METEOR

Modelling Exposure Through Earth Observation Routines

INTRODUCTION TO FLOOD MODELLING

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Fathom

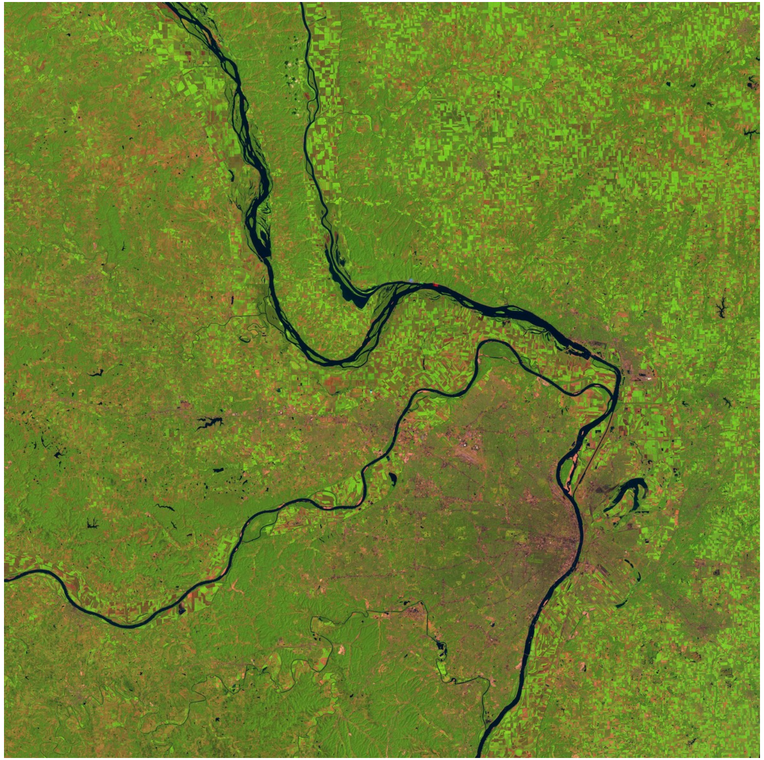
https://meteor-project.o

What is a flood model?

- A computer-based simulation of flood inundation
- More specifically, a simulation of large, low-amplitude, shallow water waves:
  - 1-1000 km in length
  - <1 hour to 6 month duration
  - Low slope 1-100cm km^{-1}
  - Gradually varying flow
  - Floodplain waves spread in two dimensions (2D) with complex dynamics
  - Major control on wetland biogeochemistry and carbon cycle
  - Extremes are a major natural hazard

