Creating story lines on floods: relating climate-change uplift to (extreme) experienced and future flooding events

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Abstract. Fluvial flooding remains one of the most significant climate-related hazards worldwide, with its impacts intensified by increasing urbanisation, land-use change, and climate change. We apply the flood-excess volume (FEV) methodology to analyse major recent flood events on the River Aire in Leeds, UK, and specifically to the 2015 Boxing Day and February 2020 floods, as a basis for evaluating the sufficiency and cost-efficacy of flood defences under current and future climate scenarios. The FEV methodology is used to assess the performance of flood-mitigation measures, integrating engineered interventions and nature-based solutions. Using UK-government climate-uplift guidance, we model how magnitude and frequency of flood events may evolve across future climate time slices. Focusing on the period 2070–2125, our results show that under a foreseen worst-case climate-change uplift of 51%, the 2020 minor flood event may produce floods with an FEV comparable to that of the major 2015 Boxing Day flood. Such abstract and difficult-to-comprehend climate-change uplift factors are hence clarified by relating two recently experienced flooding events, still fresh in Leeds' citizens' memory, by being able to relate stories of two recent floods of different magnitude. To assess the cost-efficacy and the (in)sufficiency of flood mitigations, we compare the percentage of FEV mitigated with associated costs for future climate-adjusted flood events. Long-term resilience of a future Boxing Day flood worsened by climate-change uplift factors may be insufficient without additional adaptation. We conclude that significant upgrades may thus be required to ensure protection against climate-change enhanced extremes.

1 Introduction

Flooding is among the most frequent and destructive natural hazard globally, with wide-ranging consequences for human health, infrastructure, economic stability, and ecosystems (World Health Organization, 2020). It can have a variety of causes, including prolonged rainfall, melting snow, tropical storms, or the failure of water-retaining structures. Flooding is typically categorized into seven types: fluvial (river), pluvial (surface water), groundwater, coastal, sewer, reservoir, and canal flooding (Environment Agency, 2021). We focus specifically on fluvial flooding, which occurs when rivers exceed their capacity and overtop their banks; a natural event that has proven particularly damaging in urban environments such as Leeds, UK.

The UK is highly vulnerable to fluvial flooding, with over four million properties (one in four) and buildings worth over £200 billion at risk (Energy and Climate Intelligence Unit, 2020). A notable example is the 2015 Boxing Day flood, where sustained heavy rainfall across the River Aire catchment led to record-breaking river levels and over £500 million in damage across Leeds alone (Leeds City Council, 2016a). This event exemplified the limitations of the existing flood defences in 2015 and prompted further investment through the Leeds Flood Alleviation Scheme (FAS), which combines mainly engineering but also a few nature-based interventions to reduce future risk (Bokhove et al., 2020b).

Historically, flood mitigation has evolved from basic adaptations to sophisticated strategies. Structural (engineering-based) measures include flood walls, embankments, reservoirs, and river channel modifications (Wang et al., 2022), while non-structural or nature-based solution (NBS) approaches involve Sustainable Urban Drainage Systems (SuDS), Natural Flood Management (NFM, Roberts et al. (2025)), tree planting, wetland restoration, and giving-room-to-the-river (GRR) such as riverbed restoration. Leeds' FAS, particularly phase 2, integrates both types of interventions to provide scalable and flexible protection.

To evaluate the effectiveness of these interventions, this study uses the flood-excess volume (FEV) methodology, which integrally involves three-panel graphs of water levels, discharge and rating curve(s) at a chosen river cross-section (Bokhove et al., 2019). We have summarised the entire methodology in the schematic of Figure 1. The methodology augments the notable work of Hui and Lund (2015) with the aim of clear communication between stakeholders. Consider the measured or simulated discharge through a suitable cross-section of a river. FEV is then the fraction of the overall discharge through this river cross-section over the duration of a flood that led to the flood damage (Bokhove et al., 2020b; Bokhove, 2021; Knotters et al., 2024). In joined-up three-panel graphs, both water-level and discharge data of measurements or simulations are shown, connected by their rating curve (see Figure 1(a)). Herein, given a threshold water level h_T above which more severe flooding occurs, a discharge threshold Q_T emerges graphically within these three panels. In the hydrograph, FEV then appears as the volume fraction above this threshold discharge Q_T, as shaded area in this discharge panel (see Figure 1(b)). In a subsequent square-lake "pie-chart" analysis, FEV provides a visual, graphical way to compare mitigation strategies by calculating and displaying the fraction of FEV reduced by each intervention (see Figure 1(b,c)). The cost-per-percentage FEV mitigated is then used to assess the cost-efficacy of each scheme (see Figure 1(c)) –an essential metric in a context of limited public funding and increased flood risk.

While this focus on one particular river cross-section appears to be zero-dimensional in space, a suitably located cross-section represents a river stretch of (subcritical) river flow between hydraulic control points in a flooded and flood-prone river zone. The point measurements at river gauges can thus represent stretches of river. The flow at a river gauge or cross-section downstream of a hydraulic control location (or subcritical-supercritical-subcritical flow transition), such as a non-submerged weir or rapid, can therefore not be (directly) used in an FEV analysis of floods upstream of this control point. These considerations involve fluid-dynamical insights from hydraulic or shallow-water theory, e.g., Te Chow (1959). The speed with which information can travel is in shallow-water theory maximally $u \pm \sqrt{gh}$ with u the flow speed, h the water-depth and g the acceleration of gravity. Where the flow is supercritical $|u| > \sqrt{gh}$ and (river-gauge) information cannot travel upstream, meaning that water levels at a gauge downstream of such a supercritical river stretch do not influence upstream flow levels. The reason to focus on a combined FEV and cost-effectiveness analysis at one or more tell-tale location(s) is to both acquire and facilitate comprehensible communication with decision-makers and the public. The analysis has been successfully applied to communicate flood-mitigation plans between stakeholders, such as ecologists, scientists and engineers, the public and city council members in France and Slovenia (Piton et al., 2023; Pagano et al., 2019).

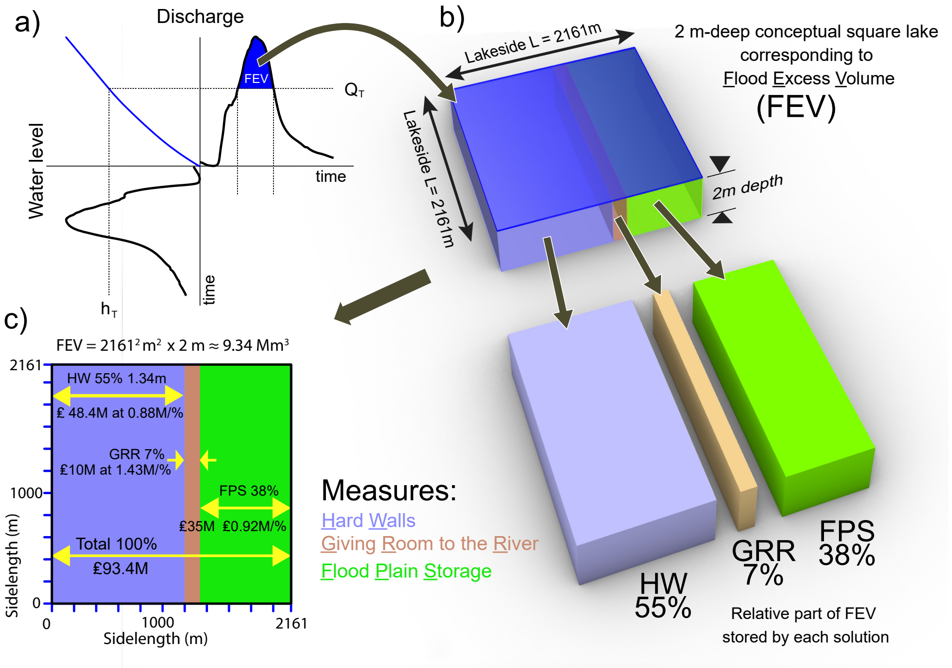

Figure 1. Schematic summary of the FEV (flood-excess volume) methodology. Adapted from Bokhove et al. (2024).

A critical and new consideration in this study is the combination of FEV analysis with the impact of climate change. Climate projections suggest that by 2070–2125 peak flows in the Aire and Calder river catchments could increase by up to 51%, potentially reducing the return period of a "1:200^{+}" year flood to "1:100" years or more frequent (Environment Agency, 2023). The return period refers to the average interval between flood events of a particular magnitude, while its inverse—the Annual Exceedance Probability (AEP)—indicates the probability of such an event occurring in any given year (e.g., AEP = 0.5% for a 1:200 year event). People find return periods notoriously difficult to understand, because the word "period" and its associated quantification suggest a more or less regular time interval or period between extreme events. That is not the case, the time intervals between extreme events are irregular, as showcased for public dissemination in the Wetropolis flood investigator (Bokhove et al., 2020a), therein on reduced accessible time scales of minutes[1]. What further complicates matters is that determining the value of such a return period for an extreme event tends to be difficult and may have a large error, because or when there are no or limited data available for such a determination. Often, return periods are longer than the data-set available, and extreme-value theory is required to obtain return-period estimates (Coles, 2001). With rising winter rainfall (+12% since 1961) and a sevenfold increase in the likelihood of extreme rainfall events (Met Office, 2020), existing defences may become rapidly outdated. This underscores the need for climate-resilient and cost-effective flood strategies.

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[1] See also the educational LIFD video at https://www.youtube.com/watch?v=yUjYfg2SfY0

We focus on analysis of River Aire floods at Armley, a historically flood-prone neighbourhood within Leeds, selected due to its flood-plain characteristics and the public data availability at its suitably-located river gauge. Analysis of the 2015 and 2020 floods at this Armley site will be presented to evaluate the effectiveness and long-term climate resilience of the Leeds Flood Alleviation Scheme (FAS), with particular emphasis on phase 2 (FAS2) and its implementation along the River Aire at Armley. This study is motivated by the increasing need to determine whether current (2026) flood-mitigation strategies remain sufficient in the context of projected climate-change impacts —specifically, increases in peak river flows, the frequency of extreme flood events, and the associated economic costs.

Projected climate-uplift factors are quite abstract and difficult to comprehend, by both specialists and the public alike, in terms of tangible experienced extreme (flooding) events. In recent years, a so-called story-line approach has been championed as a way to translate abstract climate-change concepts into comprehensible stories. Shepherd and et al. (2018) define this story-line approach clearly and comprehensibly. We focus here on the aspects therein relevant to application of the story-line approach for public dissemination. A story line is a self-consistent narrative of past and future extreme events in which probabilistic information only features in a figurative manner. One relates to this narrative through sharing of similar or actual experiences. Perceived experiences can thus be connected directly to actual risks because these risks directly relate to people's awareness and experiences. What perhaps augments our story-line telling from other story-line research and literature, is that we relate people's and victim awareness of actual flooding events and their flood damage for events with different magnitudes (return periods), between events and to future more severe events caused by climate change. Hence, we aim to and can translate climate-change uplift projections into conceivable notions of floods and flood damage, the latter based on flood events actually experienced by people.

In summary, our study has the following aims:

- To analyse historical flood events on the River Aire: using the 2015 Boxing Day and 2020 floods as case studies and using flood-excess volume (FEV) analysis to establish a baseline understanding of fluvial flood impacts in Leeds.
- To assess how these historical flood events may change by 2070–2125: applying foreseen climate change uplift percentages and FEV analysis to model future flood scenarios.
- Particularly, to translate these abstract uplift percentages into a tangible story line of floods experienced in recent years by (here Leeds') citizens: extending this experience to future, extreme floods, caused by climate-change uplifts may otherwise be too abstract and therefore too difficult to comprehend. Since this is a scientific journal generally not read by the public, we wrote a story for the general public, relegated to an appendix, that also is or can be used as standalone story for public dissemination on climate-change uplift of flooding events.
- To evaluate the cost-efficacy of existing and potential flood mitigation measures: determining the extent to which current strategies provide (in)adequate protection against future climate risks.

The outline of the paper is then as follows. The notion of flood-excess volume is introduced in section 2. A flood analysis of the 2015 and 2020 River Aire floods is provided in section 3. The meaning of climate-change uplifts for these two river floods is given in section 4, with a story-line narrative found in Appendix B. Subsequently, cost-effectiveness analyses are presented –section 5. We close in section 6 with a discussion.

2 Flood-excess volume –FEV

A flood-excess volume (FEV) representation is used to quantify and evaluate the volume of water contributing to a flood event once a critical discharge threshold has been exceeded. Such an FEV analysis will aid in understanding flood severity and aid in designing effective mitigation strategies. It was originally (re)introduced by Hui and Lund (2015) and extended in Bokhove et al. (2018a, b, 2019, 2020b) to facilitate communication of cost-effectiveness analyses of flood-mitigation measures. The FEV-representation uses in-situ river level data, either obtained by measurements or via model simulations. Preferably, there should be an ensemble of flood data relating to "design" floods with a particular targetted return period. Here, we will simply use measured data of single floods.

The river level or "stage", denoted by $h(t)$, represents a measured river depth at a specific cross-section as function of time. The discharge or flow rate $Q(t)$ in m^3/s is either directly measured or simulated, or more often obtained via a *rating curve*. The UK Environment Agency (EA) typically establishes an empirical relationship for the rating curve, commonly expressed as:

$$Q(t) \equiv Q\left(h(t)\right) = C_k\left(h(t) - a_k\right)^{b_k}, \quad \text{for} \quad h_{k-1} < h(t) < h_k, \tag{1}$$

where C_k, a_k, and b_k are stage- and location-specific coefficients and h_k are bounds separating the segments of a continuous rating curve (Environment Agency, 2016). In the UK, river stage data $h(t)$ are regularly measured at 15-minute intervals, i.e., $\Delta t = 900$s. Measurements of discharge tend to be less frequent than water-level ones. Hence, a scatter plot of data arises in the Q, h–plane through which a single-valued rating curve, e.g., of the above form, can be fitted. Sometimes, extra data are generated and added to this scatter plot using simulations for extreme flows given a lack of high-flow data. When river stage and discharge data are measured at the same time, rising and sinking limbs may emerge that lie on separated "rating" curves, displaying a hysteresis, which is often the case when the river slope is small. A single rating curve is then only an approximate relationship between river level and discharge. For rivers with steeper downward slopes such as the River Aire (upstream and in Leeds), those rising and sinking limbs tend to coincide, but in both cases error bars of the discharge hydrograph can be large.

To determine the flood-excess volume, one must first specify a threshold river level h_T, above which flooding is assumed to begin. This threshold may be defined using official flood-alert levels, field observations, or photographic evidence. Since FEV is sensitive to the choice of h_T, the selection of this value is inherently somewhat subjective and introduces variability into the final results. When a one-to-one rating curve between water level h and discharge $Q(h)$ is used, choosing h_T then implies a discharge threshold Q_T. Given such a fixed threshold discharge $Q_T = Q(h_T)$, FEV is defined over the flood duration T_f, the total time during which the river level remains above h_T. The FEV is then calculated as:

$$FEV = V_e = \int_{t_f}^{t_f+T_f} \left(Q(t) - Q_T\right) dt, \tag{2}$$

where t_f is the time the river first exceeds h_T. This integral captures the total volume of flow through a cross-section exceeding the threshold and serves as a measure of flooding that mitigation efforts seek to eliminate (i.e., $V_e = 0$ implies no flooding, of minor or major nature). The integral above concerns one flood peak with one rising and one falling limb. For more complicated floods with multiple local peaks the integral definition can readily be extended. For more complicated hysteretic rating curves, determination of the FEV is more complicated or will be much more approximate.

In practice, the continuous integral must be approximated due to the discrete nature of river-gauge measurements. A straightforward approximation of the integral (2) is:

$$V_e \approx \sum_{i=1}^{n} (Q(h_i) - Q_T)\,\Delta t, \tag{3}$$

where n is the (approximate) number of time steps during which $h(t) > h_T$, and Δt is the time between each measurement. Hereafter, the discrete approximation (3) is used in all subsequent calculations, using data provided by the UK EA at 15-minute intervals. The flood duration is thus defined as $T_f \approx n\Delta t$. Although we could use more advanced numerical approximation techniques, there is little point in doing so given the errors arising in the determination of the rating curve. Once we have determined V_e, Q_T and T_f, a mean discharge Q_m arises from a rectangular V_e-approximation, i.e.:

$$V_e = T_f(Q_m - Q_T) \Longleftrightarrow Q_m = Q_T V_e / T_f. \tag{4}$$

Introduction of the FEV is useful since it translates flood severity into an easy-to-visualise volumetric quantity. To aid communication and scenario comparison, it is visualised as a hypothetical two-metre-deep square lake with a side length $L = \sqrt{V_e/2}$. For example, a flood event with an FEV of 1Mm^3 can be conceptualised as a (dynamic) body of water occupying a square area 2m deep and 707m in side length. While we speak of a square "lake", the water comprising the lake volume is generally dynamic, the water flows, possibly rapidly. The lake concept is thus conceptual. Such a side length can be compared with the typical width and length of a river valley. For a narrow river valley, a large square lake size may reveal that flood-storage options are limited, since there is no space to partition that lake in pieces across the valley. This sense of size enables a more intuitive understanding of the scale of flooding for policymakers, planners, and the public, and also facilitates the identification of potential flood storage interventions –such as wetlands, floodplains, or retention basins– by expressing mitigation targets in terms of equivalent surface extents; several examples are found in Bokhove et al. (2019) and reviewed in Bokhove (2021). Each square-lake visualisation can subsequently be partitioned into segments corresponding to the volumetric contribution of individual flood-mitigation measures, enabling a clear and intuitive representation of their relative effectiveness, cf. the schematic in Figure 1.

