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Recent developments towards a new hydraulic solver for SWMM

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Developer of ELCOM 3D hydrodynamic model

Research areas include: numerical algorithms; modeling lakes, rivers and estuaries; oil spill modeling; upscaling high-resolution topography; hydraulic of curb inlets; supersaturated dissolved gasses below high dams.

Acknowledgement and disclaimer

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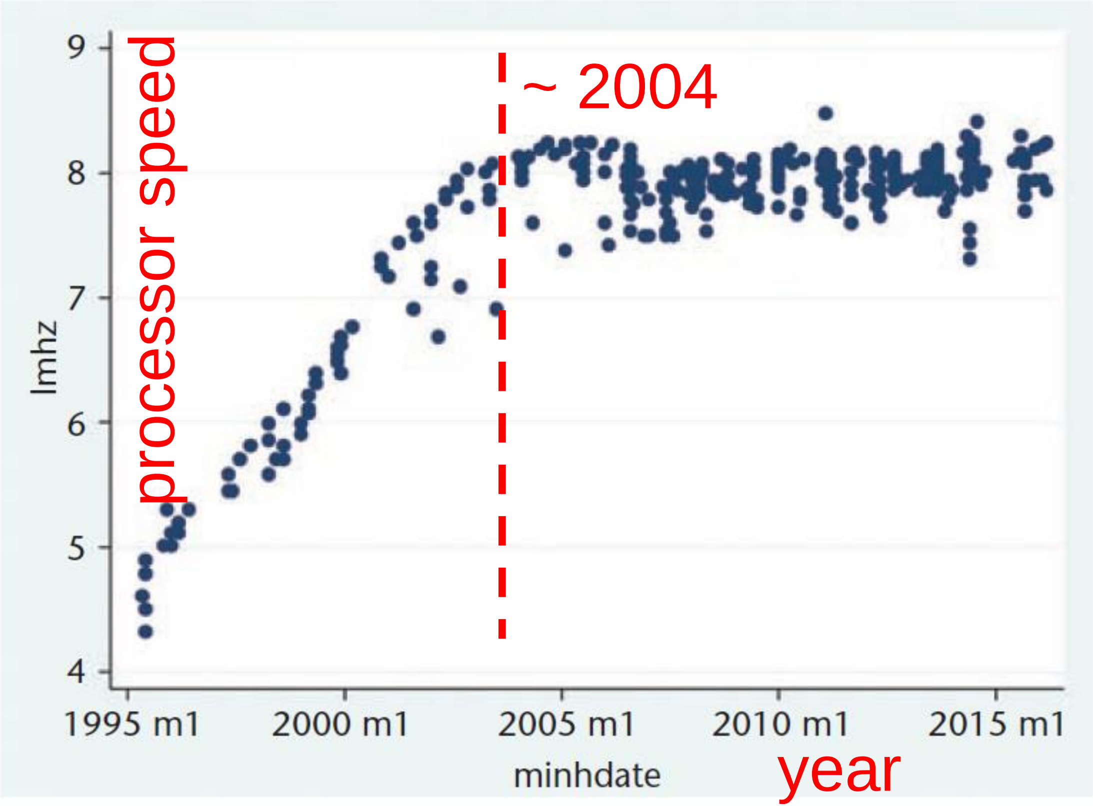
Our goal:

Building a new SWMM computational engine that is

- fast,
- stable,
- conservative,

for multi-thread parallel computation (i.e. order of 1000s of threads) on a desktop computer or cloud server

Why a parallel computational engine?



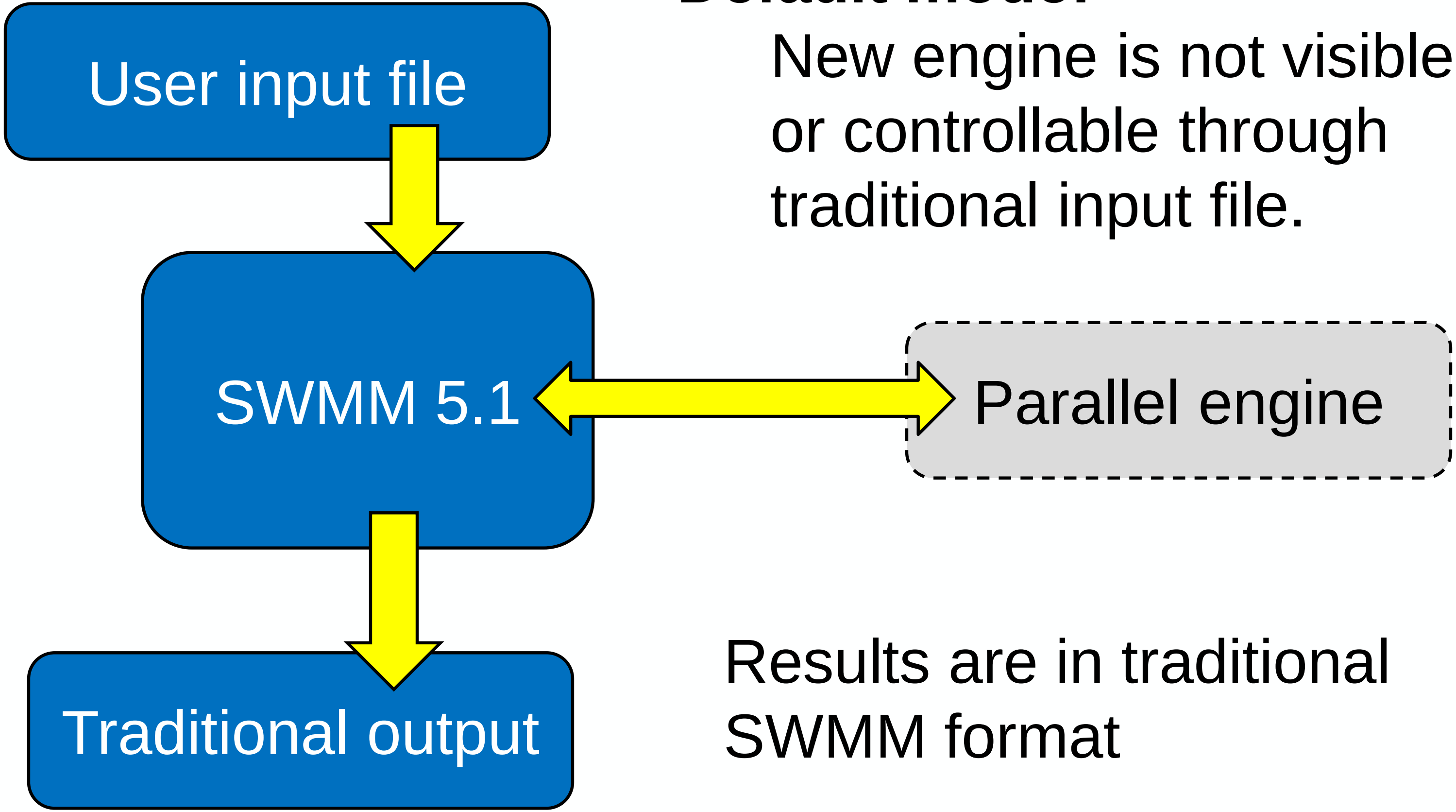
Processors aren't getting faster, they are just getting more parallel threads.

