.259	0.476	0.782
	1.83	0.233	0.409	0.638	0.213	0.425	0.679	0.218	0.436	0.658	0.227	0.416	0.683
	2	0.191	0.335	0.522	0.174	0.348	0.556	0.178	0.357	0.539	0.185	0.341	0.559
	2.17	0.132	0.232	0.362	0.120	0.241	0.385	0.124	0.247	0.373	0.128	0.236	0.387
	2.33	0.091	0.160	0.249	0.082	0.166	0.265	0.085	0.170	0.257	0.088	0.162	0.267
	2.5	0.062	0.109	0.169	0.057	0.113	0.180	0.058	0.116	0.175	0.060	0.110	0.181
	2.67	0.045	0.078	0.122	0.044	0.081	0.130	0.042	0.083	0.126	0.043	0.080	0.131
	2.83	0.032	0.055	0.086	0.031	0.058	0.092	0.030	0.059	0.089	0.031	0.056	0.093
	3	0.024	0.042	0.065	0.024	0.043	0.069	0.022	0.044	0.067	0.023	0.042	0.070
10% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.46	0.72	1.01	0.45	0.72	1.08	0.41	0.78	1.07	0.44	0.81	1.36
	0.17	0.48	0.75	1.06	0.47	0.76	1.13	0.43	0.82	1.13	0.46	0.85	1.43
	0.33	0.50	0.77	1.09	0.48	0.78	1.16	0.44	0.85	1.16	0.48	0.87	1.46
	0.5	0.49	0.76	1.07	0.47	0.77	1.14	0.43	0.83	1.14	0.47	0.86	1.44
	0.67	0.48	0.75	1.05	0.46	0.75	1.12	0.43	0.82	1.12	0.46	0.84	1.41
	0.83	0.47	0.73	1.03	0.46	0.74	1.10	0.42	0.80	1.10	0.45	0.83	1.39

	1	0.47	0.72	1.02	0.45	0.73	1.09	0.41	0.79	1.09	0.45	0.82	1.37
	1.17	0.47	0.73	1.03	0.46	0.74	1.10	0.42	0.80	1.10	0.45	0.83	1.38
	1.33	0.46	0.71	1.01	0.45	0.72	1.07	0.41	0.78	1.07	0.44	0.81	1.35
	1.5	0.45	0.70	0.98	0.43	0.71	1.05	0.40	0.76	1.05	0.43	0.79	1.32
	1.67	0.43	0.67	0.95	0.42	0.68	1.01	0.38	0.74	1.01	0.41	0.76	1.27
	1.83	0.38	0.59	0.83	0.37	0.59	0.88	0.33	0.64	0.88	0.36	0.66	1.11
	2	0.31	0.48	0.68	0.30	0.49	0.72	0.27	0.53	0.72	0.30	0.54	0.91
	2.17	0.21	0.33	0.47	0.21	0.34	0.50	0.19	0.36	0.50	0.21	0.38	0.63
	2.33	0.15	0.23	0.32	0.14	0.23	0.34	0.13	0.25	0.34	0.14	0.26	0.43
	2.5	0.10	0.16	0.22	0.10	0.16	0.23	0.09	0.17	0.23	0.10	0.18	0.29
	2.67	0.07	0.11	0.16	0.07	0.11	0.17	0.06	0.12	0.17	0.07	0.13	0.21
	2.83	0.05	0.08	0.11	0.05	0.08	0.12	0.05	0.09	0.12	0.05	0.09	0.15
	3	0.04	0.06	0.08	0.04	0.06	0.09	0.03	0.07	0.09	0.04	0.07	0.11
3.3% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.55	0.79	1.15	0.54	0.83	1.22	0.49	0.90	1.24	0.53	0.93	1.66
	0.17	0.57	0.83	1.20	0.56	0.88	1.28	0.51	0.94	1.30	0.56	0.97	1.75
	0.33	0.59	0.85	1.24	0.58	0.90	1.31	0.52	0.97	1.34	0.57	1.00	1.79
	0.5	0.58	0.84	1.21	0.57	0.88	1.29	0.51	0.95	1.31	0.56	0.98	1.76
	0.67	0.57	0.82	1.19	0.56	0.87	1.27	0.51	0.93	1.29	0.55	0.96	1.73
	0.83	0.56	0.81	1.17	0.55	0.85	1.25	0.50	0.92	1.27	0.54	0.95	1.70
	1	0.55	0.80	1.16	0.54	0.84	1.23	0.49	0.91	1.25	0.54	0.94	1.68

	1.17	0.56	0.81	1.17	0.55	0.85	1.24	0.50	0.92	1.26	0.54	0.95	1.70
	1.33	0.55	0.79	1.14	0.53	0.83	1.22	0.48	0.89	1.24	0.53	0.92	1.66
	1.5	0.53	0.77	1.12	0.52	0.81	1.19	0.47	0.87	1.21	0.52	0.90	1.62
	1.67	0.51	0.74	1.07	0.50	0.78	1.14	0.46	0.84	1.16	0.50	0.87	1.56
	1.83	0.45	0.65	0.94	0.44	0.68	1.00	0.40	0.73	1.01	0.44	0.76	1.36
	2	0.37	0.53	0.77	0.36	0.56	0.82	0.33	0.60	0.83	0.36	0.62	1.12
	2.17	0.25	0.37	0.53	0.25	0.39	0.57	0.23	0.42	0.57	0.25	0.43	0.77
	2.33	0.17	0.25	0.37	0.17	0.27	0.39	0.16	0.29	0.40	0.17	0.30	0.53
	2.5	0.12	0.17	0.25	0.12	0.18	0.26	0.11	0.19	0.27	0.12	0.20	0.36
	2.67	0.09	0.12	0.18	0.08	0.13	0.19	0.08	0.14	0.19	0.08	0.15	0.26
	2.83	0.06	0.09	0.13	0.06	0.09	0.14	0.05	0.10	0.14	0.06	0.10	0.18
	3	0.05	0.07	0.10	0.04	0.07	0.10	0.04	0.08	0.10	0.04	0.08	0.14
1% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.59	0.85	1.23	0.58	0.92	1.31	0.53	0.97	1.36	0.58	1.02	1.89
	0.17	0.62	0.90	1.29	0.61	0.97	1.37	0.56	1.03	1.43	0.61	1.07	1.98
	0.33	0.64	0.92	1.33	0.63	0.99	1.41	0.57	1.05	1.46	0.63	1.10	2.04
	0.5	0.63	0.90	1.30	0.62	0.98	1.38	0.56	1.03	1.44	0.62	1.08	2.00
	0.67	0.62	0.89	1.28	0.61	0.96	1.36	0.55	1.02	1.41	0.61	1.06	1.96
	0.83	0.61	0.87	1.26	0.60	0.94	1.34	0.54	1.00	1.39	0.60	1.05	1.93
	1	0.60	0.86	1.24	0.59	0.93	1.32	0.53	0.99	1.37	0.59	1.03	1.91

	1.17	0.60	0.87	1.25	0.60	0.94	1.33	0.54	1.00	1.38	0.60	1.04	1.93
	1.33	0.59	0.85	1.23	0.58	0.92	1.30	0.53	0.97	1.35	0.58	1.02	1.88
	1.5	0.58	0.83	1.20	0.57	0.90	1.27	0.52	0.95	1.32	0.57	0.99	1.84
	1.67	0.56	0.80	1.15	0.55	0.87	1.23	0.50	0.91	1.27	0.55	0.96	1.77
	1.83	0.49	0.70	1.01	0.48	0.76	1.07	0.43	0.80	1.11	0.48	0.84	1.55
	2	0.40	0.57	0.82	0.39	0.62	0.88	0.35	0.65	0.91	0.39	0.68	1.27
	2.17	0.28	0.40	0.57	0.27	0.43	0.61	0.25	0.45	0.63	0.27	0.47	0.88
	2.33	0.19	0.27	0.39	0.19	0.29	0.42	0.17	0.31	0.43	0.19	0.33	0.60
	2.5	0.13	0.19	0.27	0.13	0.20	0.28	0.11	0.21	0.29	0.13	0.22	0.41
	2.67	0.09	0.13	0.19	0.09	0.14	0.20	0.08	0.15	0.21	0.09	0.16	0.30
	2.83	0.07	0.09	0.14	0.06	0.10	0.14	0.06	0.11	0.15	0.06	0.11	0.21
	3	0.05	0.07	0.10	0.05	0.08	0.11	0.04	0.08	0.11	0.05	0.09	0.16
0.5% AEP	**Time (hours)**	2001-2020 lower	2001-2020 central	2001-2020 upper	2021-2040 lower	2021-2040 central	2021-2040 upper	2041-2060 lower	2041-2060 central	2041-2060 upper	2061-2080 lower	2061-2080 central	2061-2080 upper
	0	0.61	0.88	1.27	0.60	0.96	1.34	0.11	0.21	0.29	0.13	0.22	0.41
	0.17	0.64	0.93	1.34	0.64	1.01	1.41	0.12	0.22	0.31	0.13	0.23	0.43
	0.33	0.66	0.95	1.37	0.65	1.04	1.45	0.12	0.23	0.31	0.14	0.24	0.44
	0.5	0.65	0.93	1.35	0.64	1.02	1.43	0.12	0.22	0.31	0.13	0.23	0.44
	0.67	0.64	0.92	1.33	0.63	1.00	1.40	0.12	0.22	0.30	0.13	0.23	0.43
	0.83	0.63	0.90	1.30	0.62	0.99	1.38	0.12	0.21	0.30	0.13	0.23	0.42
	1	0.62	0.89	1.29	0.61	0.97	1.36	0.11	0.21	0.29	0.13	0.22	0.42

