

Wetropolis

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Bokhove

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& flooding?

Predict heavy
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Mitigate
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Discussion

Wetropolis flood demonstrator: on extreme rainfall & river flooding

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Hicks & Tom Kent



Mathematical Institute, Oxford, Dec. 2nd 2016

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In Hebden Bridge (“Science of floods”), a town in Yorkshire that has seen a lot of sustained and flash floods over the last decade, I addressed the following questions:

- Is it going to **rain more** in the future?
- Can we define **extreme precipitation & flooding events**?
- How (well) **can we predict** heavy precipitation & floods?
- How (well) can we mitigate and **control flooding**?
- How can we **elucidate** the above in an interactive, conceptual table-top demonstration “Wetropolis” ?

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I will elucidate the answers to the above and use these in the design and modelling of an interactive, conceptual table-top demonstration and experiment on rainfall, flooding as well as flood mitigation and control. The design will serve 2 purposes:

- as **public demonstration** of the concepts of flooding and
- **simplified test environment** on the science of flood modeling:
 - reliable estimation of extreme flooding events
 - improve short-term forecasts using data assimilation
 - multi-scale modelling of street-sewer networks
 - rational mathematical strategies for flood control.

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I will identify mathematical elements involved to model:

- “random” rain supply, channel/river flow,
- the hydrology of “Hele-Shaw” valleys (illustrating effects porous moors, fast run-off from tarmac, and the function of reservoirs),
- flow in bypass canals, and
- control features such as weirs and sluice gates as well as
- data assimilation using a few measurement points.

Work in progress . . .

2. Is it going to rain more in the future?

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Definitions:

- *Return period*: if 100 years of *daily rainfall* data were available, an event with a 1 in 20 year return period would be expected to occur 5 times in that data set.
- In any year such an event has on average a 5% chance to happen on one day per year.
- *Extreme events*: events with a (longer) return period of 1 in 5, **1 in 10**, 1 in 20, **1 in 30**, 1 in 50 or **1 in 100** years.



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Similarly, Michael Sanderson's UKCP09 report Met Office 2010 (data 1960–2006), for UK:

- 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.



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

3. Define extreme precipitation & flooding events?

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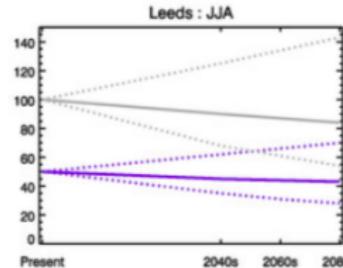
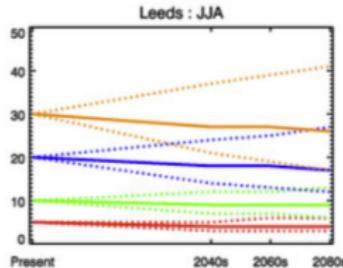
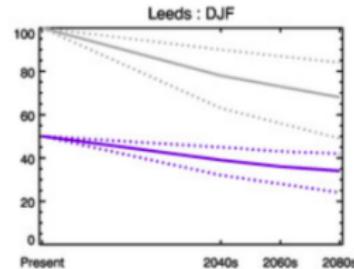
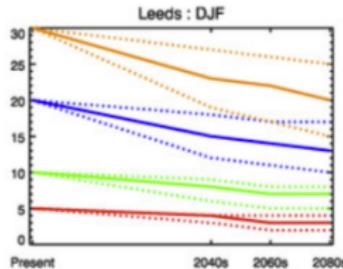
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Caution:

- The **uncertainty** in the return period for a 1 in 100 year event will be **larger** than in a 1 in 20 year event.
- **Uncertainty** will be **smaller** for larger data sets.



Extreme precipitation and flooding events?

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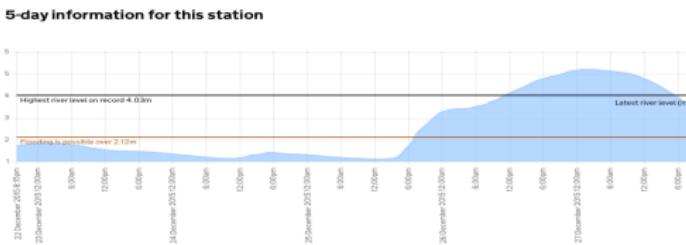
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Challenges and basic problem (Coles, 2001):

- There are very **few observations** “in the tail of the distribution”, i.e. for **extremes** with long return periods.
- **Estimates required beyond largest observed data values.**
- E.g., Aire River gauge at Armley/Leeds had highest record of **4.03m prior to 26-12-2015**; how to estimate return period for 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**.

