Using flood-excess volume to assess and communicate flood-mitigation schemes

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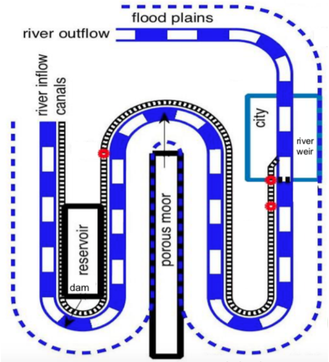
Motivation: Wetropolis

- interactive model of extreme rainfall and river flooding in an urban environment
- conceptualises many important aspects of the science of flooding and extreme events in a way that is accessible to and directly engages the public



- provides scientific testing environment for flood modelling, control and mitigation, and data assimilation. It has inspired numerous discussions with flood practitioners and policy makers . . . `https://github.com/obokhove/wetropolis20162020`

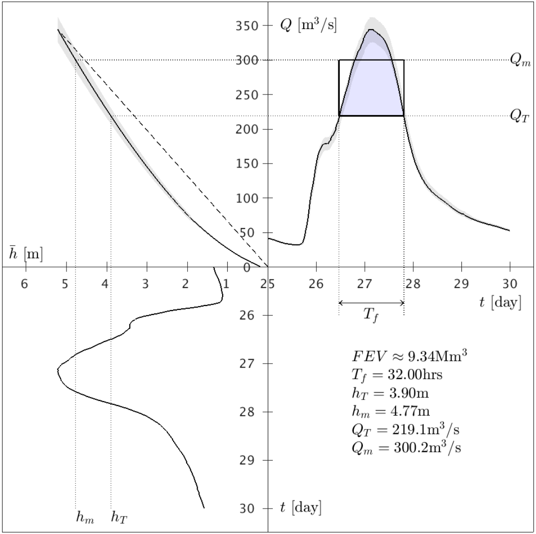
FEV revisited: River Aire data analysis, UK

Figure: Armley gauge data around the Boxing Day 2015 floods. Bottom left: water level time series (*raw data*); top left: rating curve (stage–discharge relationship); top right: resulting discharge time series.

Flood-excess volume (FEV):

$$V_e \approx \sum_{k=1}^{N_m} \left(Q(\bar{h}_k) - Q_T\right) \Delta t$$

... is the volume of flood water one wishes to mitigate (i.e., reduce to zero) by the cumulative effect of various flood-mitigation measures.



FEV: square lake representation

GOAL: to quantify and communicate the efficacy of various flood–mitigation measures in a straightforward, readily digestible and concise manner.

IDEA: to calculate the FEV for a flood event of interest and express it as the capacity of a 2m-deep square 'flood-excess lake' with side-lengths $\mathcal{O}(1\text{km})$.

OUTCOME: a graphical tool that both (i) contextualises the magnitude of the flood relative to the river and its valley/catchment and (ii) facilitates quick and direct assessment of the contribution and value of various mitigation measures.

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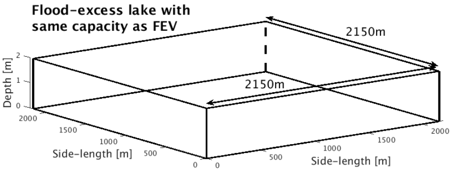
For the River Aire case, the FEV is represented as a 2m-deep 'flood-excess lake' of side-length 2.15km

$V_e \approx 9.34\text{Mm}^3 \approx (2150^2 \times 2)\text{m}^3$.



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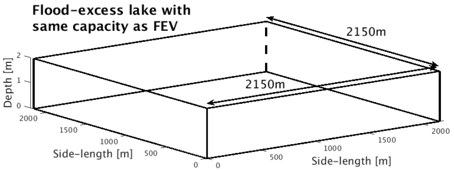
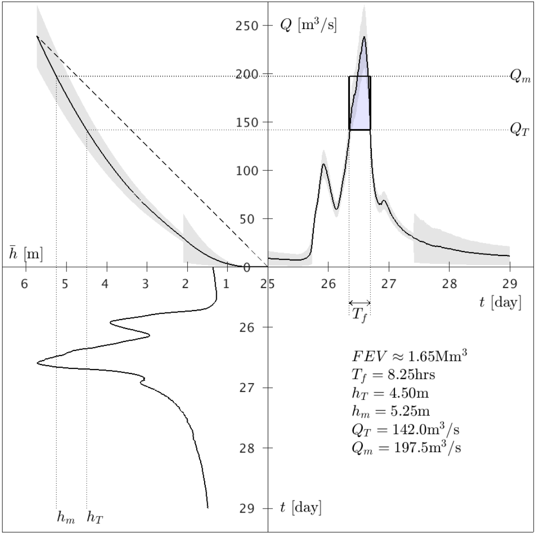


Given the size of the lake as well as the geography of the river valley concerned, one can make an estimate of both the contribution and effectiveness of flood-plain enhancement for not only flood storage but also other flood-mitigation measures.

