Managing river floods in an age of extremes: should we be more worried?

Onno Bokhove

School of Mathematics, University of Leeds, Yorkshire, UK
Teamwork: Hicks, Kelmanson, Kent, Piton, Tacnet & Zweers!
Churchtown & Wainfleet Flood Action Groups

Mathematics of Planet Earth Exhibition Jan. 15^{th}–23^{rd} 2020

Who am I?

Expertise (-):

- am applied mathematician & fluid dynamics analyst
- made easy & novel science-policy analysis on flood-mitigation plans, accessible to all
- have "hands"-on experience with flood evacuation: 2015 Boxing Day floods & Storm Ciara 09-02!

Who am I?

Expertise (-):

- interact with citizens' flood-action groups showcasing Wetropolis, giving advice/support: "Hansje Brinker's finger-in-the-sea-dike"?

Hansje Brinker: tale

"The story of Hansje/Ansje Brinker":

Reality sea dike breach 1953 storm surge

Reality river dike breach Wainfleet 2019

Reality river dike breach fixed in 1953

Introduction

Let us consider the following questions:

- Will it rain more in the future?
- Can we define extreme precipitation & flooding events? What is a return period?
- How does the Wetropolis flood demonstrator mimic rain and flooding?
- How (well) do we predict heavy precipitation & flooding?
- Just how good are things like beavers dams, NFM, . . . at mitigation floods?
- If we aren't sure, how can we test these things?
- Are we worried enough about future extreme flooding events?

Introduction: river discharge

River -	peak discharge m^3/s	as cube $\mathrm{m} \times \mathrm{m} \times \mathrm{m}/\mathrm{s}$	as $2\mathrm{m}$ deep lake $\mathrm{m} \times \mathrm{m} \times \mathrm{m}/\mathrm{s}$
Amazone	340.000	$\sim 70 \times 70 \times 70$	$\sim 2 \times 400 \times 400$
Congo	75.000	$\sim 42 \times 42 \times 42$	$\sim 2 \times 190 \times 190$
Rhine	18.000	$\sim 26 \times 26 \times 26$	$\sim 2 \times 100 \times 100$
Thames	470	$\sim 8 \times 8 \times 8$	$\sim 2 \times 15 \times 15$
Aire	344	$\sim 7 \times 7 \times 7$	$\sim 2 \times 13 \times 13$

Table : River discharge in cumecs, as cube per sec and as $2\mathrm{m}$-deep lake per second, . . . [1].

Will it rain more in the future?

IPCC (Intergovernmental Panel on Climate Change) 2013:

- No, there is low-to-medium confidence in increased average annual rainfall.
- For extreme precipitation Europe there is "high confidence: likely increases in more regions than decreases but regional and seasonal variation"

Will it rain more in the future?

UKCP09 report Met Office 2010 (1960–2006) & UKCP18 (2009-2018):

- No, annual mean daily rainfall has not increased significantly since 1766.
- But proportion of winter rainfall in heavy rainfall events has increased across UK in last 45 years.

- "Although summer rainfall may decrease, . . . concentrated into a number of intense downpours from storms".
- Summer rainfall has decreased except in NE England and Northern Scotland.

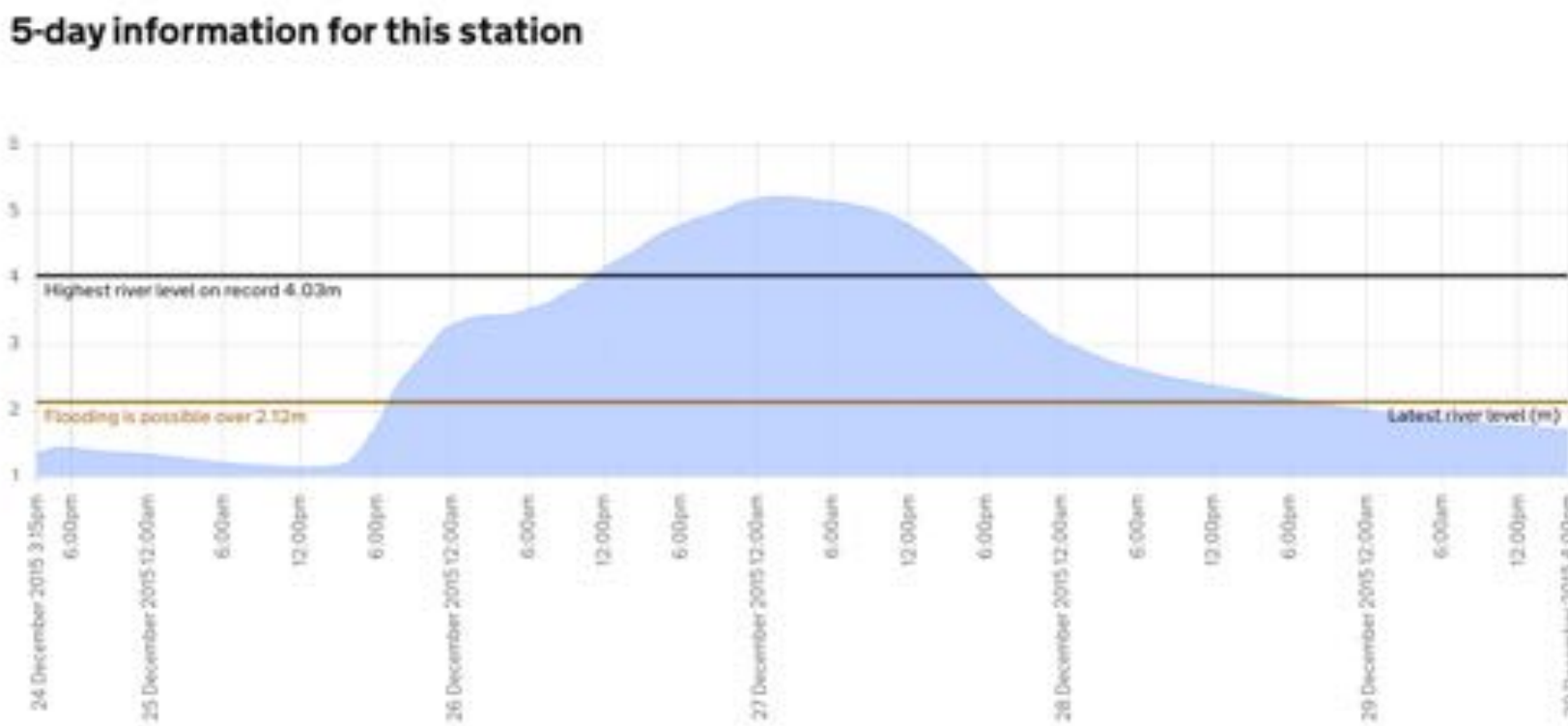
Can we define extreme precipitation & flooding events?

