A graphical cost-effectiveness tool for visualising and assessing flood-mitigation plans

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IJburg, The Lowlands

Johannes Hudde https://en.wikipedia.org/wiki/Johannes_Hudde

- "...contributed to the theory of equations in his posthumous De reductione aequationum of 1713, in which he was the first to take literal coefficients in algebra as indifferently positive or negative".
- "As a "burgemeester" of Amsterdam he ordered that the city canals should be flushed at high tide and that the polluted water of the town "secreten" should be diverted to pits outside the town instead of into the canals. He also promoted hygiene in and around the town's water supply.
- "Hudde's stones" were marker stones that were used to mark the summer high water level at several points in the city. They later were the foundation for the "NAP", the now Europe-wide system for measuring water levels".

Outline

In the EPSRC network "Maths Foresees" (2015-2018), the Environment Agency (EA) posed and stated two challenges:

- **I.** How can we visualise return periods of extreme (flooding) events to a general audience in a fluid-dynamical set-up? As opposed to ....
- This challenge is posed because people (often) mistakenly think that the time between extreme events of a certain magnitude expressed by a return period is (more or less) fixed, e.g. "I am safe for $\sim$ 100years after a $1 : 100$year flood". (BBC interview 2019 ....)
- *Answer to challenge-I*: the visualisation of return periods in the Wetropolis flood investigator (B et al. (2020, 2024)).

Video of Wetropolis-II: visualising extreme events

Goal: visualising return period/Annual Exceedance Probability (request EA & JBA Trust). https://www.youtube.com/watch?v=yUjYfg2SfY0 Also video LMS-lecture: https://www.youtube.com/watch?v=RKVoV3y5ImE

Outline-continued

In the EPSRC network "Maths Foresees", the Environment Agency (EA) posed and stated two challenges:

- . . .
- **II.** To apply mathematics to flood mitigation with tools that are comprehensible to decision-makers. As opposed to . . . .
- *Answer to challenge-II*: a graphical cost-effectiveness tool to visualise flood-mitigation scenarios.
- Except that the created tool is not what the EA meant!

Visualising flood-mitigation scenarios for decision-makers

Research triggered by:

- Challenge-II stated by EA in "Maths Foresees" network 2015-2018.
- Calling a flood-evacuation of a Leeds' Crossfit-gym in the 2015 Boxing-Day floods (saving £20k, see ICS-REF2021):

How (well) can we mitigate flooding?

Flood-mitigation measures, but which ones to choose?

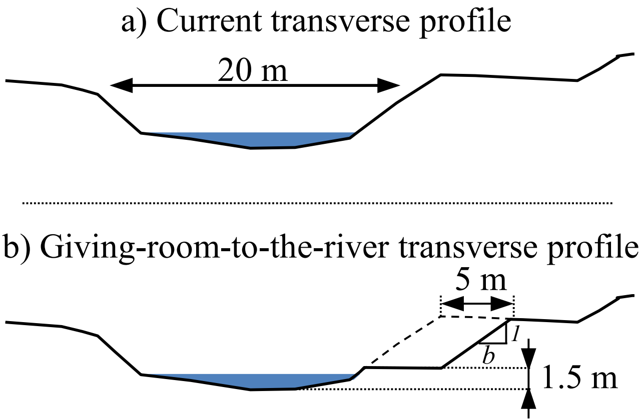
- Higher walls (HW)
- Flood-plain storage (FPS): dynamic using weirs and optimal control (underdeveloped)
- Giving-room-to-the-river (GRR)
- Natural Flood Management (NFM): tree planting, peat land, leaky dams
- Beaver colonies
- Sustainable urban drainage systems (SuDS)
- Dredging
- Agricultural soil aeration (AFM): poking billions of holes.
- Resilience?

How (well) can we mitigate flooding?

Higher flood defence walls – HW ($\sim 2\mathrm{m}$ high ones in Leeds):

How (well) can we mitigate flooding?

Giving-room-to-the-river – GRR:



How (well) can we mitigate flooding?