We will employ this FEV analysis to quantify the magnitude of the 2015 and 2020 River Aire flood events and will model how these may evolve under projected future climate scenarios. Square-lake visualisations viewed from above as "square pie-charts" will be used to evaluate the robustness of the Leeds Flood Alleviation Scheme phase 2 (FAS2), assessing its capacity to mitigate flood-excess volumes under climate change conditions.

j	h_{j-1} [m]	h_j [m]	C_j [m_j^{3-b}/s]	a_j [m]	b_j [–]	Q_{j-1} [m^3/s]	Q_j [m^3/s]
1	0.156	0.685	30.69	0.156	1.115	0.0	15.1
2	0.685	1.917	27.884	0.028	1.462	15.1	70.7
3	1.917	4.17	30.127	0.153	1.502	70.7	243.2

Table 1. Rating-curve coefficients C_j, a_j, and b_j along with limb thresholds h_j for $j = 1,2,3$ at the River Aire gauge station in Armley, Leeds. Discharge limb thresholds Q_j have been added to facilitate the climate-change uplift analysis, in which $h = h(Q)$ is needed, used later.

3 River Aire flood analysis

3.1 Background and river gauge description

The River Aire poses a persistent fluvial flood risk to central Leeds, particularly along Kirkstall valley and urban areas (Bokhove et al., 2020b). Spanning approximately 148 km, it flows east from the Yorkshire Dales through the cities and villages of Skipton, Bingley and Leeds before joining the River Ouse near Airmyn (Wikipedia, 2024). Within the city, historical development and engineered channel modifications have narrowed the floodplain, amplifying peak water levels during extreme events (Bokhove et al., 2019, 2020b).

Located circa two kilometres upstream of Leeds' railway station, the Armley gauge station has recorded Leeds' two most severe 21^{st}-century floods: the Boxing Day 2015 event (Storm Eva) and the February 2020 flood (Storm Ciara) (Environment Agency, 2016). The 2015 flood alone caused over £500 million in damages across West Yorkshire (Leeds City Council, 2024b), including flooding 2,000 businesses across the Aire, Calder, and Wharfe catchments. Leeds-specific exposure was estimated at £400 million and over 4,000 properties were at risk under such 1:200 year scenarios (Leeds City Council, 2024b, 2019), with significant impacts in Leeds due to infrastructure and heritage losses. These events prompted major public investment in Leeds Flood Alleviation Scheme (phase 1 FAS1 and phase 2 FAS2, Leeds City Council (2022)).

The Armley station is a velocity-area gauging site operated by the EA and remains a stable reference point, with bypassing of the gauge being uncommon even during major floods (Bokhove et al., 2020b). Water-level measurements occur frequently, every 15 minutes, while the velocity measurements across the total cross-sectional area to obtain the discharge are carried out regularly but less frequently by EA technicians (e.g., 8 to 15 pro year, measurement times are driven by flow conditions). Despite altering some river hydraulics in FAS (Leeds City Council, 2024a), the station's rating curve –last updated in 2016 (Environment Agency, 2016)– remains officially unmodified. Its 15-minute resolution and location near flood-prone infrastructure make it central to the flood-excess volume (FEV) analysis used in this study. Standard errors across the rating curves' three limbs for the Armley gauge are reported to be 5.42%, 3.44%, and 5.28% (Environment Agency, 2016). For simplicity, we adopt a more conservative 5.5% uncertainty and apply that uniformly across, with bounds visualised in subsequent three-panel and hydrograph figures.

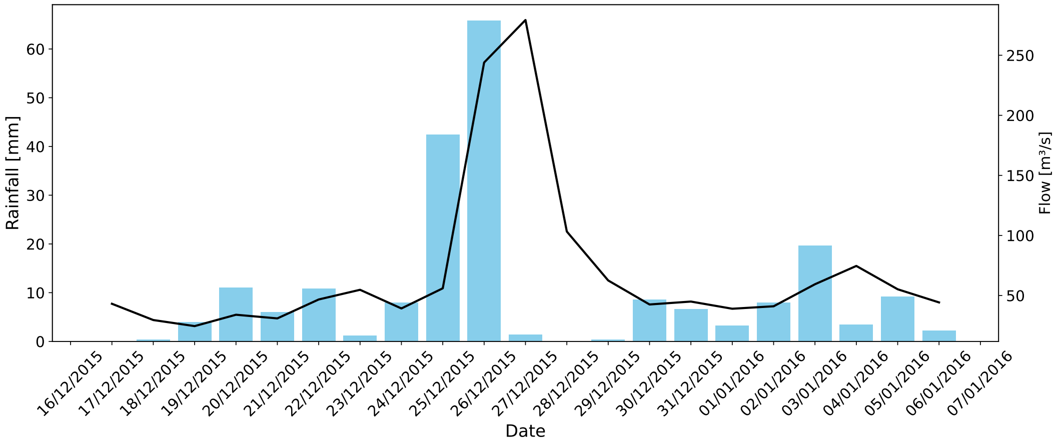

Figure 2. Daily rainfall (blue bars, in mm) at Lower Laithe, Bradford and corresponding average river flow at the Armley gauge (black line, in m^3/s) from 16 December 2015 to 6 January 2016. Created by using EA and Met Office data.

3.2 Boxing Day 2015 flood

The Boxing Day 2015 flood, triggered by Storm Eva, was the most extreme fluvial event on record for the River Aire in Leeds and serves as our benchmark. It followed weeks of rainfall, with November 2015 recorded as the second wettest on record in the UK, saturating soils across West Yorkshire, UK (The Met Office, 2016). Between 25–27 December, intense rainfall totalled 93.6mm in Bingley and 69.4mm in Bradford over 48 hours (Bokhove et al., 2020b), see Figure 2. The (upper) Aire catchment's steep terrain and low permeability caused rapid surface runoff and surging downstream flows (Upper Aire Catchment Partnership, 2025). At the Armley gauge, flooding began on the 26^{th} of December when the river exceeded our chosen $h_T = 3.9\mathrm{m}$ threshold, peaking to $5.22\mathrm{m}$ on the $27\mathrm{th}$ of December and remaining elevated above this threshold for circa 32 hours. That choice of h_T in this study was based on several local observations, in both 2015 and refined in 2020, that led to the decision that the threshold $h_T = 3.9\mathrm{m}$ on the nearby gauge was representative for the Kirkstall industrial estate (Bokhove et al., 2020b). In 2015, the measurements exceeded all historical records and were deemed to correspond to a return period of 1:200^{+} years (AEP<0.5%) (Leeds City Council, 2024b). Its magnitude and duration make it a critical reference for evaluating mitigation strategies and modelling future climate-adjusted scenarios.

To investigate the sensitivity of flood-excess volume (FEV) to the selected threshold heights h_T, a parametric analysis was performed across a range of thresholds from 2.4 m to 5.22 m. This range spans from slightly below the former EA flood alert level of 2.7 m up to the peak observed water level during the Boxing Day 2015 flood. (NB After implementation of the flood defense works that are part of FAS2 and were completed circa 2024, the "consequence" threshold, i.e. h_T, of property flooding has become $h_T = 5.35\mathrm{m}$.)

Varying the threshold level $h_T \in [2.4, 5.22]\mathrm{m}$ results in FEV values ranging from 27.6 Mm^3 to 0 Mm^3, as shown in Figure 3. This strong variation highlights the sensitivity of the calculated FEV to the choice of threshold level, since increasing h_T

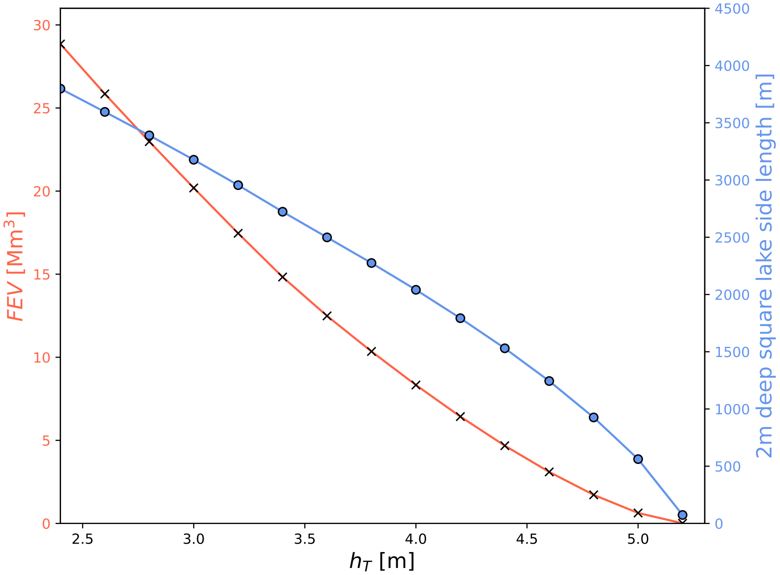

Figure 3. River Aire flood-excess volumes V_e (left axis, crosses) and equivalent square-lake sizes (right axis, circles) for various threshold levels h_T, from the Armley data of the Boxing Day 2015 flood.

reduces both the magnitude and duration of discharge exceeding the flood threshold. To aid interpretation of these volumes, the FEV is represented as an equivalent square lake which has square-root scaling with the FEV. Under this representation, as FEV decreases, so does the corresponding lake side length –from approximately $3700\mathrm{m}$ to $0\mathrm{m}$ as the threshold approaches the peak river level. While we have chosen h_T = 3.9m, its uncertainty will be around $\pm 0.25\mathrm{m}$ given that the first flooding occurred upstream of the Armley gauge station for a lower height, while the first water appeared in the streets for a higher $h_T \in [3.9, 4.16]\mathrm{m}$ (Bokhove et al., 2020b). This sensitivity highlights the importance of selecting an appropriate threshold level at each site that balances a range of sources. It also emphasises that while FEV is a robust diagnostic, its value is inseparable from the choice of h_T.

The Boxing Day 2015 flood was analysed using EA river-level data, converted to discharge rates using (1) with the rating coefficients in Table 1. Flooding at Armley began at approximately 10:15 on December 26$^{\mathrm{th}}$ when the river exceeded the locally defined threshold height $h_T = 3.9\,\mathrm{m}$, corresponding to a discharge of $Q_T = 219.06\,\mathrm{m}^3/\mathrm{s}$. The river peaked at $h_{\max} = 5.22\,\mathrm{m}$ at 02:15 on December 27$^{\mathrm{th}}$ and remained above the threshold for $T_f = (32 \pm 1)\,\mathrm{hrs}$, at a mean height of $h_m = 4.77\,\mathrm{m}$. Water-level data, the rating curve and hydrograph are graphically combined in the three-panel graph in Figure 4. Grey shading reflects an uncertainty band around the flow estimates due to rating-curve uncertainty. The lower left panel shows the corresponding river stage $h(t)$, while the top-left panel presents the stage-discharge relationship with confidence bounds. Key values include $Q_m = 300.03\,\mathrm{m}^3/\mathrm{s}$, $Q_{\max} = 344.4\,\mathrm{m}^3/\mathrm{s}$, and $h_m = 4.77\,\mathrm{m}$. Using (3) over exceedance period T_f yields an FEV of

$$V_e = (9.33 \pm 1.50)\,\mathrm{Mm}^3 \in [7.83, 10.82]\,\mathrm{Mm}^3 \tag{5}$$

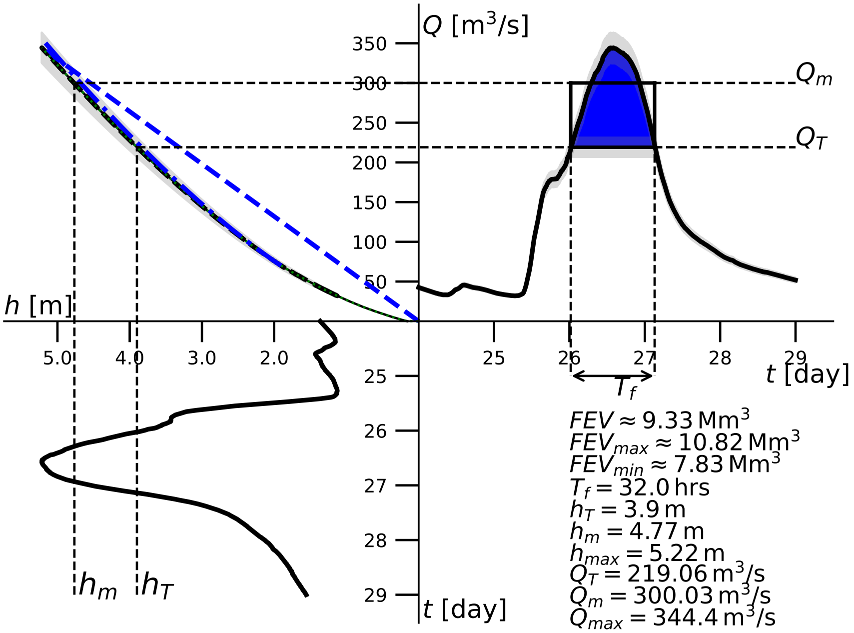

Figure 4. Three-panel hydrograph for the major 2015 Boxing Day River Aire flood at the Armley gauge station, Leeds, UK. The top-right panel shows discharge $Q(t)$, with the blue-shaded area representing the flood-excess volume (FEV) above the threshold discharge $Q_T = 219.06\,\mathrm{m}^3/\mathrm{s}$ over a flood duration of $T_f = 32\,\mathrm{hrs}$. The chosen threshold river level is $h_T = 3.9\,\mathrm{m}$, with the corresponding threshold flow rate derived from the rating curve (5.5% flow error—grey shading). The lower panel displays river stage $h(t)$; the top-left panel shows the stage-discharge relationship or rating curve. For later use, a changed rating curve due to giving room-to-the-river is displayed by the nearby blue dash-dotted line. Flow versus level measurements provided are in agreement with EA's supplied rating curve information, checked and displayed both as coinciding $Q(h)$ and $h(Q)$ curves.

equivalent to a $2\,\mathrm{m}$-deep square lake with side length $\sqrt{9.33\times 10^6/2}\mathrm{m} \approx 2161\,\mathrm{m}$. It will take about 100 minutes to walk around the circa $8600\mathrm{m}$ circumference of this lake. Using the 5.5% rating-curve uncertainty, total FEV uncertainty becomes approximately 16%.

3.3 February 2020 flood

The February 2020 flood represents the second most significant fluvial flood event in Leeds to date (2026), after the Boxing Day flood of 2015. Induced by Storm Ciara, it brought high-intensity rainfall over the River Aire catchment between February 8 to 10, 2020 (National River Flow Archive, 2020). Although the cumulative rainfall total was lower than in 2015, its greater

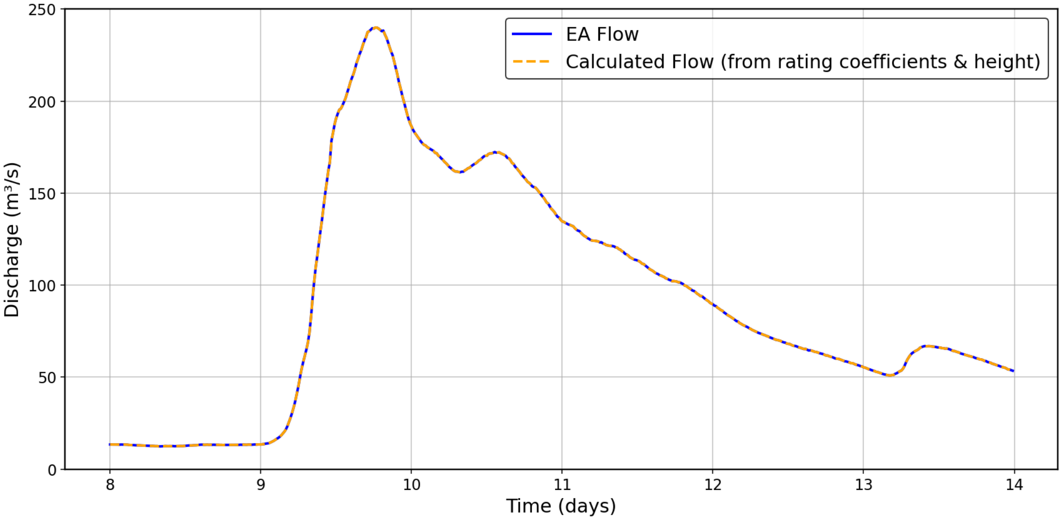

Figure 5. Comparison of given EA 2020 flow data to those calculated from the water-level data and 2016 rating curve coefficients. Reproduced result again confirms application of the 2016 rating curve coefficients by the EA.

intensity over a shorter time span produced a rapid hydrological response. The EA classified this event as having a return period of approximately 1:75 years (AEP $\approx 1.3\%$) (National River Flow Archive, 2020).