FEV: River Calder data analysis, UK

Figure: River Calder gauge data around the Boxing day floods. Bottom left: water stage time series. Top left: rating curve (stage–discharge relationship). Top right: resulting discharge time series.

Q: what fraction of the FEV is reduced, and at what cost, by particular flood-mitigation measures, i.e. a societally valuable and practical question?

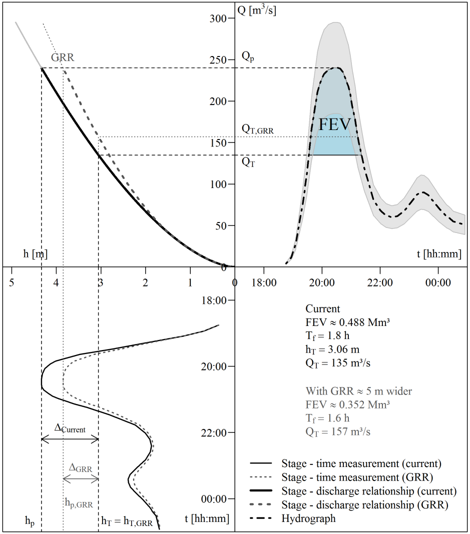


FEV: River Brague data analysis, France

Introducing **'giving room to the river'** (GRR) bed widening: increasing the river width in order to increase the discharge capacity for a similar water depth.

Figure: River Brague *reconstructed* flow data around the 2015 flash floods. Bottom left: water stage time series. Top left: rating curve. Top right: resulting discharge time series and FEV. New –GRR– rating curve reduces FEV for same h_T.

Q: what fraction of the FEV is reduced, and at what cost, by particular flood-mitigation measures?

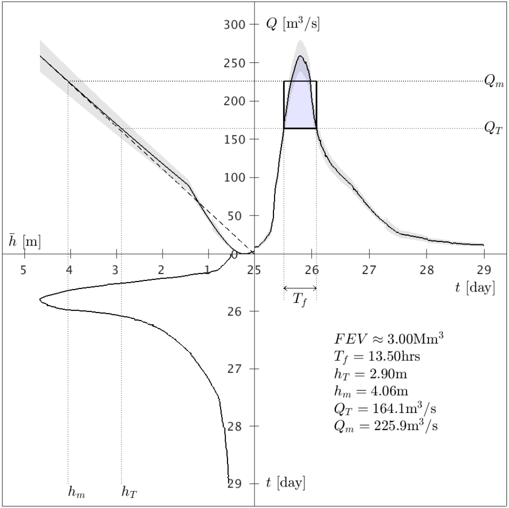


FEV: River Don data analysis, UK

Motivated by the Boxing Day 2015 floods: *flood-excess volume (FEV)* is defined as the volume of flood water one wishes to mitigate (i.e., reduce to zero) by the cumulative effect of various flood-mitigation measures.

Right: River Don gauge data of June 2007 floods (3 fatalities). Bottom left: water stage time series. Top left: rating curve (stage–discharge relationship). Top right: resulting discharge time series.

Q: what fraction of the FEV is reduced, and at what cost, by particular flood-mitigation measures?



FEV: beaver dams as flood mitigation extreme floods?

- Statement on BBC website: "Beavers should be re-introduced to England to improve water supplies, prevent floods and tackle soil loss, a researcher says".
- **"Prevent floods" by beaver dams: realistic, or not?**
- Summary of FEV 6 floods; mean $V_e = 3.35\text{Mm}^3 = 1294 \times 1294 \times 2\text{m}^3$; square-lake side length of 1294m:

River	flood date(s)	V_e	h_T	V_e/V_b	$0.5V_e/V_b$	$0.1V_e/V_b$
-	-	Mm^3	m	-	-	-
Aire	26-12-2015	9.34 ± 0.51	3.9	8490	4246	849
Calder	26-12-2015	1.65 ± 0.22	4.5	1500	750	150
Don	25/26-06-2007	3.00 ± 0.24	2.9	2727	1363	272
Brague	03-10-2015	0.488 ± 0.311	3.06	443	222	44
Tamar	23-12-2012	1.96 ± 0.20	2.95	1780	890	178
Tamar	24-12-2013	3.65 ± 0.36	2.95	3317	1658	321

Table : 6 FEVs V_e are given for threshold levels h_T indicated. Extra storage volume obtained behind 13 beaver dams of 1 beaver colony in Devon, on Tamar tributary, $V_b \approx 1100\text{m}^3$ spanning $\sim 200\text{m}$.