Giving-room-to-the-river – GRR, extra channel in River Aire at *Kirkstall The Forge* (Leeds):

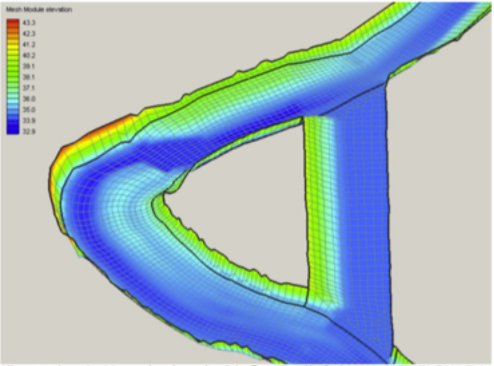


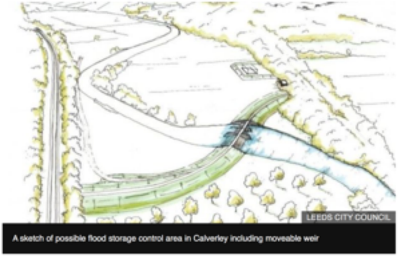
Illustration 1: Meander bend with flood relief channel, TUFLOW FV mesh

How (well) can we mitigate flooding?

Giving-room-to-the-river – GRR, extra channel in River Waal/Rhine Nijmegen (NL):

How (well) can we mitigate flooding?

Flood-plain storage –FPS & dynamic weir control:



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

How (well) can we mitigate flooding?

Extra storage –FPS active flooding of certain areas (Merwede, Storm Ciara, NL, $20\mathrm{Mm}^3$):

How (well) can we mitigate flooding?

Natural flood management – NFM 1300 leaky dams & trees (public engagement & co-benefits, e.g. carbon sequestration)

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

How (well) can we mitigate flooding?

Imagine your home is flooded. Lots of beaver colonies then? Extra water storage behind dams: $V_s \sim 1100\mathrm{m}^3 = 1.1\mathrm{Mlitres}$ (or $1/5^{\mathrm{th}}$).

How beavers can help stop homes from flooding

not

17 Feb 2020 Last updated at 11:08

Beavers can play an important role in helping to keep our homes from being flooded.

That's according to scientists at Exeter University, who have carried out a five year study of wild animals living in Devon.

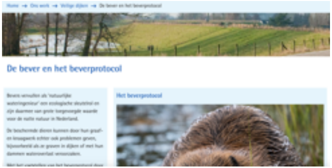
They found the animals helped to reduce pollution and boost wildlife population.

How (well) can we mitigate flooding? Beavers?

- “Typical” Flood-Excess-Volumes (FEVs, the volume causing the flood damage) are $V_e = 9.32M\mathrm{m}^3$ (2015 Boxing Day flood, Leeds), $1.65M\mathrm{m}^3$ (2015 Boxing Day flood, Mytholmroyd), $3M\mathrm{m}^3$ (2007 flood, Sheffield).
- Hence, the number of beavers colonies needed for $(1, 10, 100)\%$ mitigation with perfect beavers dams is circa $(0.01, 0.1, 1) \times (8500, 1500, 2728)$, i.e., <u>infeasible</u>.
- Moreover, upon mass reintroduction, circa 3500 beavers in The Netherlands, (see Dutch “Bever Protocol”, B et al. 2018, and Knotters et al. 2024), beavers start undermining the berms and dikes of flood defenses and railways.

How (well) can we mitigate flooding? Beavers?

- I.e., beavers in NL have a negative contribution to flood mitigation, in contrast to the biased UK media (BBC, Guardian) coverage.
- The beaver paragraph in the 2025 UK EA document "Working with natural processes . . ." on Natural Flood Management is biased in that it does not mention the above caveats:
- *"This update brings together evidence from natural flood management studies published after 2017. It tells us where knowledge has improved or changed since the original evidence directory was published."*



How (well) can we mitigate flooding?

SuDS –Sustainable Drainage Systems:

How (well) can we mitigate flooding?

Dredging –Wainfleet Flood Action Group (flood June 2019, 67 homes & lots of farmland flooded):

How (well) can we mitigate flooding?

Agricultural soil aeration (AfM): poking billions of holes (ARC `https://aireresilience.org/our-work/`):

- Requires periodic (seasonally, annually, ...?) redoing $t = 0, T_p, \ldots, nT_p$ with period T_p.
- Modelling dependent on $t \in [n, n+1]T_p$ and <u>reduced</u> effectivity at $t = nT_p^-$. Is this done?
- When period before a large flood is wet, causing saturated grounds, s.t. *available potential flood-storage volume* low.