From urban flooding…

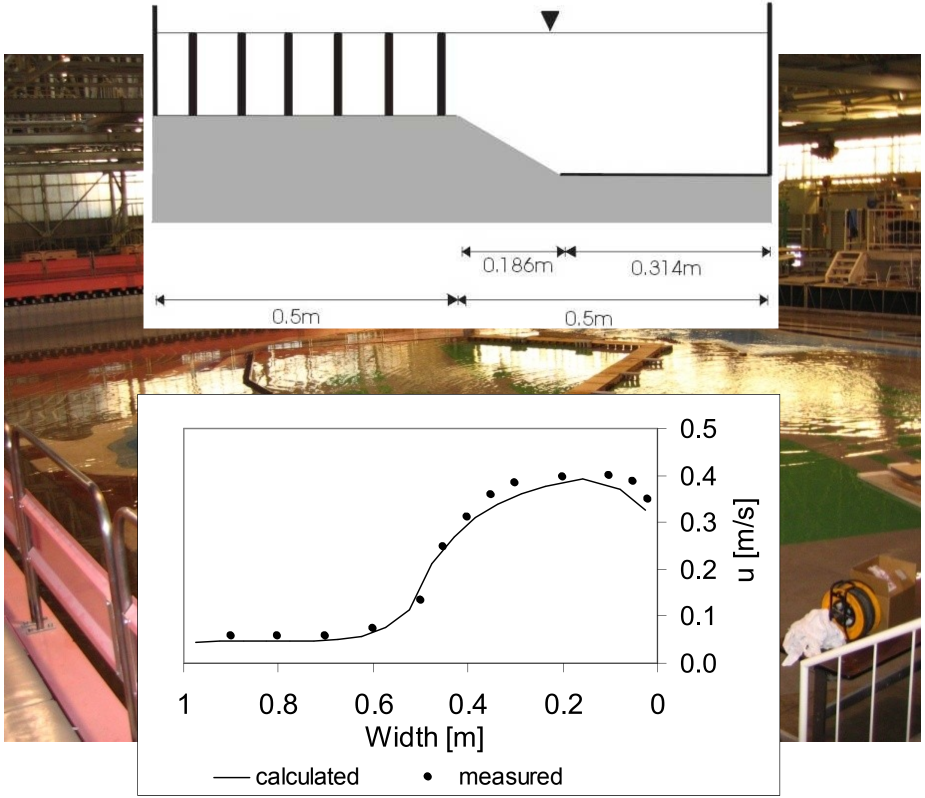
…to major continental rivers



Some history…

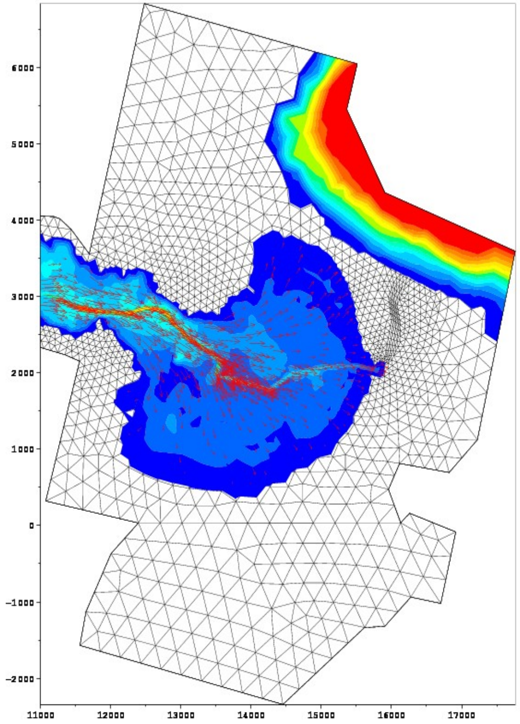
Classical model development

- Has relied on analytical solutions and laboratory data
  - Model parameters and problem geometry are well known
  - Validation data are either exact or very accurate
  - Simulations are never compute power limited
  - Leads to a paradigm of <u>incremental added complexity</u>



20 years ago modelling was felt to be well understood

- Numerical solutions of the 2D Shallow Water or 3D RANS equations
- High computational cost
- Applied to single river reaches a few km in length
- Limited field validation
- Models would improve with better physics…



In 2000 modelling needs were felt to be well understood

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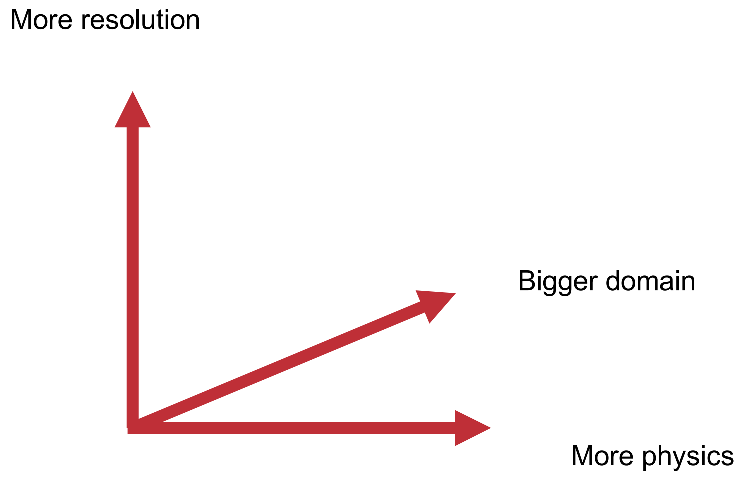


Real world applications

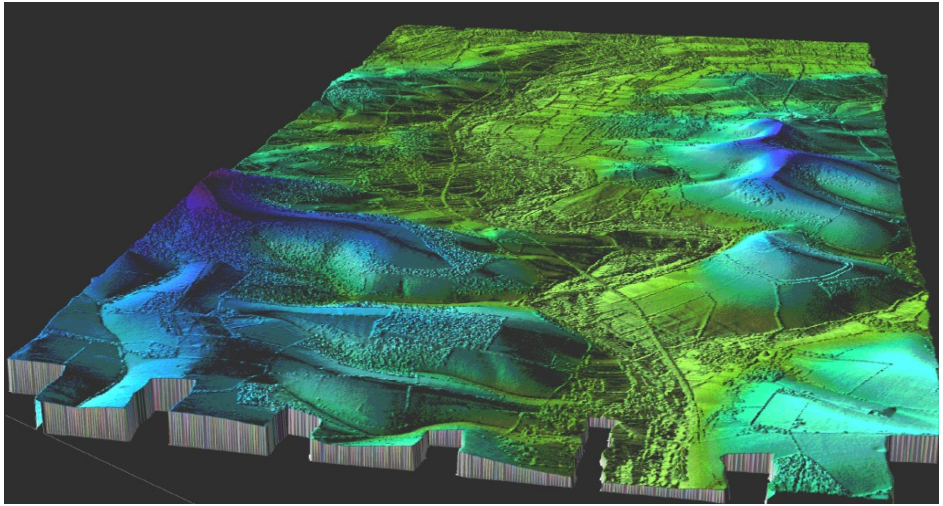
- High resolution needed
  - Always compute limited

- Models are data-hungry
  - But the data has error, and was often missing

- Large areas (whole cities, regions, countries, continents) need to be simulated