Challenges and basic problem (Coles, 2001):

- Aire River gauge at Armley/Leeds had highest record of 4.03m prior to 26-12-2015; how to classify the Boxing Day flood with 5.21m at this gauge?
- Standard statistical techniques work well when there are a lot of data, but don't work well for extremes.
- There are very few or no observations "in the tail of the distribution", i.e. for extreme events.
- Estimates required beyond largest observed data values: extreme value theory.

Can we define extreme precipitation & flooding events?

Armley River Aire station, Leeds, 2015 Boxing Day flood:



Extremes: what is a return period?

- A *return period* is a classification of the severity/magnitude of a rainfall or flooding event.
- Defining a *return period*: if 500 years of *daily rainfall or flood* data are available, then an event with a 1 in 100 year return period would be expected to occur 5 times in that data set.
- In any year such an event has on average a 1% chance to happen (on one day) per year.

Extremes: what is a return period?

Examples 1 : 100yr period in 500–year record (2000-2499):

- floods in years: 2007, 2019, 2333, 2400, 2499, or
- 2007, 2083, 2237, 2291, 2313, so not necessarily
- floods in years: 2007, 2107, 2207, 2307, 2407,
- as the lady in Fishlake thought – River Don flood 2019: "it flooded in 2007 and I bought my business after 2007 so I should have been save . . . for another 100yrs?

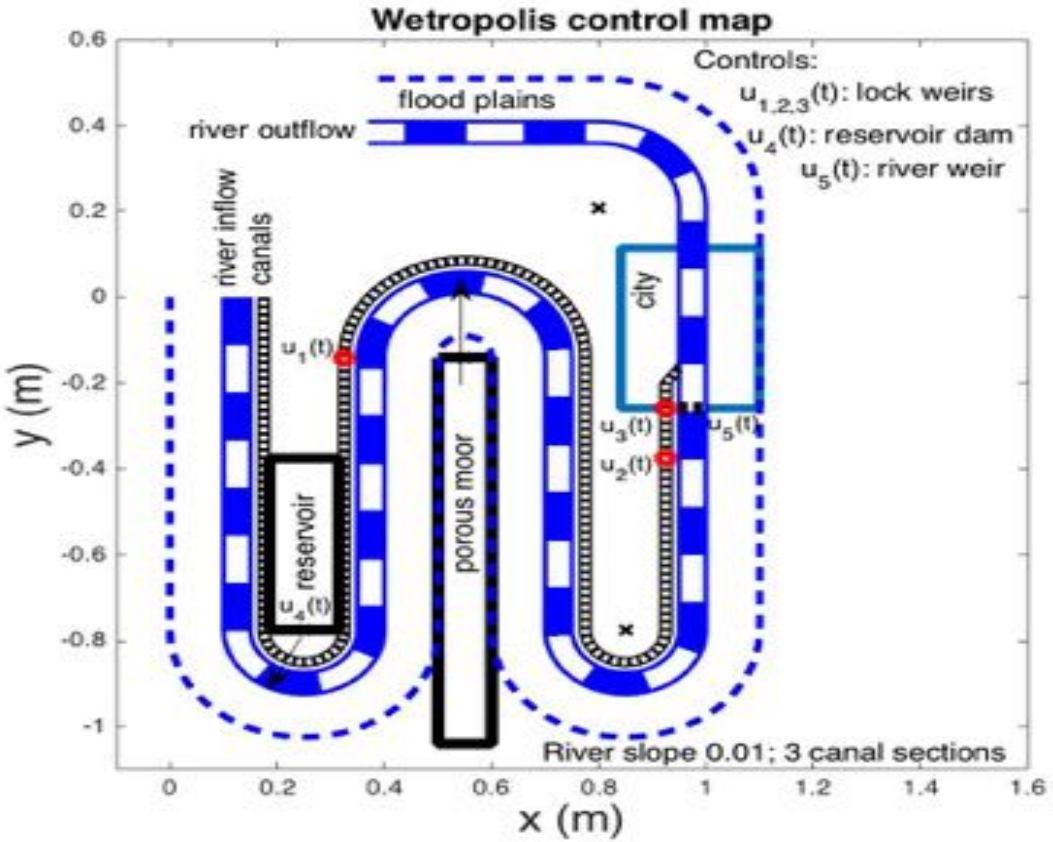
Wetropolis: conceptual table-top demo?