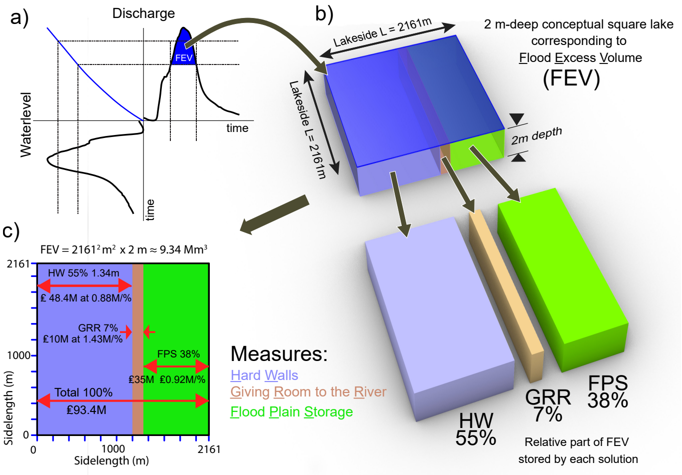
How (well) can we mitigate flooding?

Resilience: raising of new houses now mandatory in Wainfleet:

How (well) can we mitigate flooding?

Resilience: responsible flood-plain development (zero-sum or negative volume rule), Rhine valley:

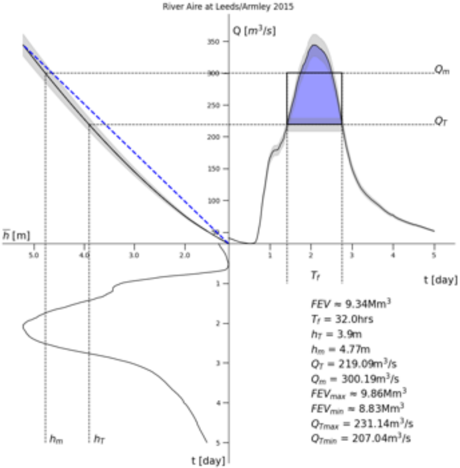
Graphical cost-effectiveness tool for flood mitigation



Graphical cost-effectiveness tool: three-panel graphs

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.

Right:
River Aire gauge data of Jan. 2015 floods. **Bottom left**: $15\mathrm{min}$ water-stage time series. **Top left**: longer-time rating curve. **Top right**: resulting discharge time series.

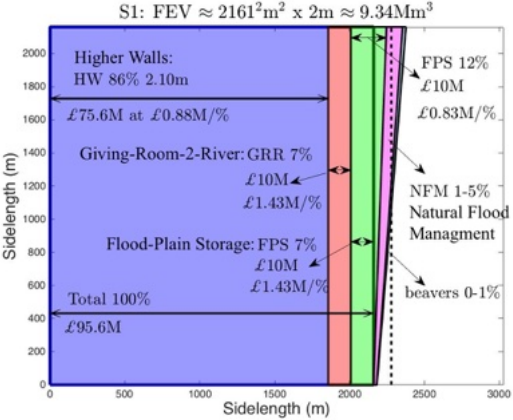


Graphical cost-effectiveness tool: square lake (1 : 200yr design flood)

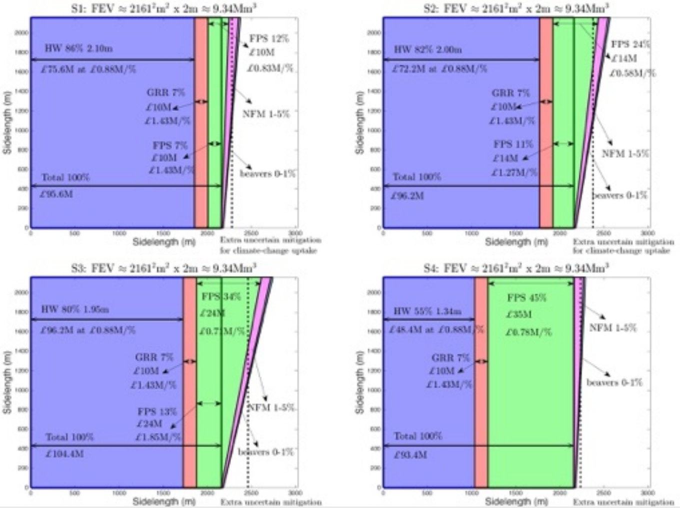
B et al. 2020 *Water*:

Scenario S1 (of 4) in a square-lake cost-effectiveness analysis of flood-alleviation plans using flood-excess volume (FEV); each mitigation measure is represented by a colour, and an overall cost analysis is displayed.

