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On Uncertainty and Probability in Predicting Natural Hazard Risks using Models

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My background

- I am a hydrologist
- I have worked at the Institute of Hydrology and Universities of Leeds, Virginia and Lancaster, with visiting positions at UC Santa Barbara, EPFL Lausanne, KU Leuven, Uppsala University, and LSE London
- I have worked on many hydrological models (Topmodel, IHDM, SHE, MIPs, DBM….) and 1D/2D hydraulic models (HEC-RAS, ISIS, JFLOW,….)
- Interests in floods, flood forecasting, future change, residence times and travel times of pollutants
- And uncertainty (Generalised Likelihood Uncertainty Estimation, GLUE, methodology)

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My background

- Started doing Monte Carlo experiments on models at the University of Virginia in 1980 (start of GLUE and equifinality concepts)
- 80's - Used Monte Carlo in continuous simulation for flood frequency estimation
- Moved to Lancaster 1985, continued GLUE work, first publication with Andrew Binley in 1992.
- Most recent thoughts on how to do science given uncertainties in *CRAS Geosciences* 2012 paper and "GLUE 20 years on" paper in *Hydrol. Process.* 2013
- Current CREDIBLE project on uncertainty in risk assessments for natural hazards for NERC
- Work has been summarised in two books.

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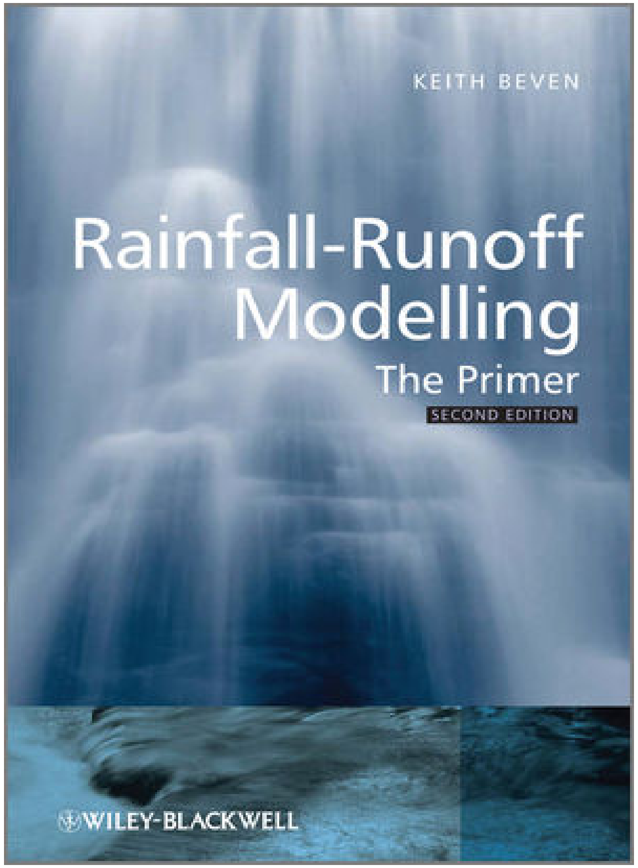
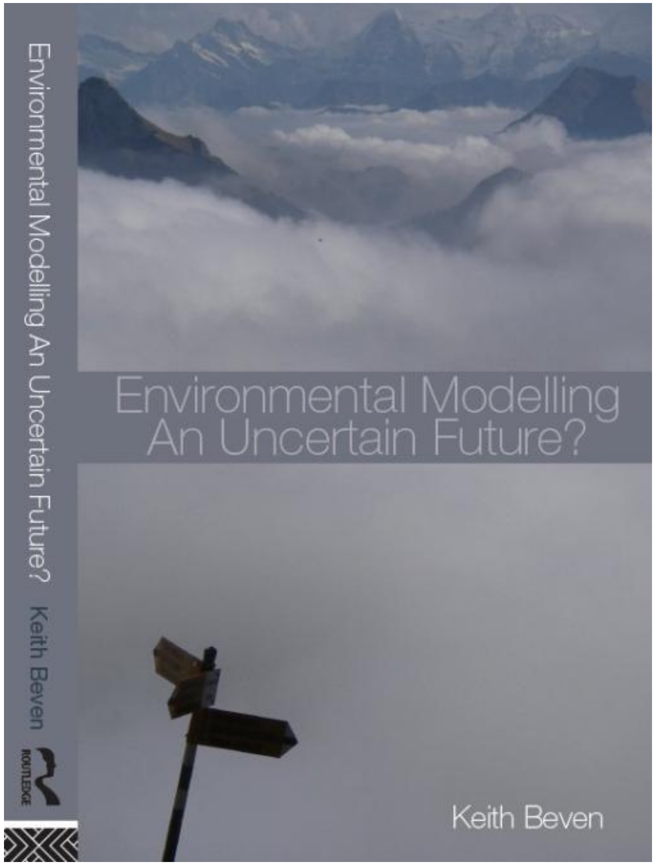
The books…





www.uncertain-future.org.uk

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The UK : Floods as a natural hazard

- Central England, Fluvial, winter/spring 1998, 2000, 2002
- Groundwater flooding; Hampshire/ Kent,
  2000/01;
- Boscastle, Cornwall, Flash flood, 2004

- Carlisle, Fluvial and Pluvial, 2005
- Central England, Fluvial, summer 2007
- Hull, Pluvial, summer 2007
- Sheffield (near dam collapse), summer 2007
- Morpeth, Flash flood, 2008
- Sheffield (near dam collapse), Cockermouth, Fluvial, 2009
- Lostwithiel, Cornwall, Flash flood, 2010
- Calder 2012 (June & July), Newcastle, Pluvial ("Toon monsoon" super-cell) 2012, Dorset tunnel collapse, 2012

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The UK : More and more floods….??

- Defra "Making Space for Water" 2004
- Foresight "Future Flooding" 2006
- Pitt Review of Summer 2007 floods
- European Floods Directive 2007

Tewkesbury 2007

- Historical rainfalls in west of England – wetter winters
- Climate change predictions – wetter winters, more extremes (but see Beven, *Hydrol. Process.* 2011)

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More and more flood damages….??

Pitt Review of Summer 2007 floods

- 48000-55000 properties damaged (20,238 by fluvial flooding)
- 7000 people rescued; 10000 trapped on M5
- 13 people died
- Total costs £3.2 bn
- Threat to electricity substations and water treatment works (parts of Gloucestershire without water up to 17 days)
- Lack of clear responsibility for pluvial/urban flood control and warning

More and more flood damages....??

Also in 2007 - Worldwide

- 200 major floods in 2007
- affecting 180m people / 8000 deaths / £40bn damages

More recently: Thailand (£2.2bn), Pakistan, Australia (twice), Mississippi, Japan Tsunami, ...

2013: Central Europe (Elbe, Danube), Colorado, Vietnam, Thailand, Saudi Arabia, India (Assam and Bihar), China, Russia, Sardinia, Alberta, Jakarta, Typhoon Haiyan, Eastern England/Netherlands (?)

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Defining Risk

Formal definition of Risk

Risk = Probability (Hazard) * Consequences

Normal to integrate over distribution of events to get the exceedance probability of risk and expected annual damages for cost-benefit analysis

But …..Uncertainties in Defining Risk

What is probability of an event?

- flood frequency - how to define probability of exceedance (choice of distribution)
- uncertainty in probability of exceedance given short data sets (sample uncertainty
- but questions of stationarity
- uncertainty in assessing area affected by potential consequences (footprint of an event)

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But .....Uncertainties in Defining Risk

What are the consequences of an event (€)?

- uncertainty in vulnerability (what is there)
- uncertainty in damages in relation to characteristics of an event (depths, velocities, debris)
- costing loss of life
- costing heritage impacts
- ....

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Defining Risk

Formal definition of Risk

Risk = Probability (Hazard) * Consequences

So in defining risk both probability and consequences are uncertain….. in uncertain ways!

Defining Risk

Formal definition of Risk

Risk = Probability (Hazard) * Consequences

So in defining risk both probability and consequences are uncertain….. in uncertain ways!

Lack of knowledge (epistemic uncertainty) might be more important than random variability (aleatory uncertainty) in both terms

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Hydrology as one of the inexact sciences

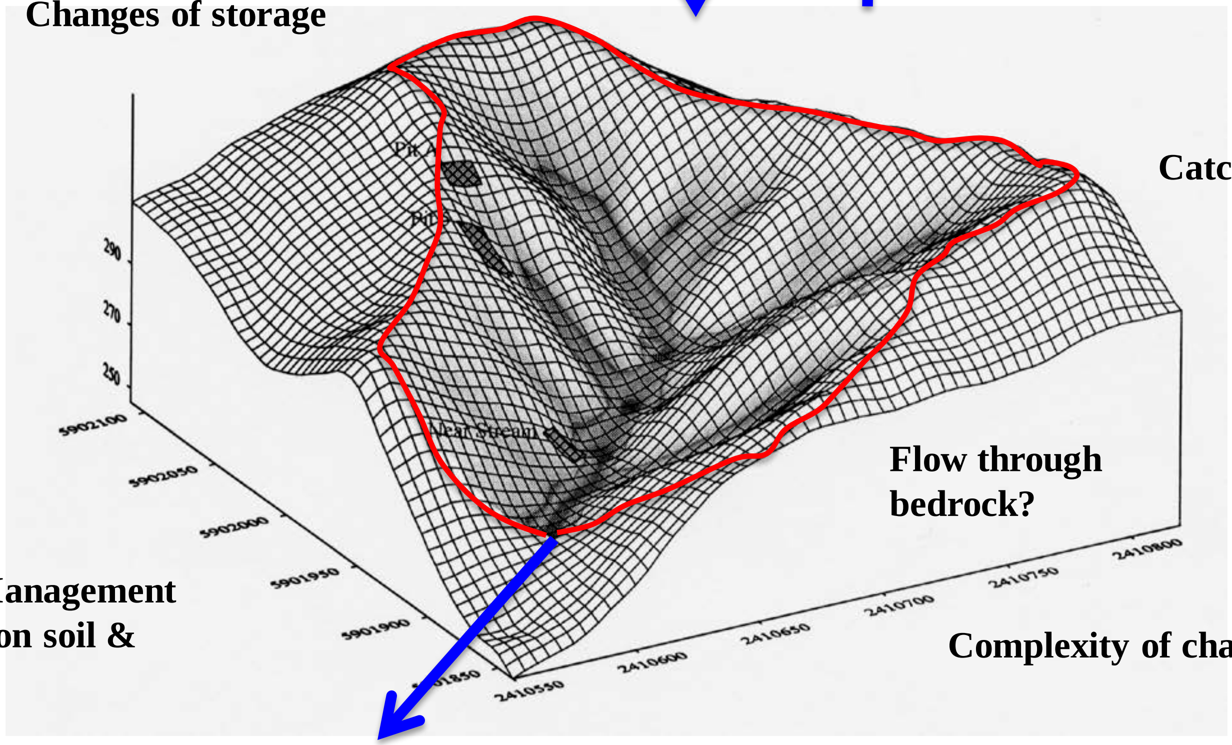
Pattern of rainfall inputs

Pattern of actual evapotranspiration

Changes of storage

Catchment area

Heterogeneity of soils & representation of flow processes



Flow through bedrock?

