



Cambridge Prisms: Water

www.cambridge.org/wat

Overview Review

Cite this article: Knotters M, Bokhove O, Lamb R and Poortvliet PM (2024). How to cope with uncertainty monsters in flood risk management? Cambridge Prisms: Water, **2**, e6, 3–13

Received: 22 August 2013

Received: 06 December 2021

Accepted: 12 January 2014

Keywords

flood risk management; decision-making; uncertainty; risk perceptions; storylines

Corresponding author:

Martin Knottens;
Email: martin.knottens@univie.ac.at

How to cope with uncertainty monsters in flood risk management?

Martin Knotters¹ , Onno Bakhuyzen², Rob Lamb^{3,4} and P.M. Poortvliet¹

¹Wageningen Environmental Research, Wageningen University & Research, Wageningen, The Netherlands; ²Leeds

Institute for Fluid Dynamics, School of Mathematics, University of Leeds, Leeds, UK; ²JBA Trust, Skipton, UK; ³Centre for Environment, Lancaster University, Lancaster, UK; ⁴UK Space Agency, Cosmonaut Communication

Abstract

Strategies are proposed to cope with uncertainties in a way that all possible kinds of uncertainty are named, recognized, statistically quantified as far as possible and utilized in efficient decision-making in flood risk management (FRM). We elaborate on the metaphor of uncertainty as a monster. We recommend two strategies to cope with the uncertainty monster to support efficient decision-making in FRM: monster adaptation and monster assimilation. We present three cases to illustrate these strategies. We argue that these strategies benefit from improving the structure and reducing the complexity of decision problems. We discuss ways to involve decision-makers in FRM, and how communication strategies can be responsive to their informational needs.

Impact statements

In decision making on flood risk management (FRM) uncertainties have to be dealt with. In this article expertise from hydrology, statistics, communication and behavioral science is combined. This collaborative approach contributes to a better understanding of the various ways uncertainties are dealt with in decision making in FRM. Moreover, with this integration of expertise the article opens ways to strategies in which uncertainties are actually assimilated and adapted by decision makers in taking efficient decisions in (focal) FRM.

Monster: exorcism, embracement, assimilation, denial (sunk cost fallacy/Concorde effect) and anesthesia.



"De hel en de zondvloed", Hieronymus Bosch, Museum Boijmans van Beuningen, Rotterdam, NL.

On monsters in flooding (research)

[et al.], Maths, Steel 11-12-3025





Johann Homann Geographische Vorstellung der jammerlichen
WasserFlutt in Nieder Teutschland 1720 (Wiki)

Johannes Hudde https://en.wikipedia.org/wiki/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 ~ 100 years 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=yUjYfg2SfYO>
Also video LMS-lecture: <https://www.youtube.com/watch?v=RKV0V3y5lM>



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 (N_FM): tree planting, peat land, leaky dams
 - ▶ Beaver colonies
 - ▶ Sustainable urban drainage systems (SuDS)
 - ▶ Dredging
 - ▶ Agricultural soil aeration (A_FM): poking billions of holes.
 - ▶ Resilience?

How (well) can we mitigate flooding?

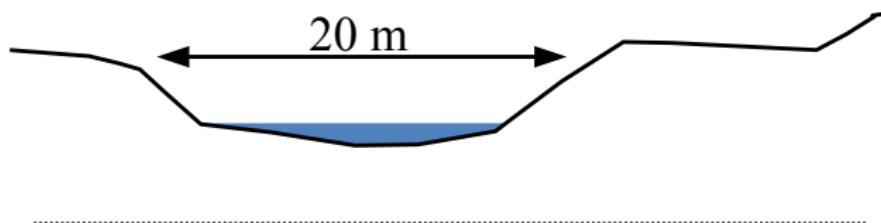
Higher flood defence walls – HW (\sim 2m high ones in Leeds).



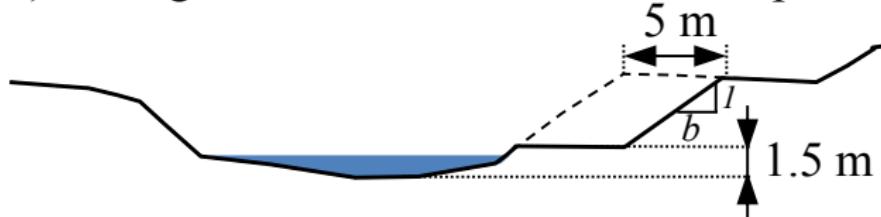
How (well) can we mitigate flooding?

