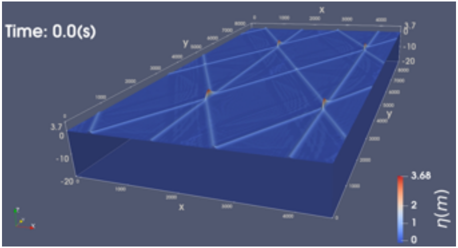
Wetropolis flood investigator

Onno Bokhove [et al.]

£€: EPSRC Maths Foresees/DARE/CDT Fluid Dynamics

Leeds Institute for Fluid Dynamics, UK –04-07-2024



Outline

On the fluid dynamics and statistics of:

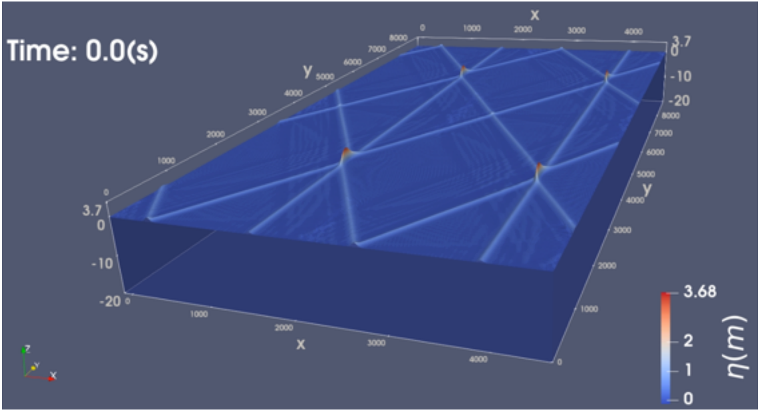
- water waves,
- Wetropolis flood investigator.

Modelling extremely high water waves

- Origin 2010 *bore-soliton-splash*:
- Definition rogue/extreme waves: $AI = H_r/H_s > 2$.
- To what extent do exact but idealised extreme- or rogue-wave solutions survive in more realistic settings?
- Will such *extreme waves* fall apart due to dispersion or other mechanisms?
- Use fourfold and ninefold KP amplifications of interacting solitons/cnoidal waves.
- What do you think: will we be able to reach the ninefold wave amplification in more realistic calculations or in reality?

Results simulation three-soliton interaction (dimensional)

Crossing seas (4 or 8 domains combined –*YouTube*)

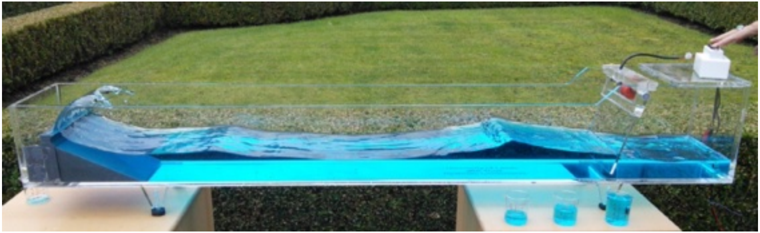


Coastal wave tank: coastal defense systems

- JBA Trust demo (10M views): https://www.youtube.com/watch?v=3yNoy4H2Z-o
- Fossbytes link (112M views):

  https://www.facebook.com/watch/?v=1151082355697392
- MSc-CDT team project JBA Trust 2015, design:

  https://github.com/obokhove/MathslaboratoryUoL/tree/master/wavetank



On Wetropolis flood investigator

Inspiration for Wetropolis: Boxing Day 2015 floods of the River Aire in Leeds

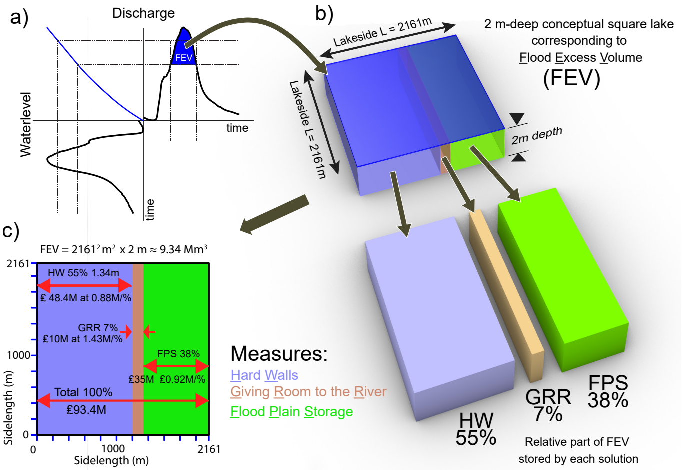
Tour of Wetropolis

Goal: visualising return period/Annual Exceedance Probability (request EA & JBA Trust). *Tour* (DARE) & *superflood* (MPE):