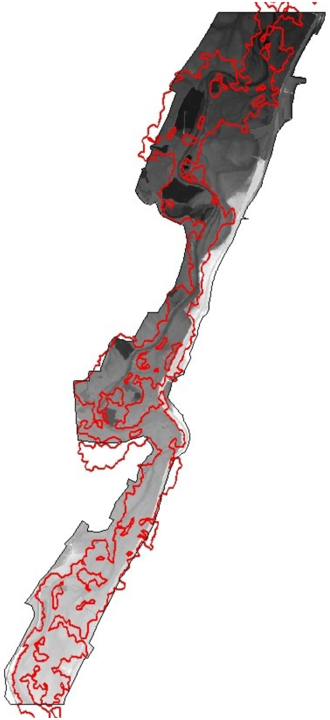
Topography data - the key breakthrough

- Airborne laser altimetry (LiDAR)
  - ~0.25-2 m spatial resolution
  - ~5 cm vertical accuracy
  - Survey rates of ~50km^2 h^{-1}



River Stour, Dorset (5 x 7 km, 3M data points)
UK Environment Agency

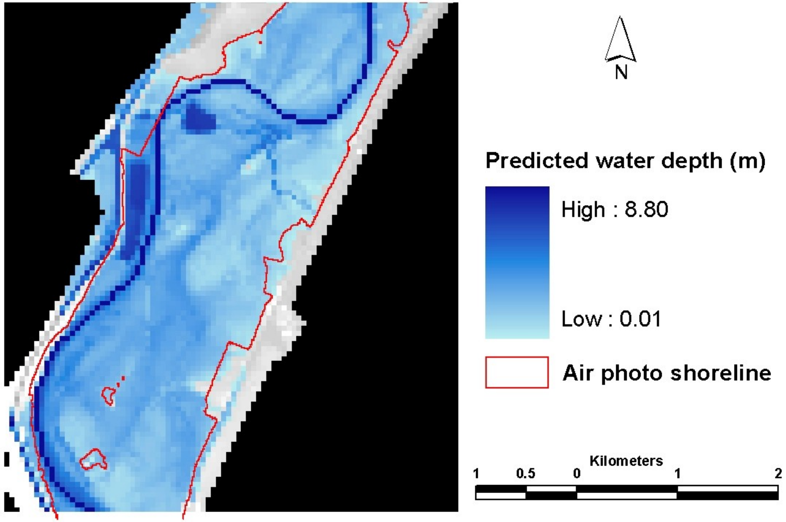
Led to a search for benchmark field data sets



- Data available for the January 1995 floods
  - High resolution topography from air photogrammetry
    - Measured inflow discharge at Borgharen
    - Measured outflow discharge at Maaseik
    - Measured stage and discharge at two internal gauges: Elsloo and Grevenbricht
    - 86 maximum water level observations
    - Air photo-derived inundation extent
    - Satellite SAR derived inundation extent

Models vs benchmark data

- Application of multiple models led to surprising conclusions:
  - Simple models did as well as complex ones, given data errors
  - Increasing model resolution was a better way to improve skill
  - Terrain data accuracy and resolution more important than physics
  - Floodplain inundation is, to first order, a simple gravity-friction balance



A new paradigm: Occam's Razor

- Quickly realized that a new modelling approach was needed
  - Faster models, often with simple physics
  - High Performance Computing
  - Finer resolutions, over bigger areas
  - Stronger focus on the data
  - For prediction we should favour the simplest models that fit the available data (to within error)

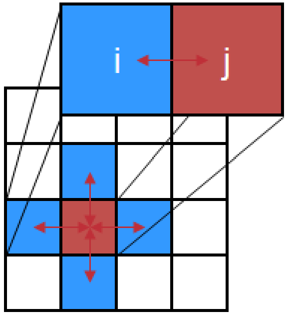
"Entia non sunt multiplicanda sine necessitate"

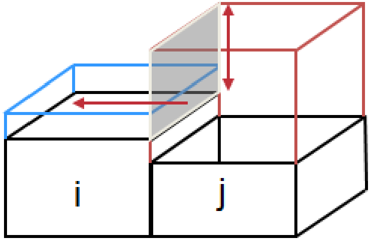
How do flood models work today?