Giving-room-to-the-river – GRR:

a) Current transverse profile



b) Giving-room-to-the-river transverse profile



How (well) can we mitigate flooding?

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

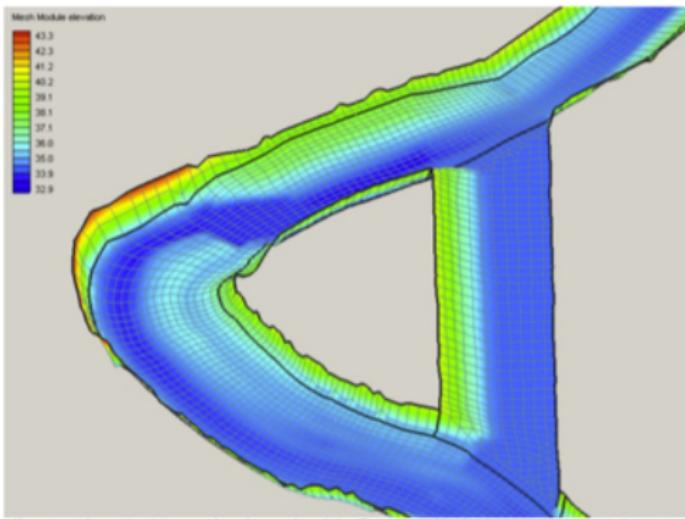


Illustration 1: Meander bend with flood relief channel, TUFLOW FV mesh

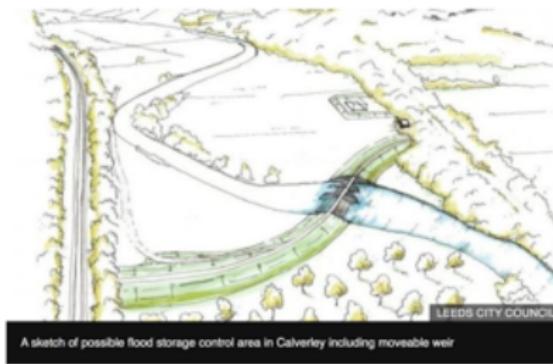
How (well) can we mitigate flooding?

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:



How (well) can we mitigate flooding?

Extra storage –FPS active flooding of certain areas (Merwede, Storm Ciara, NL, 20Mm³):



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 bands 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: $V_s \sim 1100\text{m}^3 = 1.1\text{Mlitres}$ (or $1/5^{\text{th}}$).

How beavers can help stop homes from flooding

© 17 Feb 2020 Last updated at 11:08



not

PA MEDIA

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 [REDACTED] 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 $V_e = 9.32Mm^3$ (2015 Boxing Day flood, Leeds), $1.65Mm^3$ (2015 Boxing Day flood, Mytholmroyd), $3Mm^3$ (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., infeasible.
 - ▶ 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."*

EditieNL

Bever bijt hond bijna dood: 'Wij hebben dit nog nooit meegemaakt'

Door Editie NL - 30 maart 2017 Aangeplaat: 30 maart 2017



Editie NL



De bever en het beverprotocol

Bevers vervullen als 'natuurlijke wateropslag' een ecologische functie en kunnen daardoor de waterhuishouding van de rivier stabiliseren. De beschreven diensten kunnen door hun graaf- en bosplantende gedrag groene gebieden vormen die groter zijn dan hun eigen waterinhoud: verschillend

Het beverprotocol



For Flooding's Sake



"Rely on NFM and beavers for flood mitigation, and do not analyse properly".

For Flooding's Sake



Home Research Publications Events Resources About Contact Us Search

POST

UK Parliament > POST > Subject database > Approved work: Nature based flood and drought resilience

Future research

Approved work: Nature based flood and drought resilience

Author(s): [Matthew Tizard](#), [Dr. Michaela Scott](#)

Published: 27 November 2019

Share:

Print

E-mail

What are the key challenges and benefits of using nature-based solutions for flood and drought risk climate change adaptation in the UK?