Land Management Effects on soil & surface

Complexity of channels

Discharge estimates (requires “rating curve”)

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Hydrology as one of the inexact sciences

The Water Balance Equation

$$Q = R - E_a - \Delta S$$

All of terms subject to both epistemic and aleatory uncertainties……and there may be other inputs and outputs impossible to measure

Nancy Cartwright *"This Dappled World"* – such principles are capacities rather than truths when applied in practice

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Types of error and why they are important

- Formal statistical approach to likelihoods (generally) assumes that the (transformed) errors are additive and random (*aleatory error*) conditional on the model being correct
- But in environmental modelling, many sources of error (in model structure, input data, parameter values,….) are a result of lack of knowledge (*epistemic error*) which will result in nonstationarity of error characteristics
- In extreme cases, data available for calibration might even be *disinformative*.

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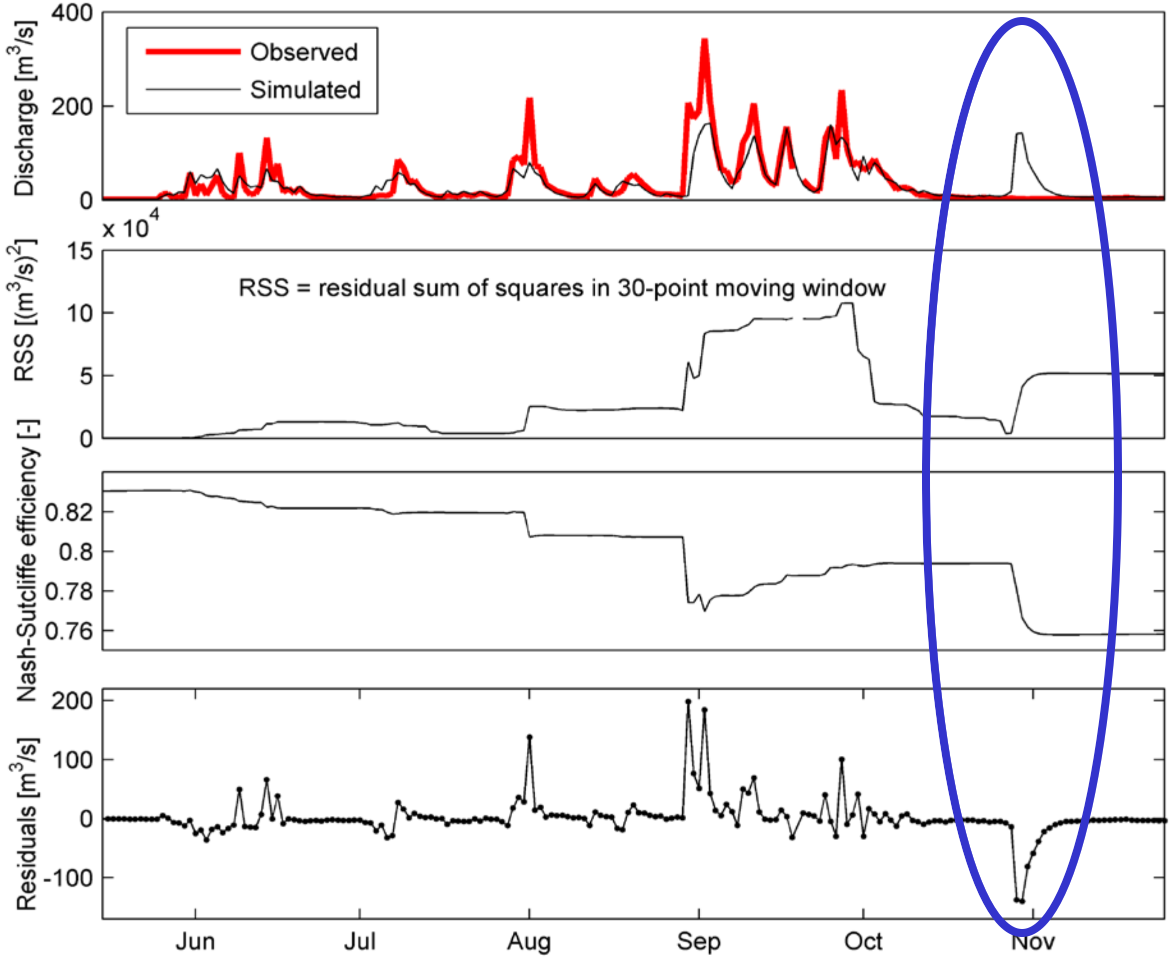
Disinformation in calibration data

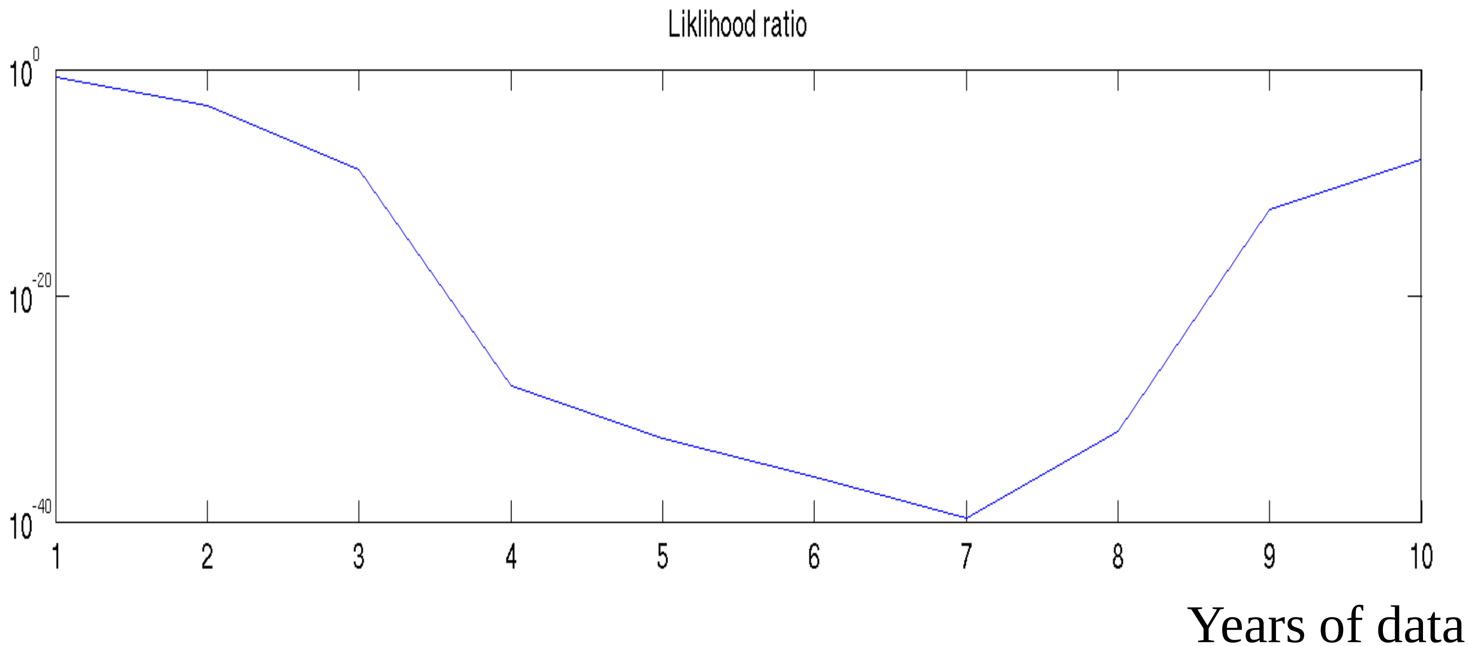


Application of WASMOD to Pasa La Ceiba, Honduras
(from Beven and Westerberg, Hyd. Proc. 2011)

Do Statistical Error Models lead to Over-Conditioning when Epistemic Uncertainty Important?

Assume standard (aleatory) likelihood with Gaussian information, mean bias, lag 1 correlation.