	1.17	0.63	0.90	1.30	0.62	0.98	1.37	0.12	0.21	0.30	0.13	0.22	0.42
	1.33	0.61	0.88	1.27	0.60	0.96	1.34	0.11	0.21	0.29	0.13	0.22	0.41
	1.5	0.60	0.86	1.24	0.59	0.94	1.31	0.11	0.20	0.28	0.12	0.21	0.40
	1.67	0.57	0.83	1.19	0.57	0.90	1.26	0.11	0.20	0.27	0.12	0.21	0.39
	1.83	0.50	0.72	1.04	0.50	0.79	1.10	0.09	0.17	0.24	0.10	0.18	0.34
	2	0.41	0.59	0.85	0.41	0.65	0.90	0.08	0.14	0.20	0.08	0.15	0.28
	2.17	0.28	0.41	0.59	0.28	0.45	0.62	0.05	0.10	0.14	0.06	0.10	0.19
	2.33	0.20	0.28	0.41	0.19	0.31	0.43	0.04	0.07	0.09	0.04	0.07	0.13
	2.5	0.13	0.19	0.28	0.13	0.21	0.29	0.02	0.05	0.06	0.03	0.05	0.09
	2.67	0.10	0.14	0.20	0.09	0.15	0.21	0.02	0.03	0.05	0.02	0.03	0.06
	2.83	0.07	0.10	0.14	0.07	0.11	0.15	0.01	0.02	0.03	0.01	0.02	0.05
	3	0.05	0.07	0.11	0.05	0.08	0.11	0.01	0.02	0.02	0.01	0.02	0.03

Catchment- and reach-scale discharge hydrographs generated at 10-minute temporal resolution for future peak discharge events.

Appendix 15

Dam	Side	Sheet	Month	Avg velocity (m/s)	a	b	c	R^2	Equation
1	Upstream	Leaky dam 1 upstream	January 11th	0.038	0.009414	0.015137	-0.000098	0.396005	Q = 0.0094143D^2 + 0.0151369D + -9.76047e-05
1	Upstream	Leaky dam 1 upstream	February 8th	0.069	0.435413	0.005887	-0.000044	0.744615	Q = 0.435413D^2 + 0.00588691D + -4.44603e-05
1	Upstream	Leaky dam 1 upstream	March 8th	0.059	0.310185	-0.000777	-0.000188	0.709308	Q = 0.310185D^2 + -0.000776907D + -0.000188296
1	Upstream	Leaky dam 1 upstream	May 10th	0.023	0.245293	-0.012086	0.000284	0.605180	Q = 0.245293D^2 + -0.0120858D + 0.000284138
1	Upstream	Leaky dam 1 upstream	June 7th	0.056	0.026661	0.030768	-0.000168	0.509410	Q = 0.0266609D^2 + 0.0307683D + -0.000168394

1	Upstream	Leaky dam 1 upstream	July 12th	0.063	-0.009235	0.043793	-0.000017	0.924133	Q = -0.00923507D^2 + 0.0437927D + -1.66231e-05
1	Downstream	Leaky dam 1 downstream	January 11th	0.137	1.965946	-0.125013	0.001800	0.808494	Q = 1.96595D^2 + -0.125013D + 0.00180036
1	Downstream	Leaky dam 1 downstream	February 8th	0.110	1.534830	-0.076947	0.000770	0.892457	Q = 1.53483D^2 + -0.0769471D + 0.000770432
1	Downstream	Leaky dam 1 downstream	March 8th	0.011	0.220977	-0.011950	0.000002	0.915390	Q = 0.220977D^2 + -0.0119504D + 1.60585e-06
1	Downstream	Leaky dam 1 downstream	May 10th	0.025	-0.028986	0.025089	-0.000235	0.748405	Q = -0.0289864D^2 + 0.0250894D + -0.000235235
1	Downstream	Leaky dam 1 downstream	June 7th	0.075	0.514788	-0.001566	-0.000113	0.835176	Q = 0.514788D^2 + -0.00156598D + -0.000112505
1	Downstream	Leaky dam 1 downstream	July 12th	0.039	0.124575	0.020746	-0.000138	0.802325	Q = 0.124575D^2 + 0.0207455D + -0.000137667
2	Upstream	Leaky dam 2 upstream	January 11th	0.074	-1.939020	0.399223	-0.014560	0.653916	Q = -1.93902D^2 + 0.399223D + -0.0145605
2	Upstream	Leaky dam 2 upstream	February 8th	0.085	0.539401	-0.074355	0.005201	0.094199	Q = 0.539401D^2 + -0.074355D + 0.00520102
2	Upstream	Leaky dam 2 upstream	March 8th	0.095	0.355312	-0.010420	0.001743	0.141549	Q = 0.355312D^2 + -0.0104202D + 0.00174292
2	Upstream	Leaky dam 2 upstream	May 10th	0.059	0.184912	0.018958	-0.000007	0.686759	Q = 0.184912D^2 + 0.0189582D + -7.13452e-06
2	Upstream	Leaky dam 2 upstream	June 7th	0.064	0.595393	-0.051135	0.002420	0.310644	Q = 0.595393D^2 + -0.0511349D + 0.00242006
2	Upstream	Leaky dam 2 upstream	July 12th	0.026	0.188999	0.003260	0.000026	0.744156	Q = 0.188999D^2 + 0.00325987D + 2.64957e-05
2	Downstream	Leaky dam 2 downstream	January 11th	0.077	2.038667	-0.054267	0.001027	0.471277	Q = 2.03867D^2 + -0.0542667D + 0.00102667
2	Downstream	Leaky dam 2 downstream	February 8th	0.050	0.849420	0.004452	-0.000021	0.886793	Q = 0.84942D^2 + 0.00445244D + -2.06032e-05
2	Downstream	Leaky dam 2	March 8th	0.054	-0.962690	0.041375	0.000430	0.304889	Q = -0.96269D^2 + 0.0413752D + 0.000430138

		downstream								
2	Downstream	Leaky dam 2 downstream	May 10th	0.061	0.741781	0.029275	0.000016	0.840808	Q = 0.741781D^2 + 0.0292749D + 1.6138e-05
2	Downstream	Leaky dam 2 downstream	June 7th	0.105	-1.402895	0.083534	0.000082	0.342248	Q = -1.40289D^2 + 0.0835342D + 8.21842e-05
2	Downstream	Leaky dam 2 downstream	July 12th	0.043	-0.657470	0.031928	-0.000006	0.311718	Q = -0.65747D^2 + 0.0319275D + -5.676e-06
3	Upstream	Leaky dam 3 upstream	January 11th	0.073	0.223718	0.049674	-0.002624	0.974278	Q = 0.223718D^2 + 0.049674D + -0.00262364
3	Upstream	Leaky dam 3 upstream	February 8th	0.218	2.615283	-0.001196	0.000035	0.986360	Q = 2.61528D^2 + -0.0011959D + 3.52034e-05
3	Upstream	Leaky dam 3 upstream	March 8th	0.193	-0.482778	0.223799	-0.006106	0.963054	Q = -0.482778D^2 + 0.223799D + -0.00610601
3	Upstream	Leaky dam 3 upstream	May 10th	0.169	-1.607309	0.101414	-0.000056	0.773353	Q = -1.60731D^2 + 0.101414D + -5.61914e-05
3	Upstream	Leaky dam 3 upstream	June 7th	0.071	0.511974	-0.012229	0.000035	0.698193	Q = 0.511974D^2 + -0.0122288D + 3.49924e-05
3	Upstream	Leaky dam 3 upstream	July 12th	0.035	-0.507828	0.038427	0.000002	0.693425	Q = -0.507828D^2 + 0.0384272D + 2.06609e-06
3	Downstream	Leaky dam 3 downstream	January 11th	0.130	1.266845	0.036556	0.000028	0.783170	Q = 1.26684D^2 + 0.0365555D + 2.76151e-05
3	Downstream	Leaky dam 3 downstream	February 8th	0.082	-1.275970	0.076451	0.000117	0.367593	Q = -1.27597D^2 + 0.0764505D + 0.000116829
3	Downstream	Leaky dam 3 downstream	March 8th	0.065	0.315397	0.048896	-0.000057	0.967926	Q = 0.315397D^2 + 0.0488958D + -5.70755e-05
3	Downstream	Leaky dam 3 downstream	May 10th	0.053	0.174757	0.010228	-0.000006	0.694189	Q = 0.174757D^2 + 0.0102276D + -6.3027e-06
3	Downstream	Leaky dam 3 downstream	June 7th	0.144	1.320264	0.074810	-0.000150	0.959076	Q = 1.32026D^2 + 0.0748095D + -0.000149936
3	Downstream	Leaky dam 3 downstream	July 12th	0.036	0.122174	0.028515	0.000000	0.979233	Q = 0.122174D^2 + 0.0285152D + -3.99261e-07