Flamm, K. (2017) "Has Moore's Law been repealed? An economist's perspective", *Computing in Science & Engineering*, Mar-Apr. 2:29-40

Basic operation

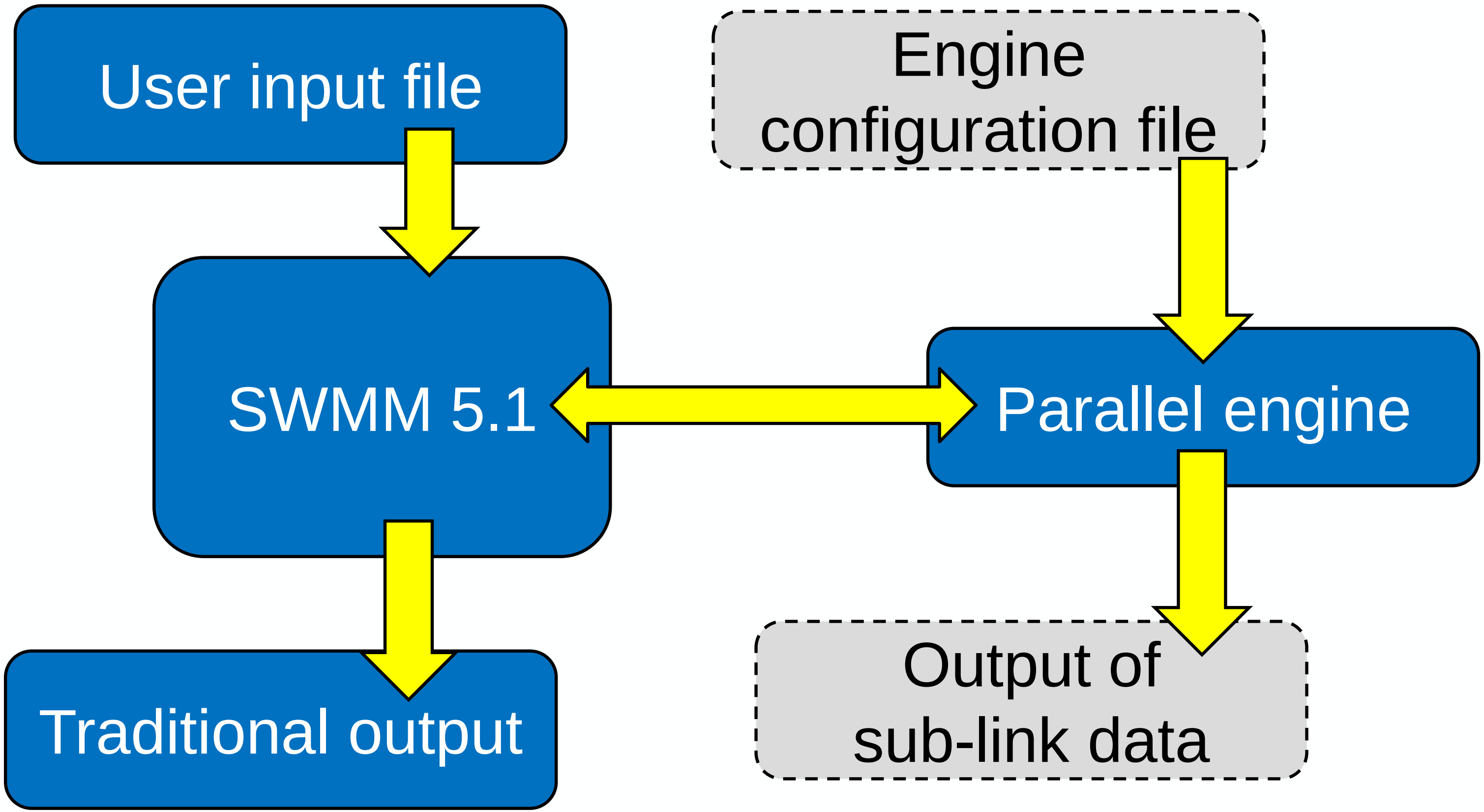
Default mode:

New engine is not visible or controllable through traditional input file.