Modelling Extreme Rainfall

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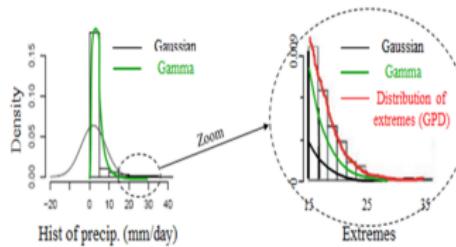
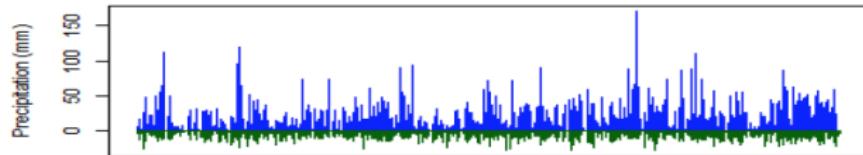
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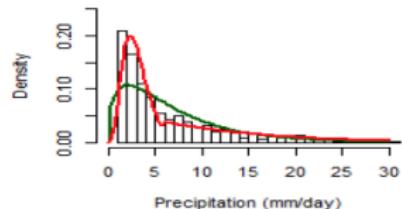
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- Wong, Maraun, ... Kent 2014, J. Climate; MSc Kent:

Kinlochewe DJF



Anglesey JJA



Modelling Extreme Rainfall

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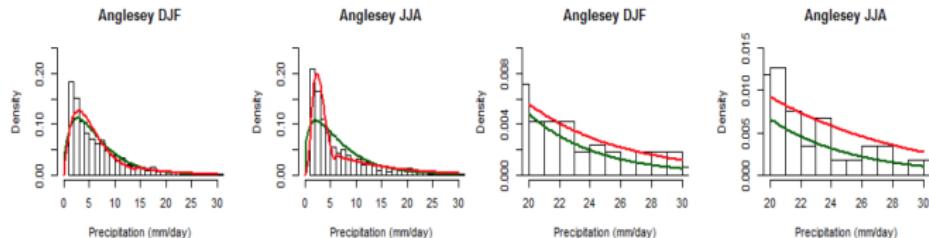
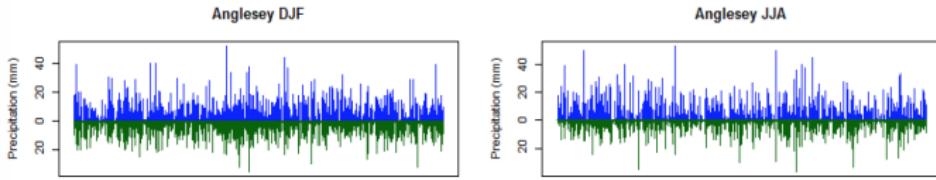
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- Fit of Γ - & generalised Pareto distributions (Ziggurat):

$$h(r; \beta) = c_\beta ((1 - w(r; m, \tau)) f(r; \gamma, \lambda) + w(r; m, \tau) g(r; \xi, \sigma\mu = 0)) \quad (1)$$



(a) The bulk of the distribution

(b) The extreme upper tail of the distribution

4. How (well) can we predict heavy precipitation and (overland) floods?

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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) can we predict heavy precipitation and (overland) floods?

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- Sustained rainfall and flooding, e.g.
Boxing Day rainfall and floods 26-12-2015
Kildwick; Bingley; Armley
- **Aire River Flood & Aire River Kirkstall The Forge**

Latest river level information for: the River Aire at Bingley

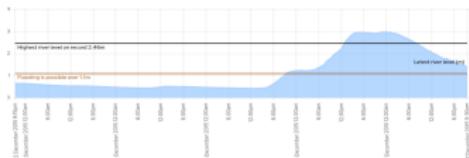
Updated Sunday 27 December 2015

Latest level:
1.42m

Recorded at 9:30pm Sunday 27 December 2015

Flooding is possible. The latest information recorded at this location indicates the river is above its typical range of 0.21 metres to 1.10 metres.

5-day information for this station



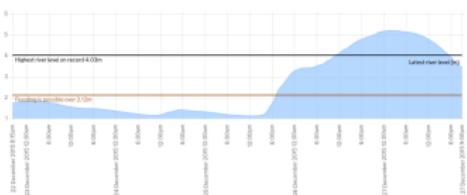
Latest level:

3.44m

Recorded at 9:00pm Sunday 27 December 2015

Flooding is possible. The latest information recorded at this location indicates the river is above its typical range of 0.29 metres to 2.12 metres.

5-day information for this station



How (well) can we predict heavy precipitation and (overland) floods?

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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.

Figure 2: <http://blog.metoffice.gov.uk> Rainfall summary 25-27 December 2015.



How (well) can we predict heavy precipitation and (overland) floods?

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- **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.
- **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, due to a lack of data.

5. How (well) can we mitigate flooding?

- Create multiple **storage buffers** upstream.
 - Lowers peak values but broadens the flood peaks.
 - May work less well for large water volumes, including consecutive heavy rainfall events.
- Create **more permeable surfaces**, green soft-surface gardens and absorbing roofs in urban areas, wadis.
- Use **bypass canals as overflow channels** to lessen peaks.
Does require maintenance and alteration to canal system.