4	Upstream	Leaky dam 4 upstream	January 11th	0.065	0.557039	-0.018647	-0.000039	0.710461	Q = 0.557039D^2 + -0.0186473D + -3.88563e-05
4	Upstream	Leaky dam 4 upstream	February 8th	0.045	0.187562	0.018666	-0.000473	0.514572	Q = 0.187562D^2 + 0.0186664D + -0.000473113
4	Upstream	Leaky dam 4 upstream	March 8th	0.037	0.448577	-0.010448	-0.000042	0.815323	Q = 0.448577D^2 + -0.0104479D + -4.21625e-05
4	Upstream	Leaky dam 4 upstream	May 10th	0.039	-0.366614	0.061430	-0.000447	0.784603	Q = -0.366614D^2 + 0.0614305D + -0.000447357
4	Upstream	Leaky dam 4 upstream	June 7th	0.078	-0.237025	0.157462	-0.006300	0.701792	Q = -0.237025D^2 + 0.157462D + -0.00630017
4	Upstream	Leaky dam 4 upstream	July 12th	0.014	-0.042805	0.009690	-0.000007	0.843058	Q = -0.0428047D^2 + 0.00968981D + -7.13349e-06
4	Downstream	Leaky dam 4 downstream	January 11th	0.021	0.312919	-0.018648	0.000246	0.934354	Q = 0.312919D^2 + -0.0186484D + 0.000245575
4	Downstream	Leaky dam 4 downstream	February 8th	0.057	-0.588772	0.189645	-0.008959	0.713225	Q = -0.588772D^2 + 0.189645D + -0.00895884
4	Downstream	Leaky dam 4 downstream	March 8th	0.028	0.671444	-0.053575	0.001250	0.771039	Q = 0.671444D^2 + -0.0535747D + 0.00124963
4	Downstream	Leaky dam 4 downstream	May 10th	0.031	-0.275481	0.030716	-0.000027	0.323327	Q = -0.275481D^2 + 0.0307161D + -2.72544e-05
4	Downstream	Leaky dam 4 downstream	June 7th	0.023	0.093807	0.003137	-0.000155	0.638853	Q = 0.093807D^2 + 0.00313738D + -0.000154533
4	Downstream	Leaky dam 4 downstream	July 12th	0.021	0.279176	0.004348	-0.000001	0.955309	Q = 0.279176D^2 + 0.00434824D + -9.88235e-07
5	Upstream	Leaky dam 5 upstream	January 11th	0.042	-0.021232	-0.009031	0.008590	0.843376	Q = -0.0212324D^2 + -0.00903104D + 0.00859015
5	Upstream	Leaky dam 5 upstream	February 8th	0.029	-0.063219	0.013891	0.004871	0.786114	Q = -0.0632195D^2 + 0.0138912D + 0.00487127
5	Upstream	Leaky dam 5 upstream	March 8th	0.017	-0.119235	0.057952	-0.003626	0.732880	Q = -0.119235D^2 + 0.0579516D + -0.00362551
5	Upstream	Leaky dam 5 upstream	May 10th	0.038	-0.108778	0.018271	0.000068	0.494239	Q = -0.108778D^2 + 0.0182713D + 6.77343e-05

5	Upstream	Leaky dam 5 upstream	June 7th	0.01	-0.17162	0.028659	0.000232	0.547321	Q = -0.17162D^2 + 0.0286586D + 0.00023197
5	Upstream	Leaky dam 5 upstream	July 12th	0.003	-0.358941	0.016009	0.000001	0.625107	Q = -0.358941D^2 + 0.0160094D + 1.27059e-06
5	Downstream	Leaky dam 5 downstream	January 11th	0.068	-0.359655	0.079962	-0.001106	0.536068	Q = -0.359655D^2 + 0.0799624D + -0.0011063
5	Downstream	Leaky dam 5 downstream	February 8th	0.058	-0.155988	0.034590	0.001191	0.390375	Q = -0.155988D^2 + 0.0345904D + 0.0011912
5	Downstream	Leaky dam 5 downstream	March 8th	0.131	-0.352718	0.090667	0.001196	0.268664	Q = -0.352718D^2 + 0.0906671D + 0.00119599
5	Downstream	Leaky dam 5 downstream	May 10th	0.048	-0.375024	0.113309	-0.004181	0.328441	Q = -0.375024D^2 + 0.113309D + -0.00418139
5	Downstream	Leaky dam 5 downstream	June 7th	0.106	-0.059188	0.032418	0.003688	0.057787	Q = -0.059188D^2 + 0.0324181D + 0.00368806
5	Downstream	Leaky dam 5 downstream	July 12th	0.037	-0.118831	0.028856	0.001139	0.076350	Q = -0.118831D^2 + 0.0288564D + 0.00113859
6	Upstream	Leaky dam 6 upstream	January 11th	0.076	0.128294	-0.010352	0.003245	0.123999	Q = 0.128294D^2 + -0.010352D + 0.00324481
6	Upstream	Leaky dam 6 upstream	February 8th	0.047	-0.312261	0.091606	-0.002241	0.784224	Q = -0.312261D^2 + 0.0916061D + -0.00224074
6	Upstream	Leaky dam 6 upstream	March 8th	0.033	0.020392	0.016440	-0.000056	0.657171	Q = 0.0203916D^2 + 0.0164399D + -5.63363e-05
6	Upstream	Leaky dam 6 upstream	May 10th	0.036	-0.004862	0.017927	-0.000136	0.792924	Q = -0.00486152D^2 + 0.0179268D + -0.000136351
6	Upstream	Leaky dam 6 upstream	June 7th	0.081	0.657652	-0.142308	0.011066	0.420315	Q = 0.657652D^2 + -0.142308D + 0.0110658
6	Upstream	Leaky dam 6 upstream	July 12th	0.024	0.022033	0.009165	0.000013	0.879248	Q = 0.0220325D^2 + 0.00916491D + 1.28712e-05
6	Downstream	Leaky dam 6 downstream	January 11th	0.141	-0.060489	0.094758	-0.000105	0.976719	Q = -0.0604886D^2 + 0.094758D + -0.000105274
6	Downstream	Leaky dam 6 downstream	February 8th	0.019	-0.058080	0.025116	0.000000	0.999841	Q = -0.05808D^2 + 0.0251164D + 1.526e-08

6	Downstream	Leaky dam 6 downstream	March 8th	0.030	0.036672	0.009571	0.000016	0.991330	Q = 0.0366718D^2 + 0.009571D + 1.56902e-05
6	Downstream	Leaky dam 6 downstream	May 10th	0.036	-0.081015	0.033356	-0.000001	0.968784	Q = -0.0810148D^2 + 0.0333556D + -8.27861e-07
6	Downstream	Leaky dam 6 downstream	June 7th	0.066	0.00271	0.040355	-0.000082	0.986613	Q = 0.00270987D^2 + 0.0403546D + -8.24142e-05
6	Downstream	Leaky dam 6 downstream	July 12th	0.009	-0.026460	0.007851	0.000001	0.976585	Q = -0.0264605D^2 + 0.00785148D + 1.06595e-06
7	Upstream	Leaky dam 7 upstream	January 11th	0.059	0.197892	-0.005886	0.000445	0.411761	Q = 0.197892D^2 + -0.00588625D + 0.000444506
7	Upstream	Leaky dam 7 upstream	February 8th	0.049	0.228566	-0.005728	0.000022	0.989886	Q = 0.228566D^2 + -0.00572804D + 2.19099e-05
7	Upstream	Leaky dam 7 upstream	March 8th	0.094	0.194916	0.016439	-0.000006	0.999814	Q = 0.194916D^2 + 0.016439D + -5.65658e-06
7	Upstream	Leaky dam 7 upstream	May 10th	0.029	0.217500	-0.002175	0.000000	0.760870	Q = 0.2175D^2 + -0.002175D + 3.32984e-22
7	Upstream	Leaky dam 7 upstream	June 7th	0.070	0.278336	-0.011274	-0.000003	0.946144	Q = 0.278336D^2 + -0.0112743D + -2.55299e-06
7	Upstream	Leaky dam 7 upstream	July 12th	0.038	-0.012645	0.008472	-0.000001	0.981558	Q = -0.0126451D^2 + 0.00847218D + -1.36177e-06
7	Downstream	Leaky dam 7 downstream	January 11th	0.025	0.043580	0.034875	-0.008232	0.316749	Q = 0.0435799D^2 + 0.0348752D + -0.00823182
7	Downstream	Leaky dam 7 downstream	February 8th	0.024	0.175652	-0.068378	0.007008	0.976473	Q = 0.175652D^2 + -0.0683782D + 0.00700792
7	Downstream	Leaky dam 7 downstream	March 8th	0.020	0.112860	-0.029953	0.002343	0.913337	Q = 0.11286D^2 + -0.0299528D + 0.00234257
7	Downstream	Leaky dam 7 downstream	May 10th	0.031	0.050574	0.018131	-0.000368	0.759614	Q = 0.0505736D^2 + 0.0181314D + -0.000368426
7	Downstream	Leaky dam 7 downstream	June 7th	0.021	-0.009309	0.02445	-0.001048	0.75893	Q = -0.00930907D^2 + 0.0244502D + -0.00104792