Goal: create a demonstrator to visualise a return period for extreme rainfall and flooding events (EA & JBA):

- rainfall supplied randomly with discrete skewed distribution coupled to
- physical yet conceptual river flow, rain & groundwater flow in moor, rain in reservoir (and no rain).
- Wetropolis has no years, but days only of $\mathrm{wd} = 10\mathrm{s}$: I don't want you to turn into dust by waiting –on average– $100\mathrm{yrs}$ [2]!

Wetropolis: conceptual table-top experiment?

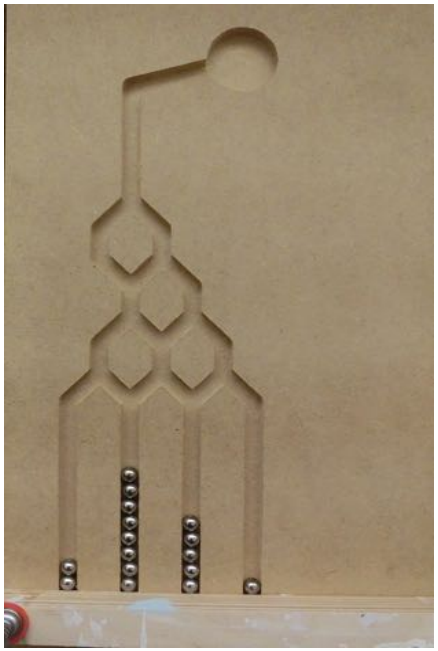
- Plan-view, *mathematical design* before construction:



- https://github.com/obokhove/wetropolis20162020

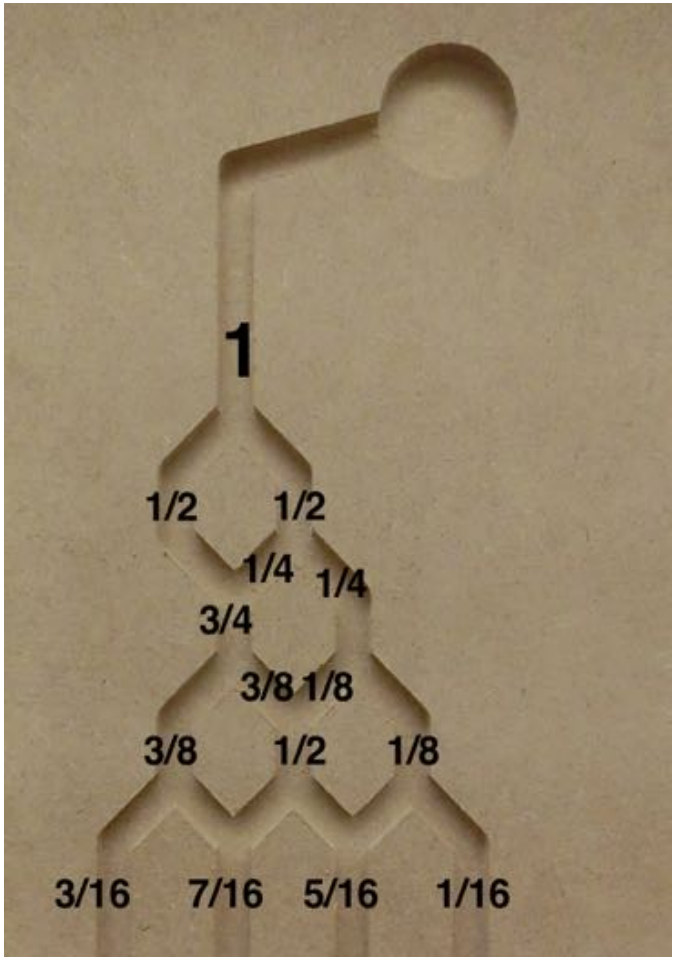
Rainfall in Wetropolis

Solution: use draws from two asymmetric Galton boards!



Rainfall in Wetropolis: skew Galton board

Peak chance at 7/16 & "rare" event at 1/16:



Rainfall in Wetropolis

Discretise rainfall events (risk) with outcomes of two Galton boards:

- Galton board 1, rainfall duration over 10s: 1s at 3/16 chance, 2s at 7/16, 4s at 5/16, extreme 9s at 1/16.
- So on average once every 16 days of 10s there is 90% (lots of) rainfall!
- Galton board 2, rain location over 10s: rain in reservoir at 3/16, moor & reservoir 7/16, moor 5/16, or (rare) no rain 1/16.
- So rain on moor and reservoir for 7 out of 16 days.
- Therefore, extreme rainfall at $(1/16) \times (7/16) = 7/256$!