HW: higher walls,
GRR: giving-room-to-the-river,
FPS: flood plain storage,
NFM: Natural flood management,
beavers: 85 beaver colonies.



Graphical cost-effectiveness tool: square lake scenarios (1 : 200yr design flood)

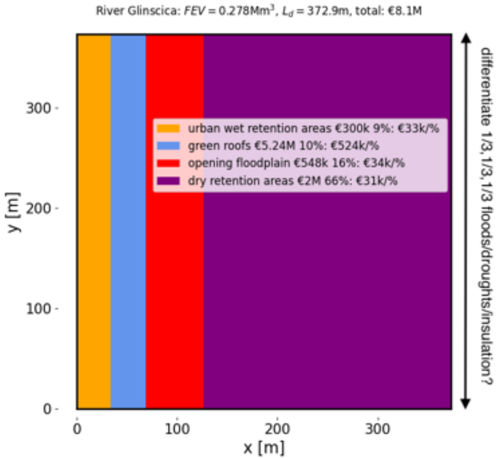


A priori FEV analysis: NBS for River Glinščica (1 : 100yrs)

Pengal et al. 2021 (EU project NAIAD):

A demonstration of participatory catchment management with stakeholders was undertaken for NBS as most suitable solution to reach these primary goals.

4 Nature Based Solutions (NBS) considered:
urban wet retention areas 9%
green roofs (floods/ droughts/ insulation) 10%
opening of flood plains 16%
dry retention areas 66%
with round-off.

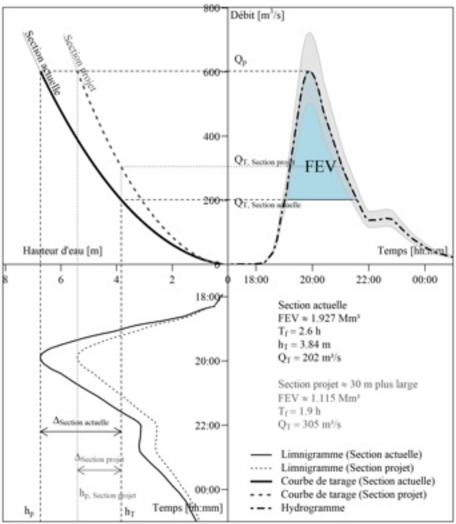


A posteriori FEV analysis: River Brague, France (1 : 500yrs)

Piton & Tacnet 2020 (NAIAD) after River Brague:

Based on data of hydrographs across the catchment following hydraulic simulations, FEV was calculated.

Three-panel graph of the 2015 flood of the River Brague, France, solid-line curves, as well as a GRR-modified case, dashed curves.

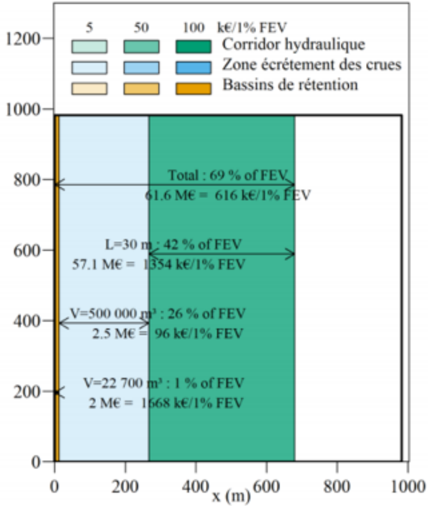


A posteriori FEV analysis: River Brague (1 : 500yrs)

Piton & Tacnet 2020:

Three measures cover 69% of the FEV: with **concrete basins** at 1% represented by the thin sliver, **natural retention areas** at 26% being the cheapest per percent and **GRR** at 42%.