Likelihood ratio for 2 models with similar error variance



See discussions in Beven JH, 2006; CRAS Geosciences, 2012

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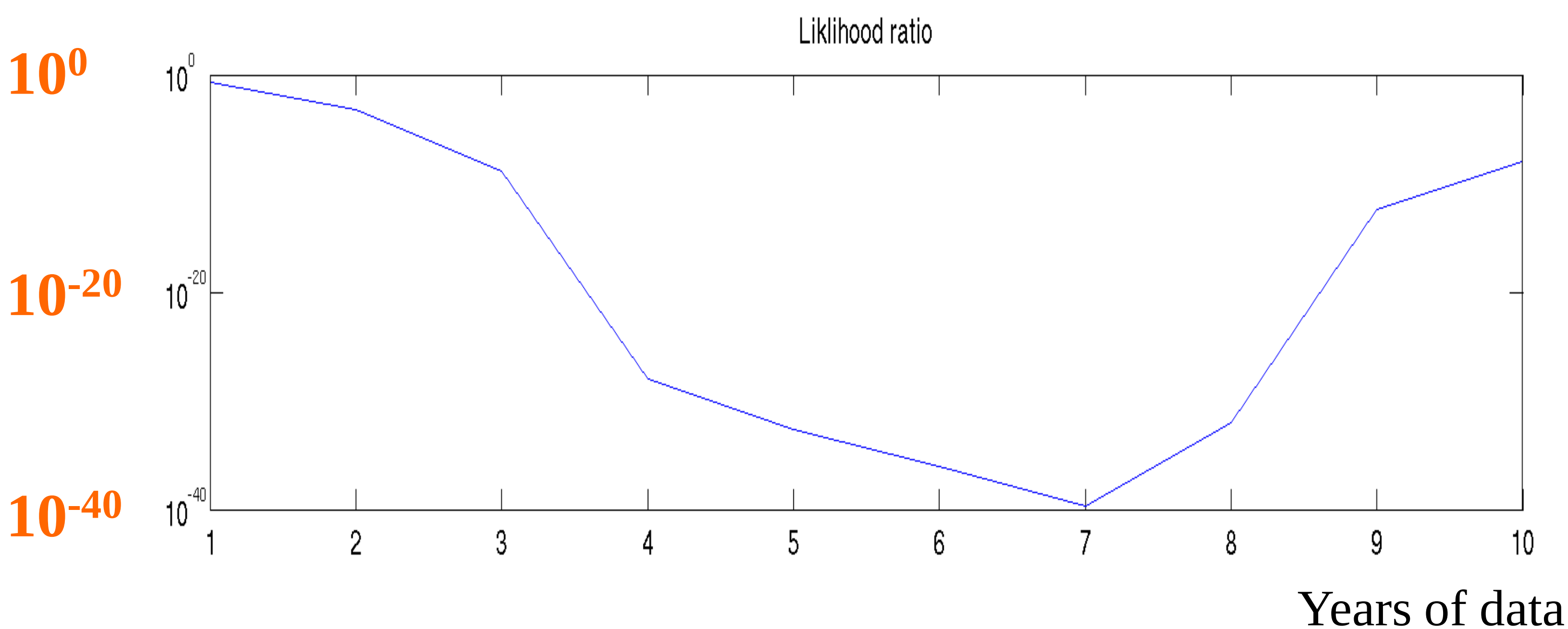
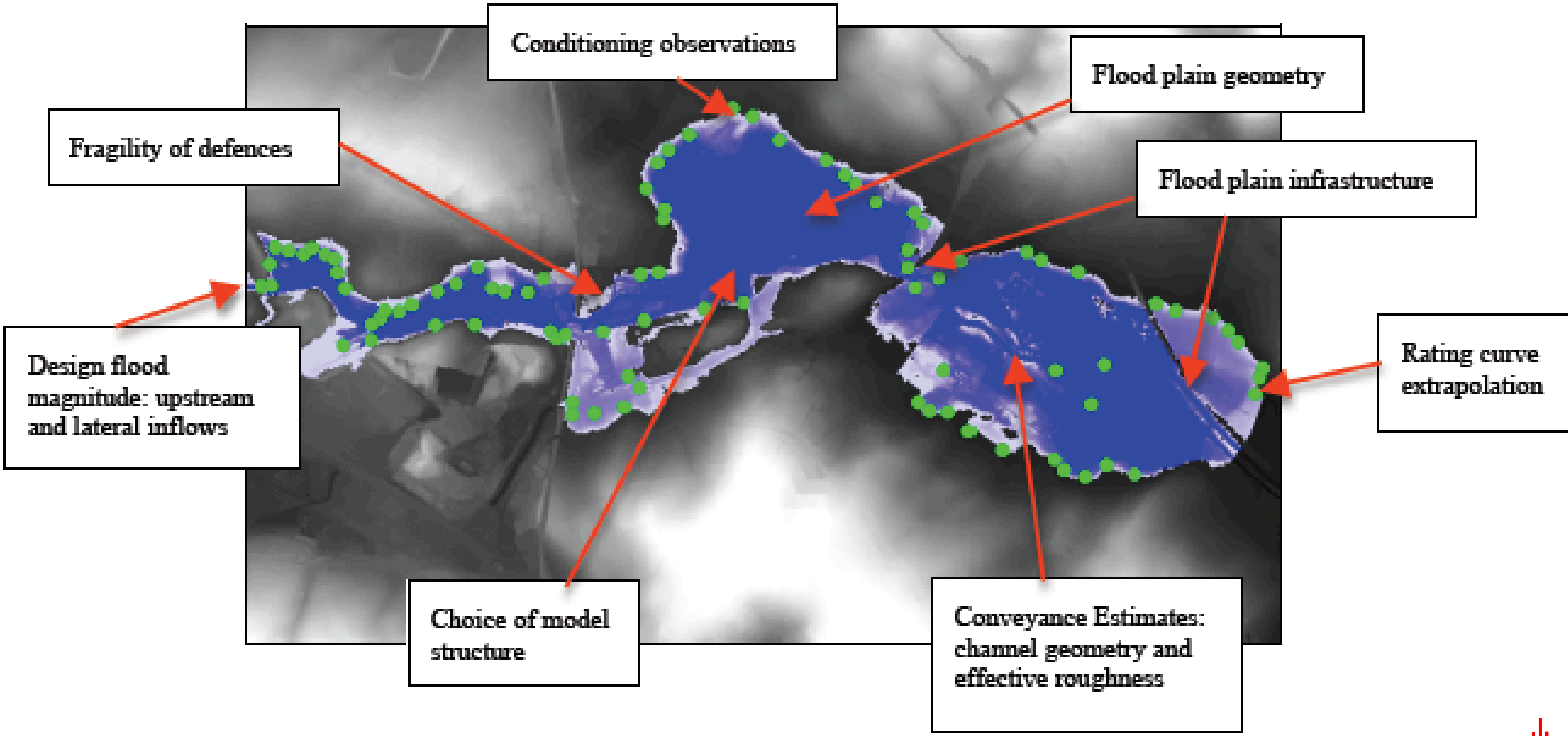


See discussions in Beven J. Hydrol., 2006; *CRAS Geosciences*, 2012

Sources of Uncertainty in Flood Risk Mapping



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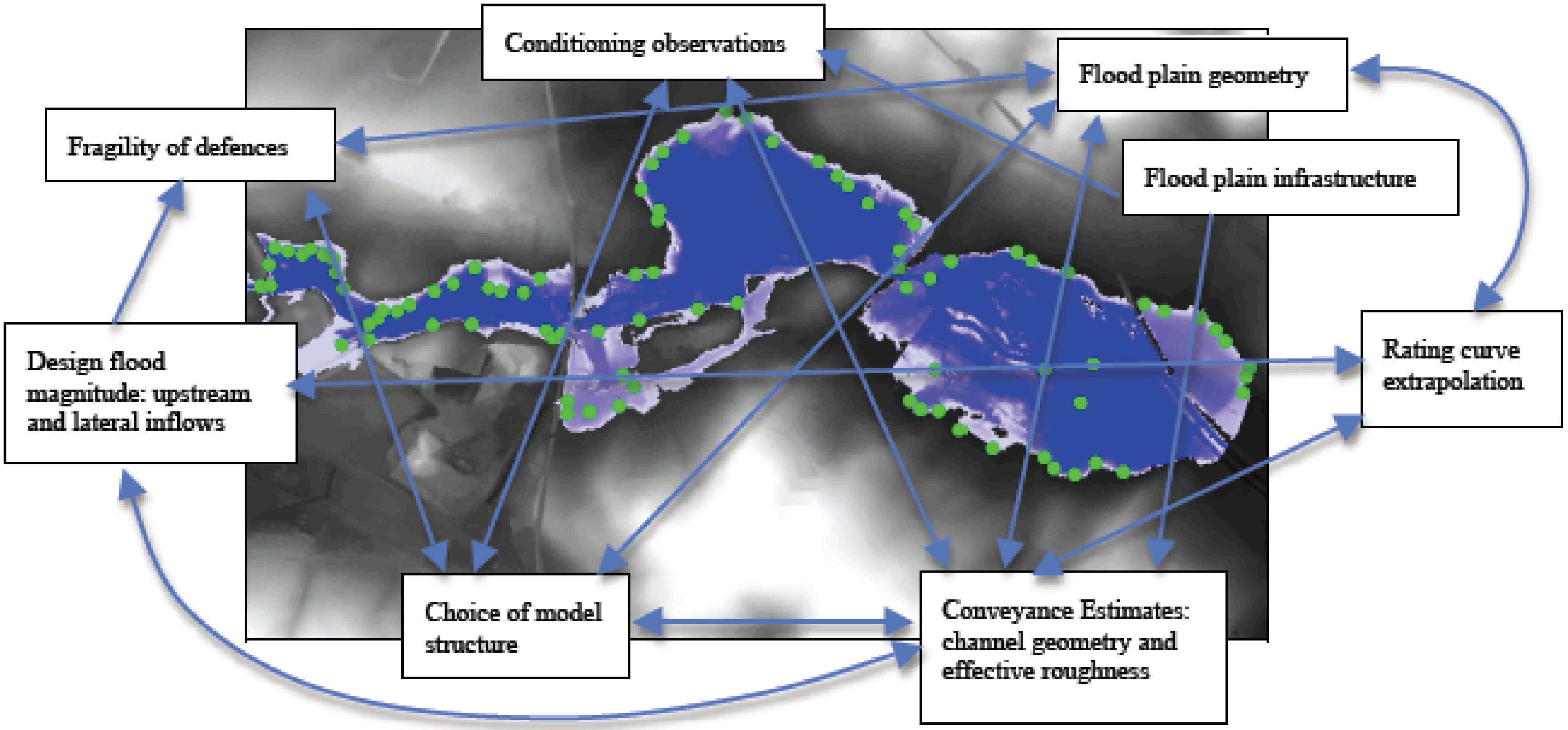
Interactions between Sources of Uncertainty



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Types of error in flood risk mapping

Source of uncertainty	Aleatory errors	Epistemic nature
Design flood Magnitude	What is the range of sampling variability around underlying distribution of flood magnitudes?	Are floods generated by different types of events? What frequency distribution should be used for each type of event? Are frequencies stationary? Will frequencies be stationary into the future?
Conveyance estimates	What is the random sampling variability around estimates of conveyance at different flood levels?	Is channel geometry stationary over time? Do conveyance estimates properly represent changes in momentum losses and scour at high discharges? Are there seasonal changes in vegetation in channel and on floodplain? Is flood plain infrastructure, walls, hedges, culverts etc. taken into account?
Rating curve interpolation and extrapolation	What is standard error of estimating the magnitude of discharge from measured levels?	Is channel geometry stationary over time? What is estimation error in extrapolating rating curve beyond the range of measured discharges? Does extrapolation properly represent changes in momentum losses and scour at high discharges?