- Given that 10s to 1000s of beaver colonies are required to mitigate 1% to 100%: flood prevention (very) unrealistic. Moreover: Reservoir Act UK, dam failure etc.

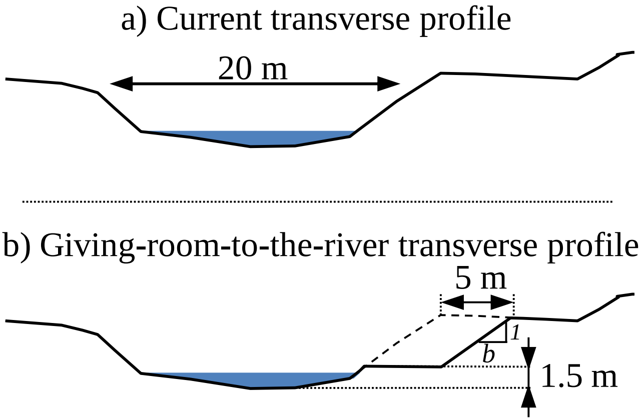
Flood mitigation: cost-effectiveness analysis & scenarios

Cost-effectiveness analysis based on square-lake representation of FEV for our hypothetical flood of River "BragueAireDonTamar" in 2015 with $V_e = 3.35\text{Mm}^3$. Flood-mitigation measures (upstream of) city of Feville aka "Mythgunnileedshef"; two scenarios S1 & S2:

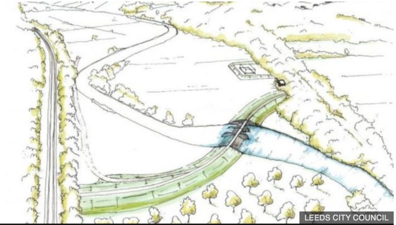
- HW – higher flood defence walls
  S1: 100% wall height 2m or S2: 50% wall height 1m at $£0.7\text{M}/\%$
- GRR – giving-room-2-the-river
  S1: 0% or S2: 25% at $£0.5\text{M}/\%$
- FPS – enhanced flood plain storage using dynamic weir with optimal control
  S1: 0% or S2: $(50 \pm 25)\%$ at $£1\text{M}/\%$
- NFM – 1300 leaky dams (including 50yrs maintenance costs)
  S1: 0% or S2: $(6 \pm 4)\%$ at $£1\text{M}/\%$ (half costs)
- 27 beaver colonies in parallel
  S1: 0% or S2: $(1 \pm 1)\%$ at $£1\text{M}/\%$ (half costs)
- Mean extra climate-change adaptation (FPS, NFM, beavers)
  S1: 0% or S2: $(19.5 \pm 17.5)\%$.
- Recall climate-change uptake often taken as 20%!

Higher flood defence walls – HW:

Giving-room-to-the-river – GRR:



Flood-plain storage – FPS & dynamic weir control:



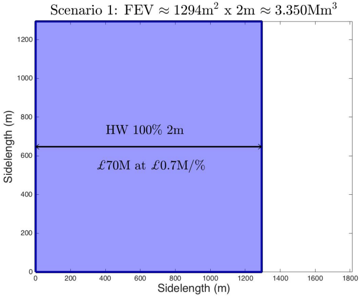
A sketch of possible flood storage control area in Calverley including moveable weir

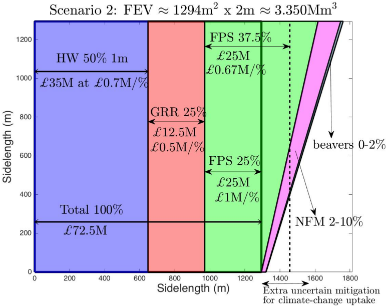
Natural flood management – NFM leaky dams (public engagement & co-benefits):

Central part of one of the two experimental timber bunds in the River Seven catchment