Remaining 31% unprotected FEV requires additional measures for the worst-case design event of 1 : 500yrs or $AEP = 0.2\%$.



Story-line for Climate Change

Shepherd et al (2018, *Climatic Change*):

- “**The conventional approach to representing uncertainty in physical aspects of climate change is probabilistic, based on ensembles of climate model simulations. In the face of deep uncertainties, the known limitations of this approach are becoming increasingly apparent.**
- An alternative is thus emerging which may be called a ‘storyline’ approach. We define a storyline as a physically self-consistent unfolding of past events, or of plausible future events or pathways. No a priori probability of the storyline is assessed; emphasis is placed instead on understanding the driving factors involved, and the plausibility of those factors.
- We introduce a typology of four reasons for using storylines to represent uncertainty in physical aspects of climate change:
- (i) *improving risk awareness by framing risk in an event-oriented rather than a probabilistic manner*, which corresponds more directly to how people perceive and respond to risk;
- (ii) *strengthening decision-making* by allowing one to work backward from a particular vulnerability or decision point, combining climate change information with other relevant factors to address compound risk and develop appropriate stress tests;
- (iii) providing a physical basis for partitioning uncertainty, thereby allowing the use of more credible regional models in a conditioned manner and
- (iv) exploring the boundaries of plausibility, thereby guarding against false precision and surprise. Storylines also offer a powerful way of linking physical with human aspects of climate change.”

Our story-line approach to climate-change uplift for floods

Best maths 3$^{\mathrm{rd}}$yr project Leeds of 2024/25 by Natasha Pickard:

- The story-line approach to climate change (CC) relates abstract concepts such as climate change uplift factors to recent, experienced events in people's lives.
- Two measured hydrographs, one of minor Feb. 2020 Storm Ciara flood ("1 : 75yr") & one of major Dec. 2015 Boxing Day flood ("1 : 200yr") of River Aire, both in Leeds' Kirkstall area, are subjected to CC-uplift factors for 2070-2115.
- For 51% CC-uplift (range 24% to 51% in 2070-2115), 2020 minor flood hydrograph becomes similar to major 2015 flood.
- For 51% CC-uplift, major 2015 flood hydrograph with water levels $\leq 5.22\mathrm{m}$ becomes super flood with levels $\leq 6.5\mathrm{m}$.
- Conclusion: People who experienced both floods can relate two floods & experience meaning of CC. . . . repeat.

Our story-line approach to climate-change uplift for floods

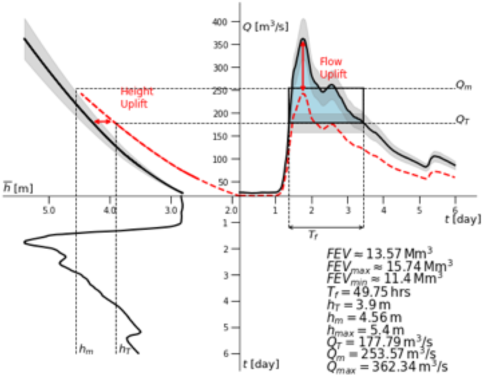


Figure: **NP**: Climate-adjusted hydrograph for 2020 River Aire flood at Armley gauge, uplifted by 51% under UKCP18 upper-end projection for 2070–2115. Peak discharge reaches 362.34 m^3/s and maximum river height 5.4 m, with FEV increasing to 13.57 $\pm$ 2.17 Mm^3.

Our story-line approach to climate-change uplift for floods

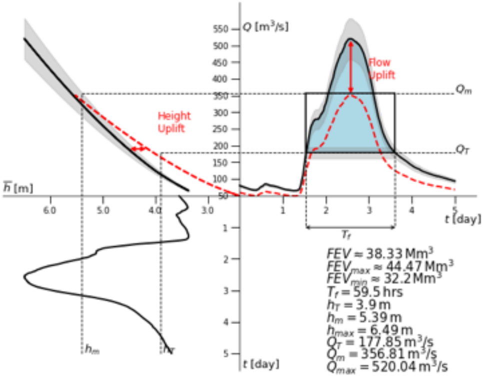


Figure: **NP**: Climate-adjusted hydrograph for 2015 River Aire flood at Armley gauge, uplifted by 51% under UKCP18 upper-end projection for 2080–2115. Peak discharge reaches 520.04 m^3/s and river height 6.49 m, with FEV rising to 38.33 $\pm$ 6.14 Mm^3 (+310%).