Rainfall in Wetropolis

- Table of rainfall amount/wd versus rain location [3]:

Table : Probability matrix times 256.

	$1\mathrm{s}$	$2\mathrm{s}$	$4\mathrm{s}$	$9\mathrm{s}$
reservoir	9	21	15	3
both	21	49	35	7
moor	15	35	25	5
no rain	3	7	5	1

- Accumulated rainfall amounts per wd per unit $1\mathrm{s}$ pumping:

$$
\begin{aligned}
0: &\quad 0.0625 = 1/16, 1: 0.0938 = 24/256,\\
2: &\quad 0.3008 = 77/256, 4: \ \ 0.3477 = 89/256,\\
8: &\quad 0.1367 = 35/256, 9: 0.0469 = 8/256,\\
18: &\quad 0.0273 = 7/256.
\end{aligned}
$$

Rainfall in Wetropolis

- The rain amount per *wd* will be determined by tuning, such that there is no flooding with rain amounts $(1, 2, 4)$ units, moderate flooding possible when $(8, 9)$ units & massive flooding for 18 units.
- Return period extreme flood in Wetropolis is on average:

$$(256/7) \times 10\mathrm{s} \approx 365.7\mathrm{s} \approx 6:06\mathrm{min}.$$

- See Wetropolis at the MPE exhibition; chance of two consecutive "2015 Boxing Days" of extreme rainfall is thus $(7/256)^2$; it happens on average every [4]:

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

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

How (well) do we predict heavy precipitation & flooding?

Distinguish between downpours & sustained rainfall:

- Downpours (short ca. 1 hour) and flash floods, e.g., *Hebden Bridge July 2012*
  `http://www.bbc.co.uk/news/uk-18778840`

Hebden Bridge hit by flash floods

How (well) do we predict heavy precipitation & flooding?

Extreme rainfall 2015 Boxing Day flood well predicted:

48hr UK RAINFALL TOTALS 9am 25 DEC - 9am 27 DEC 2015

SITE	AREA	RAINFALL (MM) TOTAL
CAPEL CURIG	GWYNEDD	210.6
STONYHURST	LANCASHIRE	100
PATELEY BRIDGE, RAVENS NEST	NORTH YORKSHIRE	97
BINGLEY	WEST YORKSHIRE	93.6
BAINBRIDGE	NORTH YORKSHIRE	89.8
BALA	GWYNEDD	89.4
SHAP	CUMBRIA	86.4
SPADEADAM	CUMBRIA	79.4
PRESTON, MOOR PARK	LANCASHIRE	73.2
MYERSCOUGH	LANCASHIRE	72.4
BRADFORD	WEST YORKSHIRE	69.4
ROCHDALE	GREATER MANCHESTER	68.2
MORECAMBE	LANCASHIRE	65.8
MONA	ISLE OF ANGLESEY	63.6
KIELDER CASTLE	NORTHUMBERLAND	61.2
DISHFORTH AIRFIELD	NORTH YORKSHIRE	60.8

This wet spell has added to the heavy rainfall through the rest of the month to make December 2015 already the wettest on record in parts of the UK.

How (well) do we predict heavy precipitation & flooding?

- Sustained rainfall and river flooding is by and large well-predicted: the Met Office and Environment Agency do a reasonably good job e.g. Aire River floods.
- Prediction of localised surface water/brook flooding is more uncertain/less good, e.g., due to a lack of data.
- Downpours, their location & amount are very difficult to predict.
- Numerical Weather Prediction (NWP is computer modelling from e.g. the Met Office) cannot handle those cases (well), due to lack of computer power and lack of insights in the physics of precipitation.
- Also, NWP uses/assimilates lots of data to bring the computer model back to reality.

How (well) can we mitigate flooding?

Flood-mitigation measures, but which ones to choose?