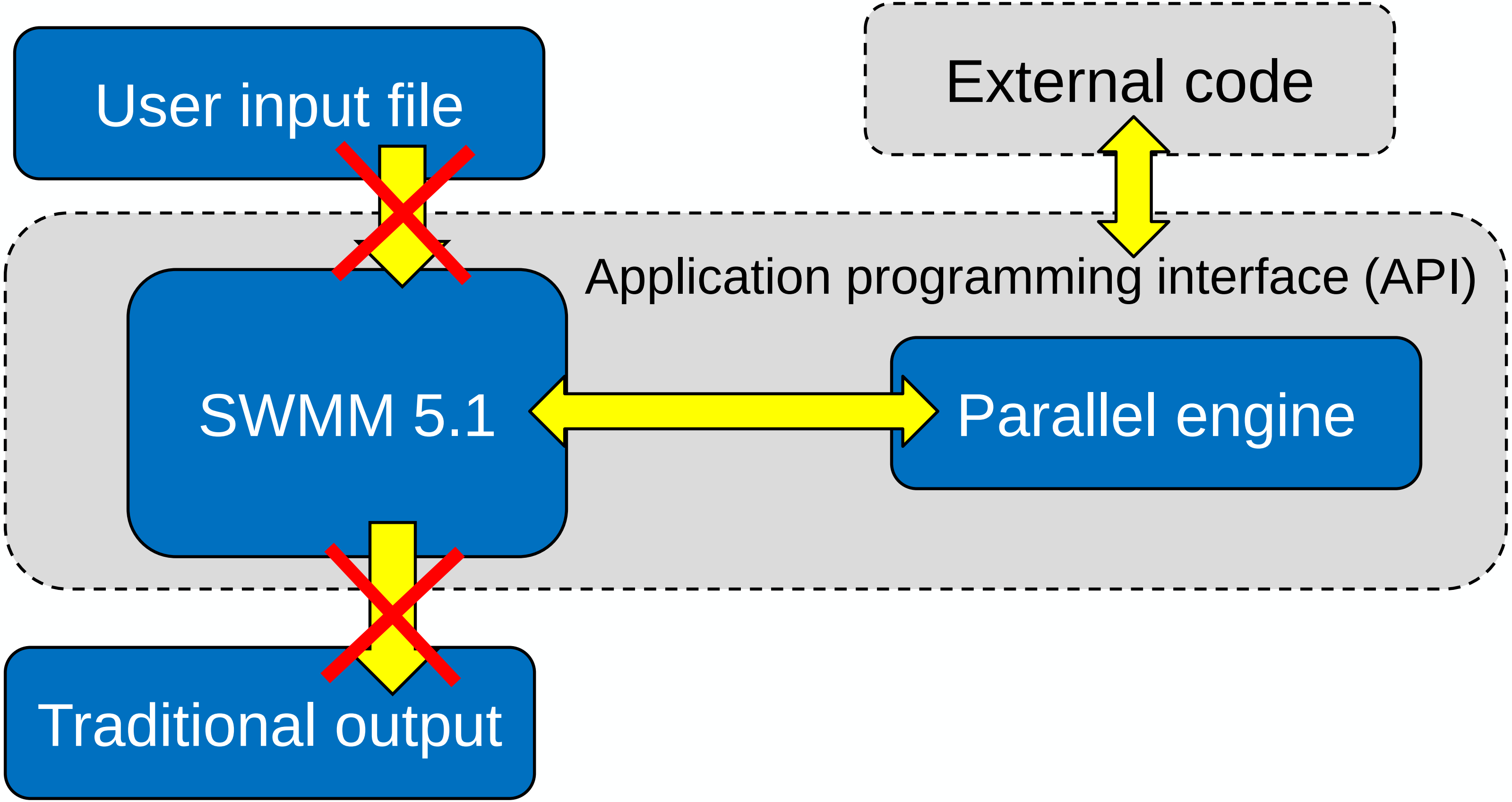


Results are in traditional SWMM format

Advanced user operation



Programming mode



Fixing mass conservation for SWMM 5+ hydraulics

Finite-volume replacing link/node approach.

Momentum and mass solved for integrated element.

Artificial compressibility for surcharged and near-surcharged pipe flow.

Controls speed of information propagation through system.

Explicit Runge-Kutta 4th-order time advance for dynamic flow eqs.

CFL-limited, but fast and ensures local information passing.

Mass convergence to machine accuracy (except with wetting/drying).

Sub-discretization of pipes and channels

Finite-Volume (FV) = subdivisions of long pipes.

Fast and parallel efficient.

Allows scalar gradients along pipe.

Retain standard link/node user file, subdivided internally.

Sub-discretization will be valuable for water quality modeling in SWMM.

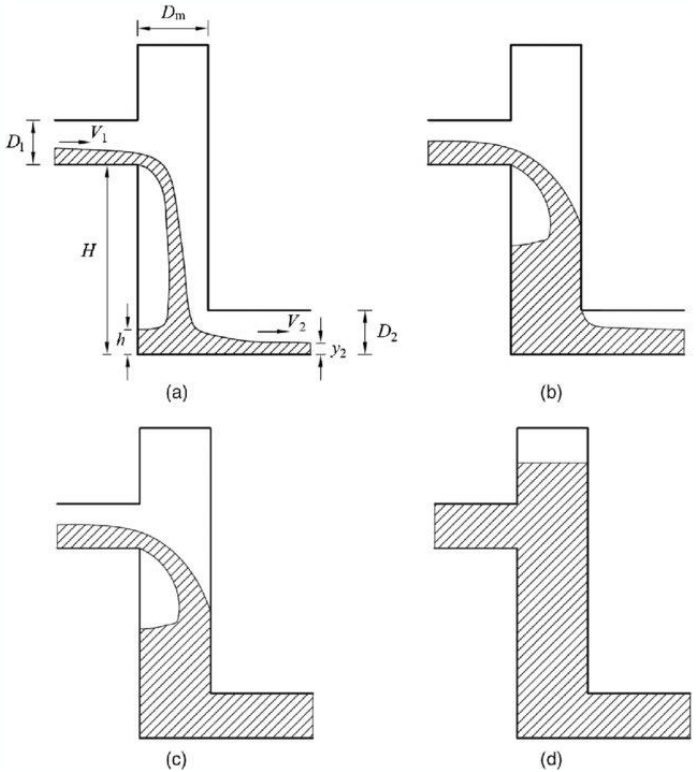
What about junctions?

SWMM 5: pipe junction = node.

One value of head per node.

But manhole has different heads for different pipes!

SWMM 5+: junction is an "element" multiple faces with different heads.



Drop manhole figure from Ma et al (2017), J. Irrig. Drain Eng. 143(12).