- Deadline for contributions: 23:59 on the 5 December 2025
- Please contribute to this POSTnote via this [link](#)
- All contributions must follow our [guidance](#)
- Publication is expected in April 2026

Londscapes can be restored in ways that reduce both flood risk and the effects of drought. For example, natural flood management measures such as blocking drainage channels, rewetting peat bogs, restoring ghost ponds and planting woodland allow the land to hold water longer, slow its release, and sustain the flow of water in rivers during dry periods that can help water conservation and reduce the risk of floods.

The 2022 roadmap for the National Flood and Coastal Erosion Risk Management (NFCERM) Strategy includes doubling the number of natural flood management projects delivered. However, this will require landowners, water companies, local authorities, regulators, environmental groups, and communities to work together to deliver shared outcomes. For example, approaches can include re-introduction of beavers, which can be contested by some landowners and communities.

This POSTnote will provide a summary of the benefits and challenges of using NBS to increase resilience to flood and drought events and update the 2020 Natural mitigation of flood risk POSTnote.

We welcome information on issues relevant to the project. To contribute to this research, please complete this [form](#).

Monster denial. Instead, look at evidence to date, be scientific and include all evidence to and fro.

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 (A_{FM}): poking billions of holes ($_{ARC}$

<https://aireresilience.org/our-work/>):

- ▶ Requires periodic (seasonally, annually, . . . ?) redoing $t = 0, T_p, \dots, nT_p$ with period T_p .
- ▶ Modelling dependent on $t \in [n, n + 1]T_p$ and reduced effectivity at $t = nT_p^-$. Is this done? No, so (deliberate) bias in favour of A_{FM} .
- ▶ 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:

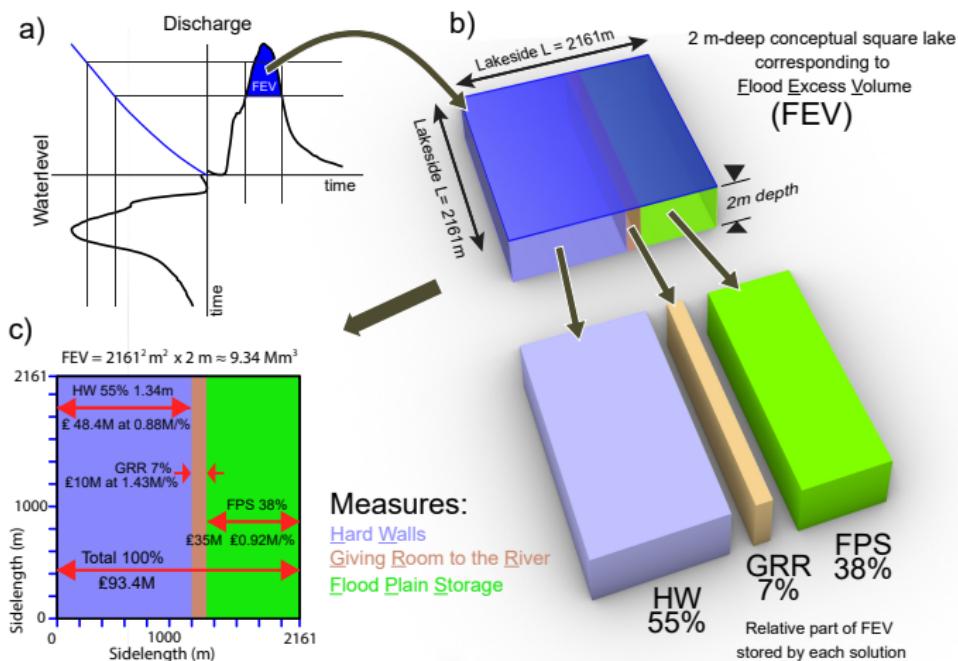


How (well) can we mitigate flooding?

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.