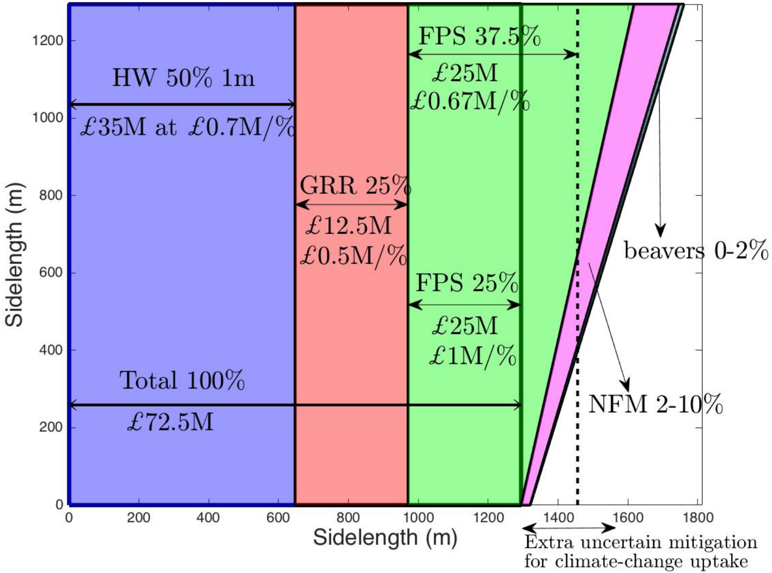
Flood mitigation: cost-effectiveness analysis & scenarios

- Cost-effectiveness analysis based on square-lake representation of FEV for exploratory flood of River "BragueAireDonTamar" in 2015 with $V_e = 3.35\text{m}^3$.
- Full cost-effectiveness analysis of two flood-mitigation scenarios summarised graphically — for policy makers!





Scenario 2: FEV $\approx$ 1294m^2 x 2m $\approx$ 3.350Mm^3



Conclusions

Details are in some sense of secondary importance here: the **take-home message** is that FEV analysis offers not only (i) a complementary way of classifying flood events but also (ii) a protocol to optimise the assessment, in a comprehensible and readily digestible way, of mitigation schemes.

Further comments:

- Exploratory cost-effectiveness analysis is based on actual mitigation plans for River Aire (Leeds' City Council) and Rivers Calder/Brague (EAs UK/France).
- Our analysis does not replace the need to perform detailed hydrodynamic modelling and should be used either prior to or in tandem with the modelling. It can, however, as alternative replace such calculations in cases where insufficient computational/detailed river data are available or form a preliminary step for screening possible strategies.
- FEV enables one to quantify the contribution of NBS/NFM measures – *this is rarely done in policy/literature* – and highlights the issue of NFM scalability.
- The square-lake representation encourages evidence-based decision-making for assessing flood-mitigation schemes.

Note: more case studies available (Rivers Aire, Calder, Don in Yorkshire, Tamar in Devon/Cornwall, Brague in France).

Thanks very much for your attention ...

References:

1 Bokhove, O., Kent, T., Zweers, W. (2017): **'Wetropolis flood demonstrator.**
Paper & design available at: `https://github.com/obokhove/wetropolis20162020`

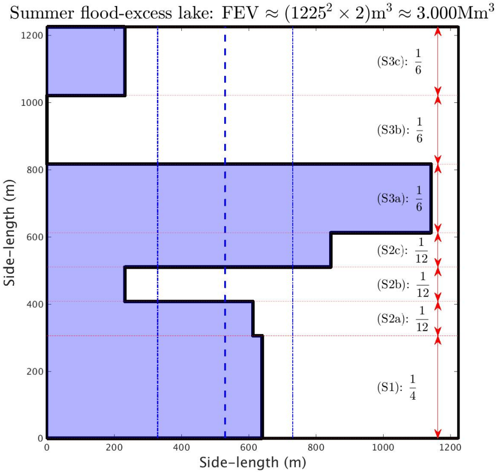
2 O. Bokhove, M. Kelmanson, T. Kent (2018a): **On using flood-excess volume in flood mitigation, exemplified for the River Aire Boxing Day Flood of 2015.**
`https://eartharxiv.org/stc7r/`

3 O. Bokhove, M. Kelmanson, T. Kent, G. Piton, J.-M. Tacnet (2018b): **Communicating nature-based solutions using flood-excess volume for three UK and French river floods.** Preliminary version on: `https://eartharxiv.org/87z6w/`

4 O. Bokhove, M. Kelmanson, T. Kent (2018c): **Using flood-excess volume in flood mitigation to show that upscaling beaver dams for protection against extreme floods proves unrealistic.** `https://eartharxiv.org/w9evx/`

Rainfall scenarios: River Don

Graphical overview of the fraction of the FEV captured by various measures in the Don catchment for seven summer-rainfall scenarios. Stacked vertically are the respective probability distributions, relative to the associated FEV, which is fixed for all scenarios. The blue shaded areas to the left of the thick, stepped, solid line denote the fractions of the FEV mitigated per scenario, to be read horizontally (*e.g.*, 93.3% for (S3a)). The mean FEV (43.25%) over all 7 scenarios and standard deviation (16.38%) are indicated by thick and thin vertical dashed lines respectively.