At the Armley gauge, river levels surpassed our flood threshold of $h_T = 3.9\,\mathrm{m}$ at approximately 18:00 on 9 February 2020, with a recorded peak stage of $h_{\max} = 4.13\,\mathrm{m}$ during the flood (River Levels UK, 2025). The duration of threshold exceedance was $T_f = 6.25$ hours. Although Leeds' FAS1, completed in 2017, implemented engineered interventions including raised flood walls and moveable weirs (Leeds City Council, 2019), these were implemented downstream of the underground "Dark Arches" rapids at Leeds' railway station, with upstream thereof river overtopping near Kirkstall Road persisting (Yorkshire Evening Post, 2020). We keep original threshold height $h_T = 3.9\,\mathrm{m}$ for direct comparison with the 2015 flood. To check continued applicability of the 2015 rating curve coefficients in Table 1, discharge was calculated from the 2020 stage data and given ratings' coefficients. The resulting values match the EA's provided flow data, as shown in Figure 5, suggesting confirmation of our continued use of one rating curve over the 2015–2020 period.

Hydrograph-based analysis of the 2020 event is presented in Figure 6. The blue-shaded area therein represents the calculated FEV over a duration of $T_f = 6.25$ hours:

$$V_e = (0.32 \pm 0.05)\mathrm{Mm}^3 \in [0.26, 0.37]\mathrm{Mm}^3, \tag{6}$$

a volume equivalent to a $2\,\mathrm{m}$-deep square lake with side length $L = 400\,\mathrm{m}$.

The hydrograph reveals a steeper and more asymmetric flood wave profile compared with the 2015 Boxing Day flood hydrograph, indicative of a shorter and more intense event. Despite the relatively short exceedance duration and smaller FEV, the 2020 flood had a peak stage of 4.13m, with localised surface flooding and infrastructure disruption across Leeds. The peak

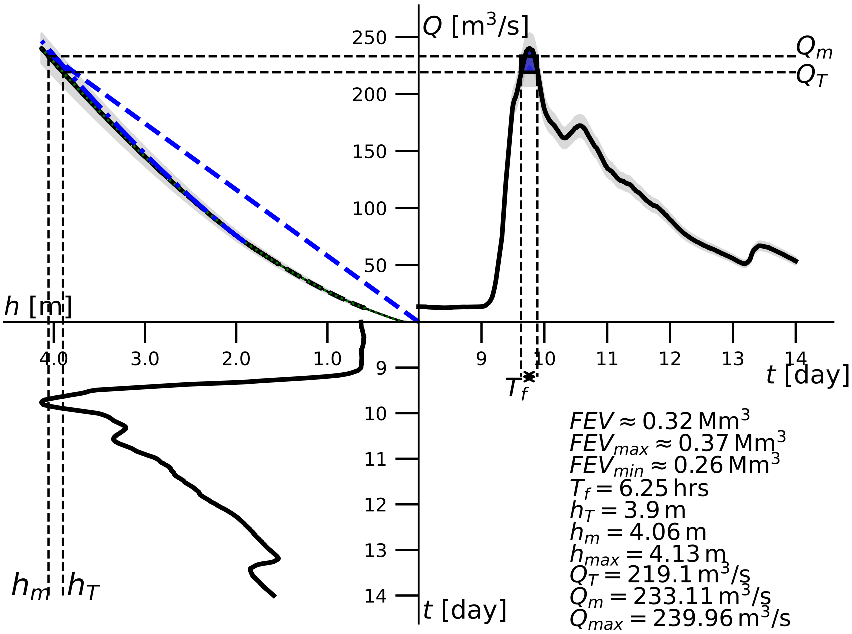

Figure 6. Three-panel hydrograph for the minor February 2020 flood at the Armley gauge station, Leeds, UK. The blue-shaded region denotes flood-excess volume above the threshold $Q_T = 219.1\,\mathrm{m}^3/\mathrm{s}$ over a period of $T_f = 6.25$ hours. Shaded regions represent uncertainty with $\pm 5.5\%$ uncertainty in the rating curve.

stage was above the top of the normal range of 2.7m (Environment Agency, 2025) at which low-lying flooding is possible. This demonstrates that residual flood risk persisted even after the implementation of mitigation measures under FAS1. Consequently, the 2020 flood provides a critical secondary benchmark for evaluating the efficacy of structural interventions and for understanding changes to similar events in future climate-change scenarios.

4 Giving meaning to climate-change uplifts of floods

Greenhouse gas emissions caused by human activity (anthropogenic), particularly CO_2 and CH_4, are intensifying the global hydrological cycle by raising atmospheric temperatures and increasing moisture capacity (IPCC, 2021). This leads to more intense and frequent rainfall events (Westra et al., 2014), already observed in the UK as wetter winters, drier summers, and more short-duration extreme rainfall, particularly in winter (Met Office, 2023; Kendon et al., 2019).

Climate change impacts are expected to significantly exacerbate fluvial and pluvial flooding. According to UKCP18 (UK Climate Projections 2018), peak river flows in the Yorkshire and Humber River Basin could increase by 23% to 51% in 2070–2125, depending on emissions scenarios (Environment Agency, 2022). Globally, the frequency of 1:100-year floods could more than double under high-emissions pathways (Hirabayashi et al., 2013; Alfieri et al., 2016). Clausius–Clapeyron scaling describes the thermodynamic relationship between temperature and the saturation vapour pressure of air, suggesting a 7% increase in atmospheric moisture per °C of warming. This enhanced moisture availability can lead to more intense short-duration precipitation, thereby intensifying extreme rainfall, causing increased runoff generation and peak river discharges (Westra et al., 2014).

These effects may already be occurring in the UK. Kay and Stone (2011) observed increased high river flows in northern catchments, and Pall et al. (2011) attributed at least a 20% increase of the autumn 2000 flood risk to climate change. Furthermore, Betts et al. (Met Office, 2022) confirmed rising rainfall intensities are consistent with anthropogenic warming. In Yorkshire (UK), this has particular implications for the River Aire, where intense frontal systems have already caused extreme events, such as the 2015 Boxing Day flood. Under projected uplifts, such events could become more frequent, with current 1:200-year floods projected to occur as frequent as 1:100-years in the future (Leeds City Council, 2022).

UK flood planning now incorporates climate allowances into infrastructure design[2]. The EA recommends applying uplifts to the entire flood hydrograph to capture increases in both volume and duration (Environment Agency, 2022). Leeds' FAS2 reflects this guidance, including adaptable design features with space for future wall raising and some upstream natural flood management (NFM) (Leeds City Council, 2019). The scheme modelled protection against a 1:200 year flood (0.5% AEP) accounting for a climate uplift of 20-50% from historic flooding (Leeds City Council, 2022). These EA climate uplift allowances have been applied to the 2015 and 2020 River Aire floods, projecting their evolution across time periods 2015–2039, 2040–2069 and 2070–2125, see Pickard (2025). The three-panel graphs with uplifted flood-excess volume (FEV) method are used, enabling quantitative reassessment of future flood risk and mitigation adequacy. To highlight our approach, here we focus analysis on the maximum uplift in the period 2070–2125 next.

4.1 Methodology climate-uplift scenario

The modelling follows EA's and Leeds City Council's SFRA guidance (Leeds City Council, 2016a), applying climate flow uplifts to the full hydrograph to calculate uplifted discharge rates:

$$\tilde{Q}(t) = Q(t)(1+F), \tag{7}$$

where F is the uplift factor, often expressed as a percentage (added). The uplift values, summarised and extended in Table 2, represent changes in river flow for different planning periods and emission scenarios.

Climate uplifts account for projected changes in rainfall. The EA has defined associated discharge uplift percentages for three periods –i.e., 2015–2039, 2040–2069, and 2070–2125– under emission scenarios:

- central: 2.4°C warming (RCP4.5/SSP2-4.5);

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[2] See EA's: https://environment.data.gov.uk/hydrology/landing

Scenario	**2015–2039**	**2040–2069**	**2070–2125**
lower end (5^{th})	-2%	-4%	-3% (0.97)
lower middle (30^{th})	7%	8%	15% (1.15)
central/mean (50^{th})	11%	13%	23% (1.23)
higher central (70^{th})	15%	18%	31% (1.31)
upper end (95^{th})	24%	31%	51% (1.51)

Table 2. Climate-change discharge uplift percentages for the River Aire and River Calder catchments Environment Agency (2023); Leeds City Council (2016a). We also added the top two rows for the 5^{th} and 30^{th} percentiles by reconstruction of the (normal) cumulative distribution functions, e.g., see Figure 7, as well as (uplift) factors $1+F$ in the last column, which we use.

- higher central: 2.8–3.2°C warming (RCP6.0/SSP3-7.0); and,
- upper end: 4°C warming (RCP8.5/SSP5-8.5).

These scenarios are based on percentiles with the central or mean, higher central and upper end allowances based on the $50^{\mathrm{th}}, 70^{\mathrm{th}}$ and 95^{th} percentiles. These three uplifts fit a normal cumulative distribution function well, so we calculated the 5^{th} and 30^{th} percentiles, in Table 2, see Figure 7 for the period 2070-2125. The spread in uplift factors is seen to be increasing (difference between 95^{th} and 5^{th} percentiles) as $0.26, 0.35$ and 0.54 for the three time periods. Uplift levels are used to guide planning: *central* is used for standard development; *higher central* for vulnerable sites; and *upper end* for critical or long-lived infrastructure such as flood defences (Leeds City Council, 2022). We adopt both the *central* and the *upper end* uplifts, reflecting mean and worst-case yet plausible emissions pathways. In particular, current global trends project warming of 3.1°C by 2100 (Dickie, 2024), making upper end scenarios a realistic stress test for infrastructure resilience.

The relationship between river flow and height is defined by a segmented rating curve:

$$Q = C(h-a)^b, \tag{8}$$

with a,b and C calibrated for each limb. Height uplift Δh from climate-induced flow increases can be estimated using log-linear approximation as: $\Delta h \approx \frac{1}{b} h \frac{\Delta Q}{Q}$. Instead, we find the uplifted height directly by inverting the rating curve (1), as follows:

$$h = a + \left(\frac{Q(1+F)}{C}\right)^{\frac{1}{b}} \quad \text{s.t.} \quad \Delta h = \left(\frac{Q(1+F)}{C}\right)^{\frac{1}{b}} - \left(\frac{Q}{C}\right)^{\frac{1}{b}}, \tag{9}$$

for each limb. Note that we (have to) extrapolate the upper-limb threshold at $h_4 = 4.17\,\mathrm{m}$ –exceeded during the 2015 flood– along with the exact inversion method (9). Using the full nonlinear inversion is required, since it is more accurate, relatively straightforward to implement and errors can be quite large away from the linearisation height.

4.2 Climate-change flood uplift: 2070–2125

In the long-term climate projection for 2070–2125, the UKCP18 upper-end scenario applies a 51% increase in peak fluvial flows, the most extreme uplift considered in their modelling framework for the River Aire. It results in significant changes to both flood magnitude and hydrograph morphology, including steeper rising limbs, higher peaks, and longer durations.

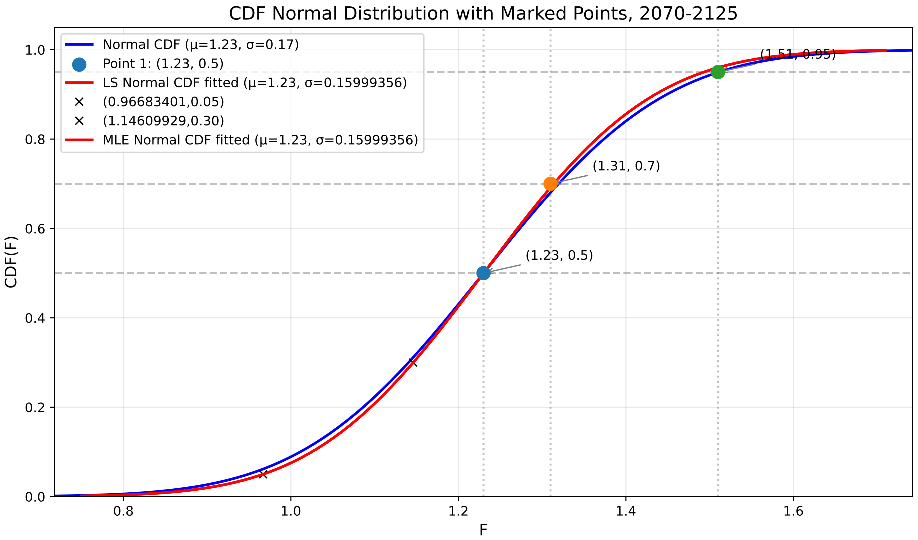
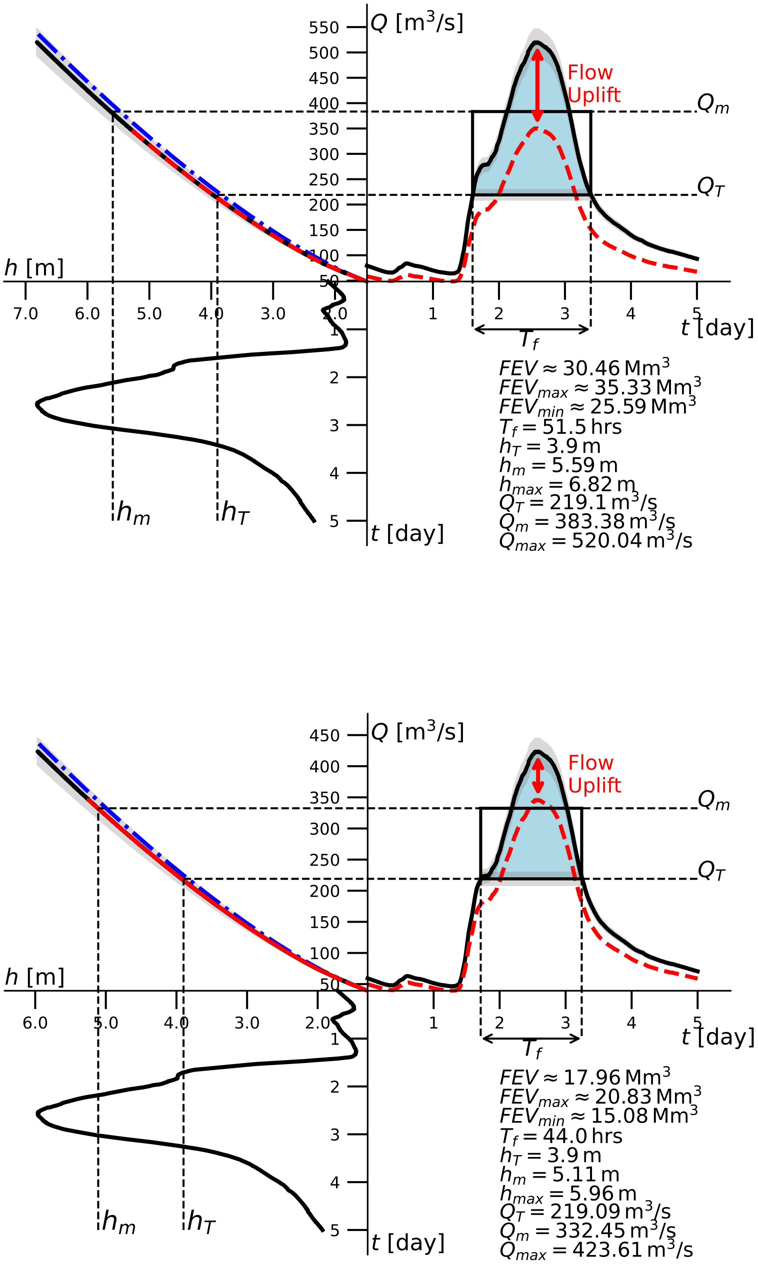


Figure 7. Cumulative distribution function (CDF) underlying the uplift factors of the River Aire for 2070-2125. Three data pairs have been given and by fitting with least squares (LS) and maximum likelihood estimation (MLE), with by definition a mean $\mu = 1.23$, the standard deviation σ is calculated, assuming a normal distribution. Given the small error of the fit (red line), a normal distribution was seemingly used. Initial guess displayed as blue line.

For the 2015 event uplifted 51% to 2070–2125 conditions in the upper-end pathway, the peak discharge increases from $344.4\,\mathrm{m}^3/\mathrm{s}$ to $520.04\,\mathrm{m}^3/\mathrm{s}$, while peak river height rises to $6.82\,\mathrm{m}$, see Figure 8(a). The FEV expands from $9.3\,\mathrm{Mm}^3$ to $(30.5 \pm 5)\,\mathrm{Mm}^3$, marking an increase of over 326%. When visualised as a 2 m-deep square lake, this equates to a side length of approximately $3903\,\mathrm{m}$, nearly double the side length of the square lake of the 2015 Boxing Day flood. Flood duration increases to $T_f = 51.5$ hours. The central uplift of 23%, yields a new FEV of $18.0\mathrm{Mm}^3$ with a new maximum water level of $6.0\mathrm{m}$, see Figure 8(b).