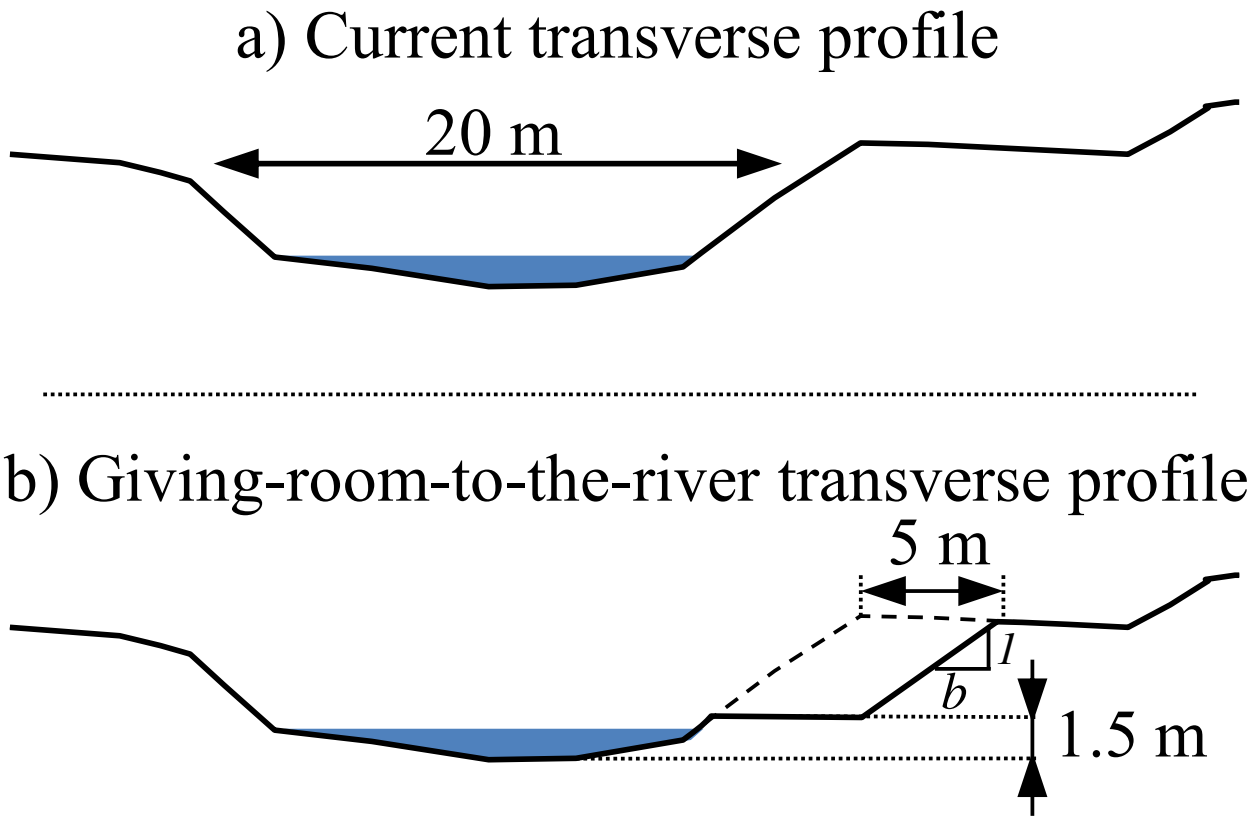
- Higher walls (HW)
- Flood-plain storage (FPS): dynamic using weirs and optimal control (underdeveloped)
- Giving-room-to-the-river (GRR)
- Natural Flood Management (NFM): tree planting, peat land, leaky dams
- Beaver colonies
- Sustainable urban drainage systems (SUDS)
- Dredging
- Resilience?

How (well) can we mitigate flooding?

Higher flood defence walls – HW ($2\mathrm{m}$ 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):

