Public empowerment in flood mitigation

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Scenario 2: FEV ≈ 1294²m² x 2m ≈ 3.350Mm³

- HW 50% 1m: £35M at £0.7M/%
- GRR 25%: £12.5M / £0.5M/%
- FPS 37.5%: £12.5M / £0.67M/%
- FPS 25%: £25M / £1M/%
- NF M 2-10%: £72.5M

Extra uncertain mitigation for climate-change uptake
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, mitigation & data assimilation. It has inspired numerous discussions with flood practitioners & 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):**

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

... 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 $2.15\text{km}$

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

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: square-lake cost-effectiveness analysis

Stage-discharge relationship: $Q_{\text{max, flood}}$ vs. $h_{\text{max, flood}}$

Discharge time series: $Q_t$ vs. Time

FEV: 2 m-deep conceptual square-lake of volume FEV

2 m-deep conceptual square-lake

$T_f$: Excess flood duration

Protection measures 1-4: FEV part VS Costs

Cumulated and elementary cost-effectiveness
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?
- Mean FEV of 6 floods; $V_e = 3.35\text{Mm}^3 = 1294 \times 1294 \times 2\text{m}^3$.
- Extra storage volume obtained of 1 beaver colony in Devon, $V_b \approx 1100\text{m}^3$.
- Given that 10s to 1000s of beaver colonies are required to mitigate 1% to 100%: flood prevention (very) unrealistic.
- For Finchingfield $V_e = 53000\text{m}^3 = 163 \times 163 \times 2\text{m}^3$ so 1 beaver colony contributes $V_b/V_e < 0.021$ i.e. < 2.1% to flood-mitigation scheme.

<table>
<thead>
<tr>
<th>River</th>
<th>flood date(s)</th>
<th>FEV $V_e$ Mm$^3$</th>
<th>$h_T$ m</th>
<th>$V_e/V_b$ -</th>
<th>0.5$V_e/V_b$ -</th>
<th>0.1$V_e/V_b$ -</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aire</td>
<td>26-12-2015</td>
<td>9.34 ± 1.50</td>
<td>3.9</td>
<td>8490</td>
<td>4246</td>
<td>849</td>
</tr>
<tr>
<td>Calder</td>
<td>26-12-2015</td>
<td>1.65 ± 0.60</td>
<td>4.5</td>
<td>1500</td>
<td>750</td>
<td>150</td>
</tr>
<tr>
<td>Don</td>
<td>25/26-06-2007</td>
<td>3.00 ± 0.71</td>
<td>2.9</td>
<td>2727</td>
<td>1363</td>
<td>272</td>
</tr>
<tr>
<td>Brague</td>
<td>03-10-2015</td>
<td>0.488 ± 0.311</td>
<td>3.06</td>
<td>443</td>
<td>222</td>
<td>44</td>
</tr>
<tr>
<td>Tamar</td>
<td>23-12-2012</td>
<td>1.96</td>
<td>2.95</td>
<td>1780</td>
<td>890</td>
<td>178</td>
</tr>
<tr>
<td>Tamar</td>
<td>24-12-2013</td>
<td>3.65</td>
<td>2.95</td>
<td>3317</td>
<td>1658</td>
<td>321</td>
</tr>
</tbody>
</table>

Table: 6 FEVs, thresholds $h_T$, beaver colonies needed for (partial) mitigation.
Flood mitigation: cost-effectiveness analysis & scenarios

Higher flood defence walls – HW:
Giving-room-to-the-river – GRR:

a) Current transverse profile

b) Giving-room-to-the-river transverse profile
Flood-plain storage – FPS & dynamic weir control:
Natural flood management – NFM 1300 leaky dams (public engagement & co-benefits) plus 30 beaver colonies:
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 $V_e = 3.35Mm^3$.
- At city of “Feville” with two flood-mitigation scenarios summarised graphically — for policy makers in square-lake format!
Scenario 2: FEV $\approx 1294^2 m^2 \times 2m \approx 3.350 Mm^3$

- HW 50% 1m
  - £35M at £0.7M/%
- GRR 25%
  - £12.5M
  - £0.5M/%
- FPS 25%
  - £25M
  - £0.67M/%
- Extra uncertain mitigation for climate-change uptake
- NF M 2-10%

beavers 0-2%
Conclusions

The **take-home message** is that our FEV cost-effectiveness analysis offers:

(i) a complementary way of classifying flood events but also
(ii) a protocol/sanity check to assess, in a comprehensible and readily digestible way, flood-mitigation schemes,

thus **empowering decision-makers and the public.**

Further comments:

- Exploratory cost-effectiveness analysis has been used as sanity check of actual mitigation plans e.g., River Aire (Leeds’ City Council) & Rivers Calder/Brague (EAs UK/France).
- 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.
- **DIY:** make your own hydrograph using a large ruler, oranges, a stopwatch & record-keeping!
- **DIY-tool** of our work in progress – as Excel spreadsheet.
Thanks very much for your attention ...

References:

   Paper & design available at: https://github.com/obokhove/wetropolis20162020


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 £0.7M/%

- **GRR** – giving-room-2-the-river
  - $S1$: 0% or $S2$: 25% at £0.5M/%

- **FPS** – enhanced flood plain storage using dynamic weir with optimal control
  - $S1$: 0% or $S2$: $(37.5 \pm 12.5)\%$ at £1M/%

- **NFM** – 1300 leaky dams (including 50yrs maintenance costs)
  - $S1$: 0% or $S2$: $(6 \pm 4)\%$ at £1M/% (half costs)

- **30 beaver colonies** in parallel (at $\sim 1100\text{m}^3$ each)
  - $S1$: 0% or $S2$: $(1 \pm 1)\%$ at £1M/% (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%!
FEV: River Don data analysis, UK

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


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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Rainfall fraction</th>
<th>Probability</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Reservoir</td>
<td>Sheaf</td>
</tr>
<tr>
<td>S1</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td>S2(a)</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td>S2(b)</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
</tr>
<tr>
<td>S2(c)</td>
<td>$\frac{1}{2}$</td>
<td>0</td>
</tr>
<tr>
<td>S3(a)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>S3(b)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>S3(c)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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

Public empowerment in flood mitigation
Q: what fraction of FEV is reduced & at what cost, by 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):
**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?

\[
\begin{align*}
FEV & \approx 1.65\text{Mm}^3 \\
T_f & = 8.25 \text{hrs} \\
h_T & = 4.50\text{m} \\
h_m & = 5.25\text{m} \\
Q_T & = 142.0\text{m}^3/\text{s} \\
Q_m & = 197.5\text{m}^3/\text{s}
\end{align*}
\]
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 data analysis, France

Introducing ‘giving room to the river’ (GRR) bed widening: increasing river width 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 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
- over 1/2 of the 25.4M€ scheme is related to the retention measures even though they manage only 25% of the problem
- most cost-effective measure is GRR