7	Downstream	Leaky dam 7 downstream	July 12th	0.023	-0.025500	0.024475	-0.000251	0.666785	Q = -0.0255004D^2 + 0.0244753D + -0.000250655
8	Upstream	Leaky dam 8 upstream	January 11th	0.041	0.709666	-0.106293	0.004530	0.671999	Q = 0.709666D^2 + -0.106293D + 0.00453014
8	Upstream	Leaky dam 8 upstream	February 8th	0.057	0.146936	0.006326	0.000238	0.517574	Q = 0.146936D^2 + 0.00632622D + 0.000237673
8	Upstream	Leaky dam 8 upstream	March 8th	0.029	-0.127296	0.025237	-0.000115	0.049158	Q = -0.127296D^2 + 0.0252365D + -0.000115273
8	Upstream	Leaky dam 8 upstream	May 10th	0.043	0.451500	-0.004515	0.000000	0.918105	Q = 0.4515D^2 + -0.004515D + -1.24972e-19
8	Upstream	Leaky dam 8 upstream	June 7th	0.122	0.727492	-0.034965	0.002161	0.536022	Q = 0.727492D^2 + -0.0349647D + 0.00216147
8	Upstream	Leaky dam 8 upstream	July 12th	0.003	0.025101	0.000202	0.000001	0.922297	Q = 0.0251011D^2 + 0.000202022D + 1.17574e-06
8	Downstream	Leaky dam 8 downstream	January 11th	0.065	0.09696596	-0.0008396	0.00202891	0.4891438	Q = 0.096966D^2 + -0.000839595D + 0.00202891
8	Downstream	Leaky dam 8 downstream	February 8th	0.028	-0.1771847	0.07175805	-0.0040639	0.50622281	Q = -0.177185D^2 + 0.071758D + -0.00406391
8	Downstream	Leaky dam 8 downstream	March 8th	0.027	-0.1394135	0.03870332	-0.0004507	0.38512595	Q = -0.139414D^2 + 0.0387033D + -0.00045073
8	Downstream	Leaky dam 8 downstream	May 10th	0.032	0.0480501	-0.0172694	0.00233729	0.23932999	Q = 0.0480501D^2 + -0.0172694D + 0.00233729
8	Downstream	Leaky dam 8 downstream	June 7th	0.05	0.18502533	-0.0224271	0.00197783	0.65359885	Q = 0.185025D^2 + -0.0224271D + 0.00197783
8	Downstream	Leaky dam 8 downstream	July 12th	0.023	-0.0333628	0.00906683	-2.175E-05	0.66212233	Q = -0.0333628D^2 + 0.00906683D + -2.17533e-05
9	Upstream	Leaky dam 9 upstream	January 11th	0.041	-0.174526	0.082352	-0.004196	0.582769	Q = -0.174526D^2 + 0.0823519D + -0.00419649
9	Upstream	Leaky dam 9 upstream	February 8th	0.036	-0.199736	0.077724	-0.003230	0.635607	Q = -0.199736D^2 + 0.0777238D + -0.00322954
9	Upstream	Leaky dam 9 upstream	March 8th	0.037	-0.012349	0.021673	-0.000279	0.422590	Q = -0.0123487D^2 + 0.0216727D + -0.00027864

9	Upstream	Leaky dam 9 upstream	May 10th	0.036	-0.065393	0.023743	-0.000070	0.475597	Q = -0.0653933D^2 + 0.0237427D + -7.04293e-05
9	Upstream	Leaky dam 9 upstream	June 7th	0.035	-0.246383	0.098310	-0.006086	0.483311	Q = -0.246383D^2 + 0.0983096D + -0.00608568
9	Upstream	Leaky dam 9 upstream	July 12th	0.020	0.150678	-0.001618	0.000038	0.867840	Q = 0.150678D^2 + -0.001618D + 3.75973e-05
9	Downstream	Leaky dam 9 downstream	January 11th	0.045	-0.203904	0.131819	-0.007874	0.586561	Q = -0.203904D^2 + 0.131819D + -0.00787432
9	Downstream	Leaky dam 9 downstream	February 8th	0.034	0.057829	0.011827	0.000444	0.595459	Q = 0.0578291D^2 + 0.0118274D + 0.000443604
9	Downstream	Leaky dam 9 downstream	March 8th	0.026	0.065237	0.002783	0.000289	0.637780	Q = 0.0652369D^2 + 0.00278343D + 0.000289279
9	Downstream	Leaky dam 9 downstream	May 10th	0.032	0.069664	0.002857	0.000800	0.600310	Q = 0.0696641D^2 + 0.00285684D + 0.000800474
9	Downstream	Leaky dam 9 downstream	June 7th	0.028	-0.036850	0.036175	-0.001263	0.414798	Q = -0.0368497D^2 + 0.0361751D + -0.00126345
9	Downstream	Leaky dam 9 downstream	July 12th	0.040	-0.253645	0.107216	-0.003587	0.636267	Q = -0.253645D^2 + 0.107216D + -0.00358748
10	Upstream	Leaky dam 10 upstream	January 11th	0.059	0.326798	-0.017650	0.000219	0.931290	Q = 0.326798D^2 + -0.0176502D + 0.000218796
10	Upstream	Leaky dam 10 upstream	February 8th	0.067	0.170762	0.028585	-0.000631	0.857461	Q = 0.170762D^2 + 0.0285851D + -0.000630849
10	Upstream	Leaky dam 10 upstream	March 8th	0.055	2.266243	-0.482837	0.027635	0.240698	Q = 2.26624D^2 + -0.482837D + 0.0276346
10	Upstream	Leaky dam 10 upstream	May 10th	0.074	-0.206130	0.047706	0.000094	0.502849	Q = -0.20613D^2 + 0.047706D + 9.35255e-05
10	Upstream	Leaky dam 10 upstream	June 7th	0.035	-0.136249	0.044388	-0.000905	0.100810	Q = -0.136249D^2 + 0.0443884D + -0.000905101
10	Upstream	Leaky dam 10 upstream	July 12th	0.017	-0.045904	0.011553	0.000002	0.943048	Q = -0.0459043D^2 + 0.0115534D + 2.36169e-06
10	Downstream	Leaky dam 10 downstream	January 11th	0.041	-0.425756	0.179999	-0.010782	0.581811	Q = -0.425756D^2 + 0.179999D + -0.0107823

10	Downstream	Leaky dam 10 downstream	February 8th	0.022	-0.191121	0.084749	-0.004412	0.626390	Q = -0.191121D^2 + 0.0847488D + -0.00441184
10	Downstream	Leaky dam 10 downstream	March 8th	0.023	-0.196035	0.088715	-0.005500	0.504321	Q = -0.196035D^2 + 0.0887153D + -0.00549971
10	Downstream	Leaky dam 10 downstream	May 10th	0.041	-0.295304	0.116578	-0.005331	0.374275	Q = -0.295304D^2 + 0.116578D + -0.00533122
10	Downstream	Leaky dam 10 downstream	June 7th	0.018	-0.223494	0.098448	-0.007209	0.468873	Q = -0.223494D^2 + 0.0984481D + -0.00720856
10	Downstream	Leaky dam 10 downstream	July 12th	0.021	-0.054762	0.025379	-0.000564	0.145729	Q = -0.0547617D^2 + 0.0253789D + -0.000563867

Stage–discharge rating curve parameters for each leaky dam, side and sampling month. Average velocity is reported in m/s. Coefficients a, b, and c define the quadratic rating curve:

$$Q = aD^2 + bD + c$$

where Q is discharge and D is water depth/stage. R^2 indicates the goodness-of-fit for each monthly rating relationship.

Appendix 16

	Without leaky dams					With leaky dams				
Event magnitude and uncertainty bound	Max depth (m)	Mean depth (m)	Flood extent (m^2)	Volume (m^3)	Time to peak (hrs)	Max depth (m)	Mean depth (m)	Flood extent (m^2)	Volume (m^3)	Time to peak (hrs)
2-year (lower)	0.393	0.0826	3421	487	3.9	0.940	0.118	6507	776	7.82
2-year (central)	0.644	0.0931	3892	598	3.5	1.76	0.128	7206	924	7.33
2-year (upper)	0.728	0.0990	4916	685	3.15	2.68	0.146	8014	1173	6.7
10-year (lower)	0.498	0.0847	3308	622	2.8	1.04	0.127	7353	979	6
10-year (central)	0.712	0.0954	4007	719	2.55	1.45	0.132	8219	1095	5.45
10-year (upper)	0.799	0.0996	7896	779	2.3	2.81	0.133	10079	1194	5
30-year (lower)	0.594	0.0789	6332	631	2.25	1.43	0.0701	8491	1157	4.75

30-year (central)	0.734	0.0824	7247	744	2.17	2.21	0.0688	9381	1264	4.47
30-year (upper)	0.822	0.0885	8445	836	1.83	3.02	0.0688	10596	1349	3.53
100-year (lower)	0.633	0.0513	6997	686	1.75	2.24	0.0697	9459	1169	3.75
100-year (central)	0.727	0.0832	8075	799	1.6	3.12	0.0728	10757	1191	2.95
100-year (upper)	0.903	0.0856	10114	980	1.45	4.31	0.185	11050	1461	2.33
200-year (lower)	0.721	0.0495	8876	588	1.35	2.58	0.0780	10892	651	2.6
200-year (central)	0.927	0.109	11905	604	1.25	3.33	0.111	12337	752	1.85
200-year (upper)	1.10	0.120	13011	821	1.15	5.27	0.136	13923	976	1.6

A summary of flood depth, extent and timing across 2-, 10-, 30-, 100- and 200-year return period events under baseline scenarios and then baseline with leaky dam scenarios for the reach scale including lower, central and upper uncertainty estimates derived from uncertainty propagation within the GEV framework.