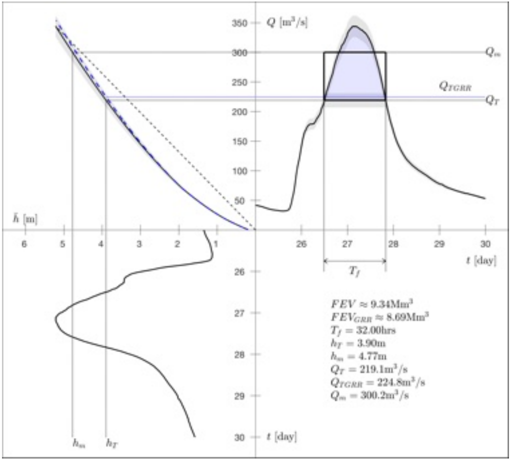
Legacy of our work on flooding

- **REF Impact case study ICS 2021:** Wetropolis & flood-mitigation effectiveness tool for decision-makers.
- **Analysis Leeds' public 2017 Flood-Alleviation Scheme II:** led to graphical flood-mitigation cost-effectiveness tool, laying bare inconsistencies in FASII. Duly reported w. no/little response; arxived reports led to several complaints in 2018-2021, in essence refuted in ICS 2022.
- **Corroboration cost-effectiveness tool:** flood cases in France & Slovenia
- Tool shows that **efficacy of Natural Flood Management** small to minute, e.g. beaver dams, somewhat contrary to overstated promotion of NFM & beavers by Environment Agency, council & media.
- **Impact Case Study** (flood link): `https://results2021.ref.ac.uk/impact/submissions/1eedb5bd-8f92-4737-a6f0-1e61c997e4f0/impact`

Graphical cost-effectiveness tool for flood mitigation



Graphical cost-effectiveness tool: three-panel graphs



How (well) can we mitigate flooding?

Flood-mitigation measures, but which ones to choose?

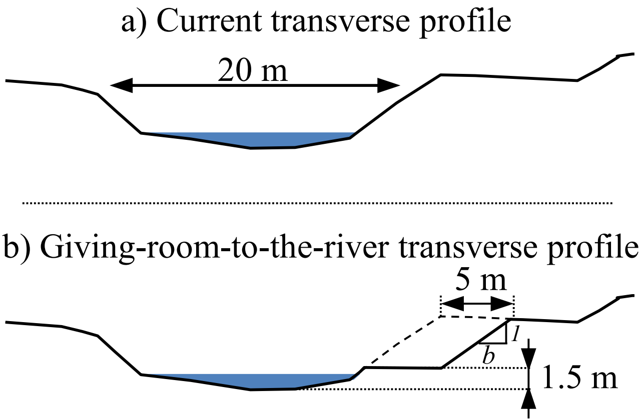
- Higher walls (HW)
- Flood-plain storage (FPS): dynamic using weirs and optimal control (underdeveloped)
- Giving-room-to-the-river (GRR)
- Natural Flood Management (NFM): tree planting, peat land, leaky dams
- Beaver colonies
- Sustainable urban drainage systems (SUDS)
- Dredging
- Resilience?

How (well) can we mitigate flooding?

Higher flood defence walls – HW (2m high proposed 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 *Aire River at Kirkstall The Forge* (Leeds):

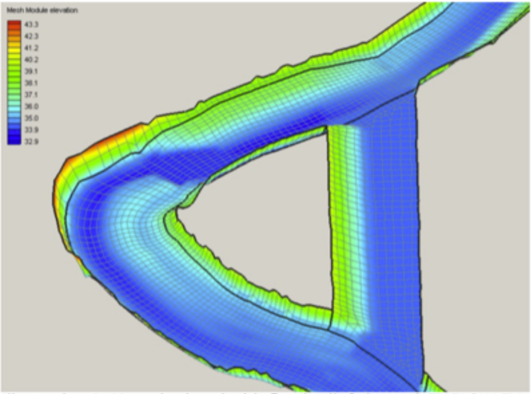


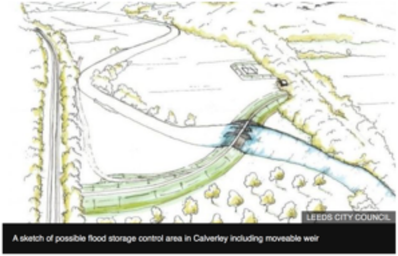
Illustration 1: Meander bend with flood relief channel, TUFLOW FV mesh

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, 20Mm^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? Beavers nonsense!