Building models: conservation laws

Conservation of Mass

$$Change\ in\ cell\ volume = Volume\ in\ - Volume\ out$$





Conservation of momentum: Newton's 2nd Law

$$Flow\ between\ cells = f(gravity, friction, area, water\ slope, time)$$

New LISFLOOD-FP formulation

Continuity Equation

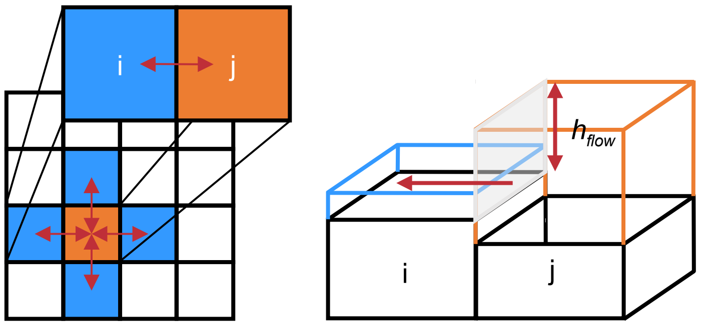
Continuity equation relating flow fluxes and change in cell depth

$$\frac{\Delta h^{i,j}}{\Delta t} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x^2}$$

Momentum Equation

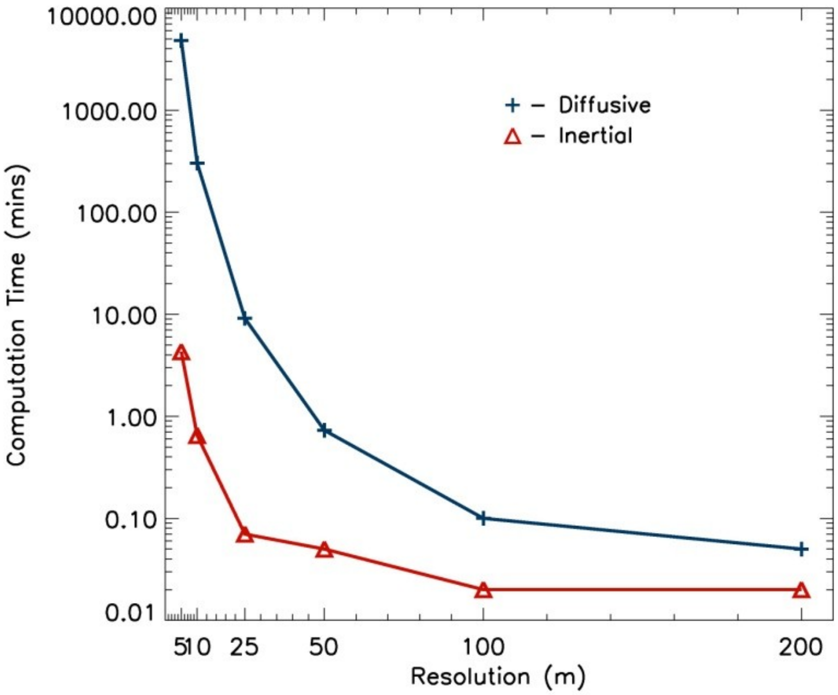
Flow between two cells now calculated using:

$$Q = \frac{q - gh_{flow}\Delta t \dfrac{\Delta(h+z)}{\Delta x}}{\left(1 + gh_{flow}\Delta t n^2 q / h_{flow}^{10/3}\right)} \Delta x$$

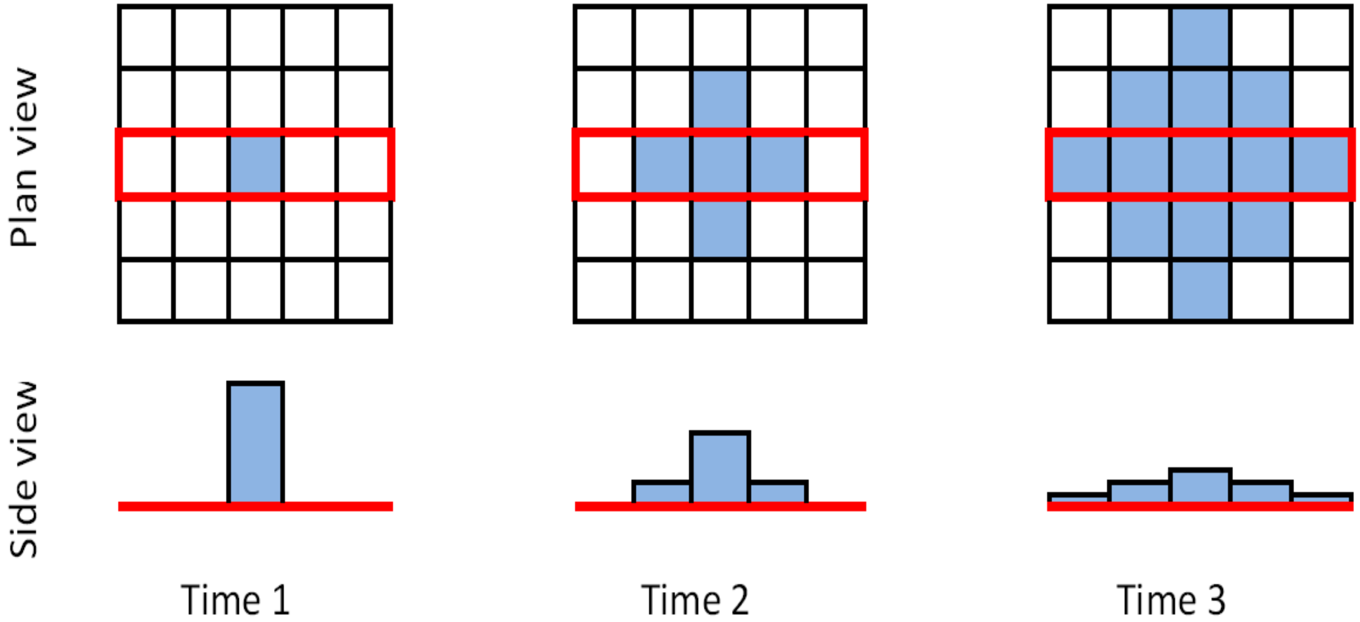


Representation of flow between cells in LISFLOOD-FP

New equation speed up



How do flood models work?