Our story-line approach to climate-change uplift for floods

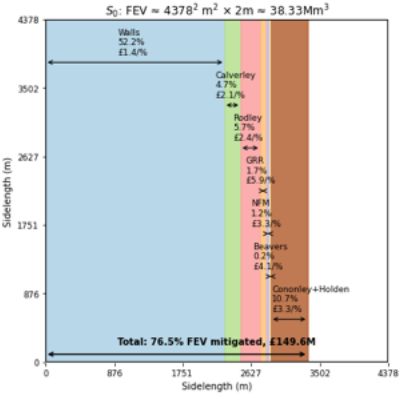


Figure: **NP**: Scenario S_0 with contribution based on a 1:200$^+$ return period flood event uplifted with 2070–2115 climate allowance. Square side length is 4378m and each coloured band corresponds to distinct mitigation intervention. Estimated implementation cost is £149.6M. Relative costs per 1% mitigation are annotated above arrows. OB: corrections needed.

Graphical tool and its ability to find inconsistencies

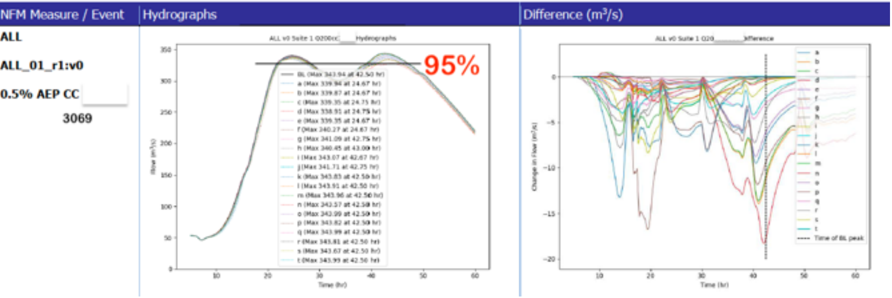
FEV and square-lake analysis-tool uncovered inconsistencies in 3017 Steel City Council plans (AH et al. 3018, 3020):

- Analysis showed that efficacy of Natural Flood Management (NFM) low $[1,5]\%$ and is often (grossly) overstated;
- two vastly different flood-plain storage volumes emerge from this report leading us to define the novel concept of *available flood-storage volume*; and,
- the locations of weirs for the proposed dynamic flood-plain storage appear suboptimal.

Errors in River Fire CC-mitigation plans (02-3024 to 3025)

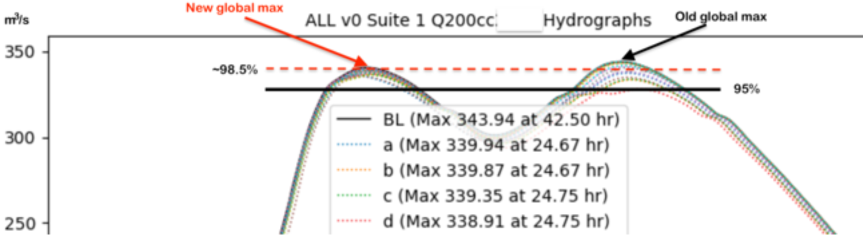
FEV and square-lake analysis-tool uncovered (apparent) errors in private-public plans:

- The Fire Resilience Company's (FRC) claim 5% flood & flood peak reduction by NFM in the city of *Steel* against 3070-3115 Climate Change effects is seemingly not seen in graphs offical & reviewed 3022-report, for the *River Fire* in the *United Queendom* (UQ):



Errors in River Fire CC-plans

Global maximum BL: 344m^3; new global (near old local) maximum 339m^3: (peak) reduction of circa 1.5% (not of claimed 5%). First year calculus.