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

How beavers can help stop homes from flooding

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.

How (well) can we mitigate flooding?

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

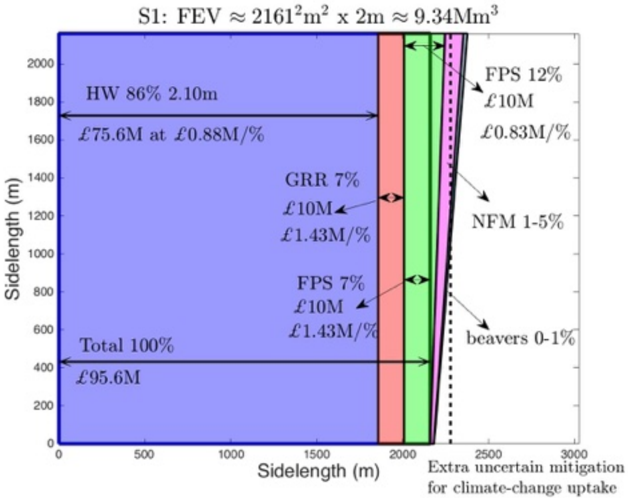
How (well) can we mitigate flooding?

Resilience: raising of new houses now mandatory in Wainfleet

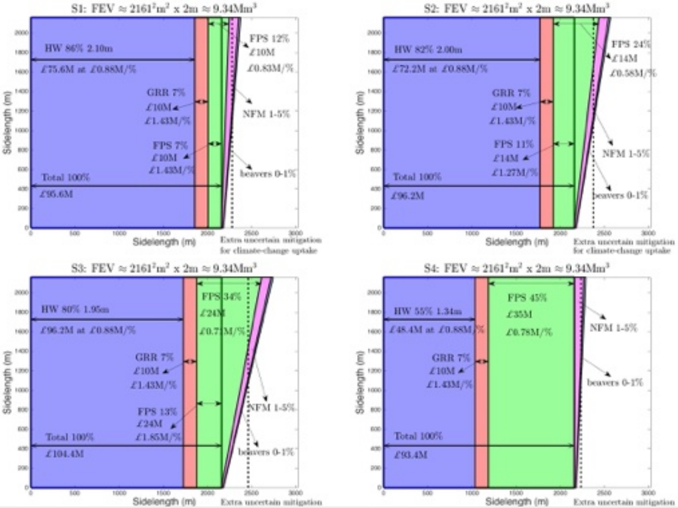
How (well) can we mitigate flooding?

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

Graphical cost-effectiveness tool: square lake

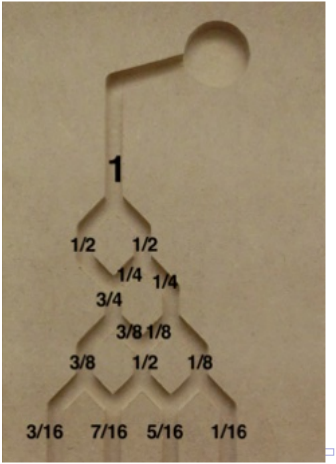


Graphical cost-effectiveness tool: square lake scenarios



Weather in Wetropolis: skew Galton boards

Ball falls through, peak chance at 7/16 & "rare" event at 1/16:



Weather in Wetropolis: two skew Galton boards

Two Galtonboards, one rain duration & one for rain location:

Wetropolis' weather: probability and statistics

- X, Q: probabilities p_i rainfall duration/wd versus q_j rain location:
- p_i, q_j with $i, j = 1, 2, 3, 4$ and $\sum p_i = 1, \sum q_j = 1$.
- For old case, $p_1 = q_1 = 3/16, p_2 = q_2 = 7/16, q_3 = p_3 = 5/16, q_4 = p_4 = 1/16$:

Table: Probability matrix $P_{ij} = p_i q_j$ times 256.