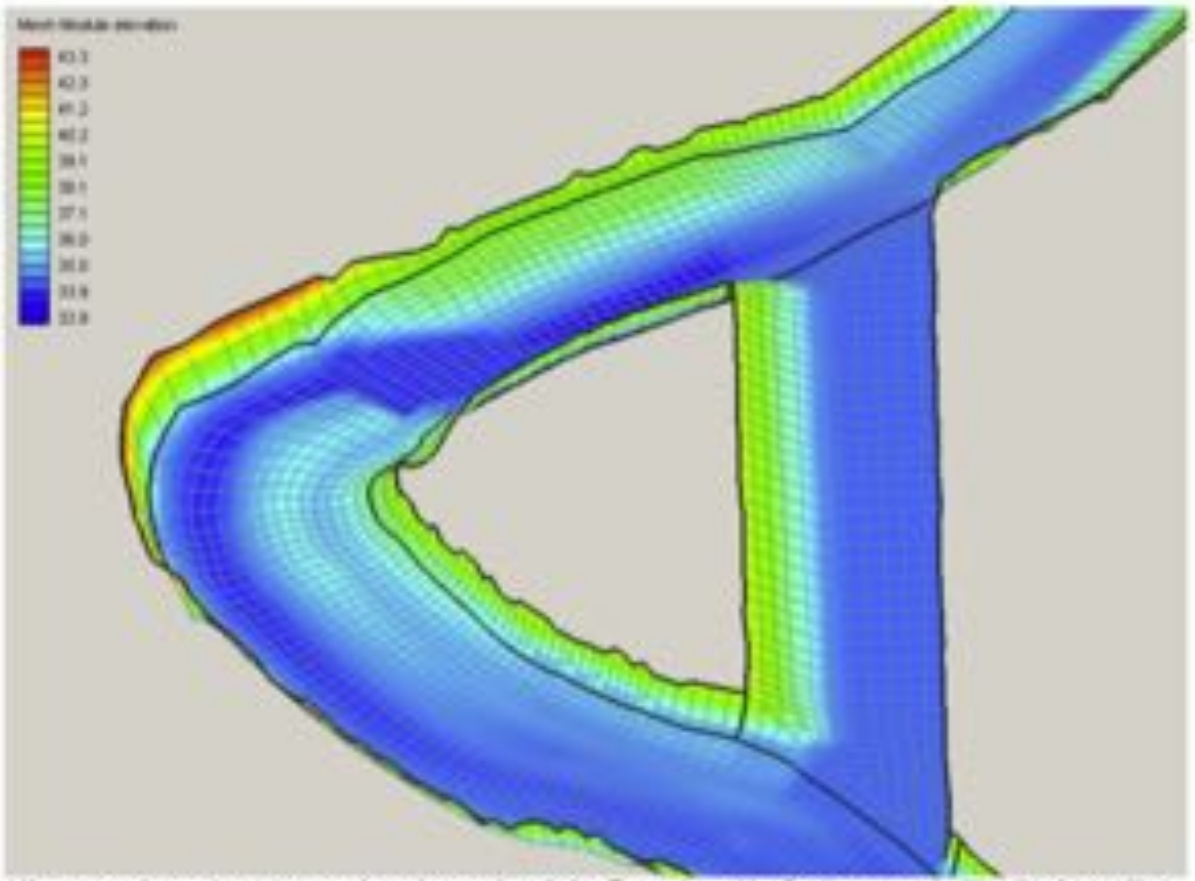


Illustration 1: Meander bend with flood relief channel, TUFLOW FV mesh

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:

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: $\sim 1100\mathrm{m}^3 = 1.100.000$litres.

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.

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

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?

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

How (well) can we mitigate flooding?

Dredging –Wainfleet Flood Action Group; 16-08-2019 "Onnootje Brinker" found another weak spot in dike within 400m of repaired breach:

How (well) can we mitigate flooding?

Resilience: raising of new houses now mandatory in Wainfleet

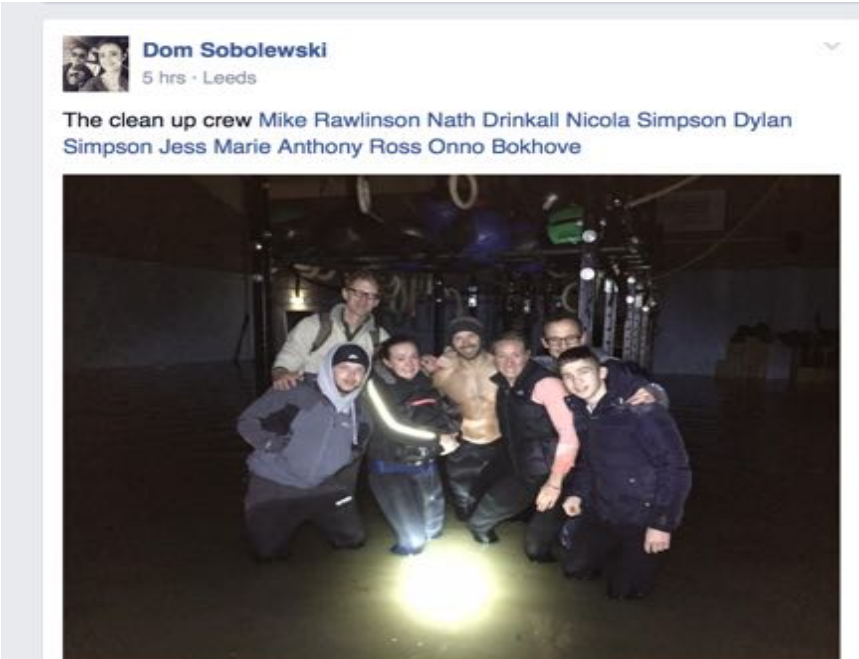
How (well) can we mitigate flooding?

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

How (well) can we mitigate flooding?

Resilience. DIY:

- Bespoke flood-evacuation plan for Xfit Leeds with estimates on how much time one has to evacuate.
- Based on in-situ $15\mathrm{min}$ Armley river-gauge data and extrapolation or "differentiation".
- On-the-day made-up version was used in 2015 Boxing Day floods of River Aire ($1:200^{+}\mathrm{yr}$) –saving ≥ 5000 pounds.



How (well) can we mitigate flooding?

Resilience. DIY:

- Lately used in Storm Ciara by several local businesses; false alarm by 10cm for Xfit & small flooding for others.
- EA's amber zone warning does not indicate how much time there is to evacuate, which requires bespoke local knowledge (numbers) and evidence.
- *What can you do yourself?* Define threshold: Armley 4.16m.

If we aren't sure, how can we test these things?