Rainfall scenarios: River Don

The ‘FEV–scenarios’ framework is simple yet elegant: information covering a range of rainfall scenarios, mitigation measures, and geographical areas of a river catchment is encapsulated in a single graphic. Moreover, it is highly flexible and can incorporate any number of scenarios, rainfall distributions, and locations.

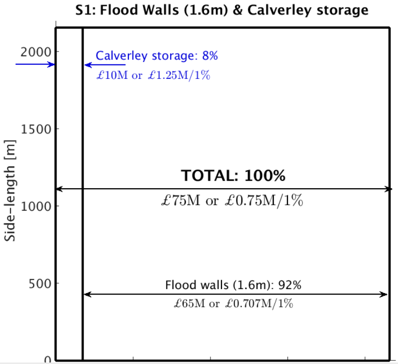
	Rainfall fraction			Probability	
Scenario	Reservoir	Sheaf	Upper Don	Winter	Summer
S1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{4}$
S2(a)	$\frac{1}{2}$	$\frac{1}{2}$	0	$\frac{1}{8}$	$\frac{1}{12}$
S2(b)	0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{8}$	$\frac{1}{12}$
S2(c)	$\frac{1}{2}$	0	$\frac{1}{2}$	0	$\frac{1}{12}$
S3(a)	1	0	0	$\frac{1}{12}$	$\frac{1}{6}$
S3(b)	0	1	0	$\frac{1}{12}$	$\frac{1}{6}$
S3(c)	0	0	1	$\frac{1}{12}$	$\frac{1}{6}$

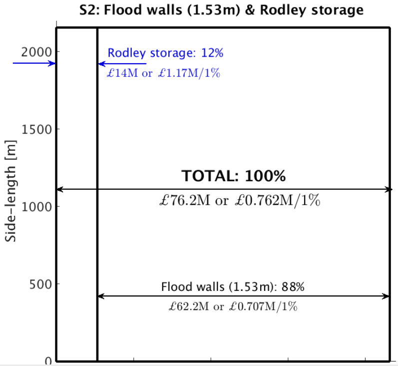
Table : Summary of 7 precipitation scenarios, with rainfall fraction for the three locations, and seasonal probabilities.

Leeds FASII+

Q: what fraction of the FEV is reduced, and at what cost, by a suite of mitigation measures?

Given a calculation (or estimate) of potential flood storage volume and associated cost of each mitigation measure, the ‘flood-excess lake’ can be partitioned accordingly and overlaid with a cost per 1% of FEV mitigated. E.g., two scenarios from the Leeds Flood Alleviation Scheme Two (FASII):

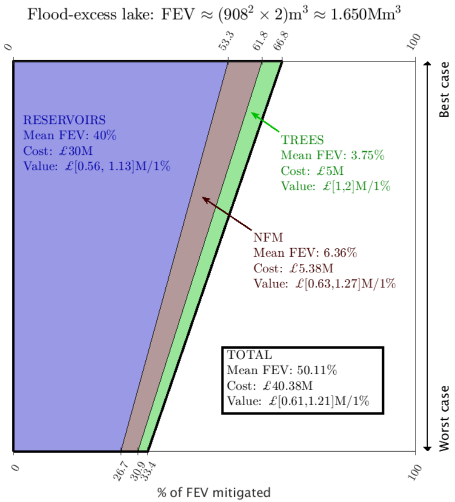




NBS assessment: River Calder

Exploratory flood-alleviation scheme comprising (i) temporary storage in reservoirs, (ii) upscaled ‘leaky’ debris dams, and (iii) tree planting.

- takes into account uncertainty in storage capacity;
- draw-down and control of reservoirs has great potential;
- major upscaling of leaky dams can have a reasonable and cost-effective impact;
- mean FEV mitigated is 50%: more measures (e.g., flood walls) required to offer full protection.



FEV assessment: River Brague

Exploratory flood-alleviation scheme comprising (i) storage in reservoirs (retention), (ii) flood walls, and (iii) GRR.

- $V_e = 0.488 \text{ Mm}^3$ is represented by a 2m-deep square lake of side 494m
- lighter colour = better value
- nearly 2/3 of the 18.4M€ scheme is related to the retention measures even though they manage only 25% of the problem
- most cost-effective measure is GRR