Similarly, the 2020 hydrograph intensifies significantly, with peak flow reaching $362.34\,\mathrm{m}^3/\mathrm{s}$ and river height $5.4\,\mathrm{m}$ –an uplift of $1.3\,\mathrm{m}$ from the baseline, see Figure 9. The corresponding FEV rises from $0.32\,\mathrm{Mm}^3$ in the actual event to $(7.5 \pm 1.2)\,\mathrm{Mm}^3$, represented as a 2 m-deep square lake with a side length of approximately $1938\mathrm{m}$. The event duration extends from $T_f = 6.25$ hours to 35.75 hours. In both volume and shape, the hydrograph for the 1:75 flood modelled for the years 2070–2125 mirrors the severity of the 2015 Boxing Day event in terms of the maximum water level, indicating a dramatic shift in flood behaviour under sustained global warming. While the peak water level is $0.17\mathrm{m}$ above the 2015 Boxing Day peak level, the FEV is circa 20% lower.

These projections indicate that by 2070–2025, a flood of the scale observed in 2015 –originally classified as a 1:200^+ year event– could become extremely devastating under projected upper-end climate-change uplifts. Meanwhile, the 2020 flood, previously estimated as a 1:75 year event, evolves to exceed the 1:200^+ benchmark in terms of discharge and peak water level, with a lower FEV. This supports growing consensus that high-intensity floods will become increasingly common under



(a)

(b)

Figure 8. Climate-adjusted hydrograph for the 2015 River Aire flood at the Armley gauge, (a) uplifted by 51% and (b) by 23% under the UKCP18 upper-end projection for 2070–2125. Peak discharges reach (a) $520.0\,\mathrm{m}^3/\mathrm{s}$ and river level of $6.82\,\mathrm{m}$, with FEV rising from $(9.3 \pm 1.5)\mathrm{Mm}^3$ (dashed red line) to $(30.5 \pm 5)\,\mathrm{Mm}^3$ (326%); and, (b) $423.6\mathrm{m/s}$ and a maximum level of $5.96\mathrm{m}$, with FEV rising to $(18.0 \pm 2.9)\mathrm{Mm}^3$. GRR-corrected rating curves shown as blue dash-dotted lines.

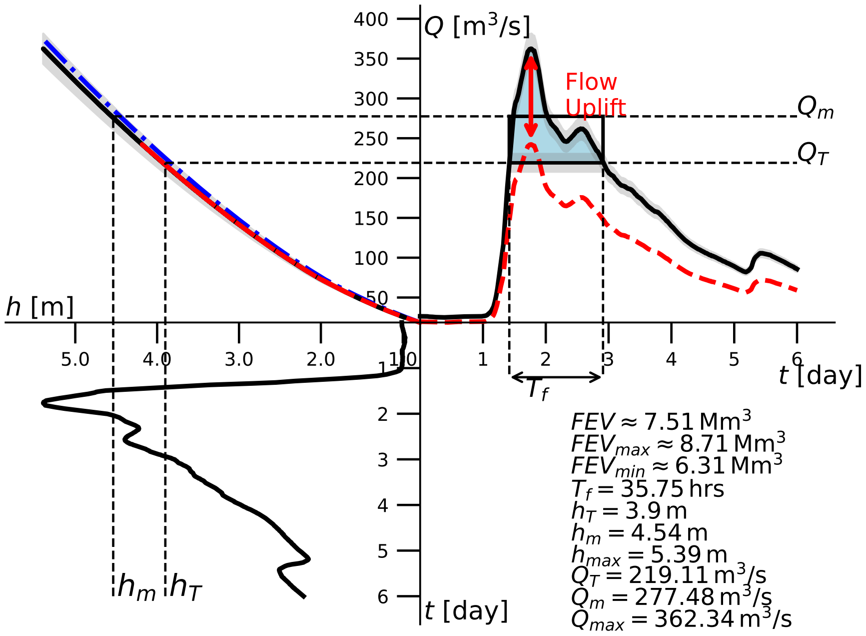


Figure 9. Climate-adjusted hydrograph for the 2020 River Aire flood at the Armley gauge, uplifted by 51% under the UKCP18 upper-end projection for 2070–2125. Peak discharge reaches $362.3\,\mathrm{m^3/s}$ and maximum river height $5.4\,\mathrm{m}$, with FEV increasing from $0.32\mathrm{Mm^3}$ to $(7.5 \pm 1.2)\,\mathrm{Mm^3}$.

long-term climate change. Flood-risk management strategies must therefore be revised to account for a future where extreme events are not rare anomalies but integral to hydrological patterns.

While projections extending to 2070–2125 inevitably carry uncertainty –owing to variables such as future emissions policies, socioeconomic development, and technological adaptation, they remain essential for long-term planning. Current global trends suggest the world is broadly on track with high-emissions pathways, driven by continued fossil-fuel reliance, uneven mitigation efforts, and accelerating climate feedbacks (IPCC, 2021; Climate Action Tracker, 2023). Under these conditions, the UKCP18 upper-end scenario is not merely hypothetical but increasingly plausible. Moreover, the 2070 horizon lies within the expected lifetime of today's infrastructure and many members of the current population. This reinforces the urgency of designing flood-management systems that are resilient not only to historical benchmarks, but to intensifying hydrological extremes projected for the coming decades.

4.3 Discussion of FEV and climate-change uplift analysis

Our combined analysis of using FEV and climate-change uplifts has enabled a dual assessment of:

- increased flood magnitude, driven by higher peak discharges and extended flood durations; and,
- evolving flood frequency, whereby moderate-return-period flood events such as the 2020 one increasingly resemble high-magnitude events like the 2015 Boxing Day flood in both scale and impact.

By systematically evaluating how historically observed events may intensify under projected climate conditions, our analysis provides a physically grounded basis for long-term flood-risk planning, supporting strategic appraisal of mitigation options under plausible high-end warming scenarios.

Across the 2015–2125 period, flood events uplifted using UKCP18 upper end climate scenarios reveal a clear and accelerating intensification of fluvial flood risk in Leeds. Floods are projected to become not only more frequent but also substantially more severe in terms of volume, duration, and destructive potential. For example, a 51% uplift applied to the 2015 event by 2070–2125 results in a 326% increase. The 2020 flood shows a similarly non-linear response, with its FEV rising from $0.32\,\mathrm{Mm}^3$ to $(7.5 \pm 1.2)\,\mathrm{Mm}^3$ under 2070–2125 projections. This non-linearity is explained by the power-law form of the stage-discharge relationship in (1), which governs the rating curve. Therefore, changes in river height h result in nonlinear increases in flow Q and the inverse applies, which by extension, impacts volumetric flood-excess.

When flood volumes are visualised spatially as hypothetical 2 m-deep square lakes, the impact becomes even more tangible. The 2015 flood square-lake side length footprint increases from $2161\,\mathrm{m}$ to $3903\,\mathrm{m}$ from the historical event to 2070–2125 projections, while the 2020 event expands from just $400\,\mathrm{m}$ to over $1938\,\mathrm{m}$. These spatial analogies highlight the rapidly escalating flood risk under upper-end climate change scenarios.

Our modelling approach has important limitations. In the most extreme case, propagated errors are $\pm 5\,\mathrm{Mm}^3$, in the 2070^+ calculation. In addition, information on the uncertainty in uplifted water levels or heights is provided by (double) the spread between central and upper end scenarios. These uncertainties mean that outputs should be interpreted as indicative of future risk trends, rather than precise predictions of event magnitudes.

Given current climate, political and social conditions, the upper-end projections modelled here are not extreme hypotheticals, but best-estimate representations of future risk. Moreover, the 2070–2125 window lies within the design lifetime of many critical infrastructure systems and within many people's life expectancy. It underscores the urgency of adapting flood risk management policies and mitigation strategies to ensure long-term resilience.

Next, we evaluate whether existing and proposed flood-alleviation measures in Leeds are sufficient to manage the increasing flood risk under these scenarios and whether the current Leeds' Flood Alleviation Scheme (FAS) offers the flexibility and scalability required to adapt to a more volatile future hydrological landscape.

5 Graphical cost-effectiveness analyses

The Leeds Flood Alleviation Scheme (FAS) is delivered in two phases in response to rising flood risk in the Aire catchment, in part as a direct response to the 2015 Boxing Day flood. Phase 1, completed in 2017 at a cost of approximately £50 million, focused on protecting the city centre of Leeds through engineered interventions including moveable weirs and raised defences downstream from Leeds' railway station to Woodlesford (Leeds City Council, 2016b; Bokhove et al., 2020b). Phase 2 (FAS2), delivered in two substages (2A and 2B), extends upstream towards Apperley Bridge and integrates both structural and a few minor nature-based measures. With a projected total cost of £112.1 million, FAS2 comprises enhanced flood walls, floodplain storage, and some minor Natural Flood Management (NFM) strategies such as tree planting and leaky dams (Leeds City Council, 2019; Bokhove et al., 2019). The NFM measures are minor in that they comprise a small fraction of the FEV to be mitigated and their (fractional) contribution may have been overstated[3]. The scheme was explicitly designed to accommodate future climate change by leaving space for wall height adaptation and enabling upstream flow attenuation (Leeds City Council, 2022; Environment Agency, 2023).

Bokhove et al. (2019, 2020b) (Bokhove, 2021) developed a transparent protocol for evaluating and communicating the cost-efficacy of a variety of flood-mitigation measures using the three-panel flood-excess volume (FEV) and square-lake cost-efficacy graphs as a diagnostic tool. The tool was used to analyse and clarify different FAS2 components under historical flood conditions. Building on that framework, we apply this diagnostic tool by evaluating whether FAS2 remains sufficiently robust under projected future climate scenarios. While the tool has not been used in the UK, as far as we know to date (2026), it has been used in the EU, both in France and Slovenia, to communicate and assess flood-mitigation scenarios with planners and city councils (Bokhove, 2021). Application of the tool will demonstrate and quantify how FEV and the efficacy of various mitigation measures change under fluvial flow climate-change uplifts.

5.1 Leeds' mitigation measures juxtaposed

To evaluate the effectiveness and robustness of flood mitigation in Leeds, a few distinct scenarios are explored, each representing a different configuration of Leeds' FAS2 and potential enhancements. The scenarios asessed –as far as possible– are:

- Actual FAS2 scheme S_0, implemented to date (2026): it includes riverbed widening or giving-room-to-the-river (GRR), completed flood walls (HW), Calverley storage (AFPC), and minimal NFM (some tree planting, partially realised). It represents a practical baseline for comparison. Recall that S_0 concerns protection against a design flood with an estimated 1:200 years return period and FEV of $9.33\mathrm{Mm}^3$ in the current climate.

- Extended FAS2$^+$ scheme S_1: it includes GRR (realised); FAS2 raised flood walls (HW, realised); floodplain storage sites at Calverley (AFPC, realised), Rodley (AFPR, added, S2 in Bokhove et al. (2020b)) and Connonley (AFPU, added, S4 in Bokhove et al. (2020b)); agricultural flood management (AFM, planned); and, several natural flood management

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[3] Bokhove et al. (2020b) provide an upper-bound estimate of the mitigation effect of the in 2017-planned tree planting; similar estimates can be made with figures of the Aire Resilience Company (ARC) from their 02-2024 presentation.

(NFM, planned) measures such as tree planting, leaky dams, and flood-attenuation by beaver dams (added, not planned). It serves as a benchmark for comprehensive mitigation against a design flood with a return period lower than 1:200 years due to a 51% climate-change uplift and FEV of $30.5\mathrm{Mm}^3$ relative to the situation in 2015.

- Extended S_2 case: similar to S_1 but for the 23% central climate-change uplift.

The flood management strategy includes a mixture of engineered interventions and natural flood management techniques. The different components vary in their contribution to the FEV. While floodplain storage, river widening, AFM and NFM such as leaky dams offer volumetric reduction, higher flood walls operate differently: they contain and redirect floodwater rather than store it. This functional distinction is critical. Although walls appear highly effective in terms of percentage FEV mitigated they do not absorb excess volume, but displace it downstream. Relying solely on containment would therefore risk shifting flood burden elsewhere in the catchment unless complemented by upstream interventions or downstream reinforcements.

We identified eight flood-mitigation measures, summarised in Table 3: giving-room-to-the-river (GRR), mainly higher walls and some embankments intermittently all the way from Apperley Bridge into Leeds (HW), available flood-plain storage in Calverley (AFPC), available flood-plain storage in Rodley (AFPR), available flood-plain storage at Cononley and Holden Park further upstream of Leeds (AFPU), available flood-plain storage via beaver dams (AFPB), agricultural flood management (AFM), and natural flood management (NFM).

The implemented Leeds' FAS2 scenario S_0 includes GRR, HW, AFPC and negligible NFM. The future (hypothetical) FAS2$^+$ scenario S_1 includes all eight measures. In order to design flood protection, here for Leeds, the concept of a design flood is generally used (see Knotters et al. (2024)). Ideally, an ensemble of precipitation, antecedent soil, groundwater and water-level conditions is created, all leading to floods of the chosen return period, here for S_0, S_1 and S_2. These return periods can be determined in terms of maximum water levels or discharge rates, at one or more critical locations in Leeds. Such model simulations of an ensemble of design floods acts as a simulated reference ensemble. Precipitation might be uniform across the catchment, likely in winter, or somewhat skewed towards extreme rainfall from Bingley to Leeds and less rainfall in the Upper Aire catchment, cf. precipitation during Boxing Day 2015 event, both with super-saturated soil conditions prior to the floods. Alternatively, extreme summer rainfall with dry soil conditions could lead to the chosen design flood, but this is probably a less likely member in the ensemble. Subsequently, all chosen mitigation members together and a subset of combinations thereof are added to the ensemble of reference simulations and their effectiveness is disentangled to assess the relative efficacy of (each group of) measures. This will lead to a series of three-panel plots in Leeds. Subtraction of the various hydrographs will then reveal what the effects are of each measure, whereby constructive or destructive interferences may take place. Given the large number of measures in S_1, only suitable groupings of measures can likely be explored. We are not aware that such an extensive exploration of flood mitigation measures for design floods, in terms of ensembles and mitigation measures, has been undertaken (for the River Aire in Leeds).

Leeds City Council (LCC) commissioned design simulations for FAS after the Boxing day flood of 2015 (see Bokhove et al. (2020b) and reference therein). Leeds City Council also created the Aire Resilience Company (ARC) with a board of stakeholders. Council and/or company commissioned design simulations to explore the additional effects of agricultural and natural

Mitigation Measure	**Implementation Status**	**Cost (£M)**	**FEV or flow mitigated (Mm^3 or $\%$)**
Giving Room to the River (GRR)	Phase 2A completed, widening near Kirkstall and Armley	10	$[0.66, 0.85]\,\mathrm{Mm}^3$
Higher flood walls (HW)	Phase 2A completed (Kirkstall to city centre); Phase 2B completed (to Apperley Bridge)	89	Higher walls mitigate FEV as first measure since they raise h_T
Available floodplain storage: Calverley (AFPC)	implemented	10	$\in [0.7, 1.26]\,\mathrm{Mm}^3$ Bokhove et al. (2020b) (under optimal weir operation)
Available flood-plain storage: Rodley (AFPR)	not implemented, not planned	14	$1.0\,\mathrm{Mm}^3$ (under optimal weir operation)
Upstream available flood-plain storage: Cononley & Holden Park (AFPU)	not implemented, not planned	35	$4.2\,\mathrm{Mm}^3$
Available flood plain storage beaver dams (AFPB)	not implemented, not planned, extra	$[0.5, 1]$	$\in [0, 1]\%$ (climate case S_1 only)
Agricultural Flood Management (AFM)	land and soil management upstream ($2 \times 1240\mathrm{ha}$), proposed, extra	$2.83 \times 10 \times 2 \times \frac{1}{4} \approx 14$	$\in [0, 6]\%$ (climate case S_1 only)
Natural Flood Management (NFM)	tree planting ($2 \times 535\mathrm{ha}$) and leaky dams upstream ($2 \times 84\mathrm{ha}$) upstream, proposed, extra	$2 \times 1.42 = 2.84$	$\in [0, 3]\%$ (climate case S_1 only)

Table 3. Summary of mitigation measures, implementation status, cost, and estimated part of FEV mitigated. Figures based on Bokhove et al. (2020b) and Leeds City Council reports (Leeds City Council, 2019, 2025; Drake et al., 2022; ARC, 2024). The Calverley total floodplain storage volume is quoted as $1.8\,\mathrm{Mm}^3$ (West Leeds Dispatch, 2023). The total Rodley floodplain storage quoted is quoted as $2.2\,\mathrm{Mm}^3$ (see Bokhove et al. (2020b) and references therein). Relevant are the available floodplain storage volumes, for which we calculate estimates. The costs for the first five measures are gross estimates, taken from Bokhove et al. (2020b) given two FAS2 reported costs of £$109\mathrm{M}$ (without Rodley) and £$123\mathrm{M}$, assuming a 50 year write-off period. Costs for beaver colonies are merely illustrative, based on costs for release, monitoring and damage mitigation/compensation. Costs for AFM and NFM stem from the Aire Resilience Company (ARC) (Drake et al., 2022; ARC, 2024), where investments stated are £$(2.83 + 1.42)\mathrm{M} =$£$4.25\mathrm{M}$. The lowered value for AFM is invoked by using a land-use practice change, enhancing and stabilising soil porosity. For FAS2, we take an indicative £$109\mathrm{M}$ as total budget since we subtracted an estimated £10 on trees planted, which was stated to do very little flood mitigation.

flood management (Drake et al., 2022). Attempts and requests, including freedom of information ones, to acquire relevant simulation data to create the three-panel graphs, calculate the FEV, and apply our cost-effectiveness plots have been unsuccessful to date (2026). While the 2022 report from Aire Resilience Company does seem to claim 5% flood (peak) reduction due to agricultural and natural flood management measures, the supplied simulation hydrographs show at best a 1.5% peak reduction. It remains unclear what is the origin of this actual or perceived discrepancy. The company does mention that the agricultural and natural flood management measures (02-2024 slides public presentation ARC (2024), see also Drake et al. (2022)) comprise areas in the Upper Aire catchment of 1240ha and $(535+84)$ha at an estimated total investment cost of £4.25M for a five-year period. Bokhove et al. (2020b) used estimates to make a hypothetical cost-effectiveness analysis. Given limited data availability, we will continue here with such a simplified exposition, serving an illustrative purpose. In turn, we will next discuss how each flood-mitigation measure is approximately quantified in absolute volumetric terms relative to the respective FEVs or as percentage reduction of the hydrograph, for the two scenarios S_0 and S_1, along with their accompanying costings.