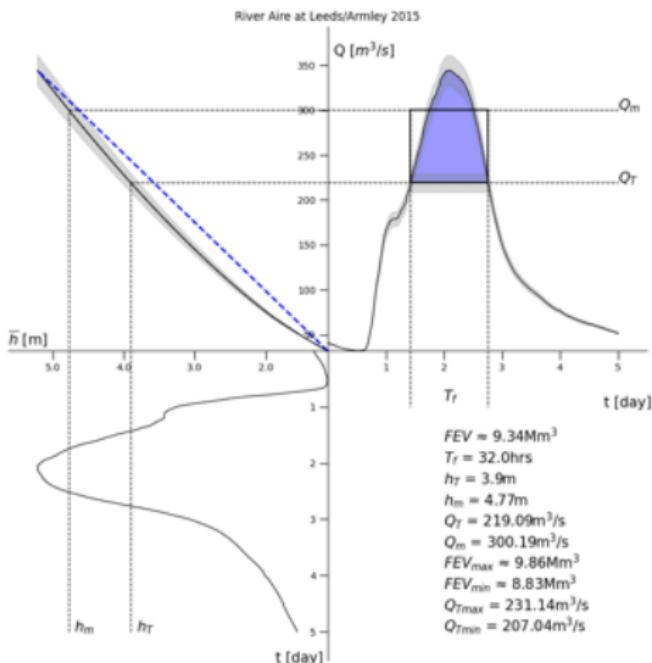
2015 floods. **Bottom left:**

15min 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 (2018):

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:

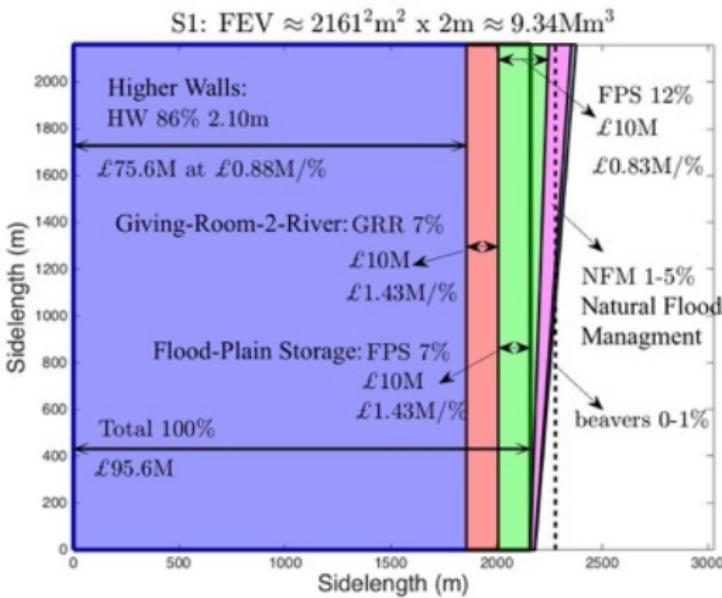
giving-room-to-the-river,

FPS: flood plain storage,

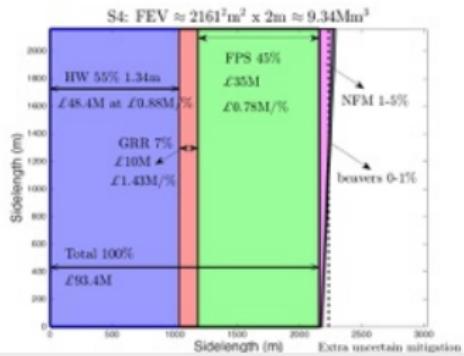
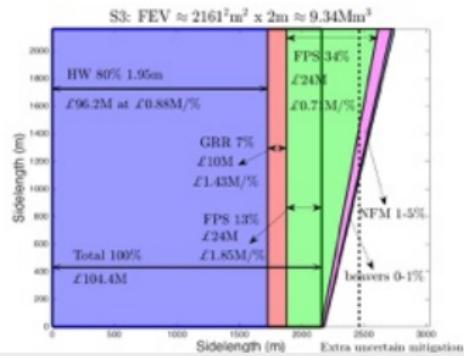
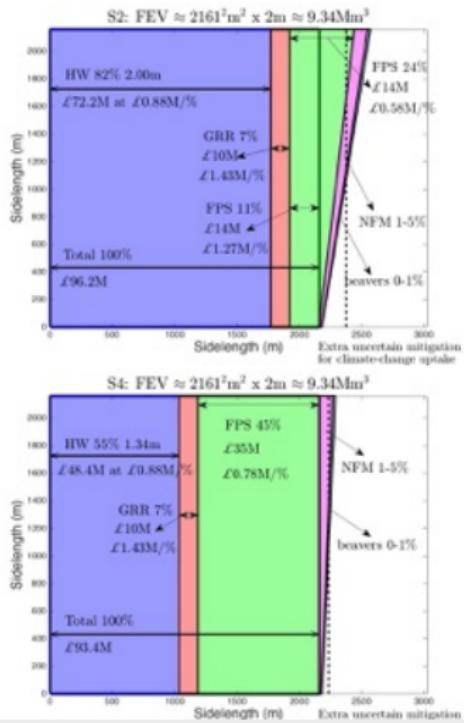
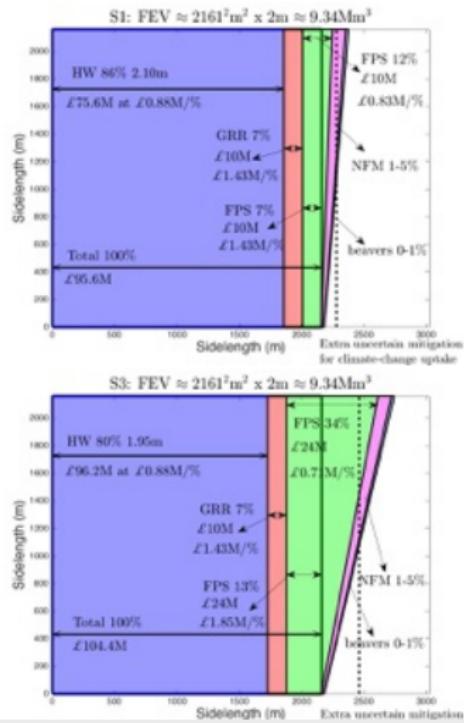
NFM: Natural flood

management,

beavers: 85 beaver colonies.



Graphical cost-effectiveness tool: square lake scenarios ($1 : 200\text{yr}$ design flood)

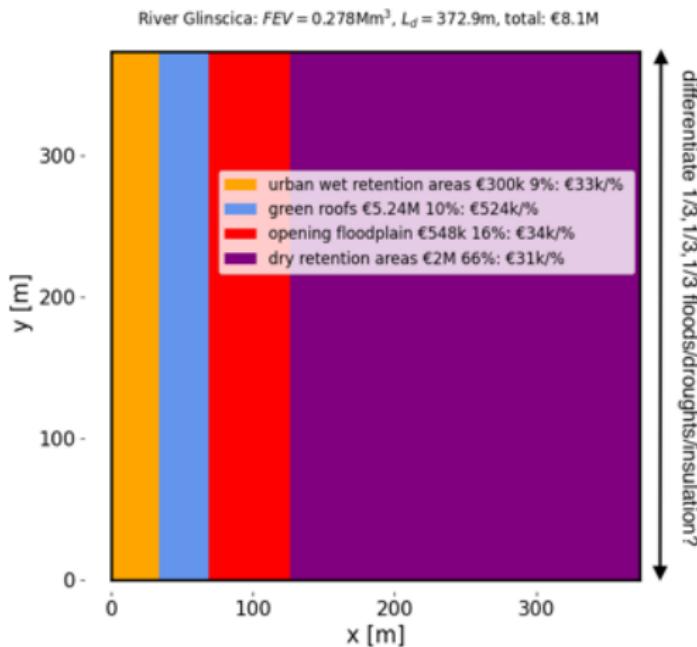


A priori FEV analysis: NBS for River Glinčica (1:100yrs)

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.