What data do they need?

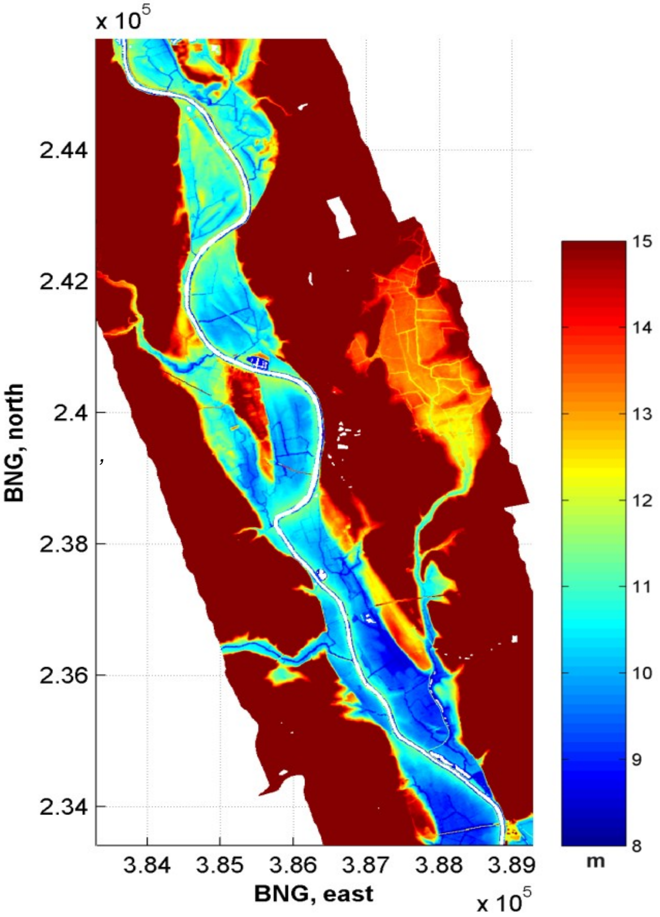
- Terrain model
- River network:
  - river geometry can be simplified to rectangular channel in all but the most precise local-scale models
  - still need location, width and depth
- Flow and/or rainfall inputs
- More complexity can be added if needed/available:
  - Flood defences, friction maps, soil types, flow structures, coastal water levels, etc.

Dynamic wave simulation (Carlisle, UK)

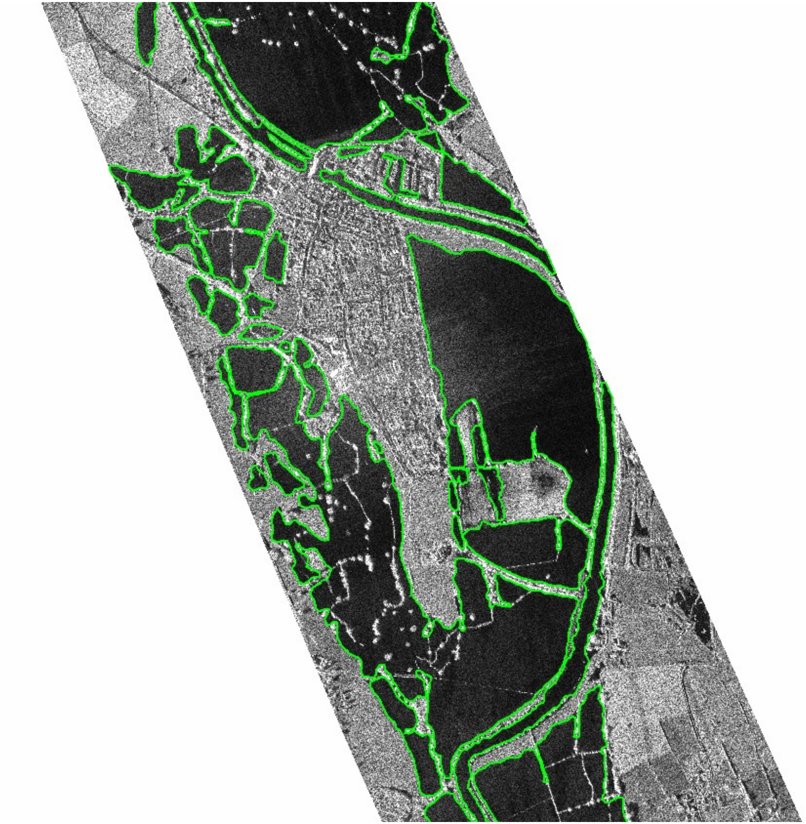
- 30 km² domain
- 10m grid
- 2 hour event
- <5 min compute time

River Severn, UK.