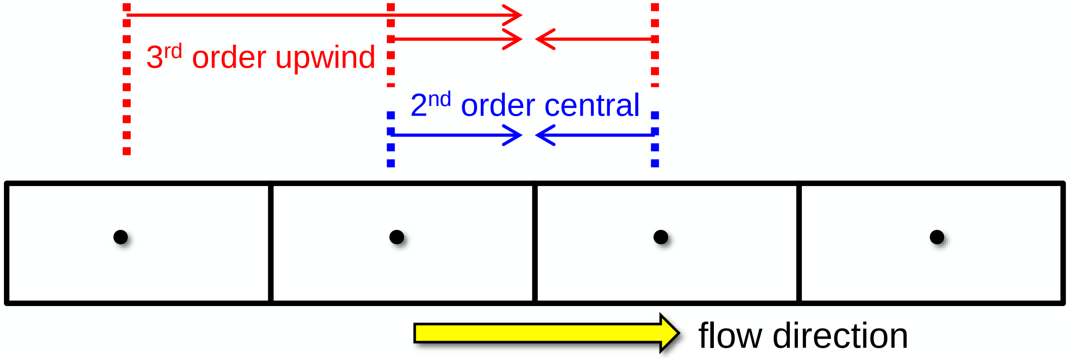
Face reconstruction in Finite Volume methods

A new idea for finite-volume methods

Face reconstruction is always a challenge.

Q,H on cell centers.

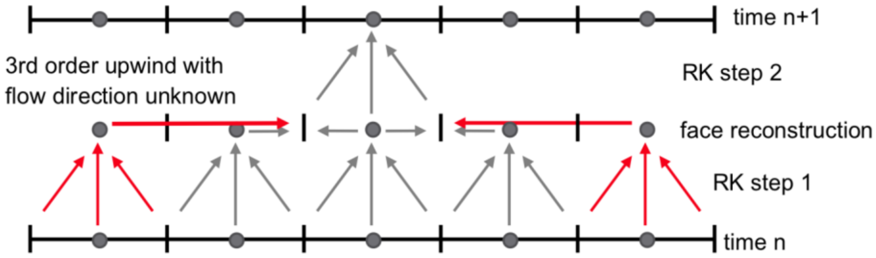
Interpolation to faces -- how many neighbors to include?



More cells require more data communication

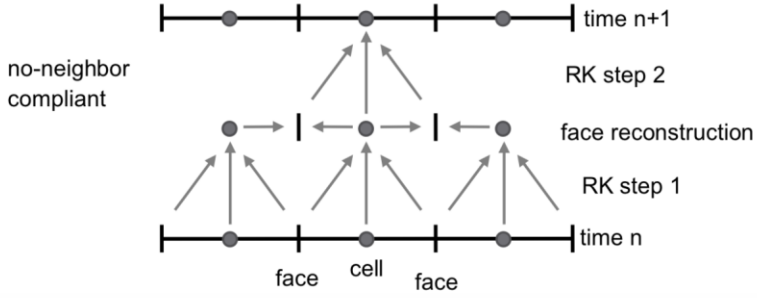
3rd order

with
RK2



2nd order

with
RK2



Prefer a "no neighbor" approach

Face only knows adjacent elements.

Elements only know adjacent faces.

No further upstream knowledge needed.

But this leaves us with:

-- 2^{nd} order central, which is prone to oscillations

-- 1^{st} order upwind, which is diffusive.

Or does it?

Time-scale based interpolation

Define time-scale for cell *i* to affect its faces *i+1/2* and *i-1/2* faces

$$\mathcal{T}_{i+1/2[-]} \equiv +\frac{L_i}{2\mathcal{C}_{i+1/2[-]}} = +\frac{L_i}{2\left(U_i + \sqrt{gH_i}\right)}$$
$$\mathcal{T}_{i-1/2[+]} \equiv -\frac{L_i}{2\mathcal{C}_{i-1/2[+]}} = -\frac{L_i}{2\left(U_i - \sqrt{gH_i}\right)}$$

Timescale-weighted interpolation so that faster signal is dominant

$$\phi_{i+1/2} = \left(\frac{\mathcal{T}_{i+1/2[+]}}{\mathcal{T}_{i+1/2[-]} + \mathcal{T}_{i+1/2[+]}}\right)\phi_i + \left(\frac{\mathcal{T}_{i+1/2[-]}}{\mathcal{T}_{i+1/2[-]} + \mathcal{T}_{i+1/2[+]}}\right)\phi_{i+1}$$

Effects of time-scale interpolation

Fr ➔ 0 ~ second-order central interpolation.

Fr ➔ 1 ~ weighting shifts towards upstream

Fr > 1 ~ first-order upwind.

Timescale interpolation is ideal for transcritical flows.

It automatically shifts the dependency based on information celerity and direction.

Open-channel Saint-Venant methods published

Hodges and Liu (2019), “Timescale interpolation and no-neighbor discretization for a 1D finite-volume Saint-Venant solver,” Journal of Hydraulic Research, (in press). https://doi.org/10.1080/00221686.2019.1671510

Hodges (2019), “Conservative finite-volume forms of the Saint-Venant equations for hydrology and urban drainage,” Hydrology and Earth System Sciences, 23:1281-1304. https://doi.org/10.5194/hess-23-1281-2019.

Email me at hodges@utexas.edu for PDF

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Challenge of data types

Hydraulics in SWMM 5.1 include

- Pumps
- Orifices
- Weirs
- Culverts
- Storage units
- Pipes
- Irregular open channels
- Outfall
- Junction
- Dividers

N data types must connect to N data neighbor types; i.e. 10 data types have 100 possible combinations.

Adding a new data type is a coding nightmare for parallelization!

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Timescale interpolation simplifies datatype moderation

Only 3 data types require moderation – depends on type of evolution equation:

- Q-only – e.g. weir
- H-only – e.g. storage unit
- H-Q – e.g. conduit

The no-neighbor timescale interpolation to faces doesn’t care about the datatype, but controls interpolation simply through the definition of the timescale.