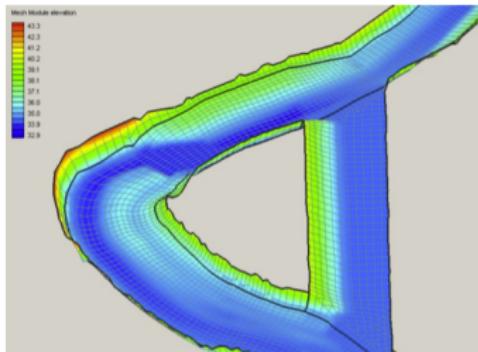


Illustration 1: Meander bend with flood relief channel, TUFLOW FV mesh

How (well) can we mitigate flooding?

- Sustainable flood plain management: designated flood plains (pay owners), houses on stilts, houses on mounts with surrounding canals/wadis.
- Legislation & “Waterschappen” (Water Governance).
- Create “Ruimte voor Water” (Space-for-Water), cf. The Netherlands & Germany 1995 & 1997 floods.



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6. Wetropolis: conceptual table-top demo?

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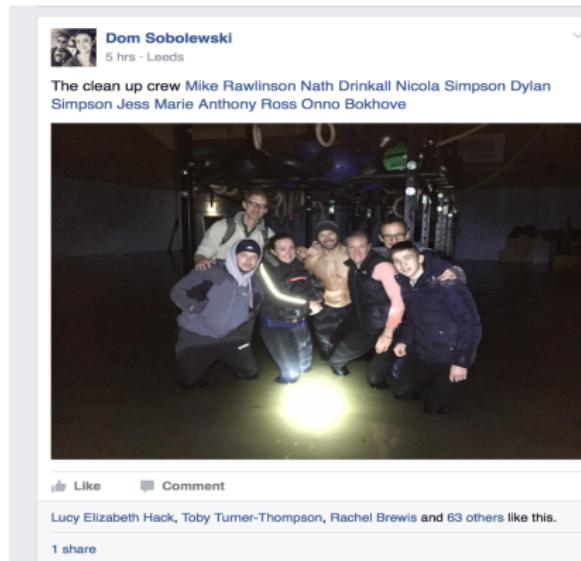
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A **demo** to highlight the **concepts of flooding**:

- Use *vertical cells* as conceptual valleys:

- spongey material=moor
- hard surface=urban asphalt,
- adjustable weirs for storage in reservoirs, etc.



Wetropolis: conceptual table-top experiment?

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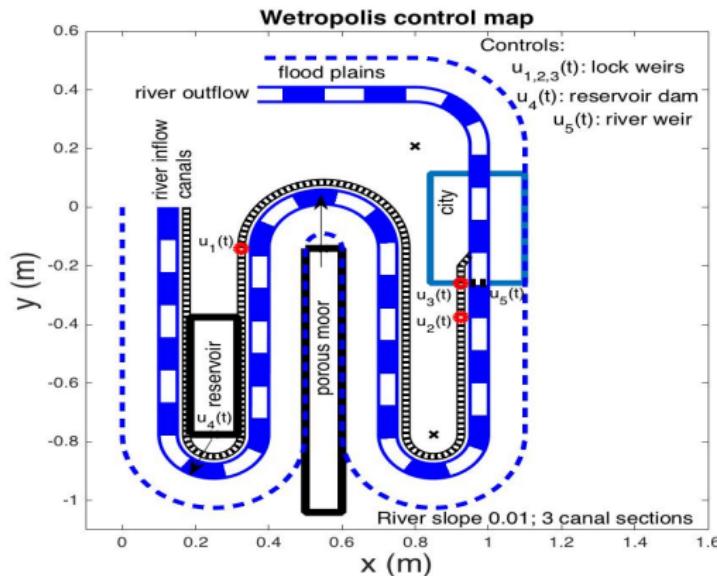
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- Plan-view, *mathematical design* before construction:



- <https://www.facebook.com/resurging.flows>

Wetropolis: conceptual table-top experiment?