The necessarily detailed and at times lengthy description of costs and effectiveness of each flood-mitigation measure presented in the next subsection can be skipped first, in favor of immediate reading of the graphical results given in subsection 5.3.

5.2 Flood-mitigation measures: details

5.2.1 GRR:

Giving-room-to-the-river (GRR) includes removing constrictions and river-bed widening. It will steepen the rating curve for higher water levels, as we will show in an illustrative calculation, such that water levels and FEV will decrease for given discharges as displayed in the hydrograph. At Armley, Leeds, one-sided river-bed widening is imposed for river levels above $z_{GRR} \approx 1.9\text{m}$ over a width of $w_{GRR} = 5\text{m}$ with an equal original and new transverse bank slope of $b_s = 2$ (see Fig. 5 in Bokhove et al. (2019)). The river slope is estimated to be $S_0 = 0.0005$ (Bokhove et al., 2020b). The Manning coefficient used is $C_m = 0.04$. The new rating curve follows by a compound sum of Manning relations for the main river section and the lowered flood plain section (Te Chow, 1959). We assume that the original rating-curve relationship remains approximately valid for the main river bed, since it is larger than the river depth, when the effect of the river-bed widening is added. Altogether, GRR yields the following, simplified rating-curve correction

$$\tilde{Q}_{GRR}(h) = Q(\bar{h}) + \frac{\sqrt{S_0}}{C_m} \frac{\left((h - z_{GRR})w_{GRR}\right)^{5/3}}{\left(w_{GRR} + \underline{(h - z_{GRR})\sqrt{(1 + b_s^2)})}\right)^{2/3}}, \tag{10}$$

the latter extra term being the additional discharge $(\sqrt{S_0}/C_m)A^{5/3}/P^{2/3}$ with added cross-sectional area $A = A(h) = (\bar{h} - z_{GRR})w_{GRR}$ and wetted perimeter $P = P(h) = w_{GRR} + (h - z_{GRR}\sqrt{1+b_s^2})$, due to the widened river bed (Bokhove et al., 2019). For case S_0, the adjusted FEV then becomes

$$V_{eGRR}^{(0)} \approx 8.67\text{Mm}^3 \in [8.19, 9.14]\text{Mm}^3, \tag{11}$$

with the new rating curve indicated in Figure 4 (dash-dotted blue line in second quadrant), yielding an FEV reduction of 0.66Mm^3 or 7% of the FEV. Given this adjusted rating curve and the flow, a new lowered water-level curve can be generated.

The same maximum discharge is seen to match with a (slightly) lower peak water level. For case S_1, the adjusted FEV then becomes

$$V^{(1)}_{eGRR} = 29.42\mathrm{Mm}^3, \tag{12}$$

with a new rating curve indicated in Figure 8 (dash-dotted blue line in second quadrant), yielding an FEV reduction of $1.04\mathrm{Mm}^3$ or 3.4%. Note that in both scenarios, the changed rating curve will raise the threshold discharge from $Q_T = 219.06\mathrm{m}^3/\mathrm{s}$ to $Q_{TGRR} = 224.89\mathrm{m}^3/\mathrm{s}$. For case S_2, $V^{(2)}_{eGRR} = 17.11\mathrm{Mm}^3$, so GRR's contribution takes $0.85\mathrm{Mm}^3$ off the FEV.

5.2.2 AFPC, available flood-plain storage, Calverley:

What matters for passive or dynamic flood-storage sites is the *available* flood-plain storage (AFP) volume as a dynamical, time-dependent available quantity rather than the total water volume stored behind natural obstructions such as constrictions or behind artificial, man-made weirs or static contractions. The available flood-storage volume is the volumetric portion of a reservoir or storage pond available and useful for attenuation of flood waters. This concept of available flood-storage volume was introduced in 2018-2020 by Bokhove et al. (2018a, b, 2019, 2020b). At the same time, it was also introduced as *effective* flood-storage volume by others (Metcalfe et al., 2018). The adjective "*available*" is a reference to *available* potential energy (APE) introduced by Lorenz (1955) (see also Shepherd (1988)) as diagnostic and dynamic quantity in dynamic meteorology. In reservoir engineering, the effective flood-storage volume tends to be a static volume. Here we refer to a –generally– dynamic available flood-storage volume since the flood waters tend to flow. Hence, we highlight and prefer the link to available potential energy.

The Calverley flood-storage site is created around a circa 200m long embankment across the River Aire valley near Calverley with in the middle of the embankment two sluice gates, which can be lowered or raised to stow up or release flood waters in order to level off peak flows or enhance throughflow downstream into Leeds. Prior to construction of the embankment and its sluice gates, the flood plains at Calverley already flooded as a natural storage site, e.g., during the 2015 Boxing Day flood, the classified 1:200-year event. That concerned a certain stored volume $v_{natural,200}(t)$. By optimally using the sluice gates in space and time, for a similar future flood a volume of $v_{sluice,200}(t)$ can be stored. At Calverley, the available storage volume

$$V_{AFPC}(t) = v_{sluice,200}(t) - v_{natural,200}(t)$$

is the volume gained relative to the natural storage volume. A challenge is to operate the sluice gates in an optimal manner such that $V_{AFPC}(t)$ is as large and mitigation as effective in time as possible. That is, consider a most suboptimal case in which the sluice gates are always closed, then the storage site is nearly always filled and water will flow over the embankment, also when the flood wave arrives. The available flood-storage can in such a situation even be detrimental, and negative at times, since it has used its available flood-storage volume at the wrong time in the flooding event. Safe and optimal operation is therefore very important and constitutes a nonlinear control challenge.

Based on the reported wall-height reductions by LCC due to the inclusion of the dynamic flood-storage site near Calverley, circa seven miles upstream of Leeds, it was estimated in Bokhove et al. (2020b) that the available flood-storage volume of that site is $V_{AFPC} = 0.08 V_{eGRR}^{S_0} = 0.7\mathrm{Mm}^3$, assuming optimal control of the sluice gates was enforced in the LCC-commissioned simulations. This contrasted the 2017 quoted $1\mathrm{Mm}^3$ by LCC, which we assumed to be the total flood-storage volume. For the factually constructed flood-storage site, a flood-storage volume of $1.8\mathrm{Mm}^3$ is mentioned (West Leeds Dispatch, 2023). Given the lack of clarification since 2018-onwards (despite requests), we take an available flood-storage volume $V_{AFPC} \in 0.7[1,1.8]\mathrm{Mm}^3 = [0.7,1.26]\mathrm{Mm}^3$ or $[7.5,13.5]\%$ of the FEV for illustrative purposes, assume that optimal control will be applied and that it was decided to build a storage site with increased capacity relative to the 2017 plans. This concerns case S_0.

For case S_1, the situation is complicated because we do not have access to v_{sluice,S_1} or $v_{natural,S_1} > v_{natural,200}$. The latter inequality arises because a higher flood would fill the natural flood plain with more flood waters. Hence, it can be expected that even the optimal available flood-storage volume will be smaller for scenario S_1 than for scenario S_0. That is, flood-storage sites are expected to be less effective under more extreme floods. Solely for illustrative purposes, we take the lower bound $V_{AFPC,S_1} = 0.7\mathrm{Mm}^3$. Without available dynamic explorations, we ignore the time-dependent aspects of V_{AFPC}, assuming that the timing of its capacity is optimal.

5.2.3 HW, Higher Walls:

For case S_0, the new threshold height, due to defense wall installation, h_{TGRR} is determined as follows: (i) intermediary threshold discharges $\hat{Q}_{TGRR} \approx [320.98, 310.12]\mathrm{m}^3/\mathrm{s}$ are found by varying h_T such that a remainder-FEV of $V_{AFPS} = [0.7, 1.26]\mathrm{Mm}^3$ is found; (ii) via a look-up table we made of the new GRR-corrected rating curve, we find $h_{TGRR} \approx [4.89, 4.78]\mathrm{m}$. (iii) In the actually constructed FAS2, the new maximum flood height at the Armley river gauge is $5.35\mathrm{m}$, $0.13\mathrm{m}$ higher than the maximum of $5.22\mathrm{m}$ seen in the 2015 Boxing Day flood. Hence, we add that $0.13\mathrm{m}$ to obtain new threshold heights $h'_{TGRR} = [5.02, 4.91]\mathrm{m}$. Otherwise said, due to the combined effects of GRR and the Calverley storage site, threshold and corresponding wall heights do not need to be raised to protect against the $5.35\mathrm{m}$ water levels but could be lowered by $[33, 45]\mathrm{cm}$. For S_0, of the FEV higher walls comprise

$$[100 - 14.5 = 85.5, 100 - 20.5 = 79.5]\%,$$

with the subtracted percentages arising from $(V_e - V_{eGRR}^{(0)} + V_{AFPC})/V_e$.

Recall that these are not wall heights, but thresholds. In-situ wall heights are probably circa $[1.21, 1.01]\mathrm{m}$. For S_1, we keep that new threshold $h'_{TGRR} = 5.02\mathrm{m}$. The remaining flood-excess volume above that wall level is $V_{rem}^{(1)} = 14.81\mathrm{Mm}^3$. We took the Calverley costs to be £10M over 50 years: see the rational for the costs of the Rodley flood storage site presented next.

5.2.4 AFPR, available flood-plain storage, Rodley:

Similar to the Calverley site, based on the reported wall-height reductions by LCC due to the inclusion of the dynamic flood-storage site near Rodley, circa five miles upstream of Leeds, it was estimated in Bokhove et al. (2020b) that the available flood-storage volume of that site is $V_{AFPC} = 0.12 V_{eGRR}^{S_0} = 1.0\mathrm{Mm}^3$, assuming optimal control of the sluice gates was enforced in the LCC-commissioned simulations. This contrasted the quoted $2.2\mathrm{Mm}^3$ by LCC (in 2017), which we assumed to be the total flood-storage volume. The FAS2 costs of £109M (without Rodley) and £123M imply the Rodley storage site costs to be £14M over a 50 year write-off period. Given that Rodley is larger than the Calverley storage, we took the Calverley costs to be £10M.

5.2.5 AFPU, upstream storage:

For case S_0, at the Cononley and Holden Park flood-storage sites much further upstream from Leeds, an available flood-storage volume of $V_{AFPU} = 4.2\mathrm{Mm}^3$ was assigned (Bokhove et al., 2020b). For case S_1, we keep $V_{AFPU} = 4.2\mathrm{Mm}^3$. Based on the Calverley and Rodley costs, we assigned a cost of £35M, since these storage areas are larger but more remote and a less fancy implementation than in Calverley was deemed feasible.

5.2.6 AFPB, beaver-pond storage:

In both scientific literature (Puttock et al., 2017; Larsen et al., 2021; Nyssen et al., 2020) and the (British) media, water storage via colonialisation of a river valley by beavers has been proposed and extensively promoted as (potential) flood-mitigation measure to reduce floods. Also the EA mentions this potential in their natural flood management manual "Working with natural processes" (Pearson and et al., 2025). There are limitations that require attention in order to assess the efficacy of beaver dams and their available flood-storage volume potential in flood mitigation:

- The upscaling of the available flood-storage volume behind beaver dams is limited, given the small storage volumes involved. The natural density of beavers dams per kilometre of viable river or tributary varies and is a limiting factor, further hampering upscaling. Flood-mitigation benefits appear to be at best local for small catchments, cf. remarks in Pearson and et al. (2025).
- Beavers can have a detrimental effect on existing flood defences, given that they are known to undermine embankments, dams can be built in the wrong places and their dams may collapse during floods. In the Netherlands beavers were introduced in 1988 into the fresh-water tidal wetlands De Biesbosch. Since that time, they have multiplied and spread across the country, with over 5000 beavers reported in 2025. Beavers are regularly in the Dutch news for their undermining of railway and flood-defense embankments or dikes (Zee, 2025), as well as their contributions to nature and rewilding. To tackle the potential damage, the Dutch government has comprised a national approach to beavers as well as local beaver protocols (den Heijer et al., 2023; Stam et al., 2025; Collaborative Beaver Protocol Utrecht, 2012). While the natural value of beavers in The Netherlands is undisputed, nowhere does this Dutch literature mention flood-mitigation benefits, given the actual damage caused by the beavers.

Nonetheless, to assess that flood-mitigation potential, it is necessary to look at available measurements of the hydrology and hydrodynamics of beavers colonies, their ponds and dams. The change in time of the storage volume V_b of a beaver pond or a series of beaver ponds depends on the influx Q_{in}, out-flux Q_{out} and evaporation rate E_v (all expressed as rates). Following the review article of Larsen et al. (2021), we find that

$$\frac{\mathrm{d}V_b}{\mathrm{d}t} = Q_{in} - E_v - Q_{out}, \tag{13}$$

in which Q_{out} can be divided further into outflow from the dam Q_{dam}, groundwater outflow Q_{gw} and return flow Q_{rf} from the floodplain downstream of the dam such that $Q_{out} = Q_{dam} + Q_{gw} + Q_{rf}$. While there is a lot of literature on beaver dams stating their alleged flood-mitigation benefits, there are fewer works containing hydrographs allowing assessment thereof. Hydrographs of inflow Q_{in} and (part of) Q_{out} are disseminated for beaver-dam complexes: (i) in a 2014 flood of the River Tamar catchment in Devon, UK (Puttock et al., 2017), (ii) during a February 2010 flood along the Chevral River in the Ardennes, Belgium (Nyssen et al., 2020), (iii) for a 1994 storm event in Tellageda Wetland, West Central Alabama, USA (Chaubey and Ward, 2006) and (iv) for a June 1988 flood in streams crossing coastal wetlands along Hudson Bay in Northern Ontario, Canada (Woo and Waddington, 1990). Hydrographs used are found in Appendix A.

The beaver colony in the River Tamar, Devon, UK, concerned 13 dams over a distance of $200\mathrm{m}$, with a reported (Puttock et al., 2017) available flood-storage volume V_{AFPBT} for a December 2014 flood of $V_{AFPBT} = 1100\mathrm{m}^3$. Approximate verification of the hydrograph up- and downstream of the complex yields $900\mathrm{m}^3$ and thus roughly confirms the value V_{AFPBT}, except that the water levels in the two hydrographs appear to concern different overall integrated water volumes. Piton et al. (2018) report that this value V_{AFPBT} may be five times lower, based on the shown low pond-level fluctuations, before and after the floods, times the shown pond area, potentially indicating that the available flood-storage volume is much lower than V_{AFPBT}. The origin of this discrepancy is unclear but may be due to extensive evaporation losses and hidden groundwater flows. The volume per dam is $1100\mathrm{m}^3/(13\,\mathrm{dams}) = 85\mathrm{m}^3/\mathrm{dam}$. Combining Woo and Waddington (1990)'s reported colony density between $3\mathrm{km}$ and $20\mathrm{km}$ with Puttock et al's results (Puttock et al., 2017), a dam density estimate for the Devon case lies between $(13/20)\mathrm{dams/km} = 0.65\mathrm{dams/km}$ and $(13/3)\mathrm{dams/km} = 4.33\mathrm{dams/km}$. Hence, by taking the best case, the available storage volume per kilometre in the Devon case becomes

$$V_{Devon,km} = 85 \times 4.33\mathrm{m}^3/\mathrm{km} = 367\mathrm{m}^3/\mathrm{km}. \tag{14}$$

The Chevral River hydrograph was particularly mentioned in the review article on beaver hydrodynamics of Larsen et al. (2021). However, an estimate of the available flood-storage volume from the flood hydrograph in the Chevral River is so high at $1.7\mathrm{Mm}^3$ and in disagreement with a rough estimate of the aerial pond-size at $300 \times 50\mathrm{m}^2$ times generous $2\mathrm{m}$ pond-level fluctuations, totaling $30000\mathrm{m}^3$, that the case is discarded, also because the authors themselves indicate "extrapolations beyond range of observation" (Nyssen et al., 2020).