Appendix 17

	Without leaky dams					With leaky dams				
Event magnitude and uncertainty bound	Max depth (m)	Mean depth (m)	Flood extent (m^2)	Volume (m^3)	Time to peak (hrs)	Max depth (m)	Mean depth (m)	Flood extent (m^2)	Volume (m^3)	Time to peak (hrs)
2-year (lower)	1.31	0.103	30850	485	9.6	1.61	0.117	25066	776	14.5
2-year (central)	2.15	0.137	35975	596	9.1	2.64	0.156	27875	953	13.9
2-year (upper)	2.46	0.159	37825	712	8.6	3.02	0.181	30944	1140	13.3
10-year (lower)	2.09	0.132	35800	579	8.20	2.47	0.146	28231	898	13.8
10-year (central)	2.52	0.161	39425	699	7.7	2.97	0.179	32368	1084	12.2
10-year (upper)	2.93	0.170	42675	794	7.20	3.11	0.188	36603	1231	11.6
30-year (lower)	2.24	0.253	44106	313	7.90	2.09	0.130	36850	823	11.7

30-year (central)	2.87	0.300	57443	431	6.50	3.72	0.258	49975	1821	10.1
30-year (upper)	3.47	0.331	69822	496	6.00	4.13	0.304	61788	2560	8.5
100-year (lower)	3.47	0.290	59275	415	6.80	4.57	0.372	56275	3298	9.4
100-year (central)	3.88	0.334	124250	528	5.40	4.94	0.324	121855	5018	6.3
100-year (upper)	4.48	0.354	141550	605	5.00	4.96	0.353	135225	5788	6.7
200-year (lower)	3.76	0.392	65879	932	5.90	4.17	0.306	62283	2515	8.3
200-year (central)	5.13	0.354	131800	2033	4.5	4.93	0.314	128233	4642	5.1
200-year (upper)	5.54	0.372	143250	2399	4.2	4.95	0.341	141110	5430	4.5

A summary of flood depth, extent and timing across 2-, 10-, 30-, 100- and 200-year return period events under baseline scenarios and then baseline with leaky dam scenarios for the wider catchment scale, including lower, central and upper uncertainty estimates derived from uncertainty propagation within the GEV framework.

Appendix 18

	Without dams				
Climate period, Event magnitude and uncertainty bound	Max depth (m)	Mean depth (m)	Flood extent (m^2)	Volume (m^3)	Time to peak (hrs)
2000-2020, 2-year, lower	0.358262	0.075299	3547.978	443.9531	4.278154
2000-2020, 2-year, central	0.668971	0.09671	3553.65	621.1875	3.369353
2000-2020, 2-year, upper	0.860668	0.117041	5811.874	809.8319	2.664442
2000-2020, 10-year , lower	0.425953	0.072446	2829.423	532.0137	3.2736
2000-2020 , 10-year , central	0.67499	0.090441	3798.714	681.6261	2.689818
2000-2020 , 10-year , upper	0.901425	0.112368	8908.197	878.8609	2.038662
2000-2020 , 30-year , lower	0.480564	0.063832	5122.775	510.4977	2.78111
2000-2020 , 30-year , central	0.677767	0.076087	6691.791	687.0005	2.350042
2000-2020 , 30-year , upper	0.918931	0.098936	9440.841	934.5817	1.636968
2000-2020 , 100-year , lower	0.494945	0.040112	5470.977	536.3857	2.238128
2000-2020 , 100-year , central	0.650971	0.074499	7230.529	715.4418	1.786868
2000-2020 , 100-year , upper	0.998284	0.094632	11181.22	1083.409	1.311601
2000-2020 , 200-year , lower	0.554703	0.038083	6828.772	452.3792	1.754723

2000-2020 , 200-year , central	0.832357	0.097871	10689.54	542.3337	1.392132
2000-2020 , 200-year , upper	1.219302	0.133015	14422.13	910.0428	1.037479
2020-2040 , 2-year , lower	0.354122	0.074429	3506.984	438.8235	4.328163
2020-2040 , 2-year , central	0.644077	0.093111	3421.411	598.0718	3.49958
2020-2040 , 2-year , upper	0.915454	0.124492	6181.829	861.3818	2.504987
2020-2040 , 10-year , lower	0.4123	0.070124	2738.733	514.9613	3.382001
2020-2040 , 10-year , central	0.683326	0.091558	3845.627	690.0439	2.657005
2020-2040 , 10-year , upper	0.962637	0.119998	9513.118	938.5409	1.909027
2020-2040 , 30-year , lower	0.470958	0.062557	5020.383	500.294	2.837831
2020-2040 , 30-year , central	0.715882	0.080366	7068.118	725.6354	2.224919
2020-2040 , 30-year , upper	0.977166	0.105206	10039.13	993.8089	1.539411
2020-2040 , 100-year , lower	0.487737	0.039527	5391.302	528.5741	2.271205
2020-2040 , 100-year , central	0.704116	0.080581	7820.819	773.8494	1.652001
2020-2040 , 100-year , upper	1.061945	0.100667	11894.26	1152.499	1.232973
2020-2040 , 200-year , lower	0.548136	0.037632	6747.929	447.0237	1.775745
2020-2040 , 200-year , central	0.909885	0.106988	11685.2	592.8484	1.273513
2020-2040 , 200-year , upper	1.288733	0.140589	15243.37	961.8633	0.981584
2040-2060 , 2-year , lower	0.33526	0.070464	3320.182	415.4493	4.571677
2040-2060 , 2-year , central	0.685849	0.09915	3643.307	636.8598	3.286438
2040-2060 , 2-year , upper	0.887736	0.120722	5994.655	835.3007	2.583201
2040-2060 , 10-year , lower	0.377933	0.064279	2510.449	472.0373	3.689539
2040-2060 , 10-year , central	0.739407	0.099072	4161.242	746.6766	2.455481
2040-2060 , 10-year , upper	0.960857	0.119776	9495.532	936.8059	1.912563
2040-2060 , 30-year , lower	0.427193	0.056743	4553.847	453.8025	3.128564
2040-2060 , 30-year , central	0.770133	0.086456	7603.749	780.625	2.068189
2040-2060 , 30-year , upper	0.99328	0.106941	10204.68	1010.197	1.514438
2040-2060 , 100-year , lower	0.441859	0.035809	4884.179	478.8548	2.507023
2040-2060 , 100-year , central	0.744541	0.085207	8269.832	818.2781	1.562305
2040-2060 , 100-year , upper	1.101622	0.104428	12338.65	1195.559	1.188566

2040-2060 , 200-year , lower	0.496175	0.034065	6108.251	404.6476	1.961707
2040-2060 , 200-year , central	0.954383	0.11222	12256.66	621.8416	1.214136
2040-2060 , 200-year , upper	1.348906	0.147153	15955.11	1006.775	0.937797
2060-2080 , 2-year , lower	0.34842	0.07323	3450.51	431.757	4.399002
2060-2080 , 2-year , central	0.654884	0.094673	3478.815	608.1061	3.441833
2060-2080 , 2-year , upper	0.921198	0.125273	6220.616	866.7863	2.489368
2060-2080 , 10-year , lower	0.408297	0.069443	2712.141	509.9612	3.415162
2060-2080 , 10-year , central	0.762764	0.102202	4292.688	770.2627	2.380292
2060-2080 , 10-year , upper	1.212759	0.151177	11984.91	1182.402	1.515305
2060-2080 , 30-year , lower	0.467011	0.062032	4978.31	496.1013	2.861815
2060-2080 , 30-year , central	0.795173	0.089267	7850.982	806.0067	2.00306
2060-2080 , 30-year , upper	1.334742	0.143704	13712.77	1357.475	1.127004
2060-2080 , 100-year , lower	0.487396	0.0395	5387.533	528.2046	2.272793
2060-2080 , 100-year , central	0.779623	0.089222	8659.502	856.8349	1.492003
2060-2080 , 100-year , upper	1.533829	0.1454	17179.57	1664.621	0.853648
2060-2080 , 200-year , lower	0.549518	0.037727	6764.936	448.1503	1.771281
2060-2080 , 200-year , central	1.006178	0.11831	12921.85	655.5897	1.151635
2060-2080 , 200-year , upper	1.906394	0.20797	22549.17	1422.863	0.663557
	With dams				
	Maximum depth	Mean depth	extent	volume	time
2000-2020 , 2-year , lower	0.846	0.105669	5791.23	618.468	8.0546
2000-2020 , 2-year , central	1.7072	0.126464	7278.06	922.041	7.4033
2000-2020 , 2-year , upper	2.8408	0.155417	8574.98	1336.065	6.633
2000-2020 , 10-year , lower	0.9152	0.110617	6323.58	733.33	6.12
2000-2020 , 10-year , central	1.4355	0.132462	8383.38	1120.809	5.45
2000-2020 , 10-year , upper	3.0348	0.144239	10986.11	1411.433	4.9
2000-2020 , 30-year , lower	1.287	0.062775	7556.99	922.123	4.7975
2000-2020 , 30-year , central	2.4089	0.074373	10037.67	1462.031	4.47
2000-2020 , 30-year , upper	3.4428	0.078122	11973.48	1730.922	3.3888
2000-2020 , 100-year , lower	2.1056	0.064891	8702.28	1001.272	3.75