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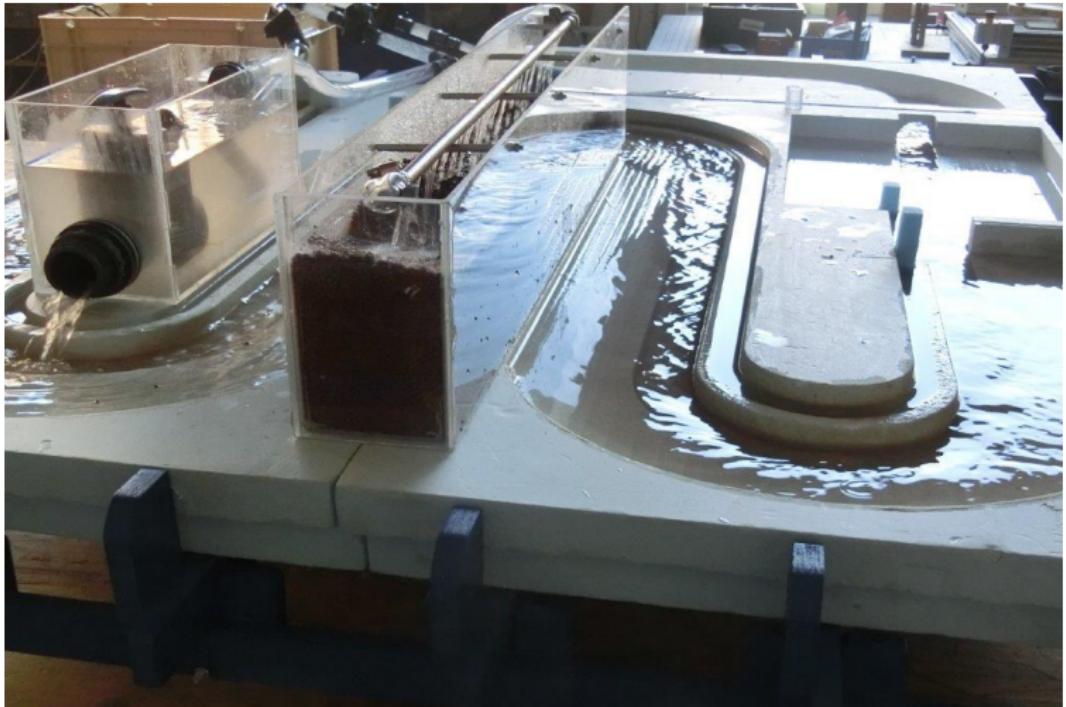
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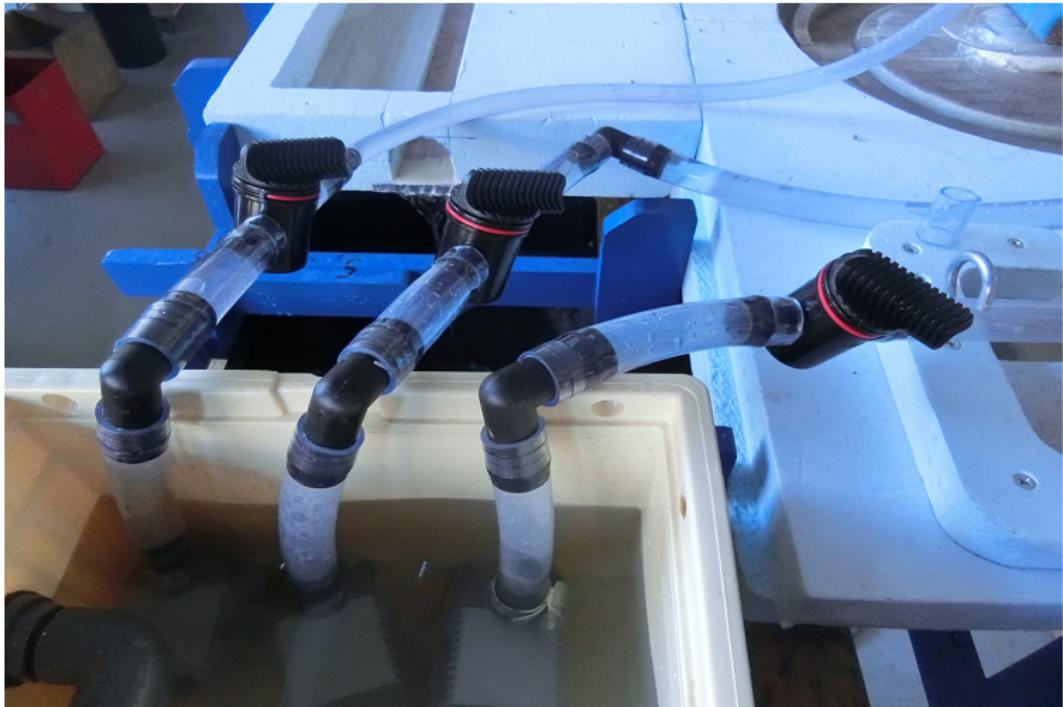
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7. Design Hydro- & Meteorological Simulator

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Prototype 0.0 with one river, one canal, one “Hele-Shaw” moor as valley, one reservoir as valley:

- River; modelled 1D, straight with depth $h_r(x, t)$ with $x \in [0, L_x]$, e.g., $L_x = 4.211\text{m}$
- River: simple kinematic model, bottom slope balances Manning friction
- Canal: modelled 1D, straight as compartment depths $h_{3c}(t)$ for $x \in [0, L_{3c}]$, $h_{2c}(t)$ for $x \in [L_{3c}, L_{2c}]$ and $h_{1c}(t)$ for $x \in [L_{2c}, L_{1c}]$
- Canal: closed at $x = 0$, weir between canals 3&2 at $x = L_{3c}$, weir between canals 2 & 1 at $x = L_{2c}$, weir between canal 1 and river at $x = L_{1c}$.

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Prototype zero with one river, one canal, one porous moor as valley, one reservoir as valley:

- “Hele-Shaw” moor: porous cell with Darcy flow and ground water level $h_m(y, t)$ orthogonal to canal; $\gamma_m \in [0, 1]$ flows via weir into canal and $1 - \gamma_m$ into the river at $x = L_w < L_{1c}$
- Reservoir: “Hele-Shaw” cell with depth $h_{res}(t)$ & weir height $P_{wr}(t)$.
- Controls: splitter and weir heights $\gamma_m(t), P_{1w}(t), P_{2w}(t)$.

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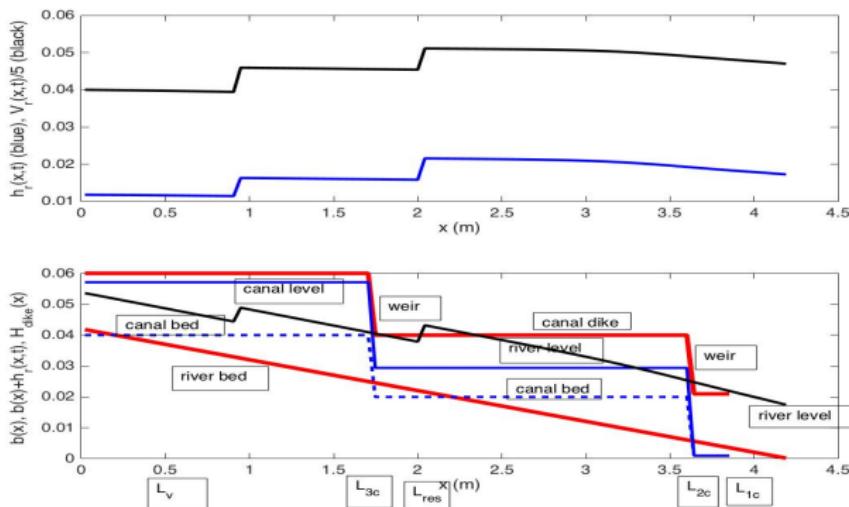
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Side view of canals & river and their bed & waterlevel profiles:



River Flow

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- Cross section $A = A(x, t) = A(h)$ with depth $h = h(x, t)$ above bottom $b = b(x)$, e.g. $A = w_r h$, velocity $u(x, t)$:

$$\partial_t A + \partial_x(Au) = F$$

$$\underline{\partial_t u + u \partial_x u + g \partial_x h} = -g(\partial_x b + C_m^2 u |u| / R^{4/3}) \quad (2)$$

- hydraulic radius $R(h) = \frac{\text{wet area}}{\text{wetted perimeter}} = \frac{w_r h}{2h + w_r}$
- Manning friction coefficient $C_m \in [0.01, 0.15]$
- Kinematic model for $u > 0$, upwind information speed $dQ(A)/dA > 0$ for flux $Q(A) = Au$ and inflow $A(h(0, t))$:

$$u = R^{2/3} \sqrt{-\partial_x b} / C_m$$

$$\partial_t A + \partial_x(A R^{2/3} \sqrt{-\partial_x b} / C_m) = F$$

$$\text{or } \partial_t(w_r h) + \partial_x(w_r h R(h)^{2/3} \sqrt{-\partial_x b} / C_m) = F. \quad (3)$$

River Flow

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- Kinematic model or **nonlinear conservation law** in h for $u > 0$ with $A = w_r h$:

$$\partial_t(w_r h) + \partial_x(w_r h R(h)^{2/3} \sqrt{-\partial_x b} / C_m) = 0$$

- Upwind information speed $dQ(A)/dA > 0$ for flux $Q(A) = Au$ and inflow $A(h(0, t))$:
- F : influx water from moor $x = L_v \approx 2.038$, $y = 0$

$$Q_m(h_m) = (1 - \gamma_m) m_{por} \sigma_e w_v g \alpha \frac{1}{2} \partial_y(h^2)|_{y=0} \quad (4)$$

- F **inflows**: canal section 1 water at $x = L_{1c}$, inflow reservoir water at $x = L_{res}$.

Groundwater Flow

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- Depth-averaged ground water model with level $h_m(y, t)$ from Barenblatt (2002) in cell of width w_v , e.g. $w_v = 0.095\text{m}$.
- Nonlinear diffusion equation for ground water level $h_m(y, t)$ for $y \in [0, L_y = 0.932\text{m}]$:

$$\partial_t(w_v h_m) - \alpha g \partial_y(w_v h \partial_y h) = \frac{w_v R}{m_{por} \sigma_e} \quad (5)$$

- Rainfall $R(y, t)$, via wider funnel, into Hele-Shaw cell
- Porosity $m_{por} \in [0.1, 0.3]$, fraction $\sigma_e \in [0.5, 1]$ pores filled with water
- $\alpha = k/(\nu m_{por} \sigma_e)$ with permeability $k = 10^{-8}\text{m}^2$ and viscosity $\nu = 10^{-6}\text{m}^2/\text{s}$

Groundwater Flow

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- Nonlinear diffusion equation in ground water level $h_m(y, t)$ for $y \in [0, L_y]$:

$$\partial_t(w_v h_m) - \alpha g \partial_y(w_v h \partial_y h) = \frac{w_v R}{m_{por} \sigma_e} \quad (6)$$

- Boundary conditions: no flux/wall at $y = L_y$
- Time-dependent canal level $h_{3c}(t)$ at $y = 0$.
- In summary: porous cell represents sub-catchment to conceptualise/visualise groundwater flow.

Canals 2 & 3

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Canal with 3 sections; canal 2,3 of width w_c and depth $h_{2c,3c}(t)$:

- section 2 for $x \in [L_{3c}, L_{2c}]$, e.g. $L_{3c} = 1.724\text{m}$:
- section 3 for $x \in [0, L_{2c}]$, e.g. $L_{2c} = 3.608\text{m}$:

$$w_c(L_{2c} - L_{3c}) \frac{dh_{2c}}{dt} = \gamma_m m_{por} w_v \alpha g \frac{1}{2} \partial_y(h^2)|_{y=0} - Q_{2c} \quad (7)$$

- Canal 3: berm at $z = 0.06\text{m}$ & bottom at $z = 0.04\text{m}$
- Canal 2: berm at $z = 0.04\text{m}$ & bottom at $z = 0.02\text{m}$
- Weirs outflow into canal 2, 1 based on Bernoulli & flow criticality at $x = L_{3c,2c}$, e.g. for subcritical downstream

$$V_c = \sqrt{gh_c} \quad \text{and} \quad h_c = (2/3)(h_{2c} - P_{2w})$$

$$gh_{2c} + \frac{1}{2} V_{2c}^2 = g(h_c + P_{2w}) + \frac{1}{2} V_c^2 = \frac{3}{2} gh_c + gP_{2w}$$

$$\text{s.t. } Q_{2c} = h_c V_c = \sqrt{g} h_c^{3/2} = C_f \sqrt{g} \max(h_{2c}, P_{2w}, 0)^{3/2}$$

Canal 1

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- **Section 1** for $x \in [L_{2c}, L_{1c}]$, e.g. $L_{1c} = 3.858\text{m}$, width w_c and depth $h_{1c}(t)$:

$$w_c(L_{1c} - L_{2c}) \frac{dh_{1c}}{dt} = Q_{2c} - Q_{1c}$$

$$Q_{1c} = h_c V_c = \sqrt{g} h_c^{3/2} = C_f \sqrt{g} \max(h_{1c} - P_{1w}, 0)^{3/2}$$

- **Canal 1** has berm at $z = 0.021\text{m}$ and its bottom at $z = 0.001\text{m}$
- **Weir** at $x = L_{1c}$ when flow into river subcritical, i.e. sufficient drop from canal 1 to river level.

Reservoir with Weir

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- Reservoir with length $L_{yy} = 0.293\text{m}$, width $w_{res} = 0.123\text{m}$, level $h_{res}(t)$:

$$\frac{dh_{res}}{dt} = R_{res}(t) - Q_w / (L_{res} w_{res})$$

$$Q_w = C_f \sqrt{g} w_{res} \max(h_{res} - P_{wr}, 0)^{3/2}$$

- Weir located at $x = L_{res} = 0.932\text{m}$, where water flows into the river.

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Discretise rainfall events (risk):

- Rainfall is discretized. In our Simulator, we discretise rainfall further into two sets of categories: location & rain amount.
- Our Wetropolis Day wd is TUs.
- Rain location has 4 categories: rain in reservoir, moor & reservoir, moor, or no rain in the catchment.
- Rain amount has 4 categories per location
 $(1, 2, 4, 9)r_0/wd$, gauged such that there is no flooding for $(1, 2, 4)r_0/wd$ rainfall, with limited flooding for $(8, 9)r_0/wd$ rain in one location & flooding for $18r_0/wd$ rain in moor & reservoir.

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- The probabilities for **rain amount** are “binomially” distributed physically using a half/stepped 8-pins Galton board: $\frac{3}{16}, \frac{7}{16}, \frac{5}{16}, \frac{1}{16}$ (risk).
- The probabilities for **rain location** are determined using another 8-pins Galton board as $\frac{3}{16}, \frac{7}{16}, \frac{5}{16}, \frac{1}{16}$.
- There are therefore **five rainfall outcomes** possible per Time Unit with probabilities: no rain at $\frac{1}{16}$
- The rain amount per *wd* will be determined by **gauging**, such that there is no flooding with rain amounts $(1, 2, 4)r_0$, moderate flooding possible when $(8, 9)r_0$ & **massive flooding** for $18r_0$.

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- Table of rainfall amount/TU versus rain location:

Table : Probability matrix times 256.

	r_0	$2r_0$	$4r_0$	$9r_0$
reservoir	9	21	15	3
both	21	49	35	7
moor	15	35	25	5
no rain	3	7	5	1

- Accumulated rainfall amounts (divided by Time Units) in catchment: $0 : 0.0625 = 1/16$, $r_0 : 0.0938 = 24/256$, $2r_0 : 0.3008 = 77/256$, $4r_0 : 0.3477 = 89/256$, $8r_0 : 0.35 = 35/256 = 0.1367$, $9r_0 : 0.0469 = 8/256$, $18r_0 : 0.0273 = 7/256$.

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Two draws from asymmetric Galton board:

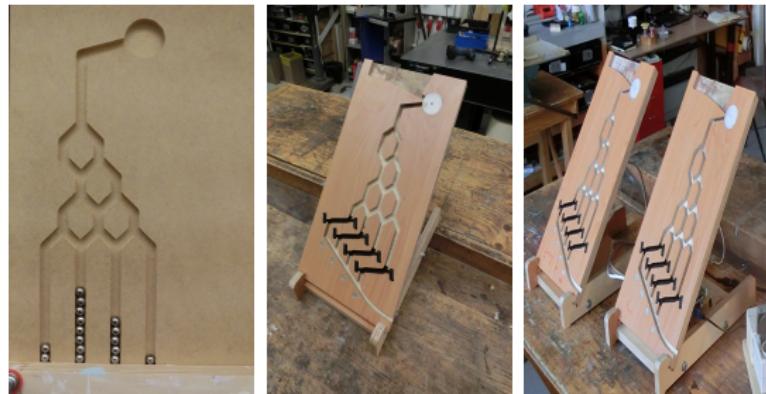


Figure : Predictions 1D synthetic model 100 random $wd = 10s$ rainfall episodes using draws from Galton board: a) Evolution water levels in 3 canals & reservoir. b) River levels upstream & downstream. c) Snapshot groundwater level in moor. d) Rainfall amounts $(1, 2, 4, 8, 9, 18)r_0$ with 2 extremes (average 2.73), coinciding with 2 flood peaks in c). Rain falls in reservoir, both, moor or not.

Sample Simulation 1

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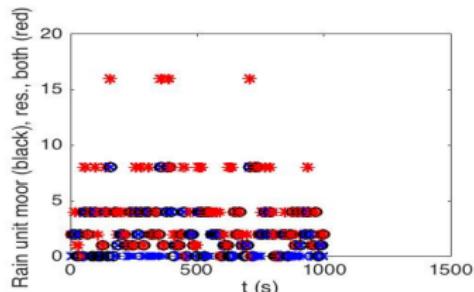
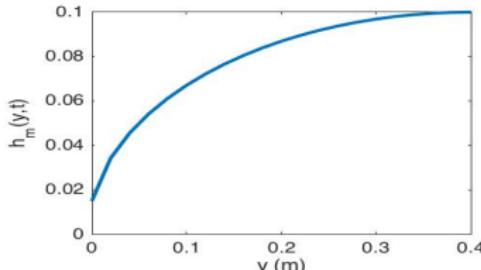
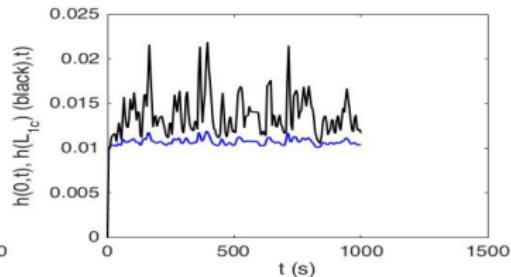
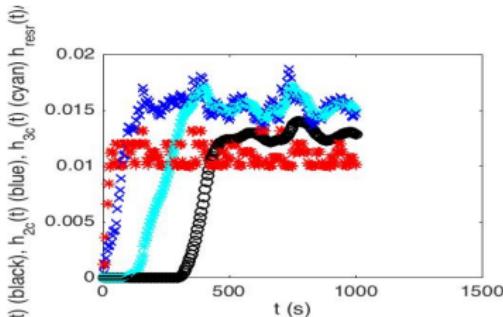
Mitigate
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At $t = 0$: canals, moor and reservoir empty. $wd = 10s$,
 $r_0 = 0.18 \text{ l}/\text{wd}$



Sample Simulation 2

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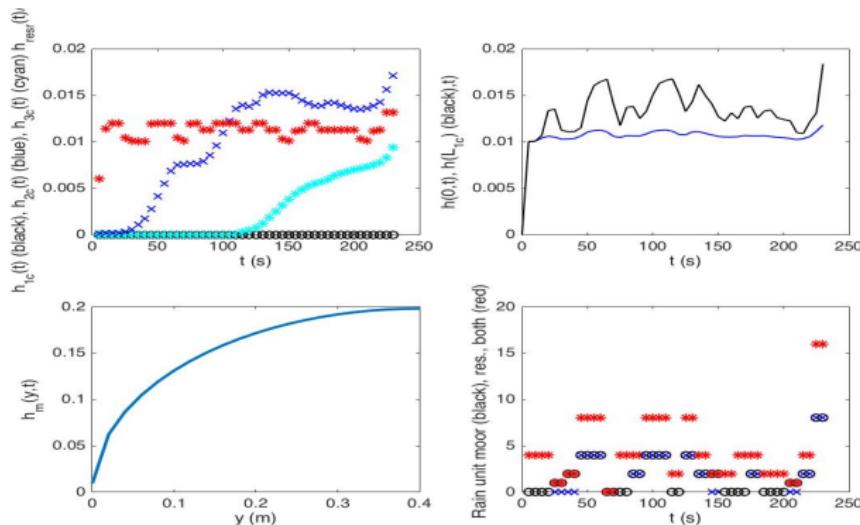
Mitigate
flooding?

Wetropolis

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Discussion

At $t = 0$: canals, moor and reservoir empty. $wd = 10s$,
 $r_0 = 0.18l/wd$



Sample Simulation 2

Wetropolis

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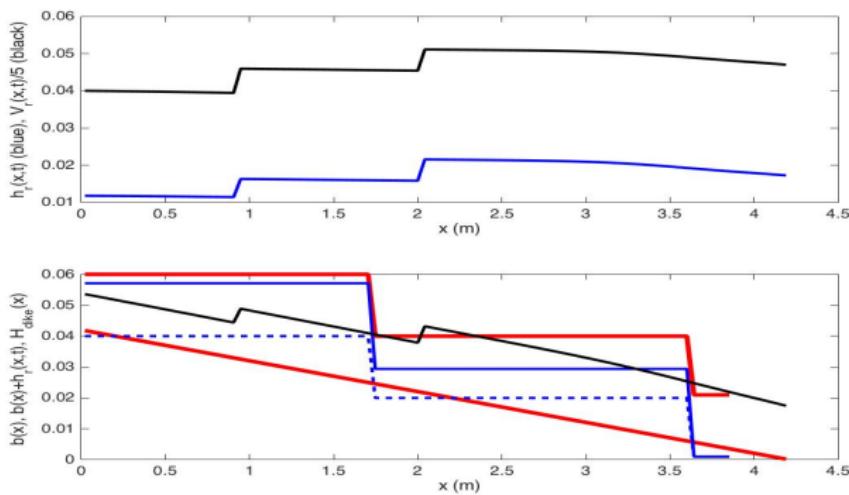
Mitigate
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At $t = 0$: canals, moor and reservoir empty. *Simulation*.



8. Discussion

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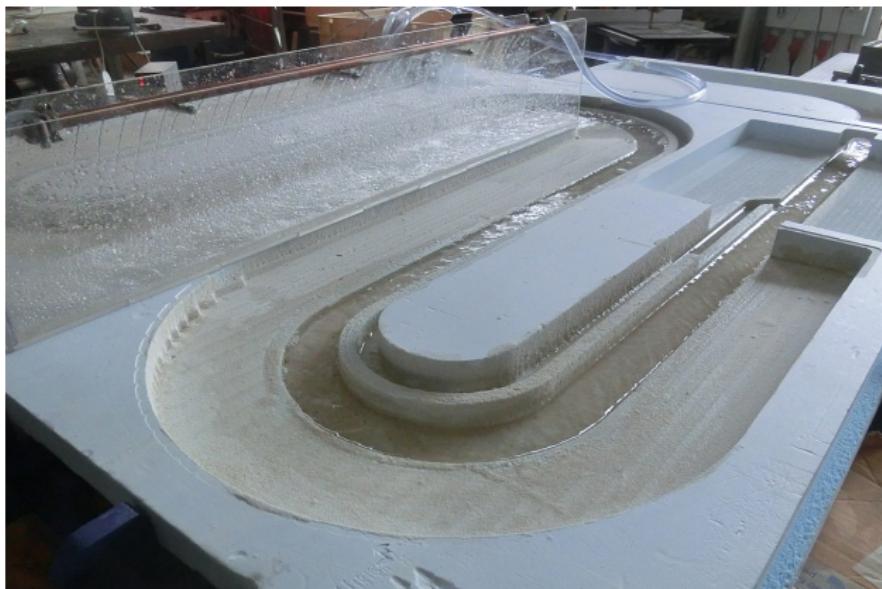
Mitigate
flooding?

Wetropolis

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Discussion

- Constructed 2-day rainfall induced *Boxing Day floods*:



- Redesign Wetropolis with deterministic location generator (chaotic, fluid dynamical) instead of probabilistic one, e.g. hydraulic & chaotic seesaw (Prof Chris Jones & Church) ☺☺☺

Discussion

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Discussion

- 0(1) **1D mathematical model** led us to **Wetropolis**:
experience extreme rainfall & flooding events.
- **To do:** control & data assimilation: **natural** measures,
river & canal levels & rainfall.
- **More advanced:** 2D shallow-water modelling, 3D Richard's
equation for groundwater, ensemble Kalman DA,
homogenisation of streets/sewers . . .
- **Invitations:** Boxing Day flood exhibit (Leeds Industrial
Museum Dec. 8 4-6pm) & etc.
- ***The End.***