	1s	2s	4s	9s
	p_1	p_2	p_3	p_4
reservoir q_1	9	21	15	3
both q_2	21	49	35	7
moor q_3	15	35	25	5
no rain q_4	3	7	5	1

Return period of floods: geometric distribution

- Rain amount per $T_d = 10\mathrm{s} = 1\mathrm{wd}$ determined by tuning: no to minor flooding for $(1, 2, 4)$ & $(8, 9)$, flooding for 18 units.
- Return period T_r of extreme flooding at $t_n = nT_d$ determined by geometric distribution with here $p_n = (1 - p_e)^{n-1}p_e$ where $p_e = P_{24} = q_2 p_4 = 7/256$, s.t.

$$T_r = \mathbb{E}(t_n) = \sum_{n=1}^{\infty} T_d n(1 - p_e)^{n-1}p_e = \frac{T_d}{p_e} \approx 365.7\mathrm{s} \approx 6:06\mathrm{min}.$$

- Standard deviation σ_r (thanks to Daan C & Jason F):

$$\sigma_r^2 = \mathbb{E}\left((t_n - \mathbb{E}(t_n))^2\right) = (1 - p_e)\frac{T_d^2}{p_e^2}$$
$$= (1 - p_e)T_r^2 \Longrightarrow \sigma_r = 36.07\mathrm{wd} = 360.7\mathrm{s} \approx 6\mathrm{min}.$$

Super- and megafloods: geometric distribution of order k

- Two consecutive "2015 Boxing Days" extreme rainfall WEP $p_e^2 = (7/256)^2$ s.t.

$$T_r^{(2)} \approx \frac{T_d}{p_e^2} = (256/7)^2 \times 10\mathrm{s} \approx 223\mathrm{min} \approx 3:43\mathrm{hr}.$$

Movie "Wetropolis Boxing Day flood" on `https://github.com/obokhove/wetropolis20162020`

- $T_r^{(2)}$ & $\sigma_r^{(2)}$ follow from geometric distribution of order $k=2$ (Viveros & Balakrishnan 1993, Koutras & Eryilmaz 2017):

$$\frac{T_r^{(k)}}{T_d} = \frac{(1-p_e^k)}{(1-p_e)p_e^k}, \quad \frac{\sigma_r^{(k)}}{T_d} = \frac{\sqrt{1-(2k+1)(1-p_e)p_e^k - p_e^{2k+1}}}{(1-p_e)p_e^k}.$$

Super- and megafloods: Wetropolis revisited design

- For floods on two consecutive days with old $p_e = 7/256$:

$$T_r^{(2)} = T_d \frac{(1+p_e)}{p_e^2} = 1374\mathrm{wd} = 13740\mathrm{s} = 3.8\mathrm{hr},$$
$$\sigma_r^{(2)} = T_d \frac{\sqrt{1-5(1-p_e)p_e^3 - p_e^5}}{(1-p_e)p_e^3} = 3.8\mathrm{hr}.$$

- Long waiting times suggest redesign, e.g. take Galton board outcome $p_e = p_2 q_2 = 49/256 \approx 1/5$ for 9s rainfall in moor & reservoir, yielding return periods for $k = 2, 3$-day floodings:

$$T_r = 5.2\mathrm{wd} = 52\mathrm{s},\ T_r^{(2)} = 32.5\mathrm{wd} = 5:25\mathrm{min},$$
$$T_r^{(3)} = 175\mathrm{wd} = 29:11\mathrm{min}, \sigma_r^{(k)} \approx T_r^{(k)}, k = 1, 2, 3.$$

Wetropolis' weather: revisited

- X, Q: probabilities p_i rainfall duration/wd versus q_j rain location:
- p_i, q_j with $i, j = 1, 2, 3, 4$ and $\sum p_i = 1, \sum q_j = 1$.
- For current case, $p_1 = q_1 = 3/16, p_2 = q_2 = 7/16, q_3 = p_3 = 5/16, q_4 = p_4 = 1/16$:

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reservoir q_1	9	21	15	3
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no rain q_4	3	7	5	1

Climate probability and statistics

Revisit rain durations by adding extra rain in upstream lake w. pump of fraction $0 \leq r_e < 1$ per unit relative & synced to the moor

Table: Rain duration with $P_{ij} = p_i q_j$ times 256.