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(from Beven and Alcock, *Freshwater Biology*, 2011)

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Types of error in flood risk mapping

Source of uncertainty	Aleatory errors	Epistemic nature
Flood plain Topography and Infrastructure	What is the standard error of survey errors for flood plain topography? What is the random error in specifying the positions of elements, including elevations of flood defences?	Are there epistemic uncertainties in correction algorithms in preparing digital terrain map? How should storage characteristics of buildings, tall vegetation, walls and hedges in geometry be treated? Are there missing features in the terrain map (e.g. walls, culverts)?
Model structure		How far do results depend on choice of model structure, dimensions, discretisation and numerical approximations?
Observations used in model calibration / conditioning	What is the standard error of estimating a flood level given post-event survey of wrack marks or gauging station observations?	Is there some potential for the misinterpretation of wrack marks surveyed after past events? Are there any systematic survey errors?

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Types of error in flood risk mapping

Source of uncertainty	Aleatory errors	Epistemic nature
Future catchment change		What process representations for effects of land management should be used? What future scenarios of future change should be used? Are some scenarios more likely than others?)
Future climate change	What is the variability in outcomes owing to random weather generator realisations?	How far do results depend on choice of model structure? What process representations in weather generators should be used? What future scenarios of future change should be used? Are some scenarios more likely?
Fragility of Defences Consequences / Vulnerability	What are the probabilities of failure under different boundary conditions? What is the standard error of for losses in different loss classes?	What are the expectations about failure modes and parameters? What knowledge about uncertainty in loss classes and vulnerability is available?

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The GLUE methodology

1. Decide on limits of acceptability prior to running model
2. Decide on prior distributions for parameters
3. Run the model with many parameter sets chosen randomly from priors
4. Evaluate the model against available observations
5. Reject models that are "non-behavioural"
6. Weight the remaining models by some likelihood measure
7. Use ensemble of models in prediction (with implicit or explicit handling of residual errors)

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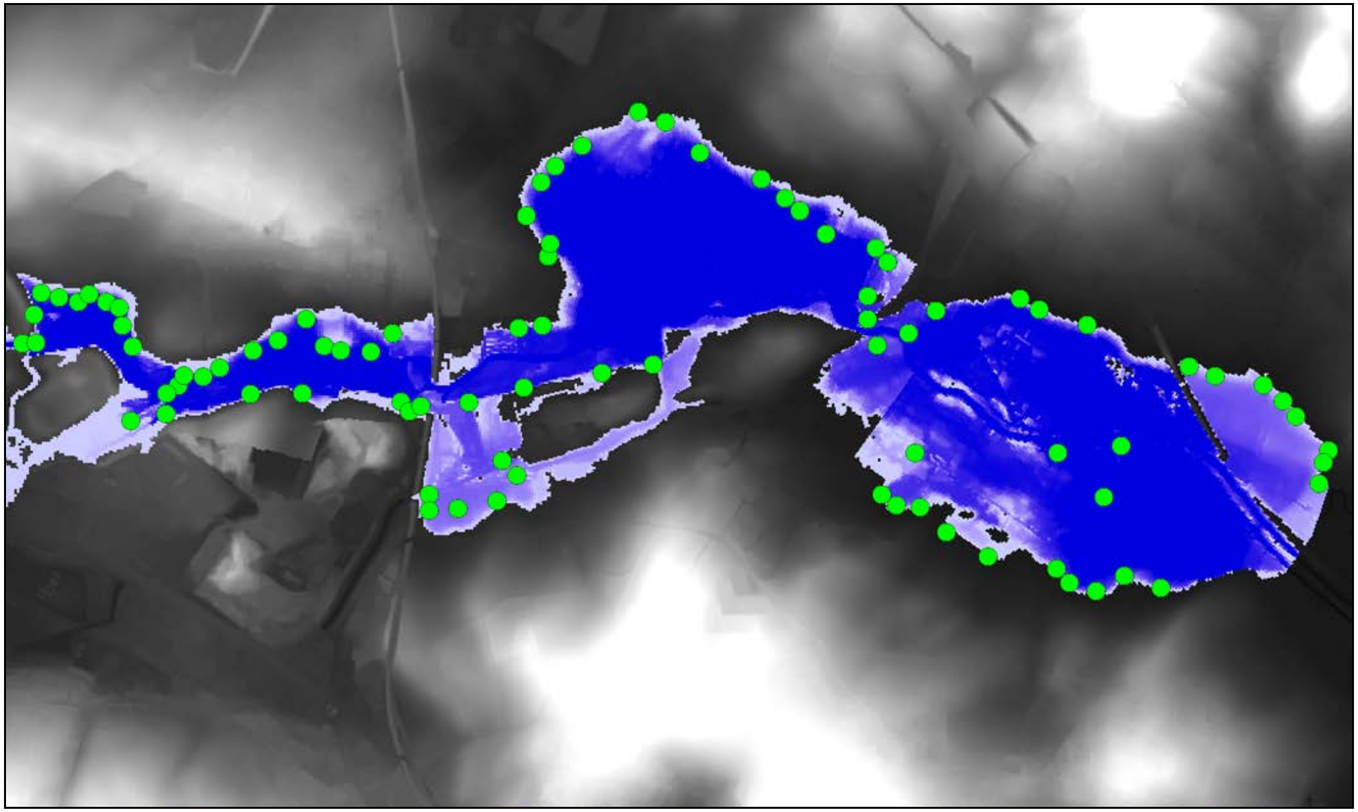
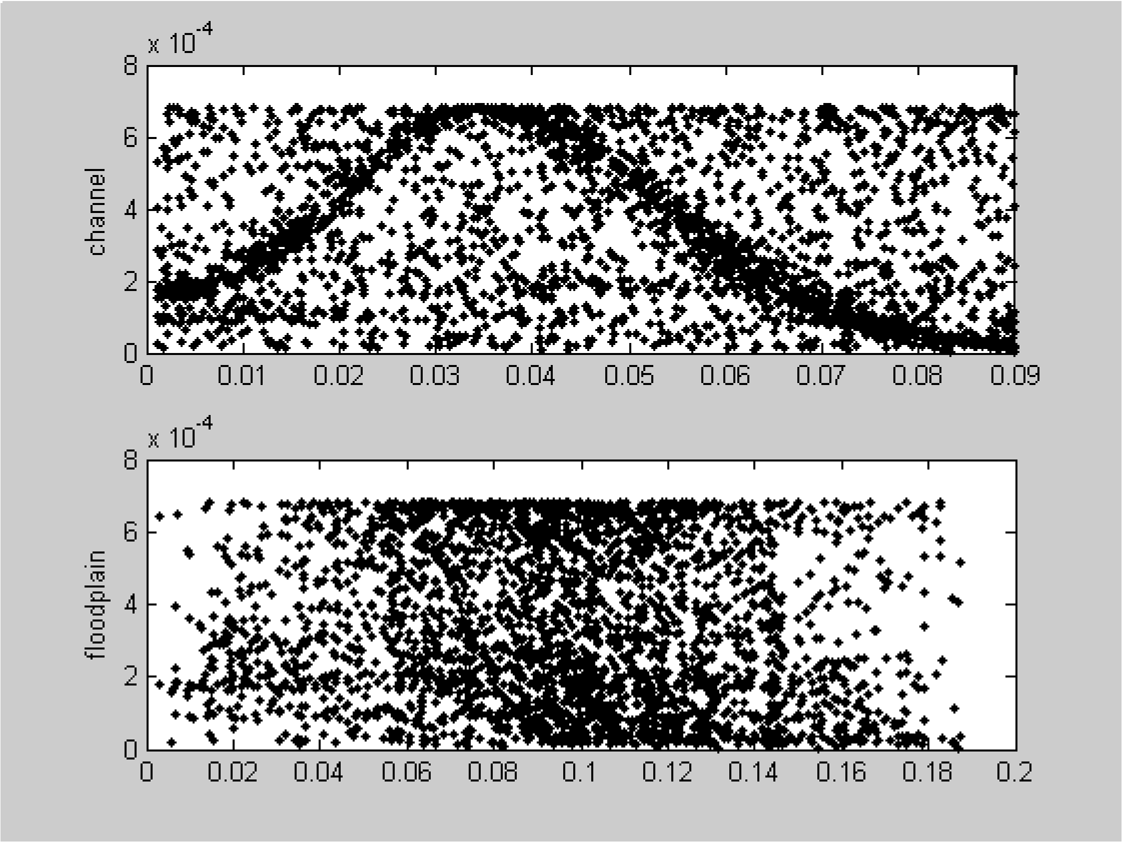
Mexborough: Summer 2007