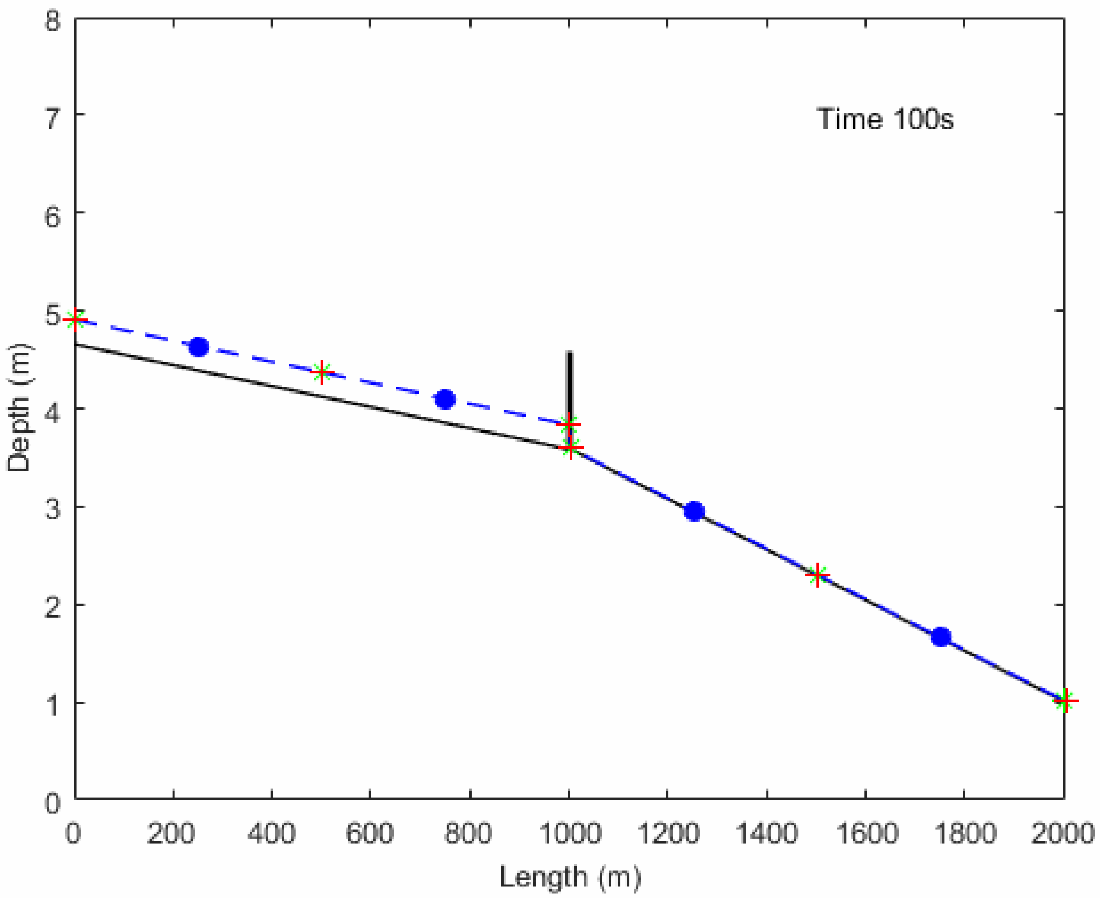
For example, with a weir is Q-only and sets the Q timescale to 0 so that the weir controls the Q on its faces, and sets the H timescale to infinity so that the upstream and downstream elements control H on the faces.

Weir hydraulics

Weir element
is "Q-only"

$T_Q = 10^{-6}$
$T_H = 10^{+6}$

Flow rate 0.3 m^3/s



Artificial Compressibility for surcharged pipes

Surcharged pipe is traditionally incompressible flow

Goal is to capture slow transients.

Unsteady solutions by series of steady-flow solutions.

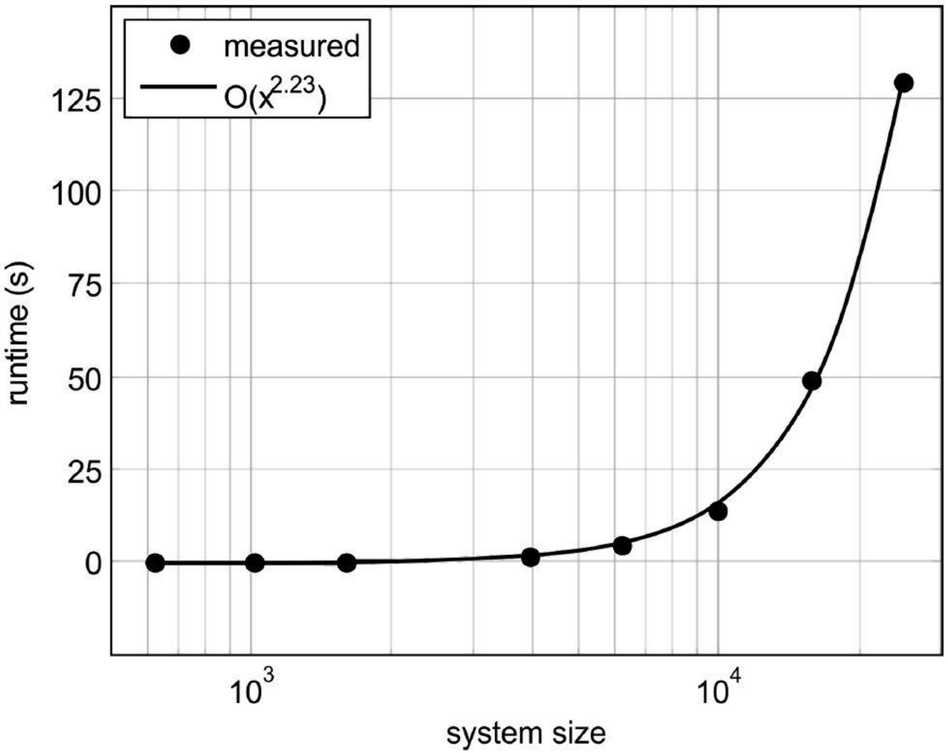
Fluid is approximated as incompressible.

Information propagates at an infinite speed.

Every pipe element and node is dependent on every other element and node.

If boundary conditions are NOT well-posed, solution will not converge.

Limitations of the incompressible solution



Algorithmic complexity of EPANET 2 code.

Runtime increases exponentially with system size.

Figure from Burger, Sitzenfrei, Kleidorfer and Rauch “Quest for a New Solver for EPANET, J. Water Resourc. Plann. Manag. 142(3) 2016

Incompressibility is not reality

Real pressure waves (information) travel at acoustic speed

We cannot handle acoustic speed, so we make information travel faster (infinite speed)?

For slow transients - a slower information speed is also possible:

- 15 minute time-scale
- 10 km of pipe
- 11 m/s information speed to reach entire domain.

Artificial compressibility

Developed by Alexandre Chorin (1967) for Navier-Stokes
Reprint available in J. Comput. Phys. Vol 135, 1997

Add ***artificial unsteady*** terms to **steady** equations

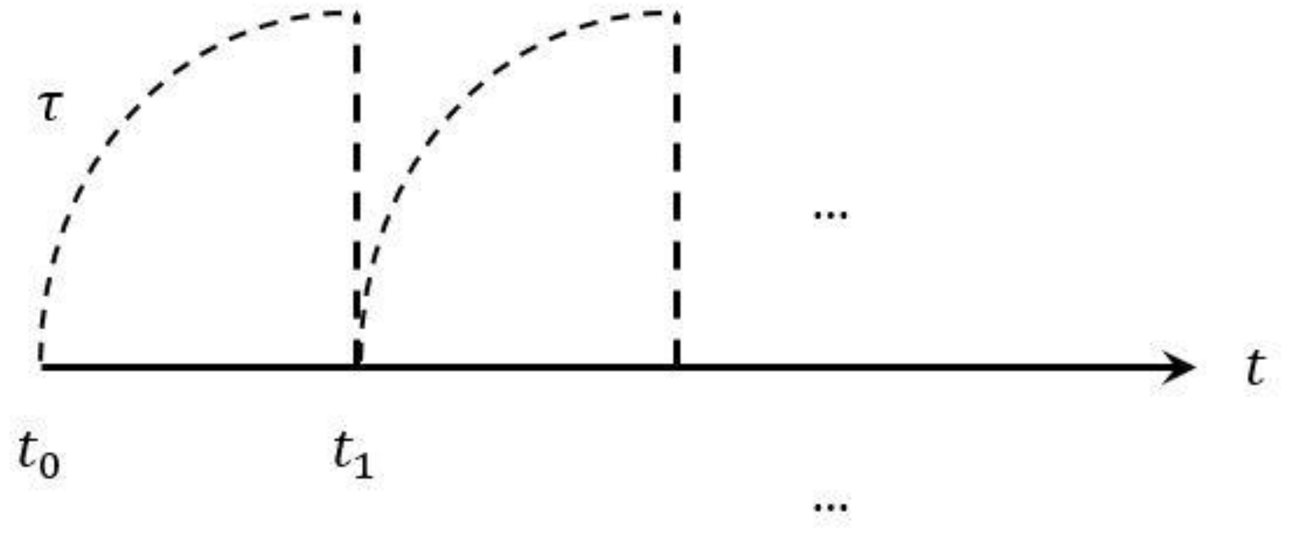
$$\frac{g}{g^2}\frac{dH}{dt} + Q_u - Q_d = 0 \qquad \frac{¶Q}{¶t} + \text{steady momentum} = 0$$

dH/dτ = 0 and dQ/dτ = 0 provides the steady solution.

Extends to full unsteady equations with d/dτ + d/dt

Rogers, Kwak and Kiris, AIAA Journal, 29(4) 1991

Pseudo and real time for unsteady solution



Pseudo-time steps from real time t_0 to t_1 are similar to iterative steps of a linear or nonlinear Ax=b matrix solver

Numerical approach

Test solver in Python

Finite-volume discretization

Open/full pipe flow

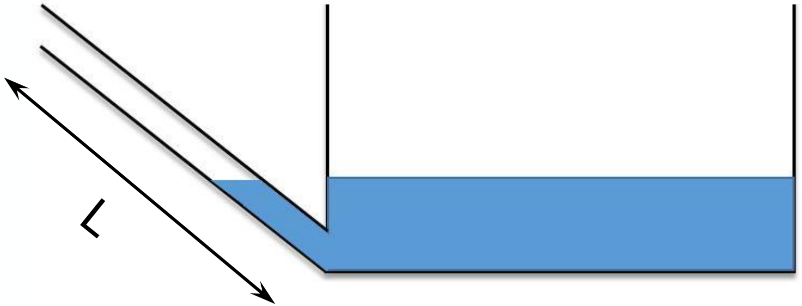
RK4 time advance in pseudo time

3rd order backwards in real time

Face reconstruction with new time-interpolation method

Gravity wave speed as information wave speed

Test Case:



L = 500 m

D = 11 m

Q = 200 m^3/s

Manning's n = 0.05

Slope = 0.13

Initially dry upstream pipe.

Supercritical flow upstream.

Hydraulic jump where it meets pool water.

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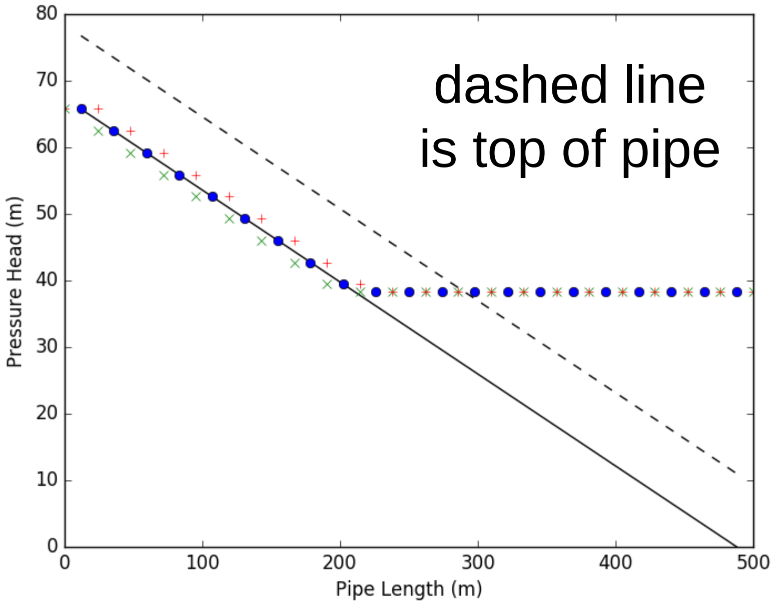
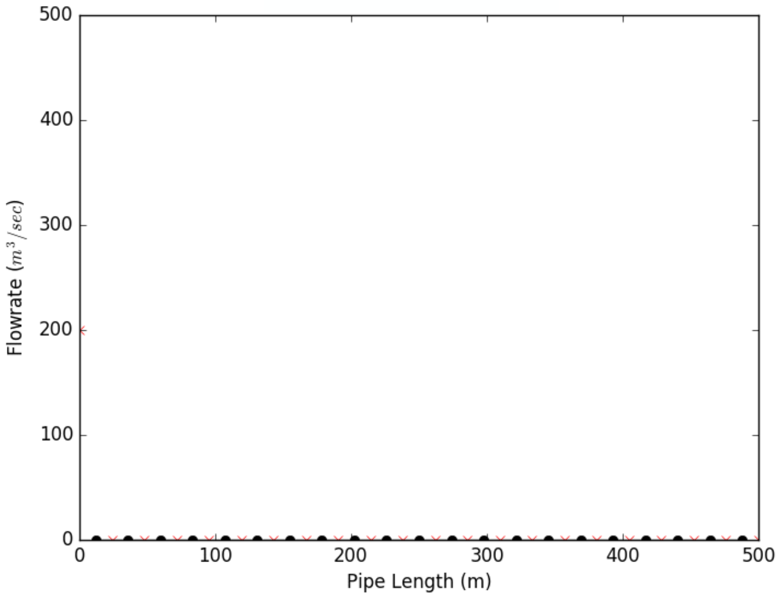
Results (movie – I hope)

Pressure (head)



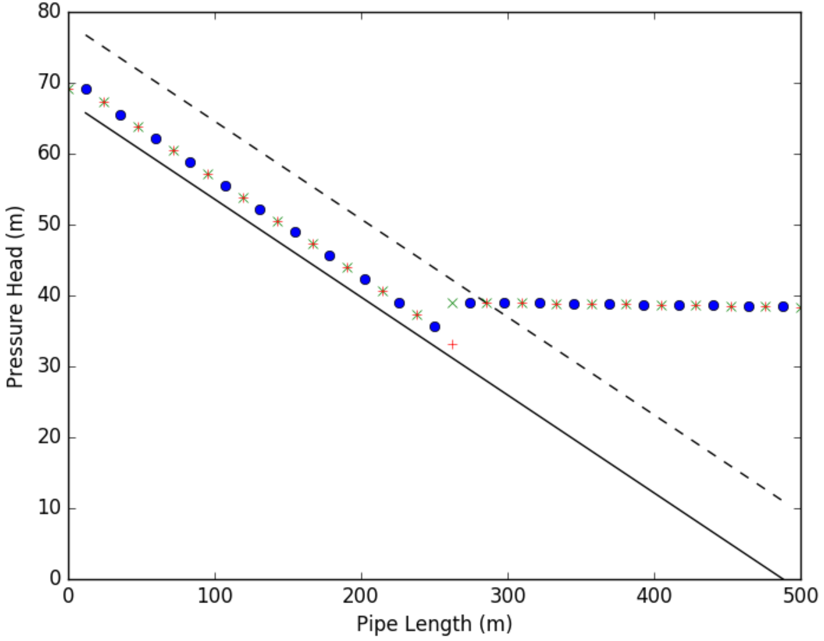
Flowrate

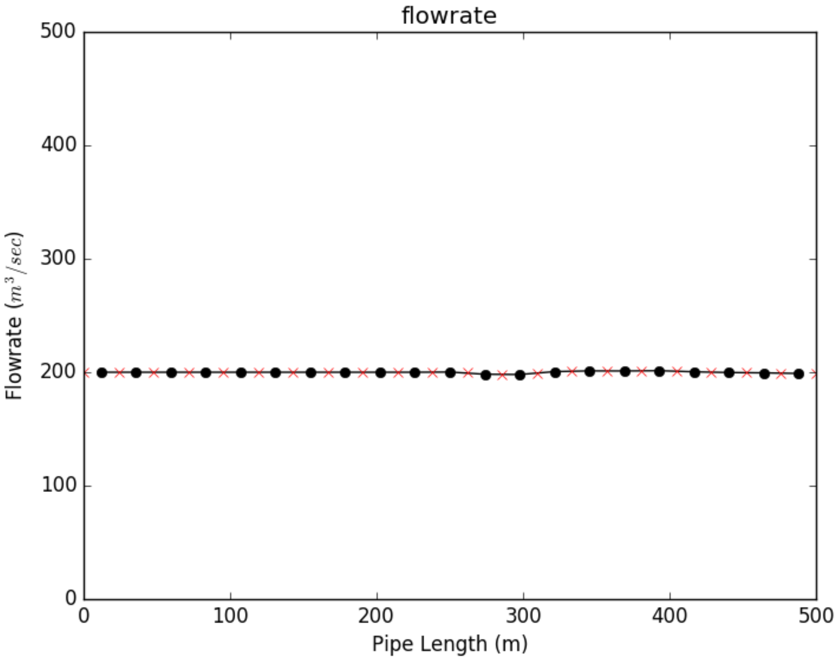


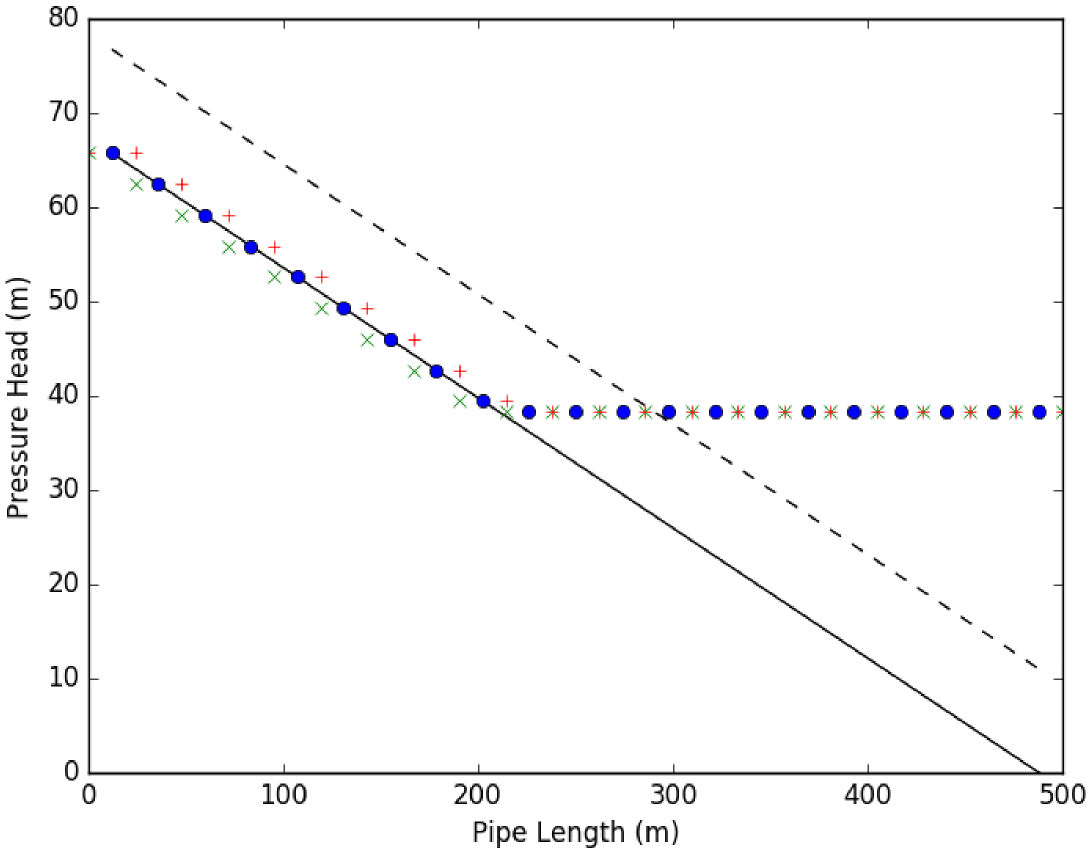
x upstream face; **o** element center; + downstream face

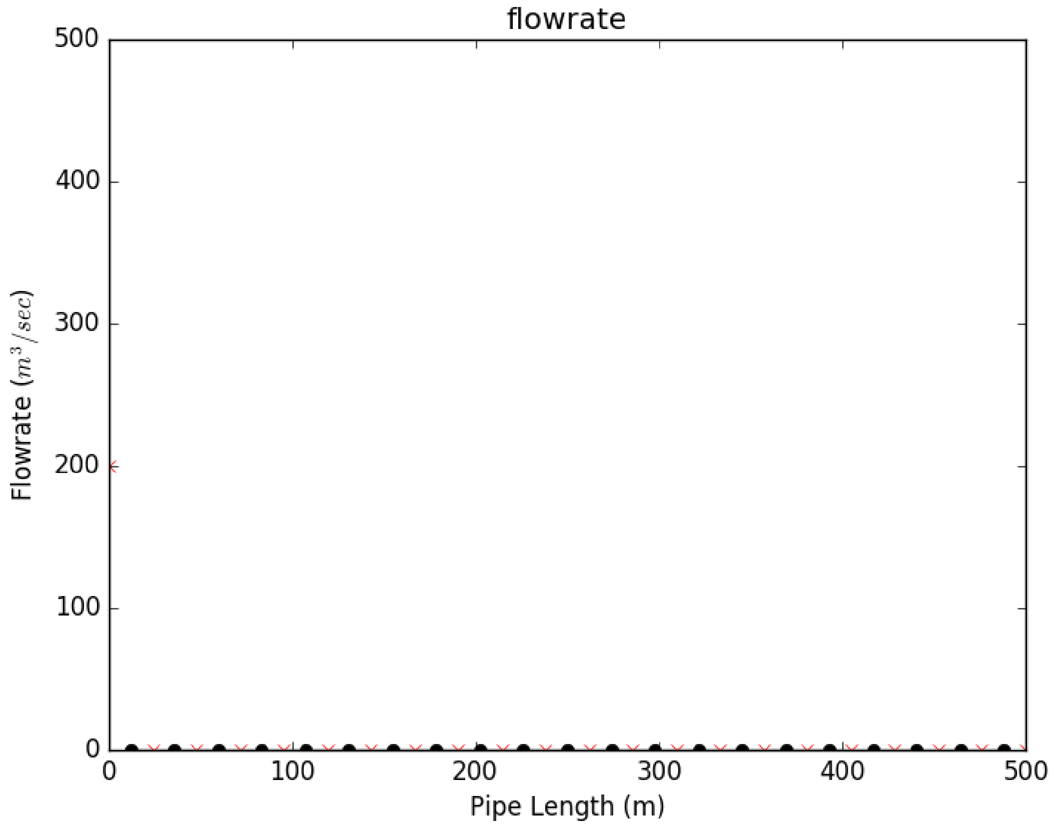
Results:

Steady-state solution from unsteady AC solver






80
70
60
50
40
30
20
10
0
Pressure Head (m)
0
100
200
300
400
500
Pipe Length (m)


flowrate
Flowrate (m^3/sec)
Pipe Length (m)
0
100
200
300
400
500

But there's no free lunch

More floating point operations than an $Ax = b$ implicit solve.

But -- all data transfer is local for reduced communication.

In large parallel systems, floating point operations are cheap and data communications are the bottleneck.

Conclusions

SWMM 5+ engine will fix many long-standing problems

Hydraulics will be mass conservative

We cannot do it all, and there are a lot of new things that we are looking to the community for future collaboration.

On some numerical details:

-- Time-scale interpolation provides a “no-neighbor” approach to face reconstruction.

-- Artificial Compressibility is a “back to the future” approach for surcharged pipes.

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I owe a great debt to the late Charles Rowney.

CIMM would not exist without his vision and drive,

and I would not be working with SWMM today.

He is missed.

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Mass conservation in present SWMM 5

Link-node finite-difference algorithm.

Surcharged pipe usually loses/gains mass.

Problems in convergence.

Incompressibility constraint is key issue.

incompressibility is not real.

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Test of transcritical flow over a bump