Chaubey and Ward (2006) report one consistent hydrograph of inflow and outflow for two storm events in 1994 in Talladega Wetland, West Central Alabama, USA. The outflow picks up after the event, releasing a volume similar in size to an estimated storage volume of $V_{AFPBTa} = 3600\mathrm{m}^3$ with a lowered outflow peak delayed by about 3 to 4 hours. There seem to be about five beaver dams over a length of $200\mathrm{m}$, making the storage per beaver dam about $720\mathrm{m}^3$ and with the highest density of $4.33\mathrm{dams/km}$ used above, the storage per kilometre of stream then becomes

$$V_{Tal,km} = 3100\mathrm{m}^3/\mathrm{km}. \tag{15}$$

Woo and Waddington (1990) consider a flood for a beaver-dam complex in flat wetlands near Hudson Bay, Ontario Canada. There are 60 dams in various states of preservation in a kilometre-squared area. Average dam density is reported to be

$14.3\mathrm{dams/km}$. In- and outflow hydrograph differences for a 21-06-1988 flood yields $V_{AFPBH} = 390\mathrm{m}^3$. Combined with the dam density that yields a storage per kilometre of stream

$$V_{H,km} = 14.3 \times 390\mathrm{m}^3/\mathrm{km} = 5570\mathrm{m}^3/\mathrm{km}. \tag{16}$$

These storage volumes per kilometre differ by a factor 8 and 15 with the one at the Devon site. It may be questionable to apply results from all these sites to the River Aire, given that the Hudson Bay landscape is quite different from the Yorkshire topography, as these Hudson Bay wetlands are remote and very flat. Translated back to storage volumes of beaver colonies these yield three available flood-storage volumes arise as $V_{AFPB} = [1100, 8800, 16500]\mathrm{m}^3$. One percent mitigation of the FEVs then require $S_0 : [85, 11, 6]$ and $S_1 : [348, 35, 18]$ beaver colonies in the Upper Aire catchment, applied to our two flooding scenarios. We take these middle figures of 11 and 35 beaver colonies. The above exposition highlights that there is a lot of uncertainty surrounding the use of beaver dams in flood mitigation, including that the net effect may be enhanced flood damage. The main benefit of reintroducing beavers remains their added nature value: water quality improvement, biodiversity uplift, carbon sequestration in beaver pond sediments, tourism and education value, on local scales. We assign overall costs of £$[0.5, 1]\mathrm{M}$ over 50 years to the introduction, monitoring of beaver activity and control.

5.2.7 AFM:

Agricultural flood management (AFM) will involve land management but mainly soil aeration. The Aire Resilience Company (ARC) states that it will involve $1240\mathrm{ha}$ of agricultural land in the Upper Aire catchment. Soil aeration involves mechanically aerating the soil, which generally involves machinery. Aeration increases the porosity of the soil otherwise compacted by grazing or machines. When land use remains the same aeration will need regular updates, since the porosity will decrease over time. Also here the available flood storage volume is the quantity of interest as well as the precursory soil moisture conditions prior to extreme rainfall. Saturated soils will have less storage capacity even after aeration. When the land use changes favorably after soil aeration, the frequency of soil aeration interventions can be decreased.

In a report and presentation of the Aire Resilience Company one- and two-dimensional simulations are considered with a mixture of eleven agricultural and natural flood-management flood-mitigation measures in a 2069 climate-change uplift scenario of circa 8% for an event of 0.5% Annual Exceedance Probability (AEP) (Drake et al., 2022; ARC, 2024). A chosen double-peaked reference flow, subject to a combination of AFM-NFM measures, led to a 5% reduction of the second flood peak but the first flood peak stayed at a peak level of 98.5%, whence only at best a 1.5% flood (peak) reduction is achieved. The ARC report (Drake et al., 2022) factually states:

> “*This is particularly the case in the 0.5% AEP CC 2069 event, which is shown to be double peaked at the Leeds City assessment point for the hydrological scenario modelled. This means that in the baseline model flow hydrograph the peak flow is observed in the second peak for this event. Although reduction in flow is shown to extend to up to nearly the entire flow reduction required for the LFAS2 NFM project at the maximum point of flow reduction (5% of the baseline 0.5% AEP CC2069 peak is ∼17.15*m^3/s*), the majority of impact is shown in terms of reduction of the second peak, with the first peak being only marginally reduced and consequently drives the maximum flow in*

> *the 'with measure' scenario. This pattern is repeated throughout the 0.5% AEP event, and means that individual sub-catchment performance is muted amongst the other inflows.*"

The relevant hydrographs of the two best mitigation simulations among hundreds of simulations were located at Calverley upstream of Leeds (one-dimensional model) or in Leeds (two-dimensional model). The report concludes with:

> "*Finally, this study has demonstrated that under a range of combinations of measures, densities and coverage throughout the catchment, it is considered that is it possible to meet the target* 5% *reduction in peak flow to the Leeds City assessment point in a* 0.5% *AEP CC 2069 event on the River Aire*".

Moreover,

> "*Based on hydrological modelling, ARC will ensure protection against a further* $5\%^+$ *rise in peak flow*" (ARC, 2024).

The mitigation measures comprised three groups: woodland creation (tree planting of various kinds), runoff management (including soil and land management) and river and floodplain management (including restoration, wetlands and leaky dams). In the Aire Resilience Company presentation of 2024 (ARC, 2024), area sizes of 1240ha, 535ha and 84ha for soil and land management, tree planting and leaky dams are mentioned, at an investment cost of £4.25M over a five year period. These factual statements and findings in report and presentation seem inconsistent and confusing since the flood (peak) reduction shown (to date in the graphs provided) is at best 1.5%. The report only mentions area coverage per micro-measure and we will assume that there is a match between area sizes in the presentation and report. Hence, over five years the agricultural flood management is estimated to cost £2.83M, using the relevant $2/3^{\text{th}}$ area fraction of the total quoted investment costs. We will increase the land area by a factor two but only include 50% of the costs to the flooding budget, allocating the other agricultural benefits to another budget post. Over the 50 year write-off period, we then only take the costs as £14M, since the main aeration component requires repeating (as in dredging), with the lower figure holding when the land use is changed to require less frequent aeration as well. This could be due to limiting animal grazing, crop change or avoidance of soil compaction in wet areas near streams and rivers, and such.

Lacking accessible and verifiable simulation data, an upper-bound calculation provides another angle on the potential flow reduction at Armley in Leeds (similar to the Appendix in Bokhove et al. (2020b)). In Kildwick, circa 25 miles upstream from Leeds the peak flow in the 2015 Boxing Day flood was $156\text{m}^3/\text{s}$ and at the Armley gauge, Leeds, it was $344\text{m}^3/\text{s}$ (Environment Agency Data Site). The River Aire catchment is circa 1000km^2 in size with circa 20% lying upstream of Kildwick, i.e. 200km^2, and the area use stated for agricultural management (ARC, 2024) is $1240\text{ha} = 12.4\text{km}^2$. Assuming the (likely unrealistic) upper-bound of 100% retention of rainfall in the AFM area, we estimate the following flow reduction at Armley in Leeds:

$$e_{absorp}\,\alpha_{area}\,q_{KA} = \beta_{peak} \quad \Longrightarrow \quad 1 \times \frac{12.4}{200} \times \frac{156}{344} \approx 0.03 = 3\%, \tag{17}$$

with $\alpha_{area} = 12.4/200$ the argicultural area fraction, $q_{KA} = 156/344$ the ratio of peak velocities at Kildwick and Armley, and β_{peak} the flow reduction at Armley. For the upper bound calculation, an absorption factor or retention of $e_{absorp} = 1$ is taken. Since AFM likely also has agricultural benefits in addition to flood-protection ones, we hypothetically enhance the aerial coverage by a factor of two to $24.8\mathrm{km}^2$ but reduce the costs allocated to the flooding budget, for 6% over 50 years, arguing that 50% or more of the costs should come from an agricultural budget to stimulate farming. Given that upper-bound estimates at best reveals only a 3% flood (peak) reduction, the twofold increase chosen implies a $[0,6]\%$ flood (peak) reduction.

5.2.8 NFM:

Natural flood management (NFM) mainly involves tree planting over $535\mathrm{ha}$ and we lump the limited area coverage of leaky dams at $84\mathrm{ha}$ to the tree planting area in terms of efficacy for simplicity. Given the rationale on agricultural management above, natural flood management will cost £$1.21\mathrm{M}$ over 50 years, since tree planting is assumed to be a one-off investment for simplicity and the leaky dam investment is simplified to be one-off too. That is not true since leaky dams degenerate but given the small area coverage we exclude a more detailed analysis here, see Bokhove et al. (2019) for a more advanced analysis with leaky dam maintenance. The proposed natural management area in the Upper Aire catchment is $(535+84)\mathrm{ha} = 619\mathrm{ha}$. Assuming the (likely unrealistic) upper-bound of 100% retention of rainfall in the area for natural flood management, we estimate the following flow reduction at Armley in Leeds:

$$e_{absorp}\,\alpha_{area}\,q_{KA} = \beta_{peak} \quad \Longrightarrow \quad \frac{6.19}{200}\times\frac{156}{344}\approx 0.015 = 1.5\% \tag{18}$$

with adapted values for α_{area} and still $e_{absorp} = 1$. We allocate the full costs of £$(619/1240)4.25\mathrm{M} =$ £$1.21\mathrm{M}$ to the flooding budget. Given that upper-bound estimates at best reveals only a 1.5% flood (peak) reduction, the same twofold increase applied to the natural flood management area would mean a $[0,3]\%$ flood (peak) reduction.

The ratio q_{KA} reflects the relative influence of the combined soil and groundwater conditions and amount of precipitation in the catchment upstream of Kildwick relative to that in the catchment upstream of Armley. Since uniform climate-change uplifts do not change that ratio, the arguments given apply with or without uplift. Given the combined agricultural and natural flood management area ratio α_{area} and given a target peak flow reduction β_{peak}, the ratio q_{KA} can be calculated. In order to get the stated 5% flow reduction (ARC, 2024), one needs to raise $q_{KA}\approx 0.55$ (from the 2015 Boxing Day flood ratio $q_{KA} = 156/344\approx 0.453$), yielding a peak velocity of $188\mathrm{m}^3/\mathrm{s}$ at Kildwick, for their $\alpha_{area} = (12.4{+}6.19)/200\approx 0.186, e_{absorp} = 1$. Given $\alpha_{area} = \frac{(12.4+6.19)}{200}\times[1,2]$, the lowest value of $e_{absorp}\approx[0.55.0.27]$ for which $q_{KA} = 1$, implying that there is no water or precipitation between Kildwick and Armley entering the River Aire. This combined upper bound of 4.5% is larger than the combined AFM and NFM measures of 1.5% discerned in the ARC report (Drake et al., 2022), which casts concern on the 5% flood (peak) reduction (cl)aimed in Leeds by ARC given the stated area sizes of the proposed mitigation measures. In case S_1, we doubled the AFM plus NFM area used, such that the upper bound doubles to 9%.

The chosen, combined AFM and NFM flow reduction of $[0,9]\%$ implies a reduction of climate-change uplift. To illustrate that choosing an ensemble matters, an ensemble of two soil condition and precipitation patterns will be used: a) one “summer” pattern at $(1/9)^{\mathrm{th}}$ chance yielding full retention and b) one “winter” pattern at $(8/9)^{\mathrm{th}}$ chance with zero retention. The mean reduction then becomes

$$\left(1\times\frac{1}{9}+0\times\frac{8}{9}\right)\times 9\% = 1\%.$$

For a case S_1', say, an alternative ensemble includes: a) one "summer" pattern at $(1/3)^{\rm rd}$ chance yielding full retention and b) one "winter" pattern at $(2/3)^{\rm rd}$ chance with zero retention. The mean reduction is then

$$\left(1\times\frac{1}{3}+0\times\frac{2}{3}\right)\times 9\% = 3\%,$$

i.e. somewhat aligned with the maximum flow reduction of 1.5% (times two) seen in the ARC report (Drake et al., 2022). While we simply chose these conditioning weights of dry conditions with full retention versus wet conditions with zero retention as illustration and for convenience, the issue of precursory conditions is an important one.

In their simulation study on the effects of Spaghnum moss reintroduction, Goudarzi et al. (2024) consider a scenario (their F4) with reintroduction of moss in 40% of the catchment relative to an uncovered case, in the upper areas of a river catchment. The hydrograph reduction seen at a downstream river location is circa 40% for a 1:100yr rainfall storm event, implying circa 100% retention. For a frontal storm in terms of rainfall, a 30% reduction was observed, implying circa 75% retention. These concerned drier ("1:2yr summer") soil conditions. A limitation may, however, be that no difference in antecedent soil conditions was imposed, such as conditions corresponding to saturated soils akin to such conditions prior to and during the 2015 Boxing Day floods. How to accurately assign weights to such dry summer and saturated winter situations or a more representative ensemble distribution seems to be an open question.

5.3 Results: cost-effectiveness graphs

The above exposition finishes pinning down all figures to make and display graphical cost-effectiveness for flood-mitigation scenarios S_0 and S_1, and underpins the overview and figures put together in Table 3. This exposition has necessarily been hypothetical and involved a series of assumptions and estimates, in part due to a lack of transparency of presumably and partially available data but also, and possibly in a substantial way, due to the intrinsic difficulty in acquiring all appropriate and necessary data to establish these cost-effectiveness analyses. Finally, the upper-bound calculations for agricultiural and natural flood management can be viewed as independent constraints to juxtapose against detailed hydrological and hydrodynamic simulations.

For S_0, the cost-efficacy overview then becomes as follows: giving room to the river (GRR) takes 7% at £10M, dynamic flood-plain storage at Calverley (AFPS) takes $[7.5, 13.5]\%$ at £10M and with a total budget of £109M, higher walls do most of the mitigation at 85.5% and take most of the budget at £89M. For the beavers at 1% flow reduction (an "uplift" of -1%), one finds $V^{(0)}_{AFPB} = 0.35\mathrm{Mm}^3$ (3.7% of FEV). The extra storage of AFPC and the beavers are added beyond the square lake. Putting all these data together, we arrive at the cost-effectiveness graph for scenario S_0 in Figure 10. Herein, we used the extra flood-plain storage for storage beyond the design flood-excess volume. Costs per percent, partial costs and fractions per measure, as well as total costs, are all displayed. The respective (fractional) lake sizes provide a sense of scale to the measures involved.

In Table 4, we have summarised six options with or without agricultural and natural flood management combined, and beaver colonies. For S_1, the cost-efficacy overview is shown in Figure 11 for the lower-bound, worst case with agricultural and natural flood management and some optional beaver ponds. For the climate-change uplift of 51%, without any new or updates

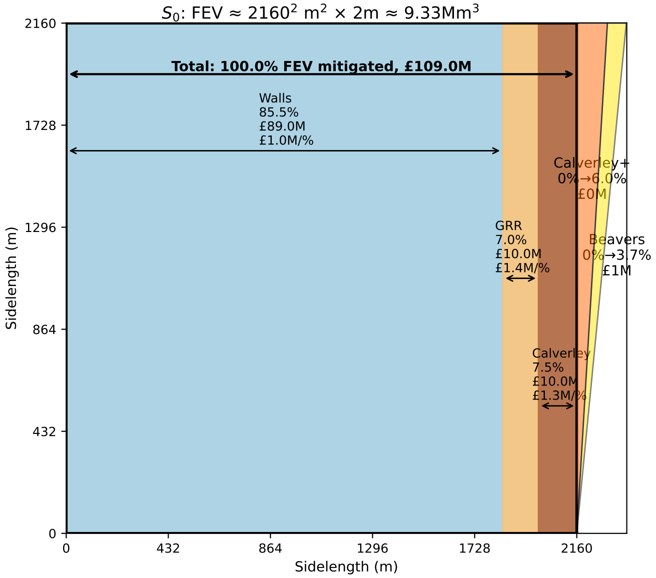

Figure 10. Square-lake cost-effectiveness plot for scenario S_0 with a contribution based on a 1:200^+ return period flood event presently, without climate allowance. The square lake side length is $2161\mathrm{m}$, such that $2161\mathrm{m} \times 2161\mathrm{m}$ times $2\mathrm{m}$ lake depth comprises the total FEV, and each coloured area-band or -triangle corresponds to a distinct mitigation intervention. The area of each mitigation measure multiplied times the $2\mathrm{m}$ lake depth then corresponds to the volume mitigated by that measure. Three measures, higher walls, giving room to the river (GRR) and available flood-storage volume in Calverley, mitigate the full flood-excess volume (FEV). Walls (blue area) cover 85.5% of the FEV, GRR (beige) 7% and the basic Calverley storage (brown area) 7.5%. Also shown are extra mitigation due to overcapacity of 0% to 6% in Calverley storage (orange area) and possible beaver dam storage of 0% to 3.7% (yellow area), beyond the basic square lake. For each measure and area, the percentage of the FEV, the costs (in pound Sterling) and relative costs per one percent are displayed below or next to the (double-sided) arrow. Total costs have been added as well. Each area corresponds to an area of the square lake with its $2\mathrm{m}$ depth and, hence, a corresponding volume of FEV mitigated. The overall estimated implementation cost is £$109\mathrm{M}$ (without beaver mitigation).