Mapped maximum inundation and model predicted flow depths for Summer 2007 floods at Mexborough, Yorkshire using 2D JFLOW model



Derivation of weights for the ISIS simulations using inundation outlines and Welsh Bridge observations



Combined likelihood weights for the 30th cross-section

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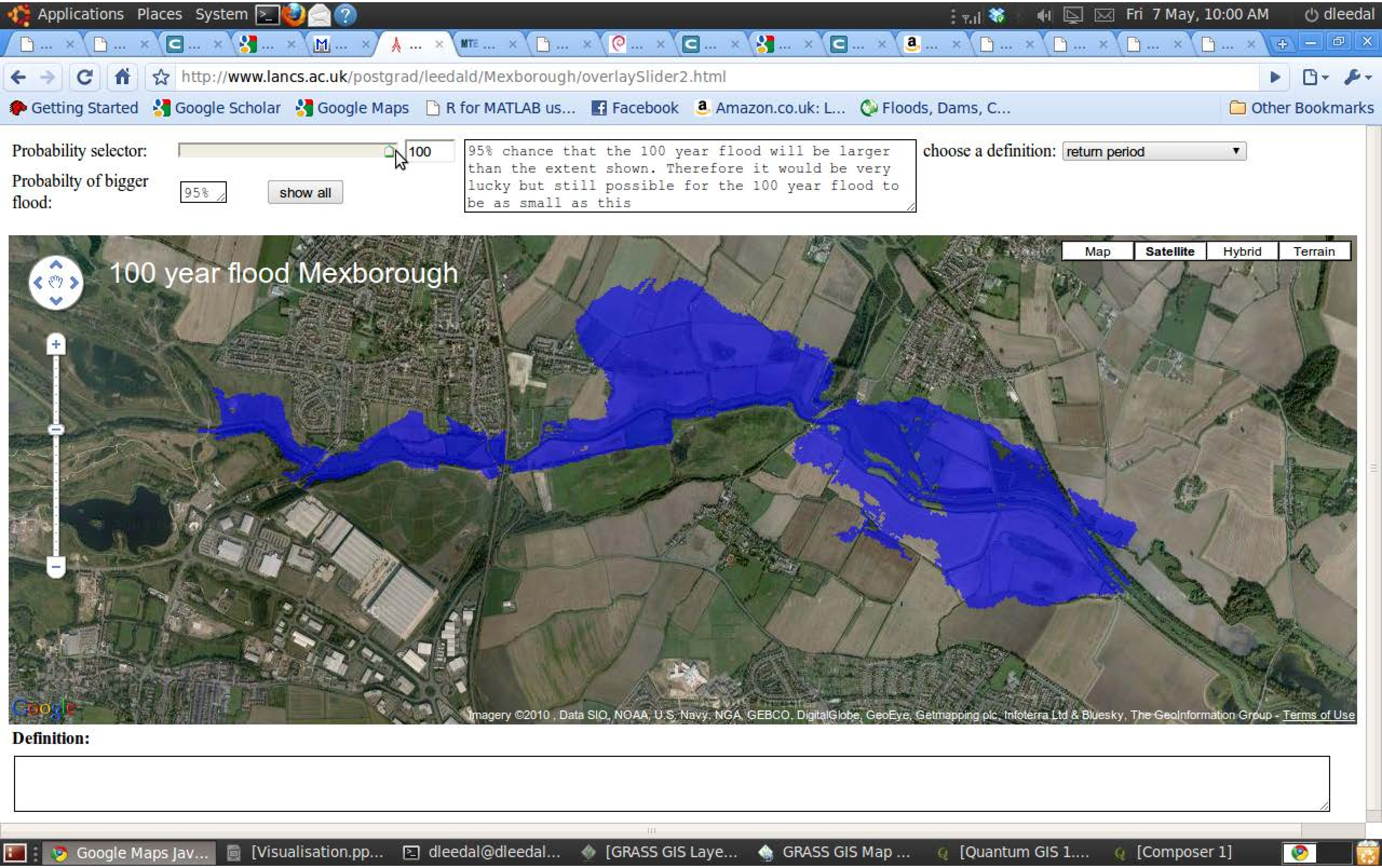
Google maps API



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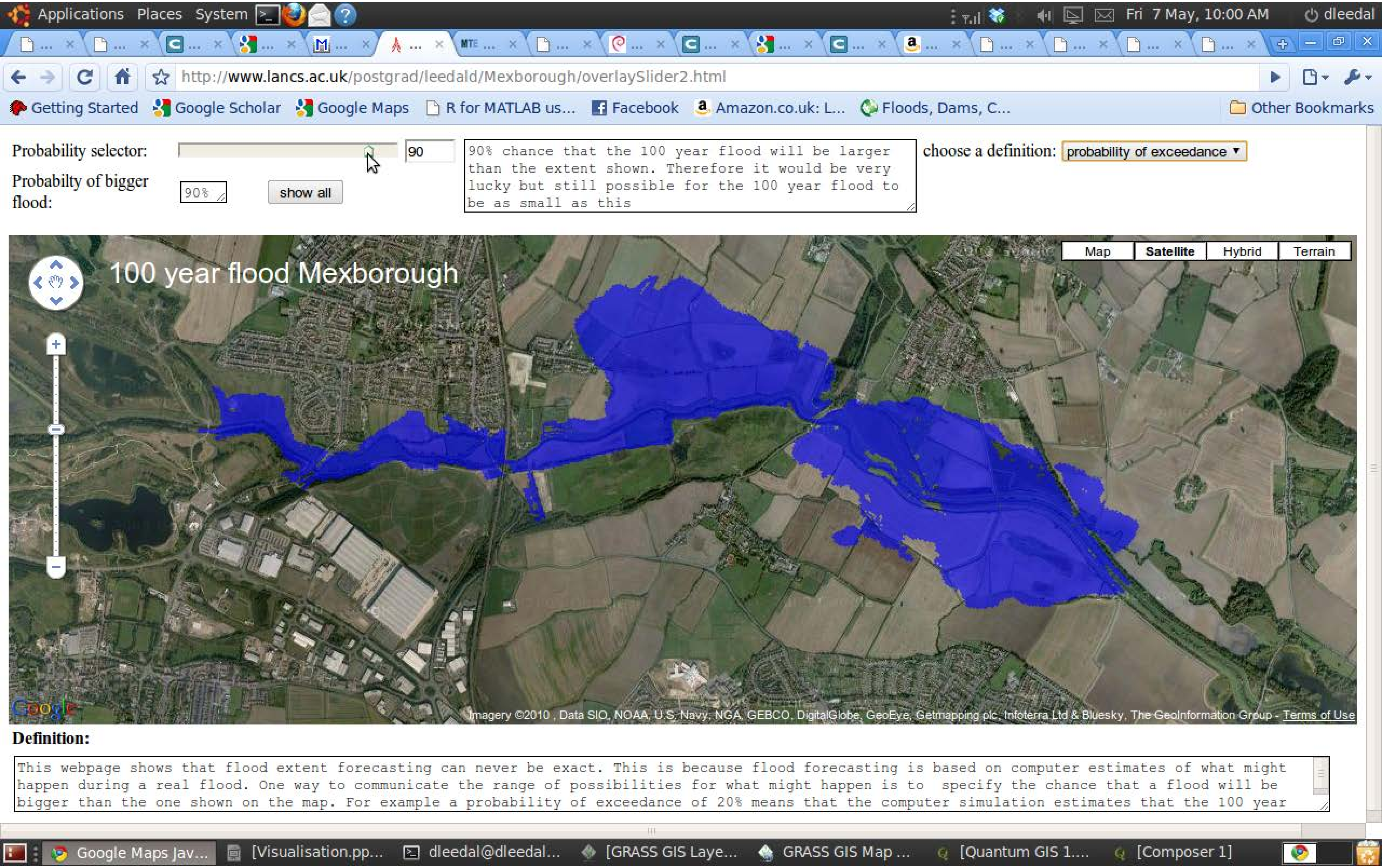

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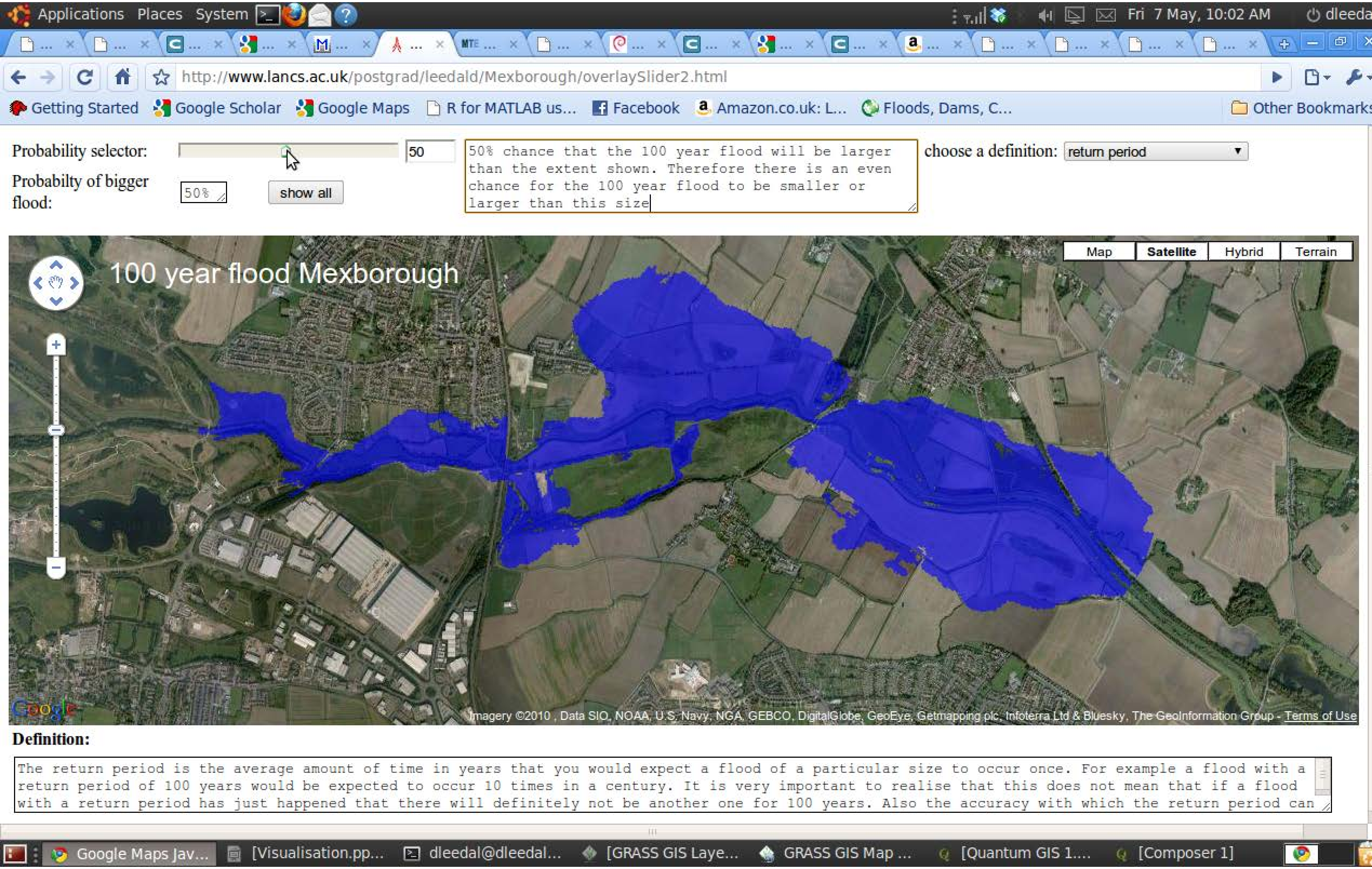