2000-2020 , 100-year , central	3.1448	0.075712	11187.28	1288.186	2.9205
2000-2020 , 100-year , upper	4.6117	0.19795	11823.5	1672.699	2.2135
2000-2020 , 200-year , lower	2.5026	0.074958	10347.4	594.33	2.6
2000-2020 , 200-year , central	3.2966	0.112721	12460.37	771.293	1.813
2000-2020 , 200-year , upper	5.2808	0.14144	15003	1055.642	1.504
2020-2040 , 2-year , lower	0.8272	0.10384	5726.16	600.934	8.1328
2020-2040 , 2-year , central	1.7424	0.127296	7206	918.918	7.4033
2020-2040 , 2-year , upper	2.9212	0.15914	8735.26	1393.641	6.566
2020-2040 , 10-year , lower	0.8944	0.108077	6176.52	699.828	6.18
2020-2040 , 10-year , central	1.4645	0.134508	8465.57	1149.279	5.45
2020-2040 , 10-year , upper	3.1191	0.14763	11187.69	1471.127	4.85
2020-2040 , 30-year , lower	1.2727	0.062074	7472.08	901.581	4.7975
2020-2040 , 30-year , central	2.4531	0.076058	10319.1	1537.087	4.4253
2020-2040 , 30-year , upper	3.5334	0.080186	12291.36	1823.821	3.3535
2020-2040 , 100-year , lower	2.1504	0.065971	8796.87	1029.006	3.75
2020-2040 , 100-year , central	3.176	0.07644	11294.85	1313.078	2.891
2020-2040 , 100-year , upper	4.6548	0.1998	11934	1704.11	2.1902
2020-2040 , 200-year , lower	2.5542	0.076167	10456.32	610.273	2.574
2020-2040 , 200-year , central	3.3966	0.11322	12583.74	782.381	1.7945
2020-2040 , 200-year , upper	5.4808	0.14144	16479.92	1055.642	1.488
2040-2060 , 2-year , lower	0.799	0.100831	5596.02	570.259	8.211
2040-2060 , 2-year , central	1.76	0.129152	7350.12	950.962	7.4033
2040-2060 , 2-year , upper	2.9748	0.161403	8815.4	1426.427	6.499
2040-2060 , 10-year , lower	0.8528	0.102997	5882.4	635.175	6.24
2040-2060 , 10-year , central	1.4935	0.137148	8629.95	1194.59	5.45
2040-2060 , 10-year , upper	3.2596	0.152485	11389.27	1546.881	4.8
2040-2060 , 30-year , lower	1.2584	0.063581	7981.54	986.435	4.845
2040-2060 , 30-year , central	2.4973	0.077434	10506.72	1593.348	4.4253
2040-2060 , 30-year , upper	3.5636	0.080874	12397.32	1855.327	3.3182

2040-2060 , 100-year , lower	2.1952	0.067992	9175.23	1106.149	3.75
2040-2060 , 100-year , central	3.27	0.076768	11402.42	1331.264	2.8615
2040-2060 , 100-year , upper	4.6117	0.198783	11934	1695.432	2.1669
2040-2060 , 200-year , lower	2.58	0.077649	10783.08	641.59	2.574
2040-2060 , 200-year , central	3.5299	0.113831	12583.74	786.6	1.776
2040-2060 , 200-year , upper	5.608	0.14144	17820	1055.642	1.472
2060-2080 , 2-year , lower	0.8084	0.104135	5921.37	623.186	8.211
2060-2080 , 2-year , central	1.76	0.128	7206	924	7.33
2060-2080 , 2-year , upper	3.0016	0.162206	8815.4	1433.523	6.432
2060-2080 , 10-year , lower	0.8736	0.110109	6617.7	763.914	6.24
2060-2080 , 10-year , central	1.508	0.138468	8712.14	1217.574	5.3955
2060-2080 , 10-year , upper	3.372	0.1596	12094.8	1719.36	4.75
2060-2080 , 30-year , lower	1.3013	0.068523	9000.46	1198.826	4.845
2060-2080 , 30-year , central	2.5194	0.079051	10881.96	1684.71	4.3806
2060-2080 , 30-year , upper	3.6844	0.083936	12927.12	2007.852	3.2829
2060-2080 , 100-year , lower	2.24	0.070955	9837.36	1237.644	3.7125
2060-2080 , 100-year , central	3.276	0.078078	11832.7	1405.082	2.832
2060-2080 , 100-year , upper	4.6548	0.20313	12376	1796.679	2.1436
2060-2080 , 200-year , lower	2.6058	0.079131	11109.84	673.648	2.574
2060-2080 , 200-year , central	3.6299	0.11433	12707.11	797.797	1.7575
2060-2080 , 200-year , upper	5.7808	0.14144	18479.92	1055.642	1.456

A summary of flood depth, extent and timing across 2-, 10-, 30-, 100- and 200-year return period events under climate change and then for climate change periods with leaky dam scenarios for the reach scale, including lower, central and upper uncertainty estimates derived from uncertainty propagation within the GEV framework.

Appendix 19

	Without dams				
Climate period, Event magnitude and uncertainty bound	Max depth (m)	Mean depth (m)	Flood extent (m^2)	Volume (m^3)	Time to peak (hrs)
2000-2020, 2-year, lower	1.197999	0.094194	34356.96	443.534	10.4975
2000-2020, 2-year, central	2.22928	0.142052	41824.41	617.9772	8.776375
2000-2020, 2-year, upper	2.90851	0.187989	52525.79	841.8126	7.273828
2000-2020, 10-year , lower	1.783663	0.112652	34127.7	494.1343	9.608319
2000-2020 , 10-year , central	2.388644	0.152608	40172.83	662.5645	8.123436

2000-2020 , 10-year , upper	3.310403	0.192071	50845.75	897.0853	6.372638
2000-2020 , 30-year , lower	1.820489	0.205618	31574.11	254.3809	9.720463
2000-2020 , 30-year , central	2.627906	0.274694	46675.08	394.6437	7.098809
2000-2020 , 30-year , upper	3.875124	0.369644	65692.84	553.9082	5.372731
2000-2020 , 100-year , lower	2.712858	0.226723	41279.22	324.4484	8.697839
2000-2020 , 100-year , central	3.495644	0.300914	66151.45	475.6958	5.993746
2000-2020 , 100-year , upper	4.957666	0.391744	90383.34	669.5062	4.518255
2000-2020 , 200-year , lower	2.890697	0.301371	48684.41	716.5238	7.674274
2000-2020 , 200-year , central	4.586793	0.316516	69137.19	1817.729	5.032928
2000-2020 , 200-year , upper	6.144312	0.412578	101414.4	2660.687	3.786917
2020-2040 , 2-year , lower	1.184157	0.093105	33959.99	438.4092	10.62021
2020-2040 , 2-year , central	2.146324	0.136766	40268.03	594.981	9.115586
2020-2040 , 2-year , upper	3.093651	0.199955	55869.32	895.3981	6.838522
2020-2040 , 10-year , lower	1.726492	0.109042	33033.82	478.2961	9.926487
2020-2040 , 10-year , central	2.418143	0.154492	40668.95	670.7469	8.024338
2020-2040 , 10-year , upper	3.535199	0.205114	54298.49	958.0029	5.967414
2020-2040 , 30-year , lower	1.784102	0.201508	30943.02	249.2964	9.918715
2020-2040 , 30-year , central	2.775692	0.290142	49299.96	416.8373	6.720847
2020-2040 , 30-year , upper	4.120702	0.39307	69855.99	589.011	5.052537
2020-2040 , 100-year , lower	2.673349	0.223421	40678.06	319.7234	8.826381
2020-2040 , 100-year , central	3.781023	0.32548	71551.96	514.5309	5.541358
2020-2040 , 100-year , upper	5.27382	0.416726	96147.16	712.2012	4.247395
2020-2040 , 200-year , lower	2.856475	0.297803	48108.06	708.0412	7.766215
2020-2040 , 200-year , central	5.014021	0.345997	75576.84	1987.038	4.604089
2020-2040 , 200-year , upper	6.494187	0.436072	107189.3	2812.194	3.582897
2040-2060 , 2-year , lower	1.121082	0.088146	32151.09	415.0571	11.21773
2040-2060 , 2-year , central	2.285524	0.145636	42879.62	633.5685	8.5604
2040-2060 , 2-year , upper	2.999981	0.193901	54177.7	868.2872	7.052045
2040-2060 , 10-year , lower	1.582582	0.099953	30280.32	438.4282	10.82914