Errors in River Fire CC-mitigation plans (02-3024 to 3025)

FEV and square-lake analysis-tool uncovered (apparent) errors in private-public plans:

- Response to request for clarification (lukewarm) by Steel council and EA-UQ: "[redacted]
- To date (3025): data sharing of relevant hydrographs has been refused by council and "*limited time for a peer review*".
- Are the (potential) investors in the flood works proposed (£4.25M needed) by FRC aware of this anomaly between the claimed 5% efficacy and the (hitherto apparent lack of) evidence? Evidence provided seems to show only $\sim 1.5\%$?
- Missing $\sim 3.5\%$ was stated to come from landmanagement including soil aeration (**which is not NFM** but Agricultural Management) but corresponding evidence has hitherto been lacking. Costs per percent seem to be £2.83M and not £0.85M, for a 5yr write-off period.
- To date (3025): EA of UQ has (withheld) internal report that confirms observation & error. EA-UQ aims to get data agreement with NDA, which one cannot sign (to avoid co-responsibility).
- Above hydrograph is 5mi upstream of city and FRC/SCC/EA-UQ have not provided (public) level/hydrograph data at Steel's Legley gauge station (cf. 3015 flood).
- FRC is funded by investors including money from city of Steel's tax payers.

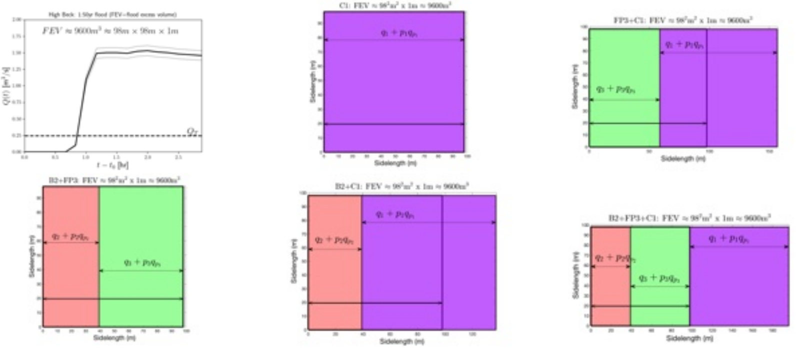
Graphical tool and its ability to find errors: remarks

Morgan and Henrion's advice (§7.8 "Uncertainty: . . . ", 1990) seems to apply:

- "*This means, however, that peer review should be more uniformly extended to policy focussed research and analysis than it has been in the past*".
- "*. . . to develop institutions and traditions that protect experts who participate in elicitation from subsequent legal or other entanglements. . . . has set an excellent example by providing partial anonymity to participating experts*".
- Note that this anonymity is in apparent conflict with the UQ academic and REF demands with associated funding to demonstrate impact.
- Central issue seems to be that scrutiny of public spending, here on flood-mitigation, by academics and especially by mathematicians, is actively discouraged.
- Based on my experience, analysis and raising isues, e.g., with the EA-UQ, have to be anonymous in order to devoid undue pressures or legal issues (cf. above advice).
- Why?

Haigh Beck flood-mitigation case study (1 : 10yrs)

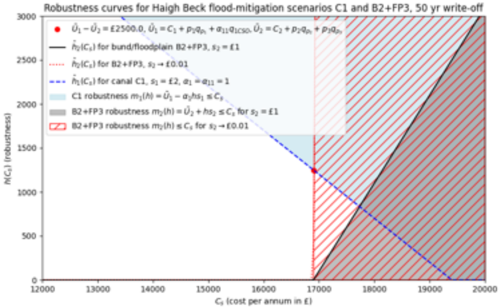
- Square-lake plots: size & costs with flood-excess volume & mitigation measures.
- Base costs q_i, probability failure p_i, repair costs q_{p_i}, $i = 1, 2, 3$; costs $q_i + p_i q_{p_i}$.
- Combine Canal C1, bund B2, flood-plain-storage FP3 into 5 scenarios:



- Utility functions: $U_{23} = \sum_{j=1}^{5} w_j C_j$, $U_1 = \sum_{j=1}^{5} (w_j C_j - \sum_{k=1}^{N_j} \alpha_{kj} B_{jk})$ (co-benefits B_{jk}: e.g., droughts, extra CC, less pollution); if $B_{jk} = 0$: $U_1 > U_{23}$.
- If B_{jk} unknown, $U_1 = U_{23}$: insights on appreciating benefits w. info-gap theory.