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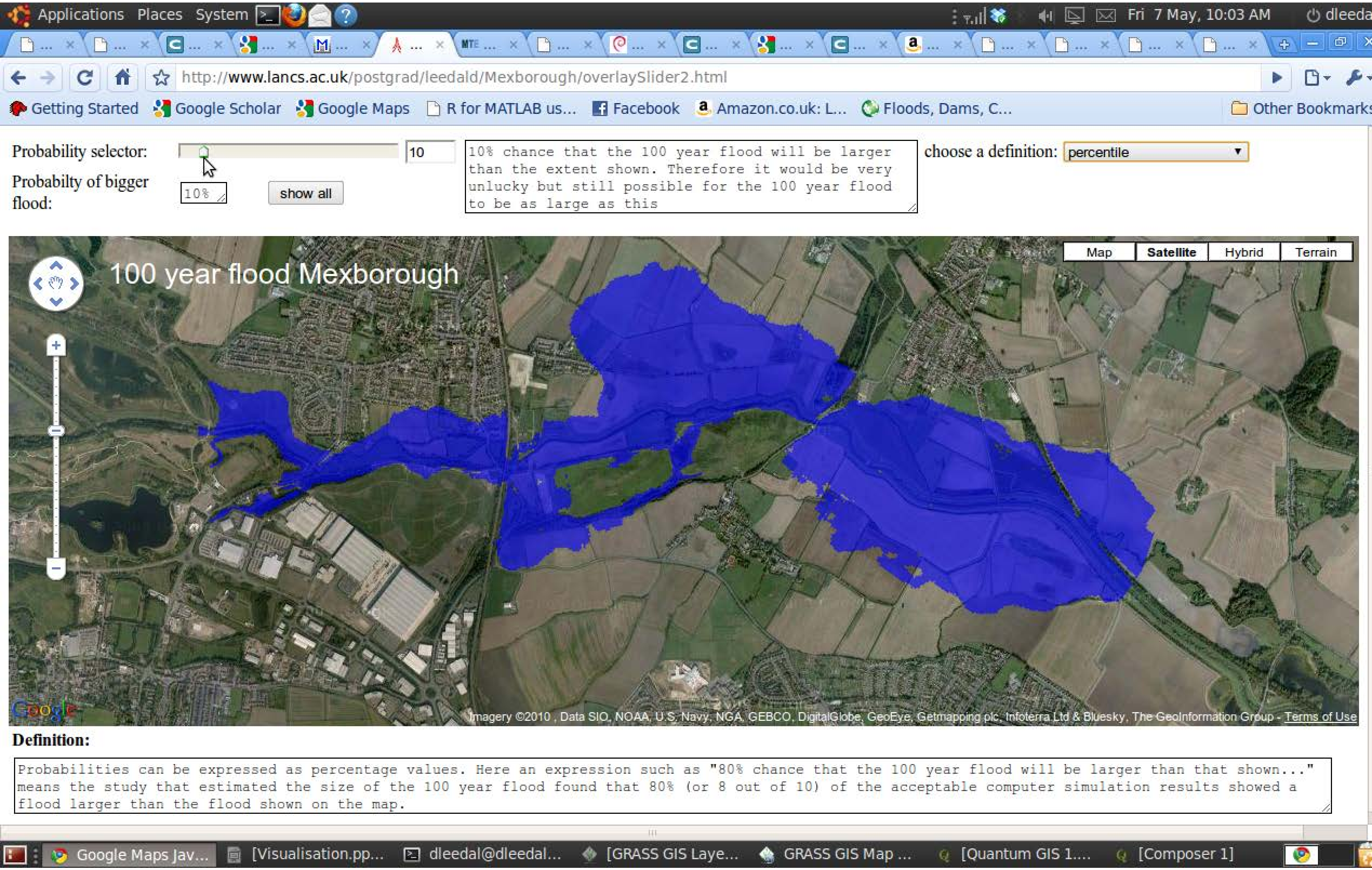

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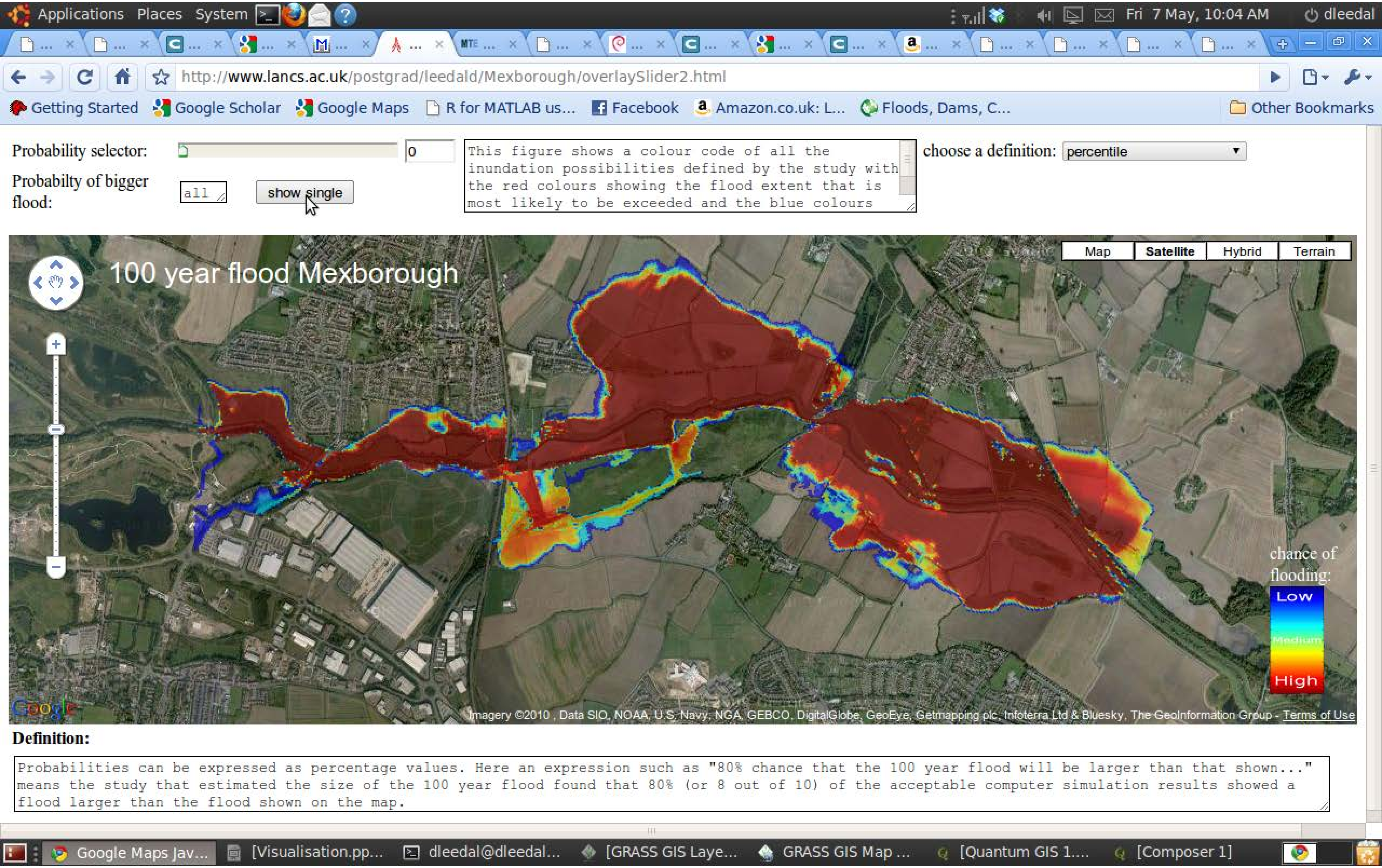