2040-2060 , 10-year , central	2.616603	0.167172	44006.69	725.7958	7.415722
2040-2060 , 10-year , upper	3.528664	0.204735	54198.11	956.2319	5.978466
2040-2060 , 30-year , lower	1.618308	0.182782	28067.53	226.1297	10.93488
2040-2060 , 30-year , central	2.986037	0.312129	53035.97	448.4258	6.247411
2040-2060 , 30-year , upper	4.188652	0.399552	71007.91	598.7237	4.970573
2040-2060 , 100-year , lower	2.421886	0.202405	36851.75	289.6492	9.742821
2040-2060 , 100-year , central	3.998101	0.344166	75659.94	544.0715	5.240488
2040-2060 , 100-year , upper	5.470862	0.432296	99739.43	738.8106	4.094419
2040-2060 , 200-year , lower	2.585692	0.269572	43547.6	640.9216	8.57952
2040-2060 , 200-year , central	5.259232	0.362918	79272.92	2084.214	4.389424
2040-2060 , 200-year , upper	6.797413	0.456433	112194.1	2943.501	3.423067
2060-2080 , 2-year , lower	1.165088	0.091606	33413.12	431.3494	10.79403
2060-2080 , 2-year , central	2.182335	0.13906	40943.64	604.9635	8.965169
2060-2080 , 2-year , upper	3.113061	0.20121	56219.86	901.0161	6.795883
2060-2080 , 10-year , lower	1.709728	0.107983	32713.07	473.652	10.02382
2060-2080 , 10-year , central	2.699257	0.172452	45396.78	748.7223	7.188646
2060-2080 , 10-year , upper	4.453751	0.258409	68406.88	1206.921	4.736682
2060-2080 , 30-year , lower	1.76915	0.199819	30683.7	247.2072	10.00254
2060-2080 , 30-year , central	3.083127	0.322278	54760.42	463.0062	6.050675
2060-2080 , 30-year , upper	5.628598	0.536907	95418.52	804.5488	3.698968
2060-2080 , 100-year , lower	2.671481	0.223265	40649.62	319.4999	8.832555
2060-2080 , 100-year , central	4.186489	0.360383	79225	569.7078	5.004671
2060-2080 , 100-year , upper	7.617284	0.601901	138870.9	1028.673	2.940681
2060-2080 , 200-year , lower	2.863675	0.298553	48229.31	709.8257	7.74669
2060-2080 , 200-year , central	5.544657	0.382614	83575.16	2197.327	4.163468
2060-2080 , 200-year , upper	9.606706	0.645071	158562.7	4160.016	2.422058
	With dams				
	Maximum depth	Mean depth	extent	volume	time
2000-2020 , 2-year , lower	1.4812	0.108166	29063.43	667.193	14.79

2000-2020 , 2-year , central	2.5872	0.15288	33827.64	915.261	14.039
2000-2020 , 2-year , upper	3.1106	0.185616	37906.26	1192.451	13.167
2000-2020 , 10-year , lower	2.223	0.1314	31399.2	727.38	14.076
2000-2020 , 10-year , central	2.97	0.178195	37238.85	1068.331	12.2
2000-2020 , 10-year , upper	3.2655	0.195708	41821.09	1319.915	11.368
2000-2020 , 30-year , lower	1.9437	0.12207	28874.3	734.157	11.817
2000-2020 , 30-year , central	3.906	0.272061	44208.36	2035.459	10.1
2000-2020 , 30-year , upper	4.5017	0.33136	58586.41	3041.536	8.245
2000-2020 , 100-year , lower	4.3872	0.363816	46745	3225.444	9.4
2000-2020 , 100-year , central	5.0388	0.33048	72272.1	5220.727	6.237
2000-2020 , 100-year , upper	5.1584	0.365532	81601.75	6173.278	6.432
2000-2020 , 200-year , lower	4.0866	0.302634	61879	2487.335	8.3
2000-2020 , 200-year , central	4.9793	0.31714	77439.73	4735.304	4.998
2000-2020 , 200-year , upper	5.0985	0.349696	92061.12	5679.834	4.275
2020-2040 , 2-year , lower	1.449	0.105827	28438.41	638.722	14.935
2020-2040 , 2-year , central	2.6136	0.15444	34172.82	934.035	14.039
2020-2040 , 2-year , upper	3.171	0.188421	38277.89	1222.342	13.034
2020-2040 , 10-year , lower	2.1736	0.12848	30701.44	695.411	14.214
2020-2040 , 10-year , central	2.9997	0.179984	37615	1089.962	12.2
2020-2040 , 10-year , upper	3.3588	0.201348	43039.18	1397.505	11.252
2020-2040 , 30-year , lower	1.9228	0.12194	29178.24	741.095	11.817
2020-2040 , 30-year , central	3.9804	0.278382	45459.54	2141.696	9.999
2020-2040 , 30-year , upper	4.5843	0.338808	60198.88	3195.494	8.16
2020-2040 , 100-year , lower	4.3872	0.36549	47212.45	3272.688	9.4
2020-2040 , 100-year , central	5.0882	0.335178	73689.2	5398.766	6.174
2020-2040 , 100-year , upper	5.1584	0.36712	82394	6260.301	6.365
2020-2040 , 200-year , lower	4.0866	0.302634	61879	2487.335	8.217
2020-2040 , 200-year , central	4.9793	0.318553	78206.46	4803.495	4.947
2020-2040 , 200-year , upper	5.049	0.34782	92061.12	5649.372	4.23

2040-2060 , 2-year , lower	1.4168	0.104013	28125.9	620.878	15.08
2040-2060 , 2-year , central	2.64	0.156	34518	953	14.039
2040-2060 , 2-year , upper	3.2314	0.192041	39021.15	1270.017	12.901
2040-2060 , 10-year , lower	2.1242	0.12556	30003.68	664.161	14.214
2040-2060 , 10-year , central	3.0294	0.18258	38367.3	1127.794	12.2
2040-2060 , 10-year , upper	3.4521	0.206142	43851.24	1457.775	11.136
2040-2060 , 30-year , lower	1.9437	0.12441	30090.06	779.735	11.934
2040-2060 , 30-year , central	4.0176	0.283284	46710.72	2239.393	9.999
2040-2060 , 30-year , upper	4.6669	0.346256	61811.35	3353.216	8.075
2040-2060 , 100-year , lower	4.4329	0.370884	48147.35	3386.749	9.4
2040-2060 , 100-year , central	5.1376	0.338418	74397.75	5503.366	6.111
2040-2060 , 100-year , upper	5.1584	0.368708	83186.25	6347.844	6.298
2040-2060 , 200-year , lower	4.1283	0.305694	62497.79	2537.61	8.217
2040-2060 , 200-year , central	5.0286	0.32028	78206.46	4829.537	4.896
2040-2060 , 200-year , upper	5.049	0.349355	92963.68	5729.926	4.185
2060-2080 , 2-year , lower	1.449	0.106353	28750.92	648.953	15.08
2060-2080 , 2-year , central	2.64	0.156	34518	953	13.9
2060-2080 , 2-year , upper	3.2616	0.193851	39392.78	1294.196	12.768
2060-2080 , 10-year , lower	2.1736	0.129794	31399.2	718.49	14.214
2060-2080 , 10-year , central	3.0294	0.183385	38743.45	1143.875	12.078
2060-2080 , 10-year , upper	3.5454	0.212628	45475.36	1559.332	11.02
2060-2080 , 30-year , lower	2.0064	0.12948	31609.76	852.496	11.934
2060-2080 , 30-year , central	4.092	0.289605	47961.9	2350.683	9.999
2060-2080 , 30-year , upper	4.7495	0.353704	63423.82	3514.701	7.99
2060-2080 , 100-year , lower	4.5243	0.378324	49082.25	3521.769	9.306
2060-2080 , 100-year , central	5.1376	0.339876	75106.3	5579.715	6.048
2060-2080 , 100-year , upper	5.208	0.372238	83978.5	6469.653	6.231
2060-2080 , 200-year , lower	4.17	0.308754	63116.58	2588.388	8.217
2060-2080 , 200-year , central	5.0286	0.321693	78973.19	4898.401	4.845

2060-2080 , 200-year , upper	5.0985	0.352765	93866.24	5842.028	4.14

A summary of flood depth, extent and timing across 2-, 10-, 30-, 100- and 200-year return period events under climate change and then for climate change periods with leaky dam scenarios for the wider catchment scale, including lower, central and upper uncertainty estimates derived from uncertainty propagation within the GEV framework.