LiDAR digital elevation model (DEM) at 3m resolution.



Airborne Synthetic Aperture Radar classified at a spatial resolution of 1m



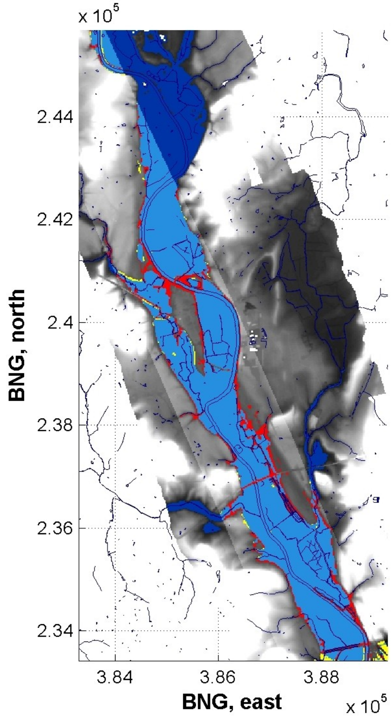
Model vs. Radar: 8 November 2000

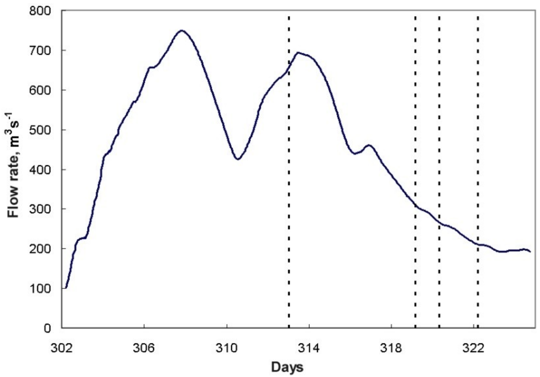
= correct

= over-prediction

= under-prediction

= predicted as flooded, no ASAR coverage

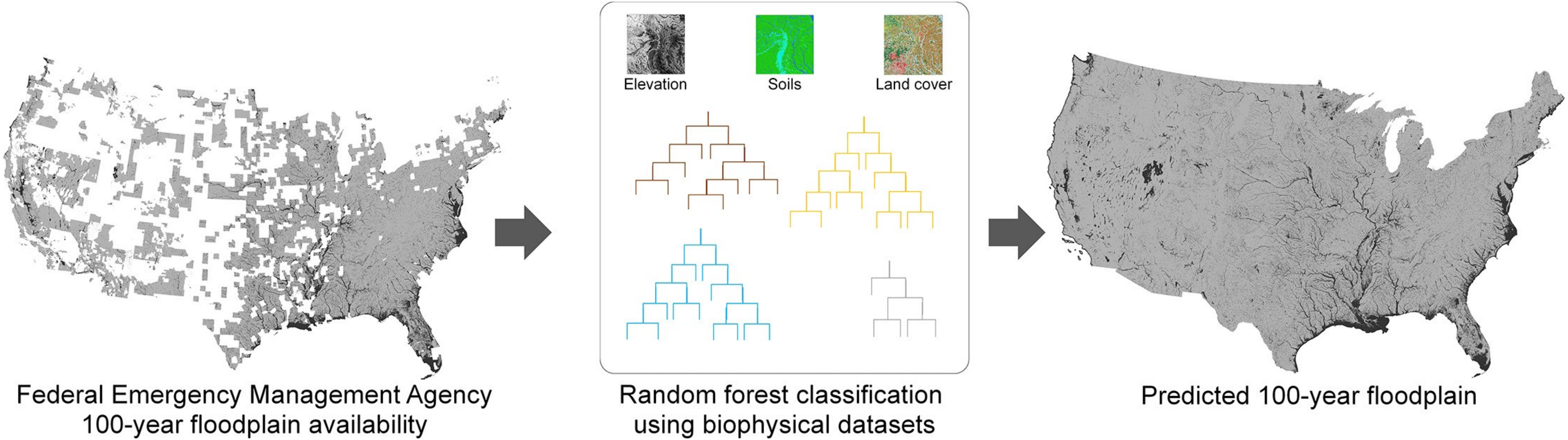




Model fit = 89%

Are dynamic models necessary? Can’t we just use GIS?