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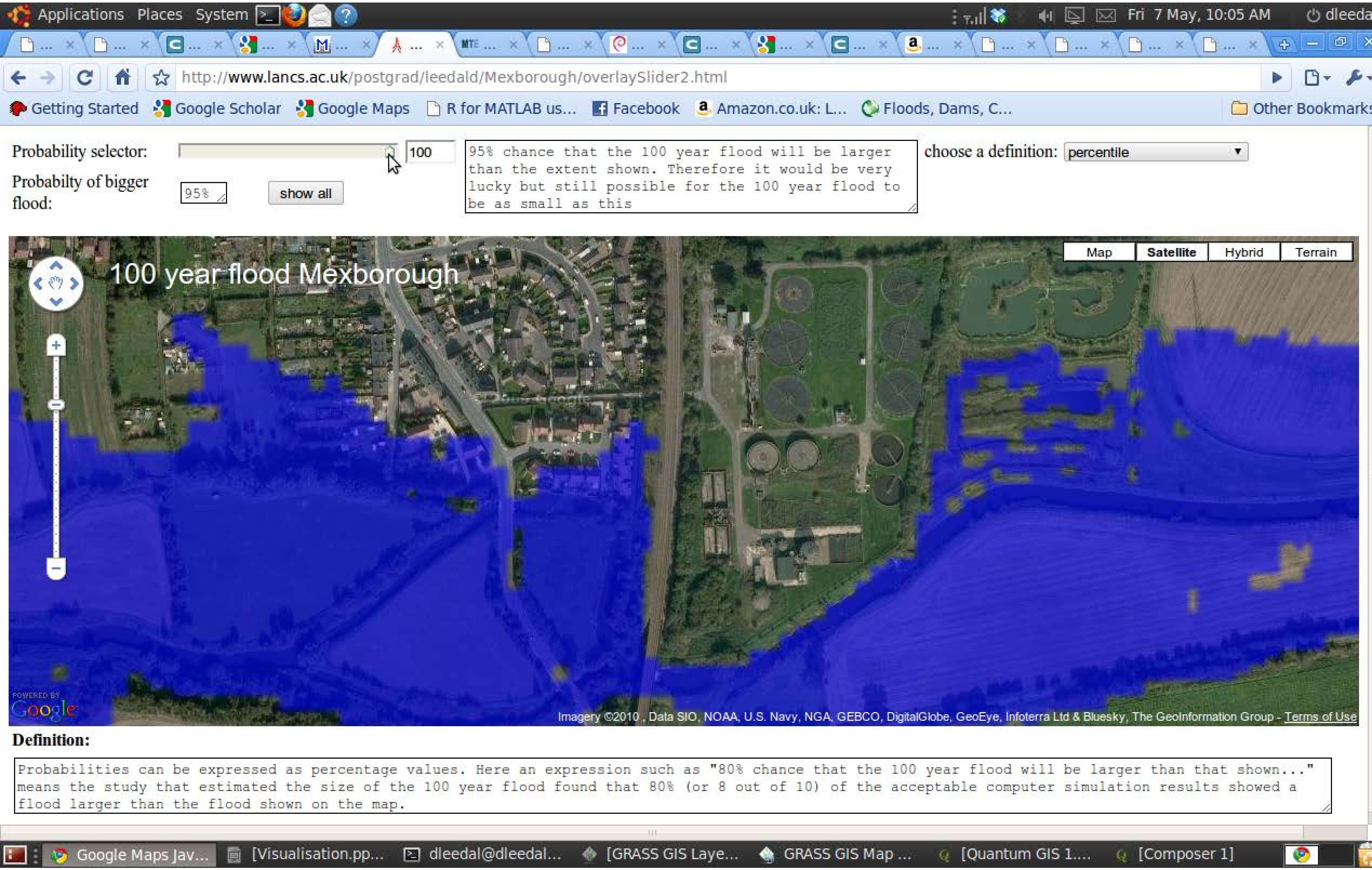

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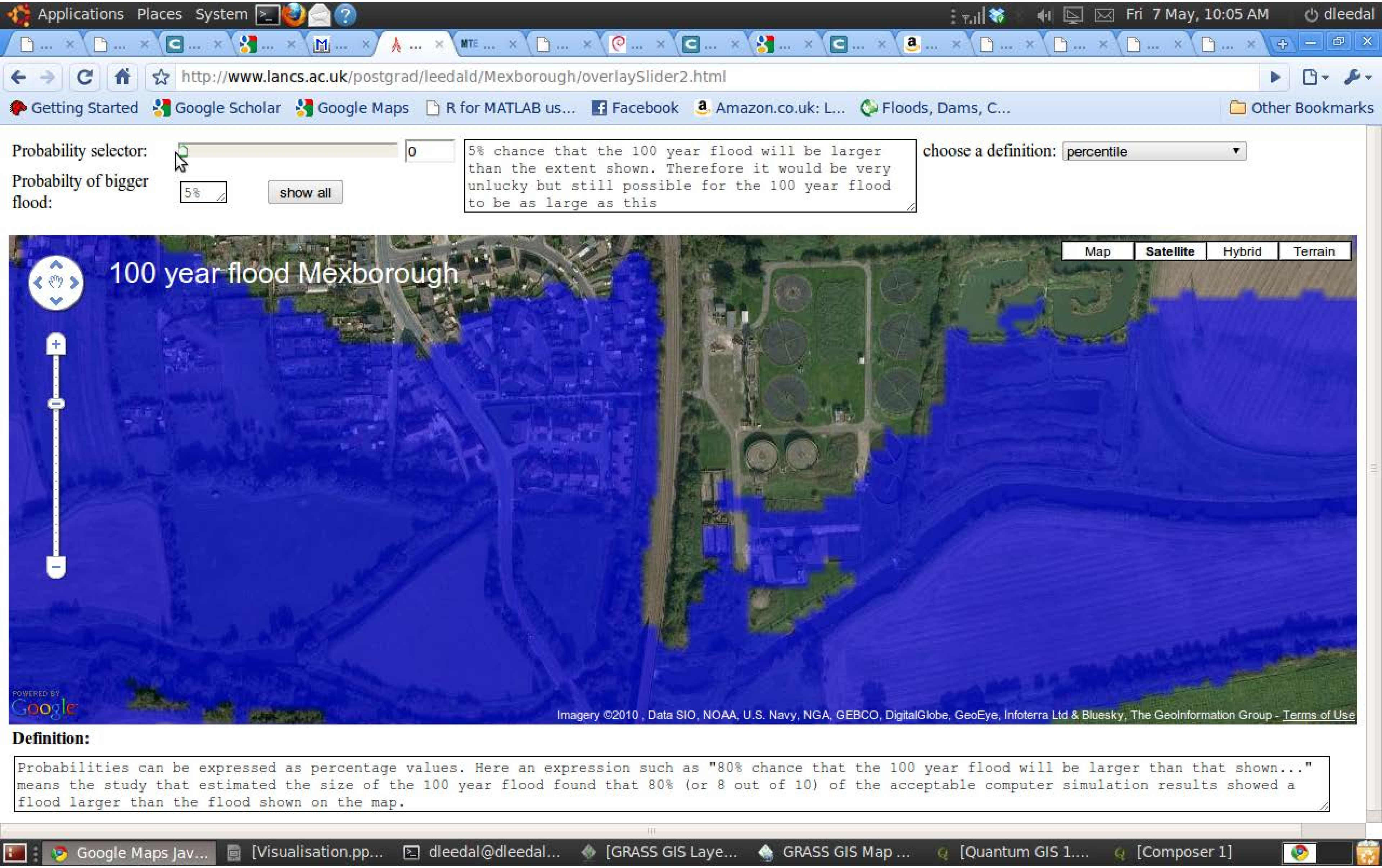

Risk Communication

- Decision makers are not interested in uncertainties (?)
- But uncertainty might make a difference to the decision that is made (being more risk averse where consequences might be catastrophic)
- But how best to convey meaning of uncertainty estimates (Faulkner et al., *Ambio*, 2007)
- AND the assumptions on which those estimates are based (Beven and Alcock, *Freshwater Biology*, 2011)

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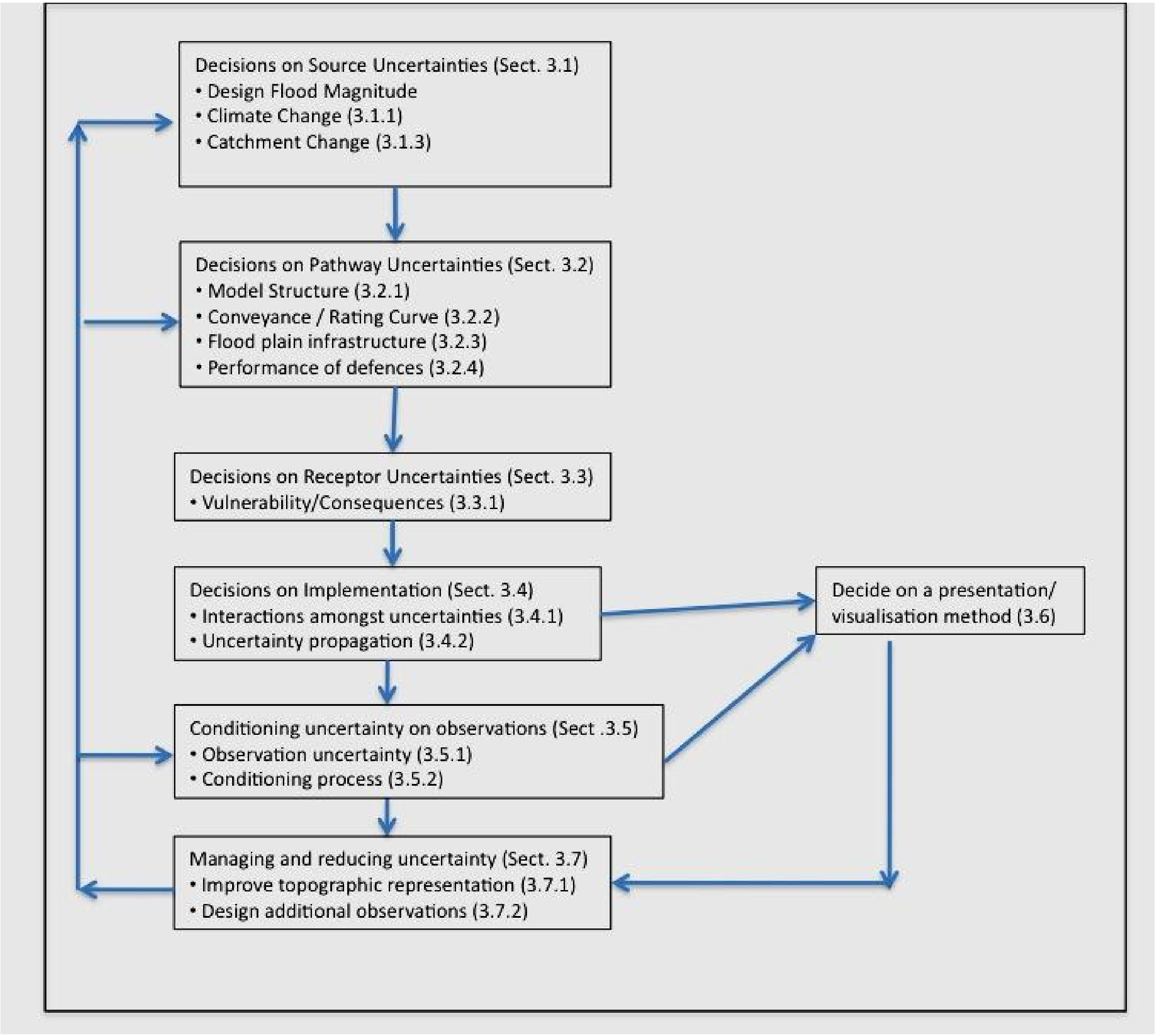
Communicating the meaning of uncertainty estimates: Case of Flood Inundation