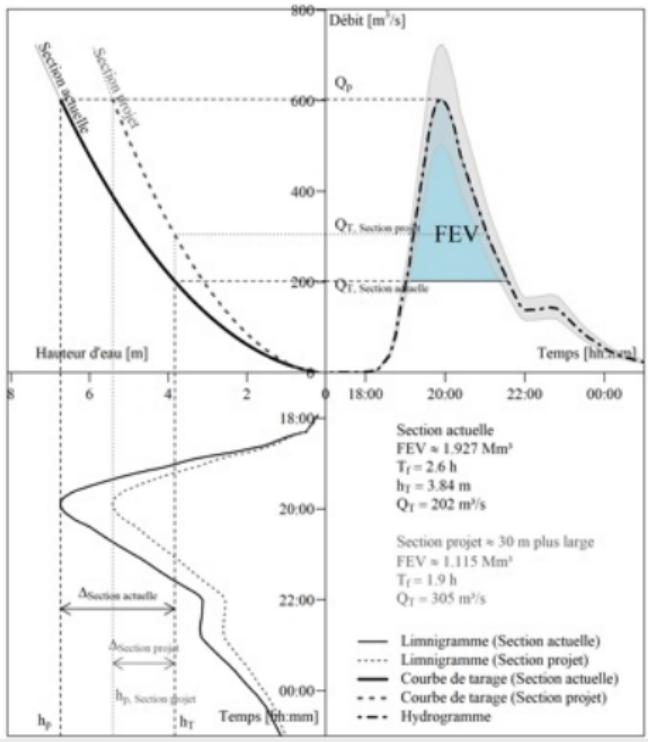


A posteriori FEV analysis: River Brague, France (1:500yrs)

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.

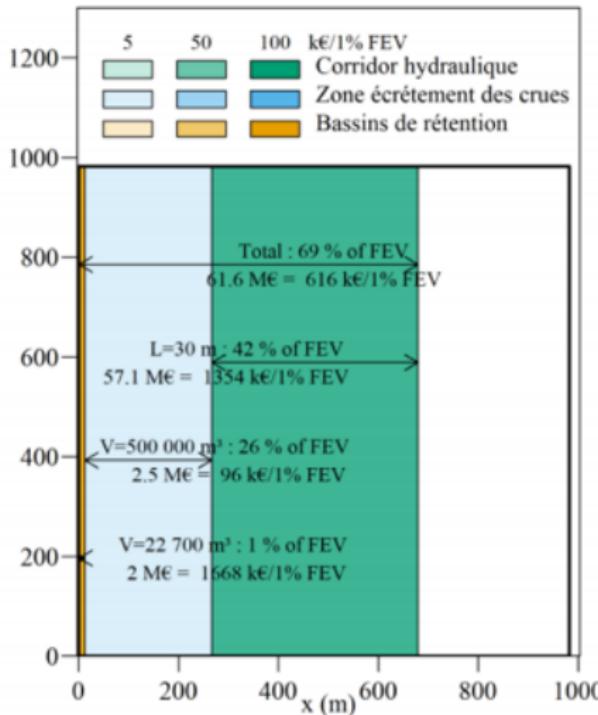


A posteriori FEV analysis: River Brague (1:500yrs)

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 3rd 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 $\leq 5.22\text{m}$ becomes super flood with levels $\leq 6.5\text{m}$.
- ▶ **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

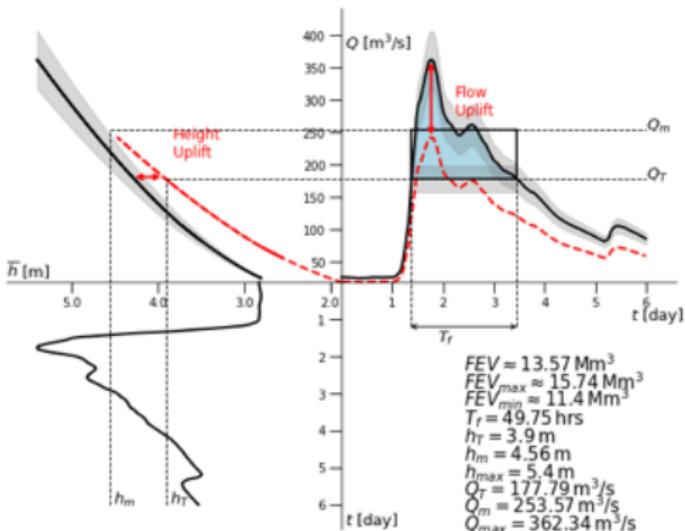


Figure: NP: Climate-adjusted hydrograph for 2020 River Aire flood at Armley gauge, uplifted by 51% under UKCP18 upper-end projection for 2070–2115. Peak discharge reaches $362.34 \text{ m}^3/\text{s}$ and maximum river height 5.4 m, with FEV increasing to $13.57 \pm 2.17 \text{ Mm}^3$.