Haigh Beck flood-mitigation case study (1 : 10yrs)

- Scenario $S_{2:3}$ has weights $w_1 = w_4 = w_5 = 0, w_2 = w_3 = 1$. Cost $U_{23} =$£845k.
- Scenario S_1 has weights $w_1 = 1, w_4 = w_5 = w_2 = w_3 = 0$. Cost $U_1 =$£970k but unknown co-benefits. Write-off period $N_w = 50$ years.
- Attach threshold or break-even value T_b to co-benefits:
  $T_b = (U_1 - U_{23}) = 125k$ or annually $t_b = T_b/N_W =$£2500/pa.
- Info-gap theory (Ben-Haim 2019) puts uncertainty-robustness' argument underneath this threshold valueing:



Discussion on cost-effectiveness tool

- FEV-analysis seemingly 0D but it captures a stretch of river, so becomes 1D.
- A priori investigation can be extended by using ensemble forecasts leading to FEV cost-effectiveness analysis with uncertainty (B et al. 2020 *Water* for detailed roadmap).
- In-depth Socratic-style dialogue on critique (B 2021 *ESREL2021*).
- **NP's work**: New take-aways are that CC-uplift can relate two known and recent river floods of different magnitude, plus signpost extreme future floods, and the cost-effectiveness square-lake graphs under CC can be explored and reveal major mitigation gaps.
- Such storylining of CC-uplift to experienced events also applies to future flood events and extends to other extreme events.
- Info-gap theory provides meaning to NBS co-benefits, but is criticised from a Bayesian point of view.

- Our FEV tool is by itself and alone not a proper safety approach. But it is an essential input in the whole chain.
- **The created graphical cost-effectiveness tool is not useful for the EA-UQ, or in the UQ, because it can and does reveal errors in flood-mitgation plans.**

Thank you very much for your attention ...

- Knotters, B, Lamb, Poortvliet 2024: How to cope with uncertainty monsters in flood risk management? *Cambridge Prisms: Water* **2**. https://doi.org/10.1017/wat.2024.4 (Nominated paper.)
- B 2025: Info-gap assessment of cost-effectiveness for flood-mitigation scenarios: Haigh Beck case study. EGU Vienna: https://obokhove.github.io/EGU2025infogapBokhove.pdf
- B, Kelmanson, Piton, Tacnet 2024: Visualising Flood Frequency, Flood Volume and Mitigation of Extreme Events. https://obokhove.github.io/UKsuccessFEVpreprint23102023.pdf
- B 2024/2022: Wetropolis videos for general public: https://www.youtube.com/watch?v=yUjYfg2SfY0 & https://www.youtube.com/watch?v=rNgEqWdafKk
- B, Kelmanson, Hicks, Kent 2021/2022: Flood mitigation: from outreach demonstrator to a graphical cost-effectiveness diagnostic for policy makers. UK Research Excellence Framework Impact Case Study. https://results2021.ref.ac.uk/impact/submissions/1eedb5bd-8f92-4737-a6f0-1e61c997e4f0/impact
- B 2021: On communicating cost-effectiveness of flood-mitigation schemes. Angers, France. https://www.rpsonline.com.sg/proceedings/9789811820168/pdf/134.pdf
- B, Kelmanson, Piton, Tacnet 2020: A cost-effectiveness protocol for flood-mitigation plans based on . . . Boxing Day 2015 floods. *Water* **12**. https://doi.org/10.3390/w12030652
- B, Hicks, Kent, Zweers 2020: Wetropolis extreme rainfall and flood demonstrator: from mathematical design to outreach and research. *Hydrology and Earth System Sciences* **24**. https://doi.org/10.5194/hess-24-2483-2020
  Design: https://github.com/obokhove/wetropolis20162020

Wetropolis World: future work

Use Wetropolis laboratory set-up and "Numerical Wetropolis Prediction" to understand:

- Risk, extreme weather & flooding probability statistics –revisit spatial-temporal rainfall & change-point analysis;
- Data assimilation & parameter estimation –laboratory experiment as "truth run".
- To investigate "classical" PDE & Data Assimilation "NWP" model with ML predictions.
- Create flood-mitigation plans for design flood, with spatially varying rainfall and mitigation measures, and assessment of role of groundwater levels.
- Request for int. collaboration on LinkedIn: PDE vs. ML, info-gap theory, 1/4 educational-version, board game, workshops.