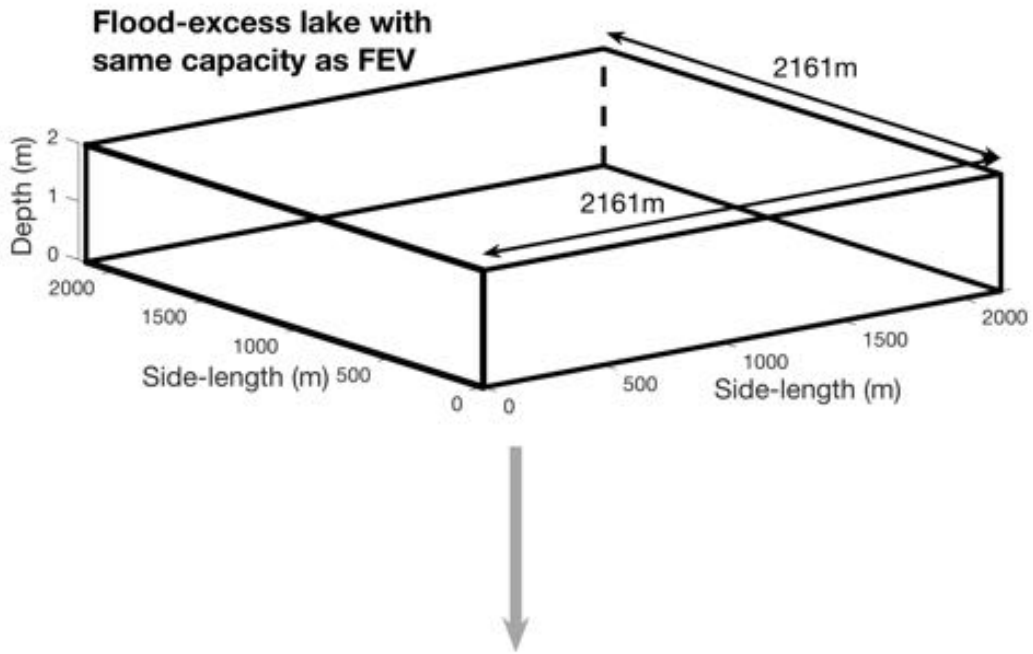
What (flood-excess) volume (FEV) causes the flood damage. By reducing FEV to zero, flood damage will be avoided.

River -	flood date(s) -	FEV Mm^3	h_T m	lake side m
Aire	26-12-2015	9.34 ± 1.50	3.9	2161
Calder	26-12-2015	1.65 ± 0.60	4.5	904
Don	25/26-06-2007	3.00 ± 0.71	2.9	1225
Brague	03-10-2015	0.488 ± 0.311	3.06	494
Tamar	23-12-2012	1.96	2.95	990
Tamar	24-12-2013	3.65	2.95	1350

Table : 6 FEVs, thresholds h_T, side length of $2\mathrm{m}$ deep lake. Recall peak flow Aire $344\mathrm{m}^3/\mathrm{s} = 2\mathrm{m} \times 13\mathrm{m} \times 13\mathrm{m}/\mathrm{s}$. Flood lasted $32\mathrm{hrs}$.

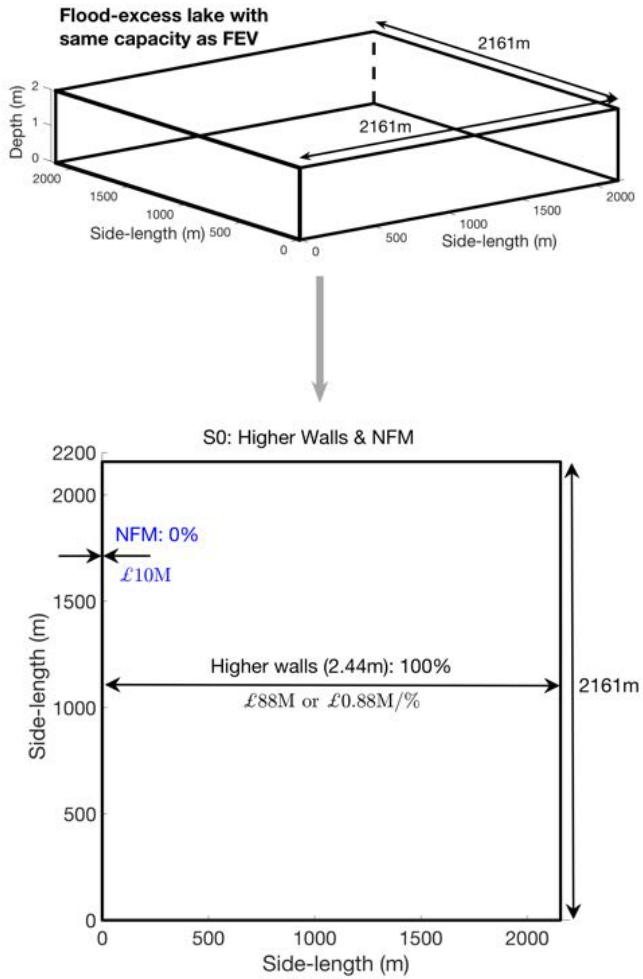
If we aren't sure, how can we test these things?

- So the flood-excess volume (FEV) of the River Aire Boxing Day flood was $\underline{9.34\mathrm{Mm}^3}$, so nine million and a bit cubic metres. How big is that?
- It is equivalent to a $\underline{2\mathrm{m}}$ deep square lake of side length $2161\mathrm{m}$:



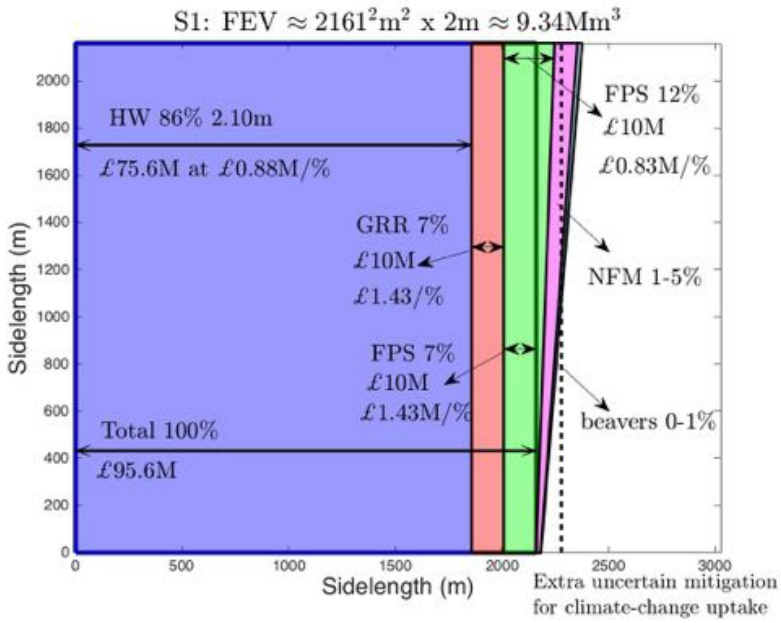
If we aren't sure, how can we test these things?

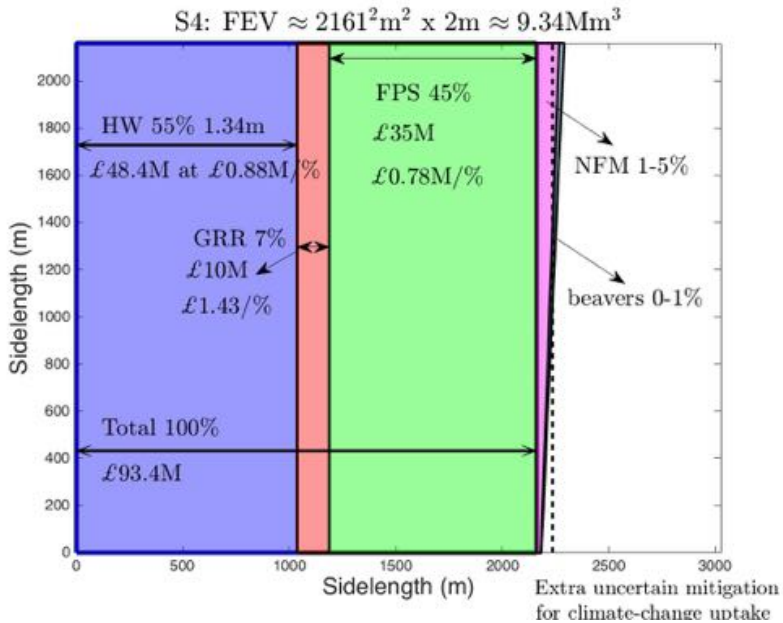
Let us test this for Leeds' Flood Alleviation Scheme FASII$^+$ (real FASII plus hypotheses for unknown/unprovided info):



If we aren't sure, how can we test these things?

Make a graph of relative contributions & costs of each flood-mitigation measure to reducing the flood lake to zero! (88 beaver colonies count for less than 1%! B. et al 2020)





Are we worried enough about future extreme flooding events?

- Since the 2008 Pitt review, the pitfalls of UK flood management are well known.
- Flood-plain storage and giving-room-to-the-river are the most promising, besides higher walls.
- The Dutch learned the hard way: near miss of (Rhine) river flooding in 1995 led to the "Ruimte-voor-de-river" philosophy –giving-room-to-the-river.

Are we worried enough about future extreme flooding events?

- The Dutch learned the hard way: the 1717 Christmas Storm surge led to 14.000 casualties in Groningen, Northern Germany and Denmark.
- The selfish regents of Groningen grossly mismanaged flood defenses, ignoring warnings by the retired sea captain Thomas van Seerrat on the abysmal state of the sea dikes.

Flood protection needs your maths!

https://izi.travel/nl/078f-1953-de-doorbraak-bij-ouderkerk-aan-den-ijssel/nl

References

- All information of the Wetropolis flood demonstrator & report Wainfleet visit: https://github.com/obokhove/wetropolis20162020
- On cost-effectiveness analysis of flood-mitigation measures:
  - Bokhove, Kent, Kelmanson, Piton, Tacnet 2019: Communicating (nature-based) solutions using flood-excess volume for three UK and French river floods. *River Res. Applications* **35**, 1402–1414. https://onlinelibrary.wiley.com/doi/full/10.1002/rra.3507
  - Bokhove, Kent, Kelmanson, Piton, Tacnet 2020: A cost-effectiveness protocol for flood-mitigation plans based on Leeds' Boxing Day 2015 floods. *Water*. Revision. Early 2018 version: https://eartharxiv.org/stc7r/
  - Bokhove, Kent, Kelmanson 2018: Using flood-excess volume to show that upscaling beaver dams for protection against extreme floods proves unrealistic. https://eartharxiv.org/w9evx/
  - Beaver bites dog in Biesbosch: https://www.ad.nl/rivierenland/bever-bijt-hond-tot-bloedens-toe~adb66601/?referrer=https://www.google.com/

Flood protection needs your maths!

- DIY flood-mitigation evacuation plan: `https://bardvantwenthe.wordpress.com/2020/02/13/kirkstall-flood-evacuation-during-storm-ciara/` (email me for password).