	$r_1 = 1$ p_1	$r_2 = 2$ p_2	$r_3 = 4$ p_3	$r_4 = 9$ p_4
reservoir q_1	r_1	r_2	r_3	r_4
both q_2	$(2+r_e)r_1$	$(2+r_e)r_2$	$(2+r_e)r_3$	$(2+r_e)r_4$
moor q_3	$(1+r_e)r_1$	$(1+r_e)r_2$	$(1+r_e)r_3$	$(1+r_e)r_4$
no rain q_4	0	0	0	0

- Accumulation yields total mean volume of rain water R entering set-up per s, scaled by pump rate r_0:

$$R/r_0 = \left((q_1 + 2q_2 + q_3) + r_e(q_2 + q_3)\right)(r_1 p_1 + r_2 p_2 + r_3 p_3 + r_4 p_4)$$
$$= 4.5 + 2.2 r_e \approx 4.5(1 + 0.2) \quad \text{for} \quad r_e = 0.5.$$

Floods, droughts & climate

Droughts –reformulate elegantly w. 2 or 3 stochastic variables?

- 4wd–drought: $T_r^d = T_d(1-q_4^4)/q_4^4/(1-q_4) = 194\mathrm{hr}$ with $q_4 = 1/16$. Too long!
- To visualise drought for $1/16^{\mathrm{th}}$ route of dry day, use outcome of 1^{st} Galton board (unused in absence of rainfall) e.g., with $(p_2+p_3, p_1+p_4) = (3,1)/4$ probability.
- For $p_1 + p_4 = 1/4$—case, enforce $4\mathrm{wd}$ drought, visualised by drink-water pipe from moor falling dry: no water supply!
- New probabilities then adjust to rainfall in reservoir, moor & reservoir, moor, no rain on $1\mathrm{wd}$ & no rain for $4\mathrm{wd}$:

$$(q_1, q_2, q_3, q_4, q_5) = (12, 28, 20, 3, 4)/67?$$

- Drought return period: $T_r^d = 67x10\mathrm{s} = 11:10\mathrm{min}?$
- New return period: $T_r = (16x67/28)x10\mathrm{s} = 6:23\mathrm{min}?$

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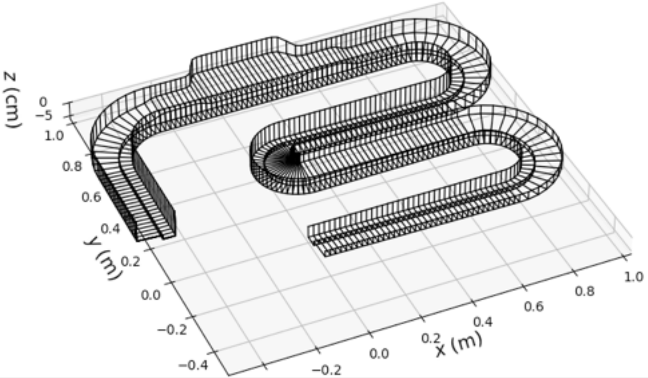
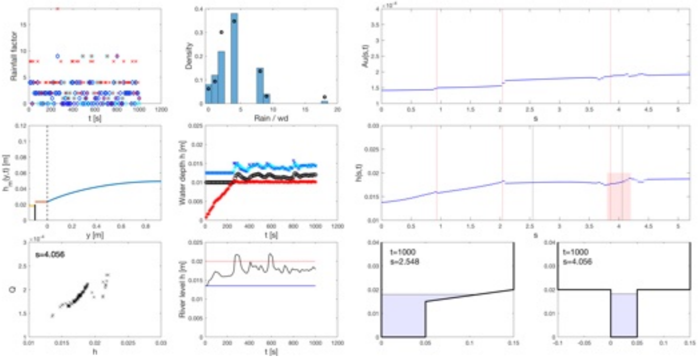
Wetropolis models

Kinematic river flow in design model; 1D predictive shallow-water river model with ground-water & reservoir dynamics, in progress (PDEs & ODEs: B. et al, HESS, 2020). Bathymetry:



Wetropolis modelling

Simulations, https://github.com/tkent198/hydraulic_wetro:



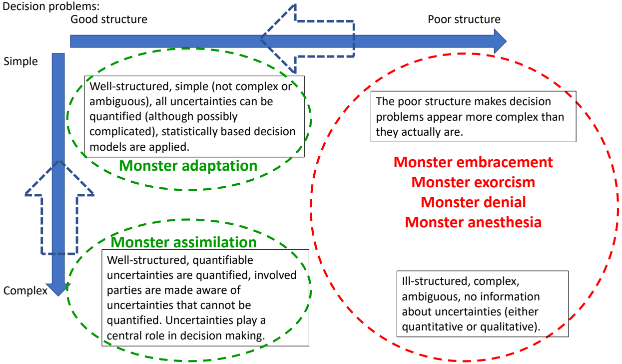
Wetropolis investigator

How can a Wetropolis laboratory set-up and a Numerical Wetropolis Prediction model be used to understand:

- risk, extreme weather & flooding probability statistics –revisit spatial-temporal rainfall & change-point analysis;
- rare-event simulations (for events of "intermediate rarity");
- flood control –e.g., reservoirs in Wetropolis;
- data assimilation & parameter estimation –experiment as "truth run"; test (failure of) machine learning.
- spatial-temporal nature of flood-mitigation measures –see linear algebra in B, Kent, Kelmanson 2018?
- Wetropolis for urban surface flash flooding? *Can be done!*

Monster assimilation & adaptation in floods

High Beck fluvial flood-mitigation case study: Knotters, B., Lamb, Poortvliet (2024) Cambridge Prisms Water.



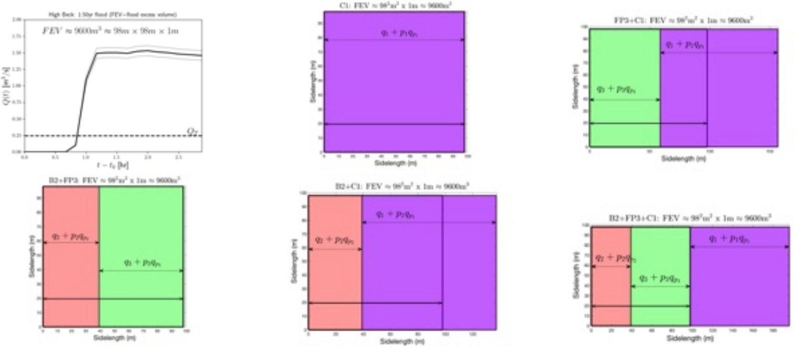
Uncertainty monsters in Flood-Risk Management (FRM)

Knotters et al. (2024) use the monster metaphor to propose six (coping) strategies to deal with uncertainties FRM. **Monster**

- exorcism, reduce uncertainty even if it is not realisable.
- embracement, trivialization by magnifying uncertainties.
- denial, Concorde effect: limited viability yet continued investment, e.g., of some NFM (upscaling fails, e.g. using beavers) of higher-and-higher flood walls.
- anesthesia, uncertainty "prevented" by striving for consensus or agreeing about quality of information.
- adaptation, adjust uncertainty, rationalise risk mitigation & optimise chosen utility (function). UK-EA: blended approach.
- assimilation, learn from uncertainty (quantification) & accordingly make changes.

High Beck flood-mitigation case study (50yrs)

- 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: $U_1 = \sum_{j=1}^{5} w_j C_j$, $U_2 = \sum_{j=1}^{5} (w_j C_j - \sum_{k=1}^{N_j} \alpha_{kj} B_{jk})$ (co-benefits B_{jk}: e.g., droughts, extra CC, less pollution), decision tree.
- Difficult to get 9 values but U_2 yields **new insights on appreciating benefits**.

Thanks very much for your attention ...

- Knotters, B, Lamb, Poortvliet 2024: How to cope with uncertainty monsters in flood risk management? *Water Prisms*. https://doi.org/10.1017/wat.2024.4
- B, Kelmanson, Piton, Tacnet 2024: Visualising Flood Frequency, Flood Volume and Mitigation of Extreme Events. https://obokhove.github.io/UKsuccessFEVpreprint23102023.pdf
- B 2022: **Wetropolis video for general public** https://www.youtube.com/watch?v=rNgEqWdafKk
- B, Kelmanson, Hicks, Kent: 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. ESREL. https://www.rpsonline.com.sg/proceedings/9789811820168/html/134.xml
- B, Hicks, Kent, Zweers 2020: **Wetropolis extreme rainfall and flood demonstrator: from mathematical design to outreach and research.** *Hydrology and Earth System Sciences* **24**. Full design: https://github.com/obokhove/wetropolis20162020
- Pacala, S. and Socolow, R. 2004: **Stabilization wedges: solving climate problem for next 50 years w current technologies.** *Science* **305**
- Maths laboratory designs: https://github.com/obokhove/MathslaboratoryUoL