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

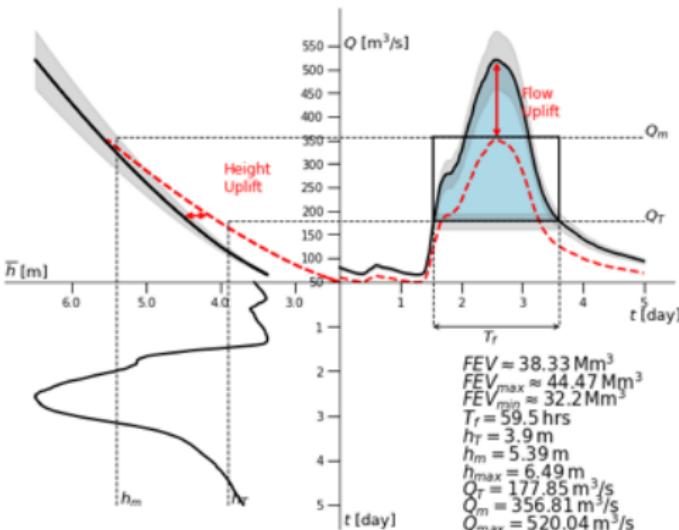


Figure: NP: Climate-adjusted hydrograph for 2015 River Aire flood at Armley gauge, uplifted by 51% under UKCP18 upper-end projection for 2080–2115. Peak discharge reaches $520.04 \text{ m}^3/\text{s}$ and river height 6.49 m, with FEV rising to $38.33 \pm 6.14 \text{ Mm}^3$ (+310%).

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

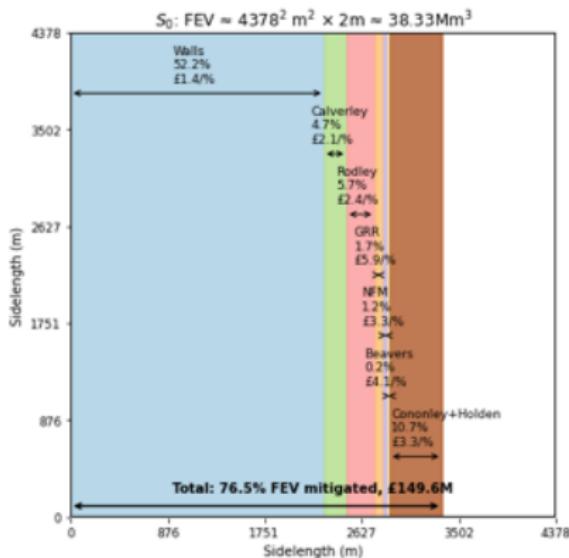
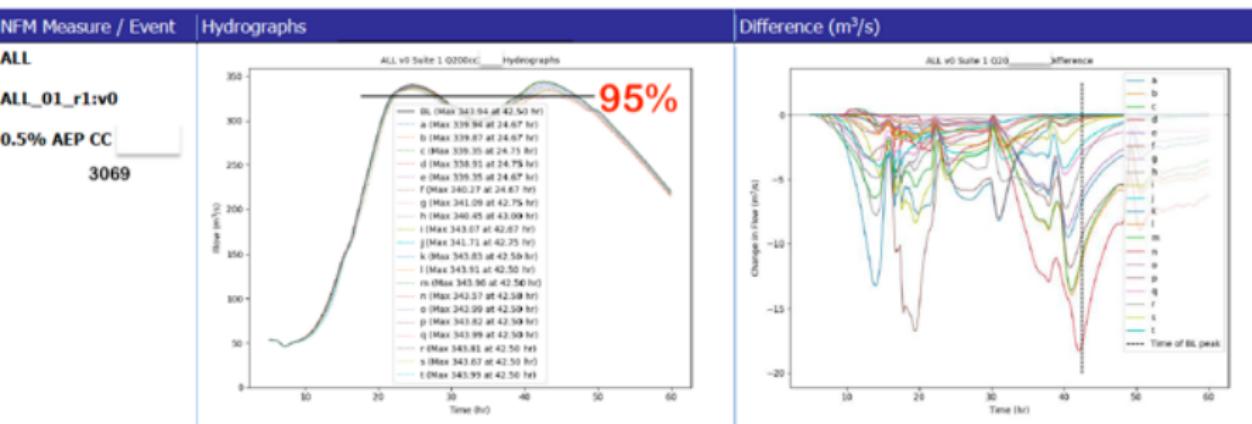