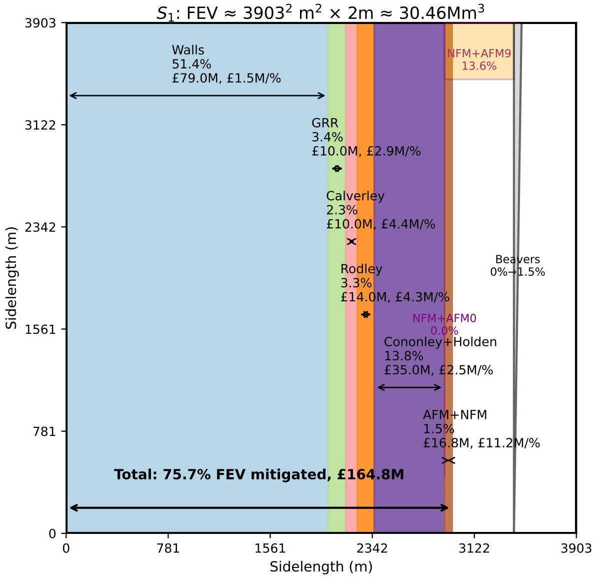

Figure 11. Scenario S_1 with a contribution based on a 1:200$^+$ return period flood event uplifted with 2070–2125 climate allowance. The square side length is 3903m and each coloured band corresponds to a distinct mitigation intervention. The total FEV for S_1 is $3903\mathrm{m} \times 3903\mathrm{m}$ times the $2\mathrm{m}$ lake depth. The estimated implementation cost is £$164.8\mathrm{M}$. Relative costs per 1% mitigation of flood-excess volume (FEV) are annotated above arrows. Four main measures include: walls (blue area at 51.4%), GRR (green area at 3.4%), flood-plain storage Calverley (pink area at 2.3%), flood-plain storage Rodley (orange area at 3.3%) and flood-plain storage further upstream in Cononley and Holden Park (purple area at 13.8%). Beaver-dam storage is added as silver sliver area for extra storage between 0% and 1.5%. Agricultural flood management (AFM) and natural flood management (NFM) measure contain much more uncertainty. AFM and NFM are displayed as 1.5% mean with their two-ensemble overlays of 13.6% of FEV with weight $(1/9)^{\mathrm{th}}$ (9% flow reduction (labeled as the NFM+AFM9 block comprising only $(1/9)^{\mathrm{th}}$ of the lake side) and 0% for weight $(8/9)^{\mathrm{th}}$ (labeled as NFM+AFM0). The remaining white area parts of the square lake concern uncovered or unmitigated FEV.

S_1 **AFM/NFM:**	0% (8/9)	9% (1/9)	1% (mean)
Uplift AFPB 0%	$51\%, 30.46\text{Mm}^3$	$42\%, 26.33\text{Mm}^3$ (86.4%)	$50\%, 30.00\text{Mm}^3$ (98.5%)
Uplift AFPB 1%	$50\%, 30.00\text{Mm}^3$ (98.5%)	$41\%, 25.88\text{Mm}^3$ (85%)	$49\%, 29.53\text{Mm}^3$ (97%)

S_1' **AFM/NFM:**	0% (1/3)	9% (2/3)	3% (mean)
Uplift AFPB 0%	$51\%, 30.46\text{Mm}^3$	$42\%, 26.33\text{Mm}^3$ (86.4%)	$48\%, 29.07\text{Mm}^3$ (95.4%)
Uplift AFPB 1%	$50\%, 30.00\text{Mm}^3$ (98.5%)	$41\%, 25.88\text{Mm}^3$ (85%)	$47\%, 28.61\text{Mm}^3$ (93.9%)

Table 4. S_1 and S_1': Climate-change flow uplift 2070–2125 adjusted by the effects of agricultural flood management (AFM) and natural flood management (NFM) that can reduce discharge and, hence, flood-excess volume (FEV), percentage-wise. Percentages and resulting effective FEVs are shown and between parentheses fraction of full FEV. Between parentheses in the top row displayed is the ensemble weight or the mean.

measures, 24.3% of the FEV remains unmitigated. The AFM and NFM measures are quite expensive, also per percent for the $(1/9), (8/9)$–ensemble. For case S_1' shown in Figure 12, AFM and NFM measures perform much better on average but in both cases there is zero coverage in wet periods. NB. The 51.4% coverage by higher walls is unrelated to the 51% climate-change uplift factor.

For the central uplifted case S_2 with the uplifted FEV of 17.96Mm^3, adding Rodley, Connonley and Holden Park dynamic storage sites beyond the current FAS2 would provide more than 100% full coverage (assuming optimal operations) of the FEV with respective coverages: HW at 12.14Mm^3, GRR at 0.85Mm^3, AFPC at 0.7Mm^3, AFPR at 1.0Mm^3 and AFPU at 4.2Mm^3.

Finally, the 2020 uplifted flood reaches a maximum height of 5.39m, which is above the current protection level of 5.35m, yet its FEV is lower than the 2015 flood. After subtracting the storage volume of 0.7Mm^3 at Calverley, the effective FEV is such that it protects against an effective threshold of $\tilde{h}_T = 4.99\text{m}$, which is lower than the effective threshold of 5.11m implemented under FAS2. Hence, due to the flood-storage sites some floods, including this uplifted one with higher water levels than the design flood level but lower FEV, are still mitigated under the FAS2 flood-mitigation measures.

What one can discern from comparing these square-lake cost-effectiveness charts is the following:

- Higher walls become percentage-wise more effective (recalling that in S_0 the Rodley and Cononley Park storage sites are absent) because the higher base of the hydrograph with the raised h_T affects more (flood-excess) volume.
- Floodplain storage becomes less effective, in part because the flood-water volume before any intervention increases with flood severity, such that there is less available flood-storage volume left.
- Measures that scale relative to flood peaks, such as the measures that scale with area, do scale up with flood severity. This holds for giving room to the river. It also holds for agricultural and natural flood management measures such as tree planting and soil aeration, but for these latter measures the efficacy may be poor or fluctuate wildly due to unknown and varying retention. Justifiably picking a representative ensemble is very important[4]. Historical accounts thus suggest that

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[4] The exclusion of extreme, saturated-soil flood events (such as an uplifted 2015 Boxing Day flood) from baseline ensembles in flood-mitigation investigations may be physically inconsistent with the historical record. In addition to the 2015 Boxing Day flood, also the catastrophic 1866 Leeds' flood —which

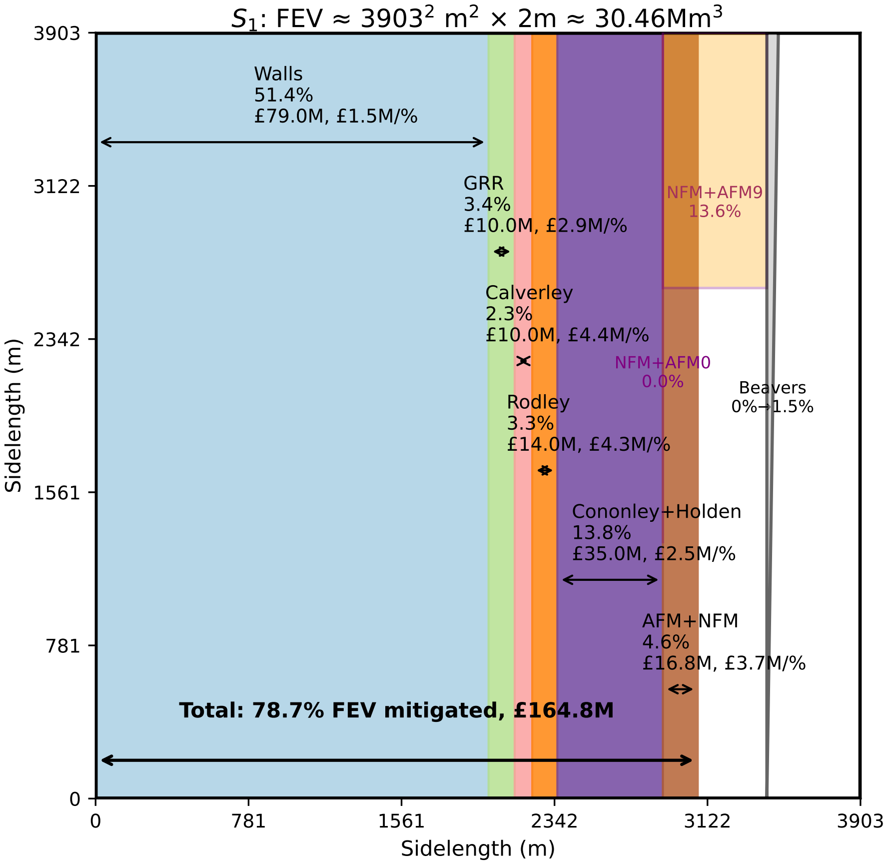

Figure 12. Square-lake cost-effectiveness graph for scenario S_1' with a contribution based on a 1:200$^+$ return period flood event uplifted with 2070–2125 climate allowance. Similar as scenerario S_1 except for the different distribution of AFM and NFM measures. The square side length is 3903m and each coloured band corresponds to a distinct mitigation intervention. The estimated implementation cost is £$164.8\mathrm{M}$. Relative costs per 1% mitigation are annotated above arrows. Beaver-dam storage is added as silver sliver. The white parts are uncovered. AFM and NFM are displayed as mean with their two-ensemble overlays of 13.6% of FEV with weight $(1/3)^{\mathrm{rd}}$ (9% flow reduction) and 0% for weight $(2/3)^{\mathrm{rd}}$.

soil saturation accompanies heightened and extreme (peak) discharge, cf. 2015 conditions (Kirkstall Valley Park, 2024; G Fink-Nottle, 2021). Retention-based flood-mitigation approaches, such as AFM and NFM, are expected to perform poorly under such saturated conditions.

6 Conclusions and discussion

We have investigated the fluvial flood risk in Leeds through a flood-excess volume (FEV) analysis, using the 2015 Boxing Day and 2020 River Aire flood events at the Armley gauge as benchmarks. We further explored the implications of climate change on future flood risk and assessed the cost-efficacy of the Leeds Flood Alleviation Scheme phase 2 (FAS2) using visual and volumetric FEV diagnostics.

Firstly, historical flood analysis using a pre-FAS2 threshold revealed a stark contrast in severity: the 2015 event produced an FEV of (9.33 ± 1.50) Mm^3 over 32 hours, while the shorter-duration 2020 flood produced only (0.32 ± 0.05) Mm^3 over 6.25 hours. Despite similar peak discharges (both exceeding 230m^3/s), flood durations and total flood-excess volumes diverged significantly, affirming that FEV provides a more comprehensive indicator of flood impact than peak flow alone.

Secondly, climate change scenarios were modelled following UKCP18 guidance, applying uplift factors to river height to simulate projected increases in flood severity. 23% central and 51% upper-end uplifts were applied and analysed for 2070–2125. These were implemented through a method of discharge uplifts applied across the hydrograph and nonlinear height uplift using the existing rating curve. While this method does not fully capture site-specific hydraulic complexities or nonlinearities in floodplain response, it offers a tractable approximation for long-term flood risk assessment.

The projected flood-excess volumes (FEVs) under these upper end uplifts rose substantially: by 2070–2125 the flood FEV will increase to approximately 30.46 Mm^3 from its $9.33\mathrm{Mm}^3$ value in 2015, reaching water levels of nearly $7\mathrm{m}$ under a 51% uplift scenario, while the 2020 flood –with an FEV originally estimated at 0.32 Mm^3– by 2070–2125 reaches an FEV of approximately 7.51 Mm^3 with a maximum water level of $5.39\mathrm{m}$, exceeding the baseline water-level severity of $5.22\mathrm{m}$ in the 2015 event. It suggests that climate change could transform lower-return-period events (e.g., 1:75 years) into rare, high-impact floods (e.g., 1:200$^+$ years). Although these projections are subject to uncertainty –both from rating curve errors (estimated as $\pm 5.5\%$) and from applying catchment-scale uplift allowances to a single gauge– the estimates demonstrate flood protections broadly consistent with the aims of the Leeds Flood Alleviation Scheme phase 2 (FAS2) design guidance.

The effects of climate-change uplifts are readily explained in hands-on terms to the public by relating recently experienced flood events to similar future ones affected by climate change. The minor 2020 Armley flood event in Leeds triggered flood evacuation at the Kirkstall climbing gym with ankle-deep, i.e. 10 to 20 centimeter deep, flood waters on the gym floor. Meanwhile, the evacuated CrossFit gym across the road stayed dry. Once this 2020 flood water rushing through the River Aire is uplifted by the 22$^{\mathrm{th}}$ century climate-change factor of one-and-a-half, the crisis situation becomes akin to the Boxing Day flooding crisis of 2015, when water levels reached up to one's hip in these gyms. Luckily, due to the mixture of mitigation

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resulted in 20 fatalities with knee-deep waters on Kirkstall Road as opposed to the 2015 waist-deep waters– was preceded by days of continuous heavy rain (Mayhall, 1878; Chris Nickson, 2016; Yorkshire Post and Leeds Intelligencer, 1866) interventions of FAS2, we are protected in such an early 22nd century uplifted flood event. That is not the case for a one-and-half times uplifted 2015 Boxing Day flood, in the early 22nd century, since even under the current FAS2 protection, it will lead to severe flooding of both gyms and other premises with water levels reaching well above our upwardly stretched hand, as one Crossfit coach put it[5]. The above translation of abstract concepts and water levels into ordinary language is an example of a story-line approach to climate change. It readily emerged from our three-panel FEV analysis. Our story of comparing two pairs of current and future extreme events is not limited to floods but can be applied to other pairings of extreme events, e.g., concerning extreme temperatures in heat waves, devastation by wildfires, and crop failures during droughts.

Lastly, cost-efficacy analysis of FAS2 showed that while the implemented scheme mitigates 100% of the historical 2015 flood and surprisingly also of the uplifted 2020 flood with its maximum water level exceeding the FAS2 protection maximum of $5.35\mathrm{m}$, it is currently unlikely to be sufficient against a future 1:200 year event with upper-end climate change uplift. Square-lake visualisations provided a clear representation of the mitigation capacity of different components, such as raised walls, (additional) floodplain storage, (additional) agricultural and natural flood management and giving-room-to-the-river interventions. We also show that some interventions remain powerful while others weaken under more severe events. On the one hand, while agricultural and natural flood management scale roughly with the area size fraction across a sub-catchment, leading to proportional flow reduction and larger FEV reduction, their retention capacity appears to be quite variable. On the other hand, urban development can lead or has led to reduced retention due to an increase of hard surfaces and faster run-off; it also scales with area size fraction. A question is whether it is necessary to reverse the negative effect of this increase of hard surfaces (e.g., through a massive sustainable and affordable introduction of SuDS and green roofs) and whether that increase can be offset by agricultural or natural management schemes. In particular, by 2100 the current flood defenses being implemented may only protect against 75.7% to 78.7% of the FEV from a flood similar to that of 2015, but uplifted by the upper-end climate change scenario.

In conclusion, we argue that FEV is a powerful and adaptable tool for assessing flood magnitude, mitigation potential, and climate risk. While modelling simplifications (e.g., height uplifts, absence of full hydrodynamic simulations) and rating curve uncertainties must be acknowledged, our findings suggest that the current FAS2 aligns well with present-day design objectives. However, without further adaptation, it may fall short under future climate scenarios earlier than 2069 as intended. Future research should focus on integrating high-resolution hydraulic models, spatially variable climate data, and socio-economic resilience planning to better inform adaptive and cost-effective flood risk strategies in Leeds and comparable urban catchments.

Code and data availability. Codes for and instructions to create most figures are found at https://github.com/obokhove/storylineappCCupfloods and frozen into Zenodo at [zenodo-freezing TBD]. In particular, please note that if improved data become available, given effective data restrictions and scarcity to date (2026), an update of the results via our codes is straightforward, given our open and openly shared methodology.

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[5] Presenting such a story-line approach for the public in this scientific journal constitutes a conflict, since the public generally does not read scientific articles. For public dissemination, we have therefore also created a story on (recent) past and future flooding events for the public. It is found in Appendix B.

Appendix A: Hydrographs in catchments with beaver dams

In the main text, we refer to integrations of hydrographs of in- and outflow across beaver-dam complexes. We have taken some graphs from the respective literature and overlaid boxes to facilitate simplified integration in order to attain available flood-storage volumes, see Figure A1, Figure A2 and Figure A3, discussed in turn next.

Regarding the effects of beaver dams in the River Tamar, UK, the appropriateness of the value of $V_b \approx 1100\mathrm{m}^3$ is, futhermore, straightforward to check from one of Puttock et al.'s hydrographs, adapted in Figure A1, showing a roughly estimated volume of circa $900\mathrm{m}^3$.

The next beaver site considered is located on flat wetlands near Hudson Bay in Northern Ontario, Canada (Woo and Waddington, 1990). This region is extremely flat and numerous beaver ponds have been observed. Approximate integration by drawing in a rectangle of equivalent area to the actual area between the two hydrographs around the peak flow, i.e. by using eyeball measures and subsequent estimates of the rectangle's sides, yields an effective storage volume of

$$V_b = (10/6.33) \times 24 \times 3600 \times 2 \times 10/7\mathrm{m}^3 = 390\mathrm{m}^3$$

behind one dam, cf. Figure A2.