Appendix 20

	Existing dams			Optimised dams		
	30yrbaseline lower small dams	30yrbaseline central small dams	30yr baseline upper small dams	30yr baseline lower small improved dams	30yr baseline central small improved dams	30yr baseline upper small improved dams
Maximum depth	1.43	2.21	3.02	2.1862	2.7204	2.2687
Mean depth	0.070138	0.0688	0.0688	0.143842	0.163258	0.103496
Maximum extent	8491	9381	10596	11100	15337	20149
Volume	1157	1264	1349	155.925	728.293	346.712
Time to peak magnitude	4.75	4.47	3.53	11.1	10.2	9.3
	30yr2060lower small dams	30yr2060central small dams	30yr2060upper s mall dams	30yr 2060 lower	30yr 2060 central	30yr 2060 upper
Maximum depth	1.3013	2.5194	3.6844	2.2709	2.2825	2.9435
Mean depth	0.06852	0.07905	0.08394	0.126515	0.175112	0.218565
Maximum extent	9000.46	10882	12927.1	16975	19805	22502
Volume	1198.83	1684.71	2007.85	477.596	813.397	1153.587
Time to peak magnitude	4.845	4.3806		10.1	9.4	7.8

Maximum depth, flood extent and time to peak magnitude between existing and optimised leaky dam configurations for the 30-year event under baseline and future (2060–2080) conditions.

Appendix 22

Climate period	Event scenario	Depth (m)	Extent (m²)	Sum depth-damage (£)	Baseline damage (£)	Reduction from baseline (£)	Cost benefit ratio
Baseline	30-year (lower)	3.41	36225	4548	5078	530	0.000
	30-year (central)	3.95	41325	12262	18064	5802	0.004
	30-year (upper)	4.56	43275	43001	120068	77067	0.047
	100-year (lower)	4.30	43200	11815	195630	183815	0.112
	100-year (central)	5.71	62050	33908	580811	546903	0.334
	100-year (upper)	6.40	80025	115274	745214	629940	0.385
2000-2020	30-year (lower)	2.61	26750	3621	120130	116509	0.071
	30-year (central)	3.62	35500	18099	221008	202909	0.124
	30-year (upper)	4.63	44250	90070	420070	330000	0.201
	100-year (lower)	4.43	43850	12598	285778	273180	0.167
	100-year (central)	5.02	43875	61253	650000	588747	0.359
	100-year (upper)	6.03	76750	173078	1011691	838613	0.512
2020-2040	30-year (lower)	4.09	42500	9956	150064	140108	0.085
	30-year (central)	4.75	45300	27738	280137	252399	0.154
	30-year (upper)	5.93	72625	142291	520009	377718	0.231
	100-year (lower)	4.55	43800	13681	271485	257804	0.157
	100-year (central)	5.55	48125	84750	674700	589950	0.360
	100-year (upper)	6.74	143725	259241	1079478	820237	0.501
2040-2060	30-year (lower)	4.22	43050	11051	165000	153950	0.094
	30-year (central)	5.71	58025	43346	656532	613186	0.374
	30-year (upper)	6.77	124298	254459	800000	545541	0.333
	100-year (lower)	5.04	46300	16660	226886	210226	0.128
	100-year (central)	6.71	128300	145234	750884	605650	0.370
	100-year (upper)	7.80	159775	381547	1150000	768453	0.469
2060-2080	30-year (lower)	4.63	44650	23388	220067	196679	0.120
	30-year (central)	5.95	74525	92177	481908	389731	0.238
	30-year (upper)	6.74	149000	431010	900450	469440	0.287

	100-year (lower)	5.59	49025	19158	351687	332529	0.203
	100-year (central)	6.74	143725	416538	850009	433473	0.265
	100-year (upper)	6.79	149400	671080	1269038	597958	0.365

Modelled flood depth, extent and associated damages for the NFM scheme (offline storage, detention basins and improved leaky dams) across baseline and projected climate periods (2000-2080) under 30-year and 100-year event scenarios. Values include total depth-damage (£), baseline damage (£), reduction from baseline (£), and cost-benefit ratios, calculated using a total scheme cost of £1,638,170.

Appendix 23

Climate period	Event scenario	Depth (m)	Extent (m²)	Sum depth-damage (£)	Baseline damage (£)	Reduction from baseline (£)	Cost benefit ratio
Baseline	30-year (lower)	3.85	51550	1108	5078	3970	0.000
	30-year (central)	4.57	59125	2232	18064	15832	0.000
	30-year (upper)	4.93	113400	3683	120068	116385	0.029
	100-year (lower)	4.93	118950	61799	195630	133831	0.033
	100-year (central)	4.98	130075	68345	580811	512466	0.128
	100-year (upper)	4.99	138775	78573	745214	666641	0.167
2000-2020	30-year (lower)	4.60	3950	3902	120130	116228	0.029
	30-year (central)	4.77	62975	18523	221008	202485	0.0506
	30-year (upper)	4.94	122000	32922	420070	387148	0.097
	100-year (lower)	4.94	121500	63504	285778	222274	0.056
	100-year (central)	4.97	129925	67984	650000	582016	0.146
	100-year (upper)	4.98	133975	86630	1011691	925061	0.231
2020-2040	30-year (lower)	4.92	96000	49707	150064	100357	0.0251
	30-year (central)	4.95	113712	32068	280137	248069	0.062
	30-year (upper)	4.98	131425	47371	520009	472638	0.118
	100-year (lower)	4.94	116575	67519	271485	203966	0.051
	100-year (central)	4.96	126800	76234	674700	598466	0.150
	100-year (upper)	5.00	145825	97577	1079478	981901	0.245
2040-2060	30-year (lower)	4.93	120075	61440	165000	103560	0.026
	30-year (central)	4.98	130275	83236	656532	573296	0.143
	30-year (upper)	4.98	130475	55175	800000	744825	0.186

	100-year (lower)	4.95	126925	67374	226886	159512	0.040
	100-year (central)	5.00	139125	83109	750884	667775	0.167
	100-year (upper)	5.03	152250	84625	1150000	1065375	0.266
2060-2080	30-year (lower)	4.94	124025	65556	220067	154511	0.039
	30-year (central)	4.98	132600	74832	481908	407076	0.102
	30-year (upper)	4.98	126075	99966	900450	850484	0.213
	100-year (lower)	4.97	129325	69247	351687	282440	0.070
	100-year (central)	5.00	145825	86210	850009	763790	0.191
	100-year (upper)	5.04	162325	105967	1269038	1163071	0.291

Modelled flood depth, extent and associated damages for the hard engineered scheme across baseline and projected climate periods (2000-2080) under 30-year and 100-year event scenarios. Values include total depth-damage (£), baseline damage (£), reduction from baseline (£), and cost-benefit ratios, calculated using a total scheme cost of £4,000,000.

Appendix 24

Climate period	Event scenario	Depth (m)	Extent (m²)	Sum depth-damage (£)	Baseline damage (£)	Reduction from baseline (£)	Cost benefit ratio
Baseline	30-year (lower)	2.61	26750	821	5078	4257	0.000
	30-year (central)	4.00	40800	1095	18064	16969	0.002
	30-year (upper)	4.65	42800	3034	120068	117034	0.017
	100-year (lower)	4.37	42575	988	195630	194642	0.030
	100-year (central)	6.40	61975	8836	580811	571975	0.082
	100-year (upper)	6.56	74500	11788	745214	733426	0.105
2000-2020	30-year (lower)	3.40	38525	2849	120130	117281	0.017
	30-year (central)	4.06	41150	7202	221008	213806	0.031
	30-year (upper)	4.73	43775	20238	420070	399832	0.057
	100-year (lower)	4.51	43525	5981	285778	279797	0.040
	100-year (central)	5.39	49975	11140	650000	638860	0.092
	100-year (upper)	5.73	61725	19695	1011691	991996	0.143
2020-2040	30-year (lower)	4.14	41725	5358	150064	144706	0.021
	30-year (central)	4.86	44575	11356	280137	268781	0.039
	30-year (upper)	6.02	68200	24555	520009	495454	0.071

	100-year (lower)	4.64	43275	6108	271485	265377	0.038
	100-year (central)	5.69	47525	13284	674700	661416	0.095
	100-year (upper)	6.89	133125	23963	1079478	1055515	0.152
2040-2060	30-year (lower)	3.82	41850	4664	165000	160336	0.023
	30-year (central)	6.40	54325	31909	656532	624623	0.090
	30-year (upper)	6.91	132775	50515	800000	749485	0.108
	100-year (lower)	5.16	45600	6704	226886	220182	0.032
	100-year (central)	6.59	68125	14520	750884	736364	0.106
	100-year (upper)	6.90	142450	27961	1150000	1122039	0.161
2060-2080	30-year (lower)	4.73	44175	6082	220067	213985	0.031
	30-year (central)	6.09	71050	13832	481908	468076	0.067
	30-year (upper)	6.90	136850	40689	900450	859761	0.124
	100-year (lower)	5.73	48350	9370	351687	342497	0.049
	100-year (central)	6.89	133125	17129	850009	832871	0.120
	100-year (upper)	7.01	152400	35019	1269038	1234019	0.177

Modelled flood depth, extent and associated damages for the hybrid scheme across baseline and projected climate periods (2000-2080) under 30-year and 100-year event scenarios. Values include total depth-damage (£), baseline damage (£), reduction from baseline (£), and cost-benefit ratios, calculated using a total scheme cost of £6,958,170.