Machine Learning inundation models - Woznicki et al (2019)



Woznicki et al. (2019). Development of a spatially complete floodplain map of the conterminous United States using random forest. *Science of The Total Environment*, **647**, 942-953. https://doi.org/10.1016/j.scitotenv.2018.07.353

Machine Learning inundation models - Woznicki et al (2018)

Hit rate = ~80% (vs FEMA training data)

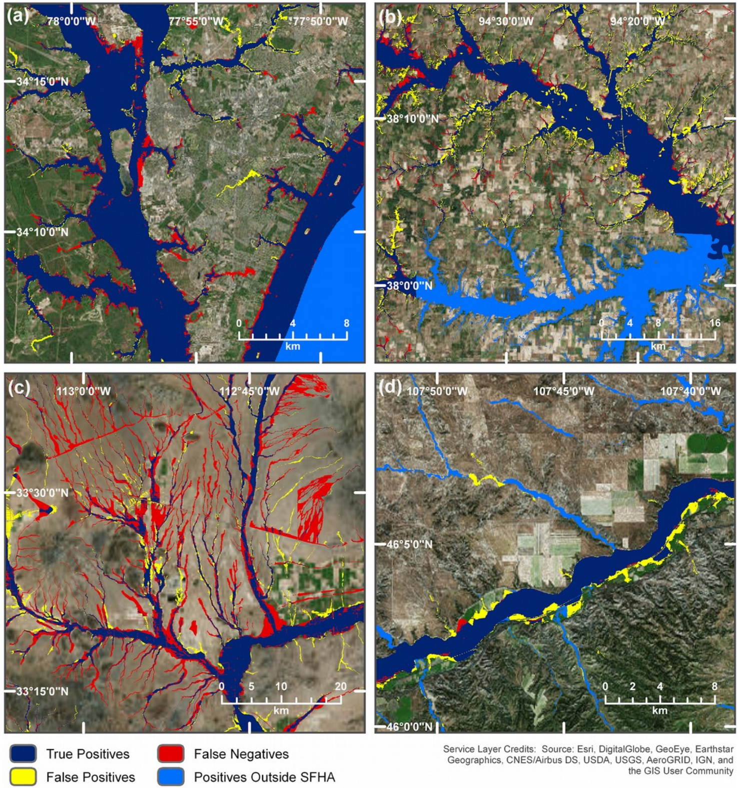
Pros

- Can emulate existing model output
- Speed

Cons

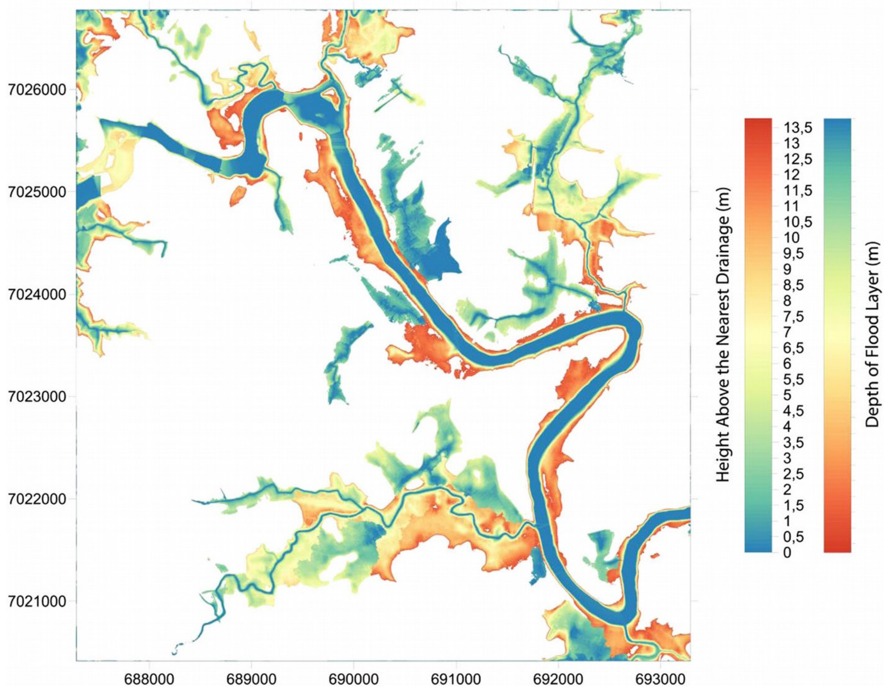
- Inherits errors in the training data
- Can’t predict different return periods
- Can’t simulate land use and climate change