Figure: NP: Scenario S_0 with contribution based on a $1:200^{+}$ return period flood event uplifted with 2070–2115 climate allowance. Square side length is 4378m and each coloured band corresponds to distinct mitigation intervention. Estimated implementation cost is £149.6M. Relative costs (in M) per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

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

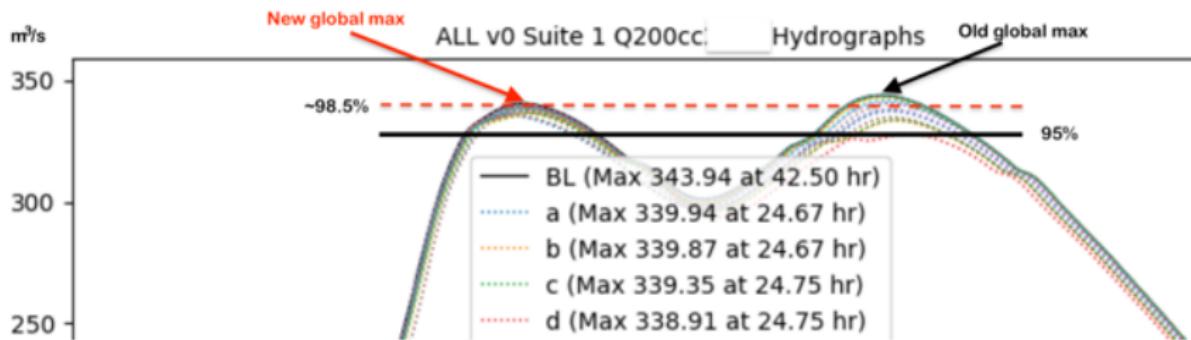
FEV and square-lake analysis-tool uncovered (apparent) **errors** in private-public plans:

- 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 official & reviewed 3022-report, for the *River Fire* in the *United Queendom* (UQ):



Errors in River Fire CC-plans

Global maximum BL: 344m³; new global (near old local) maximum 339m³: (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 ~ 1.5%?
- ▶ Missing ~ 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 issues, e.g., with the EA-UQ, have to be anonymous in order to devoid undue pressures or legal issues (cf. above advice).
- ▶ **Why?** a) Unfair treatment of honest proposals, e.g., info-gap theory Haigh Beck. b) No retaliation on reporting. c) Long(er) way 1.5% to 51%'s CC.

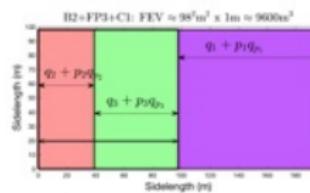
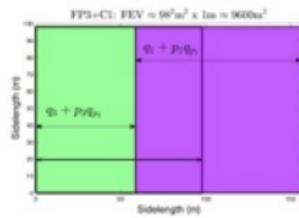
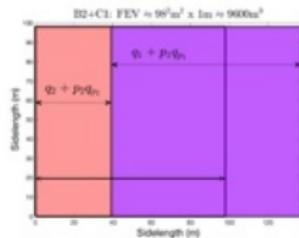
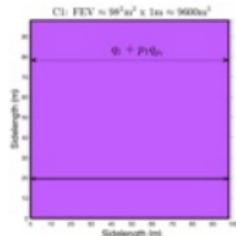
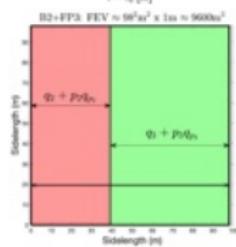
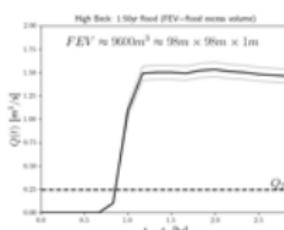
Discussion on cost-effectiveness tool

- ▶ 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 known, 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.

- ▶ 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-mitigation plans.**
- ▶ **Info-gap theory** values unvalued NBS co-benefits, but may be criticised from a Bayesian point of view?

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 $t_b = T_b/N_W = £2500/\text{pa}$.
- ▶ Info-gap theory (Ben-Haim 2019) puts uncertainty-robustness' argument underneath this threshold valueing:

