Mathematical and numerical modelling of the Wetropolis flood and rainfall demonstrator

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LIFD ECR forum – 29 October 2020

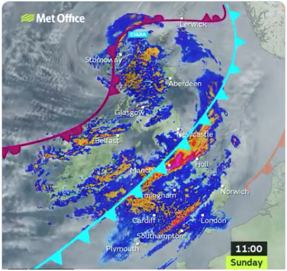
Talk outline

- **Motivation:** extreme rainfall and flooding
- **Wetropolis flood demonstrator:** background and description
- **Mathematical and numerical modelling of rivers:** open-channel flow
- **Simulations:** the Wetropolis 'live' dashboard
- **Current/next steps:** ...

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

Motivation: high-impact weather

E.g., Storm Ciara (Feb. 2020): from **numerical weather prediction** to **flooding** (in Leeds)



Source: Met Office and LeedsLive.

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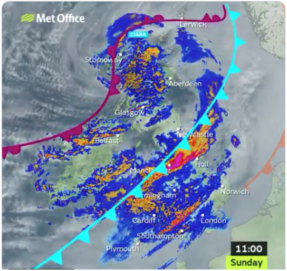

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Urban flooding is a major hazard worldwide, brought about by intense rainfall and often exacerbated by the built environment.

Flood mitigation requires accurate predictions **(good models + data)** as well as **effective communication and engagement** of stakeholders and the public.

Introducing Wetropolis (Est. 2016)

- **interactive table-top model** of extreme rainfall and flooding (outreach project)
- conceptualises many important aspects of the **science of flooding and extreme events** in a way that is accessible to and directly engages the public...

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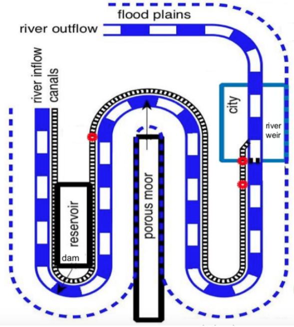
- Also of interest from a **(fluid dynamical) modelling** perspective: (i) design model and (ii) testbed for predictive modelling and data assimilation.

Introducing Wetropolis: design and set-up

GOAL (2016): to demonstrate random extreme rainfall and flood events in a physical model on reduced spatial and temporal scales.



Components:

- a winding river channel with parallel canal,
- a reservoir for water storage,
- a porous groundwater cell (analogous to a moor)
- and random daily rainfall.

Water enters the river channel in four places:

(i) the upstream inflow;

(ii) overflow from the reservoir;

(iii) overflow from the groundwater cell; and

(iv) via the canal in the city.

The river bed is sloping down (uniformly with gradient 1 in 100); different channel cross-sectional areas in floodplain regions and urban/city region (more later on).

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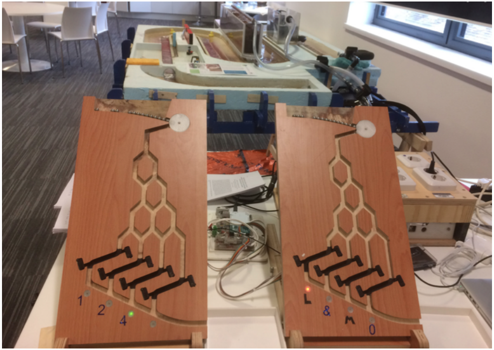

Rainfall is supplied randomly:

- in space at four locations **(reservoir, moor, reservoir and moor, or nowhere)**
- in time at four rainfall rates corresponding to **10%, 20%, 40%, or 90%** of a Wetropolis day (wd)
- joint probabilities (rain amount times rain location) determined daily via **two asymmetric Galton boards** (16 possible outcomes)

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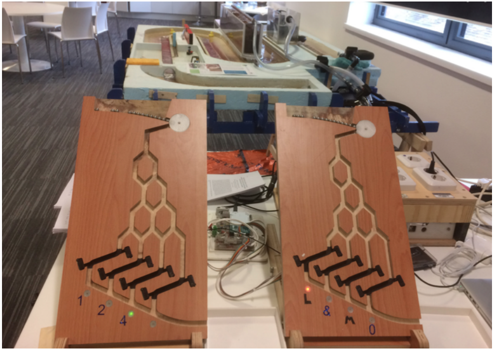

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The most extreme daily rainfall event thus involves rainfall on both moor and reservoir for 90% of a Wetropolis day with probability $7/256 = 0.027\ldots$; i.e., we must wait on average $256/7 \approx 36$ wds for an 'extreme' rainfall event.

Wetropolis: modelling

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Achieved! How? Numerical design model to determine the relevant time and length scales prior to construction: crude, inexpensive but sufficient for rapid exploration of design choices.
Outcome: pump flow-rates determined, length of channel, Wetropolis day = 10 seconds, etc... lots of fun!

Recall: we must wait on average $256/7 \approx 36$ *wds for an 'extreme' rainfall event, so just over* 6 *minutes in real-time... important concept of return period.*

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GOAL (2020): to develop the hydrodynamic modelling further and improve the visualisation of its output, with a view to conducting real-time simulations with data assimilation.

Why?

- to enhance the outreach experience with a live display of the (real-time) numerical simulations in tandem with the physical set-up
- to investigate potential issues that arise when combining (imperfect) models and data in an idealised environment

Open-channel flow

- **Examples in our environment:** natural (e.g., rivers and streams) and man-made waterways (e.g., conduits, canals, drainage and sewer systems).
- Fluid flows through channels of varying geometries with a free surface.
- Fluid mechanical modelling of such flows is termed hydraulic modelling
- Unsteady open-channel flow is typically modelled using the St. Venant equations in one (along-channel) spatial dimension with along-channel coordinate.

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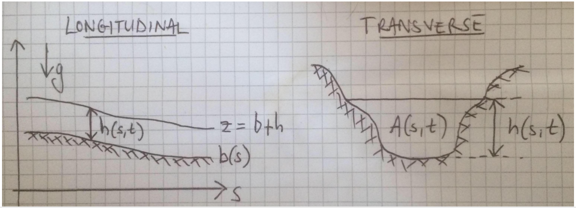
St. Venant equations

Equations of motion: hierarchy

Navier-Stokes $\xrightarrow[\text{average}]{\text{depth-}}$ 2D SWEs $\xrightarrow[\text{average}]{\text{area-}}$ 1D St. Venant

Assumptions:

- flow is hydrostatic, i.e., horizontal length and velocity scales well exceed their vertical counterparts such that vertical fluid accelerations are negligible;
- flow is one-dimensional, i.e., the transverse free surface is horizontal and the velocity is approximately uniform in a cross-section;
- channel curvature is small and the bed slope is small,
- sediment and bed motion are neglected on the timescales considered.



St. Venant equations

Model variables: cross-sectional area $A = A(s,t)$ and velocity $u = u(s,t)$, both functions of the along-channel spatial coordinate s and time t.

$$\text{Continuity:} \quad \partial_t A + \partial_s (Au) = S_A(s,t), \tag{1a}$$

$$\text{Velocity:} \quad \partial_t u + u\partial_s u + g\partial_s h - g\left(S_o - S_f\right) = 0, \tag{1b}$$

where:

- $S_A(s,t)$ is the mass source term [units $\mathrm{m}^2\mathrm{s}^{-1}$],
- $S_o = -\partial_s b$ is the bed slope [dimensionless], where $b = b(s)$ is the bathymetry,
- S_f is the friction term [dimensionless],
- and g is the gravitational acceleration [units ms^{-2}].

Note that water depth $h = h(s,t)$ appears in (1b) and is known via the (invertible) function $h = h(A(s,t), s)$; it depends explicitly on both $A = A(s,t)$ and s.

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The **Manning relation** for friction:

$$S_f = \frac{C_m^2}{R^{4/3}} u|u|, \tag{2}$$

where $R = R(h) = \frac{\text{wet area}}{\text{wetted perimeter}}$ [units m] is the hydraulic radius and C_m is the Manning friction coefficient.

Kinematic approximation

When the dominant balance is between the Manning friction and the bed slope – or when water depth, bed-slope and velocity are constant – we obtain the kinematic velocity approximation:

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Substituting the kinematic velocity into the continuity equation, we obtain the kinematic model:

$$\partial_t A + \partial_s\left(\frac{AR^{2/3}}{C_m}\sqrt{-\partial_s b}\right) = S_A(s,t). \tag{4}$$

This **kinematic model** for river flow has been used to determine suitable time- and length-scales efficiently for design purposes prior to construction of the physical Wetropolis set-up.

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To perform accurate predictions of the hydrodynamics in Wetropolis, more advanced models, e.g., the **St. Venant equations**, are likely required, in combination with an efficient **data assimilation** algorithm to constrain the model.

St. Venant equations: conservative form

Combining the continuity and velocity equations, the evolution equation for the momentum, or discharge, $Q = Au$ [units $\mathrm{m}^3\mathrm{s}^{-1}$] can be derived:

$$\partial_t(Au) + \partial_s\left(Au^2\right) + \underline{gA\partial_s h} = -g\left(A\partial_s b + \frac{C_m^2 Au|u|}{R(A)^{4/3}}\right) + uS_A(s,t). \qquad (5)$$

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Noting that the pressure term (underlined above) is in nonconservative form, it can be expressed as follows:

$$A\partial_s h = \partial_s\left(A\,h\right) - h\partial_s A. \qquad (6)$$

The $A\,h$ term is now in conservative form and the derivative no longer acts on h directly but on the dependent variable $A = A(s,t)$.

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The conservative form of the St. Venant equations can be re-expressed as:

$$\partial_t A + \partial_s(Au) = S_A(s,t), \tag{7a}$$

$$\partial_t(Au) + \partial_s\left(Au^2 + gA\,h\right) - \underline{gh\partial_s A} = -g\left(A\partial_s b + \frac{C_m^2 Au|u|}{R^{4/3}}\right) + uS_A(s,t), \tag{7b}$$

where the nonconservative product has been underlined.

St. Venant: hyperbolic?

St. Venant equations in vector form:

$$\partial_t \boldsymbol{U} + \partial_s \boldsymbol{F} + \boldsymbol{G} \partial_s \boldsymbol{U} = \boldsymbol{S}, \tag{8}$$

with vector of unknowns $\boldsymbol{U} = \boldsymbol{U}(s,t)$, flux $\boldsymbol{F}$, nonconservative product matrix $\boldsymbol{G}$ and source/sink vector $\boldsymbol{S}$ defined by

$$\boldsymbol{U} = (A, Au)^T, \quad \boldsymbol{F} = \boldsymbol{F}(\boldsymbol{U}) = (Au, Au^2 + g\,h\,A)^T,$$

$$\boldsymbol{G} = \boldsymbol{G}(\boldsymbol{U}) = \begin{pmatrix} 0 & 0 \\ -gh & 0 \end{pmatrix}, \quad \boldsymbol{S} = \boldsymbol{S}(\boldsymbol{U}) = \left(S_A, -gA\partial_s b - g\frac{C_m^2 Au|u|}{R^{4/3}} + u\,S_A \right)^T. \tag{9}$$

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The Jacobian matrix $\boldsymbol{J} = \partial \boldsymbol{F}/\partial \boldsymbol{U} + \boldsymbol{G}$ for system (8) is then given by

$$\boldsymbol{J} = \begin{pmatrix} 0 & 1 \\ -u^2 + gA\partial h/\partial A & 2u \end{pmatrix}. \tag{10}$$

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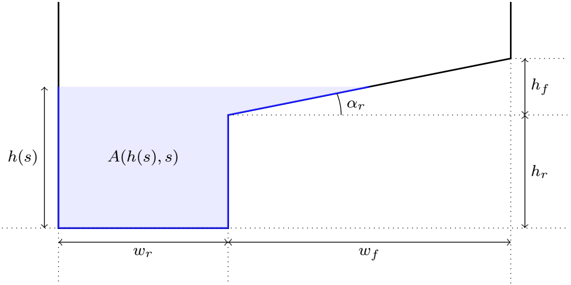
and its eigenvalues of $\boldsymbol{J}$ are

$$\lambda_{\pm} = u \pm \sqrt{gA\,\partial h/\partial A}. \tag{11}$$

If $\partial h/\partial A$ is positive, the eigenvalues are real and therefore the system is hyperbolic. There exist novel numerical methods for integrating (nonconservative) hyperbolic systems of PDEs ... e.g., FV or discontinuous Galerkin FEM.

Wetropolis: channel geometry I

Schematic of the channel geometry with a one-sided sloping floodplain: the cross-sectional area $A = A(h, s)$ (blue shaded area) with associated wetted perimeter $W = W(h)$ (thick blue line), in this instance for $h_r < h < h_r + h_f$. When $h < h_r$, the water flows in the rectangular channel of width w_r.



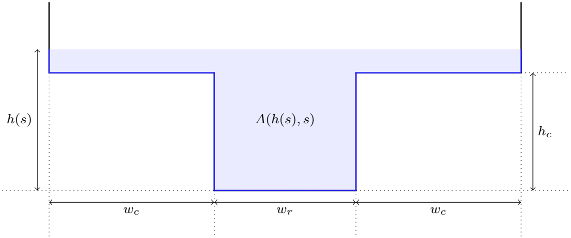
Water depth h as a function of cross-sectional area A and along-channel coordinate s:

$$h(A, s) = \begin{cases} A/w_r & \text{when } A < A_1; \\ h_r - w_r \tan\alpha_r + \sqrt{w_r^2 \tan\alpha_r^2 + 2(A - w_r h_r)\tan\alpha_r} & \text{when } A_1 < A < A_2; \\ \frac{(A + w_f(h_r + \frac{1}{2}h_f))}{w_r + w_f} & \text{when } A > A_2; \end{cases}$$

with $A_1 = w_r h_r$ and $A_2 = (h_r + h_f)(w_r + w_f) - w_f(h_r + \frac{1}{2}h_f)$. Note that $\partial h/\partial A > 0$.

Wetropolis: channel geometry II

Schematic of the channel geometry in the city: the cross-sectional area $A = A(h, s)$ (blue shaded area) with associated wetted perimeter $W = W(h)$ (thick blue line), in this instance for $h > h_c$ **(in flood)**. When $h < h_c$, the water flows in the rectangular channel of width w_c.



Water depth h as a function of cross-sectional area A and along-channel coordinate s:

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with $A_c = w_r h_c$. Note that $\partial h / \partial A > 0$.

The **full Wetropolis system** of river, moor, canals, and reservoir, all coupled together with weir relations, for the unknowns $A(s,t)$, $u(s,t)$, $h_m(y,t)$, $h_{res}(t)$, $h_{1c}(t)$, $h_{2c}(t)$ and $h_{3c}(t)$ is as follows:

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$$\text{River:}\quad \begin{cases} \partial_t A + \partial_s(Au) = S_A \\ \partial_t(Au) + \partial_s\left(Au^2\right) + gA\partial_s h = -g\left(A\partial_s b + \frac{C_m^2 Au|u|}{R^{4/3}}\right) + uS_A \end{cases} \quad \text{on } s \in [0,L]$$

$$\text{with } h = h(A(s,t)), \quad h(s,0) = h_0(s), \quad u(s,0) = u_0(s),$$

$$\text{and } S_A(t) = (1-\gamma)Q_{res}(t)\delta(s-s_{res}) + Q_{moor}(t)\delta(s-s_{moor}) + Q_{1c}(t)\delta(s-s_{1c}) \tag{37a}$$

$$\text{Moor:}\quad \partial_t(w_v h_m) - \alpha g \partial_y\left(w_v h_m \partial_y h_m\right) = \frac{w_v R_{moor}(t)}{m_{por}\sigma_e} \quad \text{on} \quad y \in [0, L_y]$$

$$\text{with } \partial_t h_m|_{y=L_y} = 0, \quad h_m(0,t) = h_{3c}(t), \quad h_m(y,0) = h_{m0}(y) \tag{37b}$$

$$\text{Reservoir:}\quad w_{res}L_{res}\frac{\mathrm{d}h_{res}}{\mathrm{d}t} = w_{res}L_{res}R_{res}(t) - Q_{res}, \text{ with } h_{res}(0) = h_{r0} \tag{37c}$$

$$\text{Canal–1:}\quad w_c(L_{1c} - L_{2c})\frac{\mathrm{d}h_{1c}}{\mathrm{d}t} = Q_{2c} - Q_{1c}, \text{ with } h_{1c}(0) = h_{10} \tag{37d}$$

$$\text{Canal–2:}\quad w_c(L_{2c} - L_{3c})\frac{\mathrm{d}h_{2c}}{\mathrm{d}t} = Q_{3c} - Q_{2c}, \text{ with } h_{2c}(0) = h_{20} \tag{37e}$$

$$\text{Canal–3:}\quad w_c L_{3c}\frac{\mathrm{d}h_{3c}}{\mathrm{d}t} = \gamma Q_{res} - Q_{3c}, \text{ with } h_{3c}(0) = h_{30}, \tag{37f}$$

$$\text{Influxes:}\quad Q_{1c} = C_f\sqrt{g}\, w_c \max(h_{1c} - P_{1w}, 0)^{3/2} \tag{37g}$$

$$Q_{2c} = C_f\sqrt{g}\, w_c \max(h_{2c} - P_{2w}, 0)^{3/2} \tag{37h}$$

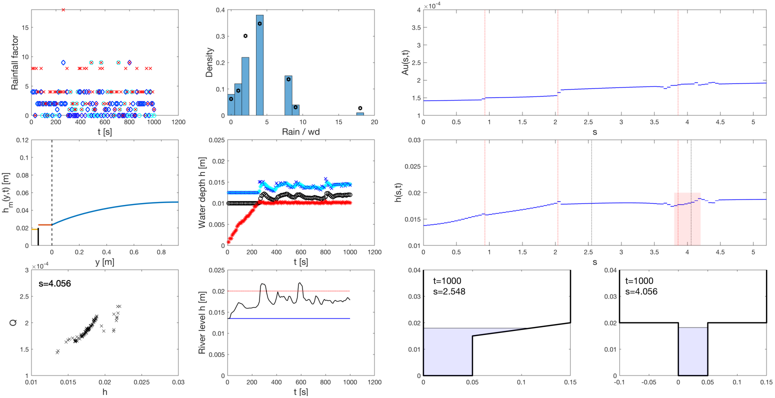
$$Q_{3c} = C_f\sqrt{g}\, w_c \max(h_{3c} - P_{3w}, 0)^{3/2} \tag{37i}$$

$$Q_{moor} = \frac{1}{2} m_{por}\sigma_e w_v \alpha g (\partial_y h_m)^2|_{y=0} \tag{37j}$$

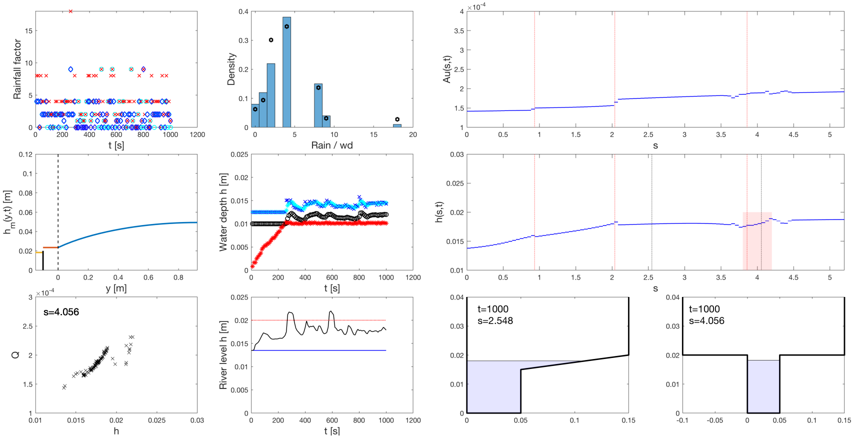
$$Q_{res} = C_f\sqrt{g}\, w_{res} \max(h_{res} - P_{wr}, 0)^{3/2} \tag{37k}$$

Simulations

- Taster: https://github.com/tkent198/hydraulic_wetro#taster
- Full system: https://github.com/tkent198/hydraulic_wetro#preliminary-simulations
- Many more online, including code and running instructions...



Wetropolis dashboard: control via reservoir storage?



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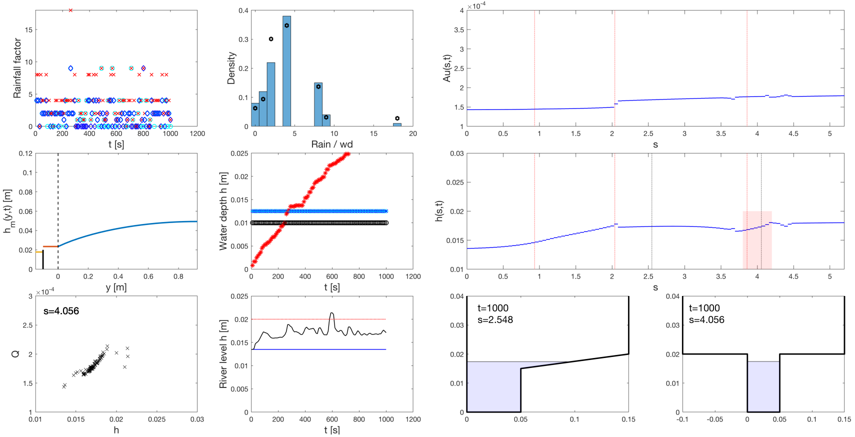
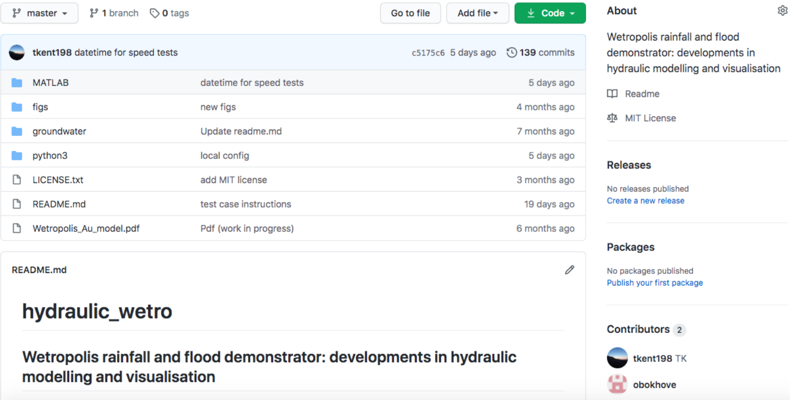
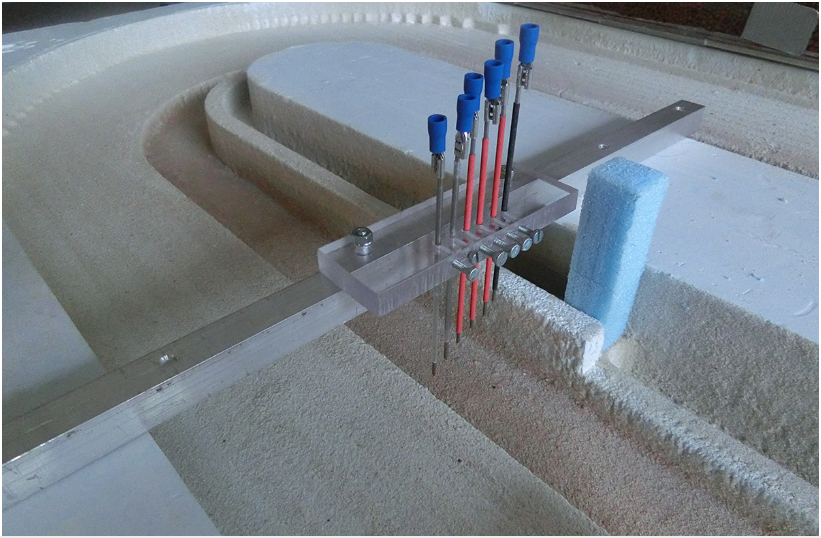


GitHub repository: hydraulic_wetro



Future: WetroDA



Thanks very much for your attention ... any questions?

References:

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- Kent, T. (2020): Wetropolis rainfall and flood demonstrator: developments in hydraulic modelling and visualisation [hydraulic_wetro], *Open-source code and manual: https://github.com/tkent198/hydraulic_wetro.*
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Research: interests

Mathematical and statistical modelling of atmospheric and environmental phenomena, including:

- geophysical fluid dynamics;
- numerical methods (in particular for hyperbolic problems);
- hydraulic and shallow water-type modelling;
- numerical weather prediction and (ensemble-based) data assimilation;
- flood modelling and mitigation;
- statistical downscaling and bias correction.