i.e. can only interpolate, not extrapolate



Flood spreading algorithms

- Non mass-conserving
  - E.g. Height Above Nearest Drainage (HAND) method



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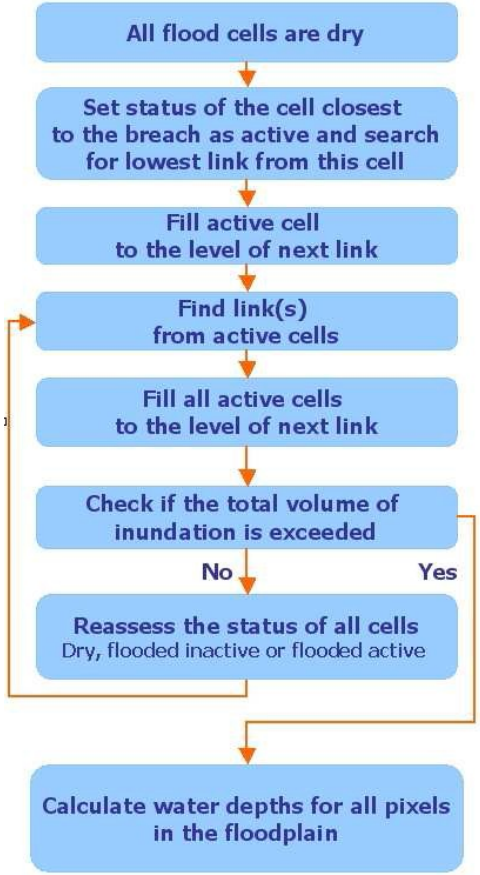
  - GIS routines to distribute known flood volume from a starting point to lowest connected cells



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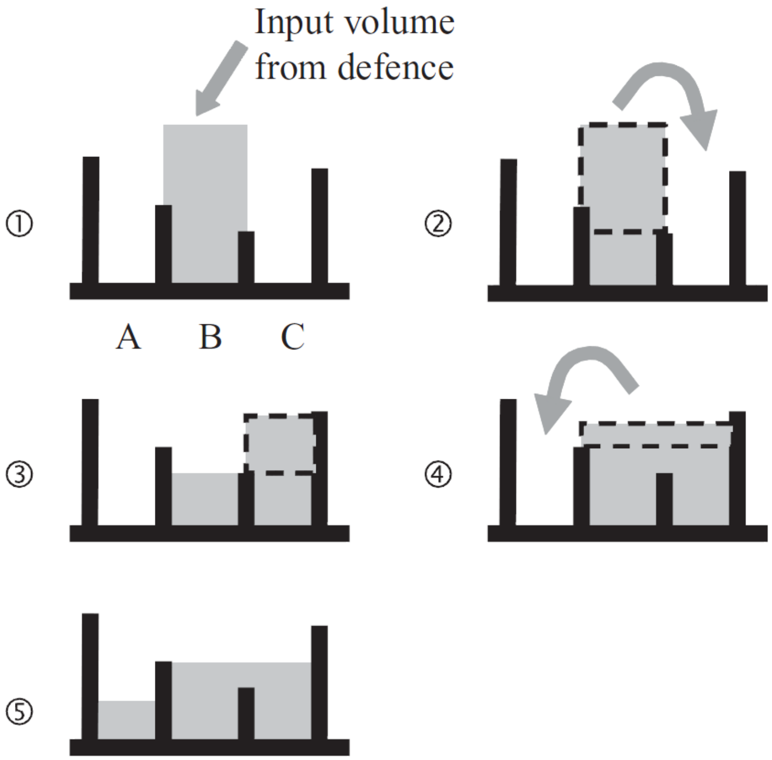
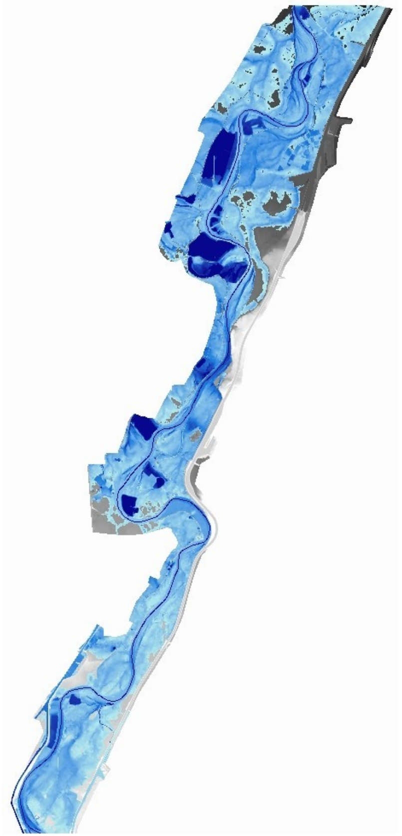


Can we replace dynamical models?

- Pure ML approaches
  - Restricted spatially to where training data exist
  - Can't predict new scenarios beyond training data event scale (i.e. cannot predict larger unobserved floods)
- Rapid Flood Spreading Algorithms
  - Either non-mass conserving, or cannot simulate transient behaviour
  - Fail at reproducing many benchmark test cases



Conclusions

- Many large scale river flows can be represented by simplified shallow water physics
- Given finite computing resources, model skill is improved more by increasing resolution than improving the physics
- Highly resolved models now possible
  - ~ 1 - 2 m over whole major cities (where data permits)
  - ~30 - 100 m over whole continents (using globally available data)
- Fusing models, ground and space data is yielding new insights into surface water dynamics

Thank you for your interest

For further information please see
http://meteor-project.org