The review article of Larsen et al. (2021) includes two hydrographs around 28-02-2010 with Q_{in} and (part of) Q_{out} from Nyssen et al. (2020), shown and adapted here in Figure A3, concerning a beaver colony along the Chevral River in the Ardennes in Belgium. What is immediately clear is that the storage volume $V_b = 1.782\mathrm{Mm}^3$ is not released later in the Q_{out} hydrograph, so there is water volume missing, either due to evaporation, groundwater flow or floodplain flow around the point of outflow measurement? As independent estimate, one observes that there are six beaver dams over a river stretch of $300\mathrm{m}$. Using Figs. 3 (taken at lower water levels than the peak on 28-02-2010) and 6 of Nyssen et al. (2020), a generous estimate yields a water-covered area of $A_s = 300 \times 50\mathrm{m}^2 = 15000\mathrm{m}^2$ and by taking a generous pond-height difference $\Delta h = 2\mathrm{m}$, a volume estimate of $V_B = A_s \Delta h = 30000\mathrm{m}^3$ results, far off the difference between the two hydrographs. To be clear, the authors indicate "extrapolations beyond range of observation".

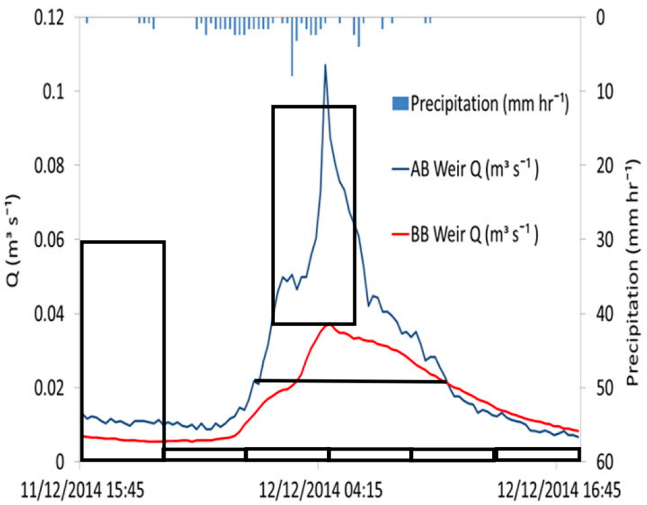

Figure A1. Hydrographs at weirs upstream (AB, blue line) and downstream (BB, red line) of a beaver colony for a flood peak in a tributary of the River Tamar, in Devon, UK. Taken and adapted Fig. 3 (bottom-left) from Puttock et al. (2017) with the approximate (eye-ball) integration technique displayed. The rectangular box drawn in is roughly equivalent to the desired area of integration between the two hydrographs of the flood peak. Measurements of that rectangle ($0.06\mathrm{m}^3/s$ over $23/6$hr) along the respective axes indicate that it concerns rectangle sides of $\sim 0.06 \times (25/6) \times 60 \times 60\mathrm{m}^3 = 900\mathrm{m}^3$. Note that more precision is not required for obtaining an estimate.

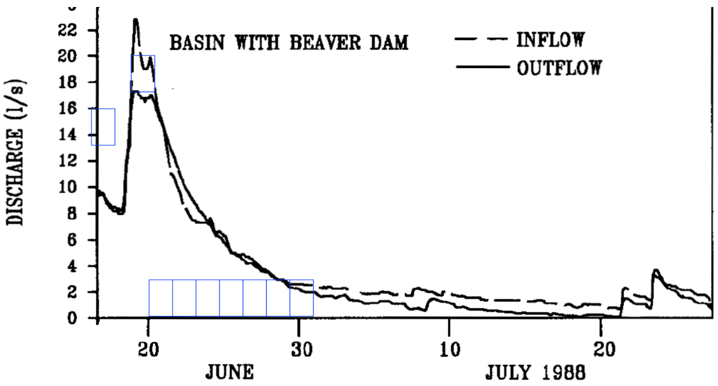

Figure A2. Taken and adapted Fig. 8 from Woo and Waddington (1990) with integration techniques displayed. The rectangular box drawn in is roughly equivalent to the desired area of integration between the two hydrographs of the flood peak. Measurements of that rectangle along the respective axes indicate that it concerns rectangle sides of $\sim (10/6.33)$days and $\sim 2 \times (10/7)$l/s yielding $V_b = 390\mathrm{m}^3$. Again note that more precision is not required for obtaining an estimate.

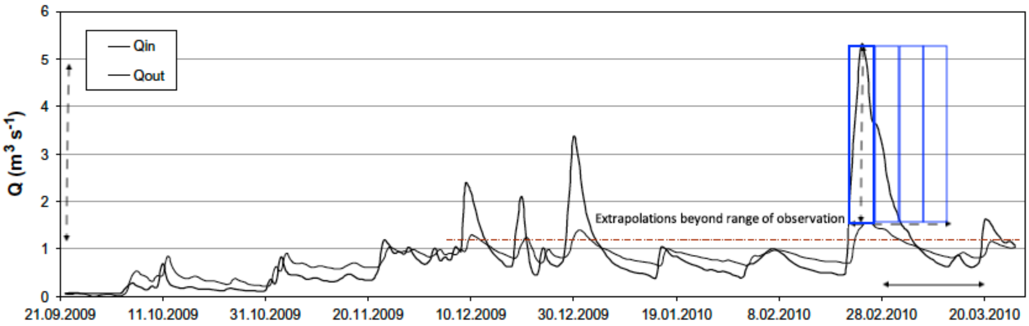

Figure A3. Taken and adapted Fig. 12 from Nyssen et al. (2020) with integration techniques displayed. The rectangular box drawn in is roughly equivalent to the desired area of integration between the two hydrographs of the flood peak. Measurements of that rectangle along the respective axes indicate that it concerns rectangle sides of $\sim (20/4) \times 24 \times 3600\text{hr}$ and $\sim 4\text{m}^3/\text{s}$ yielding $V_b = 1.728\text{Mm}^3$.

Appendix B: One and a Quarter or One and a Half and the Number on the Bridge

"Are you okay, Onno?" Six thirty in the evening, Boxing Day, 2015. The river had been climbing for days. Two weeks earlier, on the 12th of December, Onno had sent Rawlo down to the footbridge over the River Aire near the gym to eyeball the river level. Rawlo came back with a report at a quarter to eight: “Roughly 0.5 metre”. From the bridge Rawlo had seen that the water still had about half a metre to go before it would reach street level. His CrossFit gym was safe, for the time being. Given the time on the clock that evening, Onno related Rawlo’s remark to a level of 3.65 metres on the Armley gauge in Kirkstall, a measuring station in Leeds a short walk from the Kirkstall industrial estate.

Rawlo could also have thrown Pooh sticks in the river from the bridge, Onno thought. By timing how fast each stick would get across the bridge or to the next one, he could get a measure of the speed of the dirty river water. Dirty it was at these high river levels. Polluted by multiple sewage overflows. Poo sticks being a more apt name.

The morning of the 9th of February 2020, Onno was in bed with bronchitis, laptop balanced on his knees, a half-edited scientific paper open on the screen. Outside, somewhere over the Pennines, Storm Ciara was loading the hillsides with rain.

He typed a message into Facebook at eleven in the morning, addressed to the membership page of Shirefit, the new gym where he trained on better days. “I don’t see how to make a new post so I place it here.” It was not quite the opening of a thriller. But it was the start of something. Max, the head coach at Shirefit, picked it up within minutes. “Hi Onno, how have you been? We’ve not seen you in a while. Shirefit is empty without you, mate.” “Bronchitis” Onno typed back (in hindsight it was Covid). “So, lying low. Nothing I can do but sit still. To my dismay.”

His dismay was genuine. What Onno knew—what he carried in his head the way other people carry shopping lists or song lyrics—were numbers or levels. Specifically, one level above all others: 3.9 metres. That was the height of the River Aire at the Armley gauge, at which point the river was likely to begin entering the ground floor of CrossFit The Forge, the gym owned by a man everyone called Rawlo. Onno had arrived at this conservative threshold level of 3.9 metres on the Armley river gauge the old-fashioned way: by standing in the hip-deep floodwaters of the 2015 Boxing Day floods in Leeds, UK.

December 12th, 2015. Half a metre, Rawlo had said. Onno filed that away. On the 26th of December 2015, the gauge reached 4.16 metres by noon. A member called JW went to the gym late that morning but couldn't get in—no key. She sent a photograph: the street outside beginning to glitter with water pushing up through the drains. By three in the afternoon, when Onno and a group of members finally got inside, the gauge was at roughly 4.4 metres, he saw via his iPhone. They grabbed rowing machines, kettlebells, barbells—anything they could lift—and hauled it all to higher ground within the building. The wooden plyo boxes flooded. The rubber matting needed a deep clean. Ten rowing machines alone were worth thousands of pounds. In the end, Rawlo reckoned they'd saved twenty thousand pounds of equipment.

Then they had to leave. The river kept rising. Onno called quits. Rawlo took the group photo. Kirkstall Road, running north of the gym, had become a river in its own right. The water was hip-deep and the colour of murky brown tea. You could not see the kerbs, the dropped sections of pavement, the potholes. Onno had his bicycle around his shoulder—he wasn't leaving it—and a rucksack, and his cycling helmet with a light on the front. He was the only one with a serious light. They went in a line. Onno was last, burdened by the bike, feeling the current push and press at his thighs. From somewhere ahead, Rawlo's voice came back through the dark brown murk: "Are you okay, Onno?" Onno took a breath. He pitched his voice low, steady, authoritative—the voice of a man with no concerns whatsoever. "Yes" he called. "I am fine."

He was lying. He was frightened in a way that was difficult to articulate afterwards: the particular fear of not being able to see your own feet, of not knowing whether the next step was solid ground or a drop into something deeper, all while carrying a bicycle around your shoulder in moving water. But he kept walking, and eventually the water shallowed, and they were through. Dry grounds. The team of seven gym rescuers dispersed quickly into the night: "Bye, well done".

In the week after the flood, while other members pitched in to clean the gym, Onno was conspicuously absent. He was at home, writing a flood-evacuation plan. He felt guilty about this. He told himself he was making himself useful in a different way, and this was true, but the guilt was also true. He wrote the plan anyway. He also told himself, writing it, that such a plan would likely never be needed again in his lifetime. These were hundred-year floods, perhaps two-hundred-year floods. The statistics of rare events suggested the river had, in some loose probabilistic sense, spent its violence for a generation. He believed this with the conviction of a man who understood the numbers and trusted them. He was somewhat wrong within four years.

Back on the 9$^{\mathrm{th}}$ of February 2020. Onno, propped up in bed with his bronchitis and his laptop, watching the gauge at Armley tick upward on the government's flood-monitoring website. 3.22 metres when he first messaged, just after eleven. 3.42 metres by the time he checked again. Rising at roughly a third of a metre per hour.

He typed to Max: "No need for action till 3.9 metre." And then, to Rawlo, whom Max had now reached via coaches at the Forge: "River level at Armley is 3.42 metre. Recall that mid-December 2015 when you looked at it in the evening, the level was 3.65 metre, and that JW took a picture on 26-12 around noon when it was 4.16 metre—then the gutters on the street in front of CrossFit started to overflow. Keep an eye on the Armley gauge." He attached a link. He asked Rawlo to confirm receipt. He mentioned, almost in passing, that the scientific paper he and his colleagues had written about the 2015 flood was currently in revision—that he was, literally, editing the proofs that morning from his sickbed, the numbers on the page the same as the numbers on the screen.

He did not mention that he had recently been warned he might face serious professional consequences if he didn't moderate the tone of his public statements about flood protection. He mentioned it to Max instead, with a laugh embedded in the syntax: "I need some CrossFit to shake off such comments! Ha, ha."

The gauge kept climbing. By half-past three in the afternoon, it was reading 3.88 metres. Onno typed: "This is alarm level." At the gym, Rawlo's team were already moving. They'd been lifting things onto boxes, shifting equipment upstairs, working through the evacuation plan that Onno had written four years earlier and that, until now, everyone had quietly assumed would never be seriously tested. They did it in under ninety minutes, with the help of members who simply showed up. The gauge peaked at 4.13 metres, just after five o'clock.

Across the road, a climbing studio took some flood water in. The floor of CrossFit The Forge, in Unit 8, stayed dry—but only just. The difference in ground level between the two units was about twenty centimetres. Eight inches. The height of a paperback novel. "It could easily have been another ten to twenty centimetres," Rawlo messaged Onno the following Tuesday, "which would have made a huge difference to us, especially if we hadn't acted." And then, with the particular tone of someone who has been through something and come out the other side and is already half-thinking about next time: "Good practice for next time!!!"

During Storm Franklin, in 2022, an old railway bridge was blown away in a collision with a pontoon, whose mooring lines had snapped. Flood protection works had been well underway, but faced delays after floating construction material was swept away. The nearby footbridge survived. In that year, the chief medical officer of England, well known at this end of the Covid pandemic, had declared sewage in water a growing health problem.

In 2024, after garbage removal of a polluted beck or small stream at the edge of Leeds, Onno developed a fungal skin problem due to the infection of a minor scrape on his leg. The water in the beck smelled foul and had a gray wastewater color. A sewage overflow pipe was seen oozing into it. The treated fungus developed over time into eczema, according to the dermatologist.

2026: Now here is where the story changes register—where the personal account and the scientific paper converge, and where numbers that live in a footnote of an academic journal become something you can feel in your legs. In their research of 2024-2026, Natasha and Onno examined what climate change does to floods like these. Not in vague terms—not “floods will get worse”—but quantitatively, using something called flood-excess volume: the specific volume of extra water, well beyond the river’s normal capacity, that actually causes the damage. Mitigate that volume, and you mitigate the flood damage. Their results, looking ahead to 2100, may be stark.

The 2015 Boxing Day flood—already severe enough to fill Kirkstall Road to hip height—becomes, under a projected climate-change factor of roughly *one and a quarter or one and a half*, a catastrophe that exceeds the capacity of Leeds’ current flood defences. (A factor of 1.23 or 1.51, to be precise. We do not know which factor will materialise yet.) Water levels reaching well above an upwardly outstretched hand, as one of the CrossFit coaches put it when Onno explained it to him. Not hip-deep. Above our heads or even above our raised arms.

And the 2020 flood—the one that soaked the floor of the climbing studio by twenty centimetres while the CrossFit gym stayed dry by a small margin—becomes, uplifted by that same worst-case factor of one and a half, something resembling the 2015 Boxing Day event itself. Ankle-deep water becomes hip-deep water. A minor disruption becomes a crisis. A gym that closed for eleven hours becomes one closed for eleven weeks. This is what climate-change uplift means, in a place where people actually live and work and train and get their kit off the floor before the river comes through the door. It is not a model. It is not a percentage. It is Rawlo’s voice coming across the floodwaters: “Are you okay, Onno?” And the answer, the next time, might genuinely be: “No.”

Onno still knows those faded critical levels by heart: 3.9 metres for concern, 4.0 for serious worry, 4.4 and above for what happened on Boxing Day 2015. He knows them the way you know a threshold you’ve crossed in the dark and hoped never to cross again. They are no longer valid since the city of Leeds put in mitigation measures such that the critical threshold on the Armley gauge has become 5.35 metres. The plan he wrote in the weeks after 2015, the one he felt guilty about writing while others cleaned the matting, was used in 2020. Its faded numbers—3.9, 4.0 and 4.4 metres—are no longer valid.

But Onno wasn’t wrong. There will be a next time. The only question—and this is the question the numbers in the scientific paper are trying to answer—is how will we deal with the flood waters when they come. “Good practice for next time,” Rawlo had written. In 2100, far beyond the 5.35 metre level of current protection, climate change predicts extreme flood levels of six to nearly seven metres on the river gauge—7.00 metres. Descendants from 2100, if they could, would like to ask: “Will we be okay? Yes or no?” Who knows. Presently, the answer is: “1.23 or 1.51. One and a quarter or one and a half.”[a]

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[a] OB fed notes from the 2015 and 2020 flood evacuations (see https://bardvantwenthe.wordpress.com/2020/02/29/kirkstall-flood-evacuation-during-storm-ciara/) and the conclusion into the AI-program Claude, and requested a first draft. Hereafter, errors were removed, numerous edits, rearrangements and additions made, resulting in the story. See also: “The House of Pooh Corner” (Milne, 1928), “Sewage in water: a growing public health problem” (Whitty et al., 2022) and the bridge collapse recorded at: https://www.youtube.com/watch?v=yWWFGjHKrm0 (accessed 31-03-2026).

Author contributions. The presented work is adapted and abbreviated from NP’s 2025 Bachelor thesis at the School of Mathematics in Leeds (Pickard, 2025). NP developed the work on climate-change uplift factors, by extending and using provided software on FEV and cost-efficacy analyses, which had been developed by OB and co-workers since 2018. The three-panel graphs and cost-effectiveness quantifications were reworked and expanded by both authors. The text and codes were jointly edited. OB realized and brought in the story-line dimension to the work. (There is no conflict of interest and the work presented does not require an ethics statement.)

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