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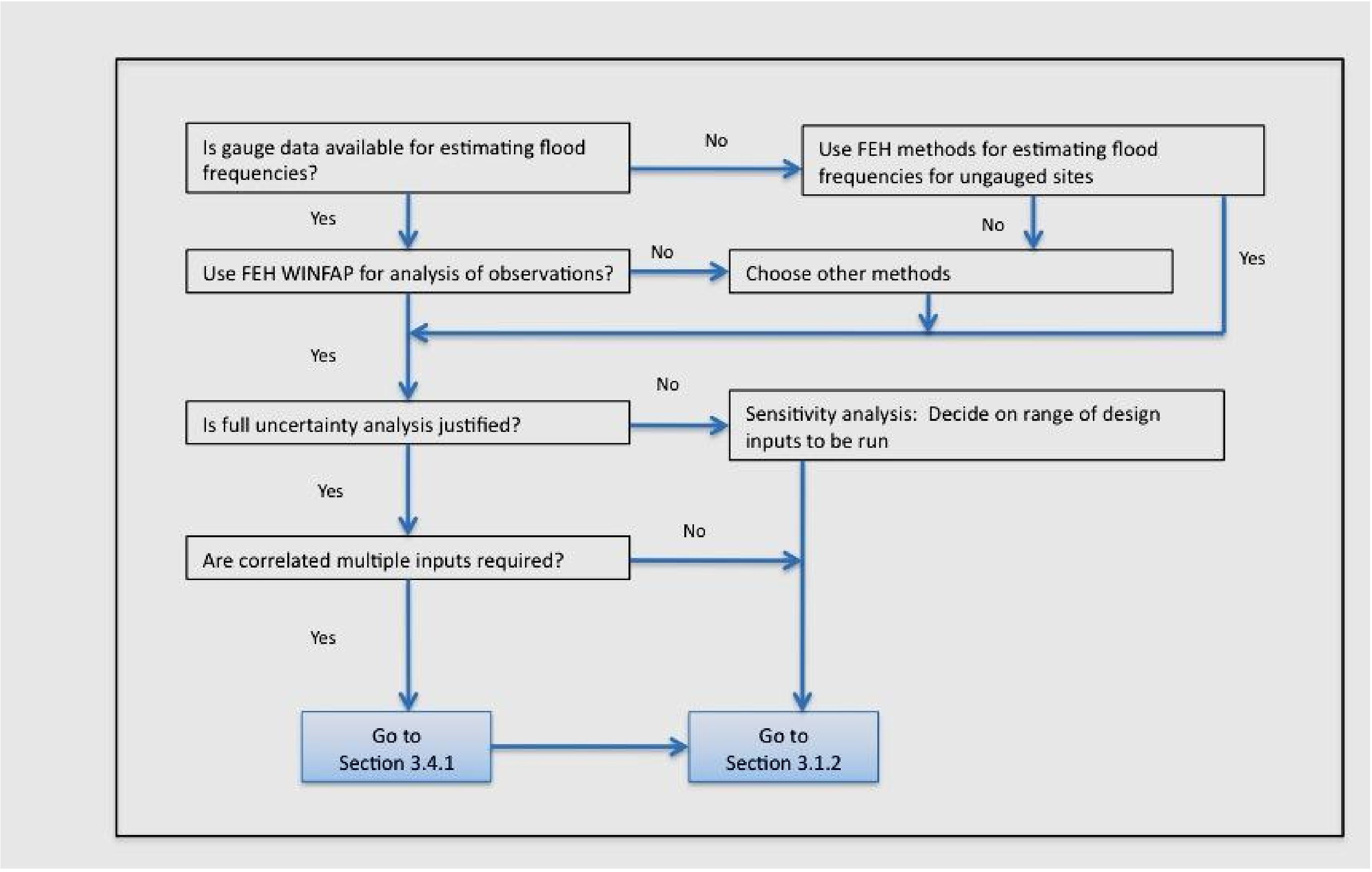
Guidelines for Good Practice as Condition Trees

e.g. Decision Structure for design flood estimation



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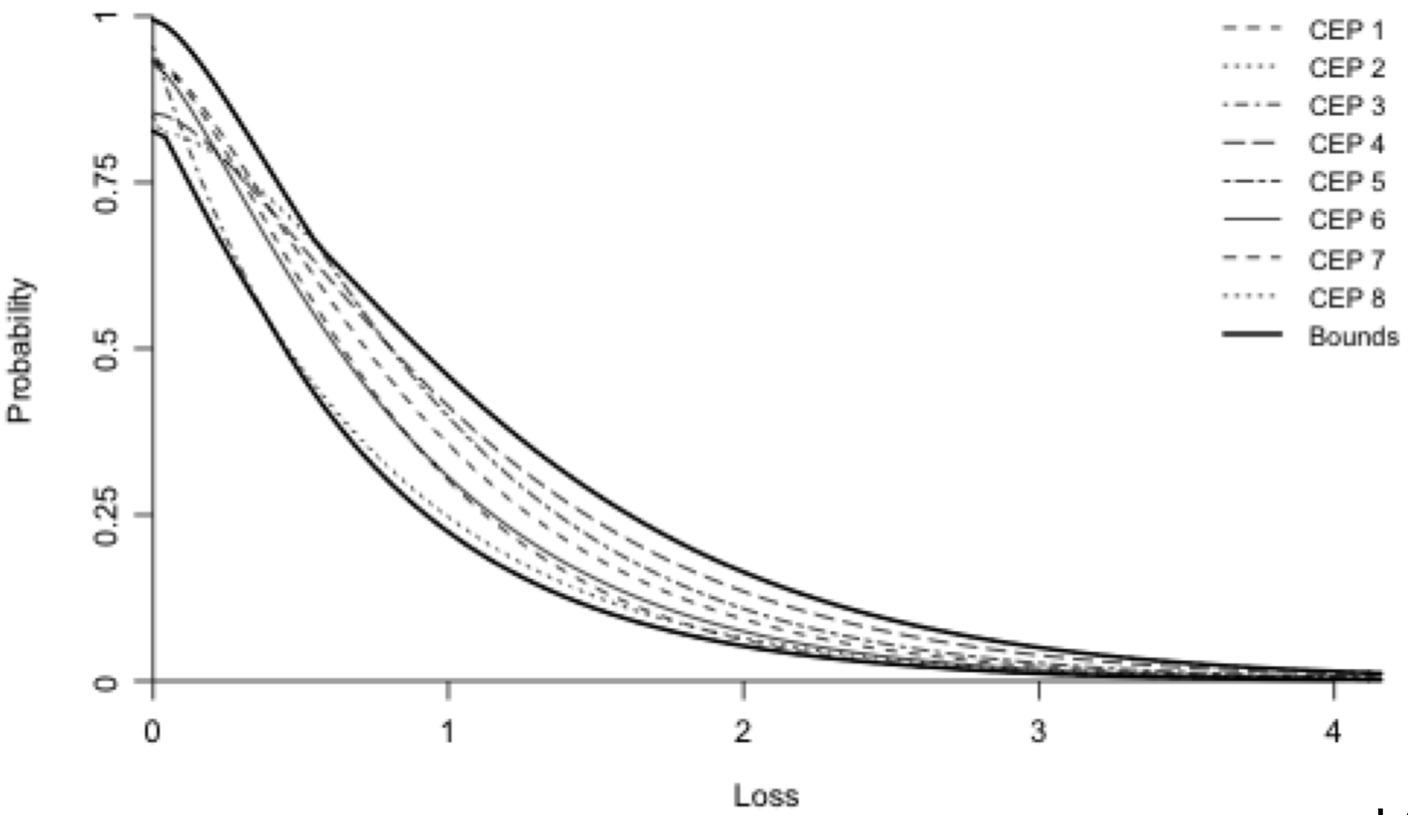
Conditional Risk Exceedance curves: comparing different assumptions



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And why is there so much uncertainty about uncertainty in natural hazards modelling?

- There is no right answer
- Multiple sources of uncertainty are not easily separated
- Model structural uncertainties are important (but statistical methods assess uncertainty assuming that model is correct)
- Input uncertainties are often nonstationary and are processed nonlinearly through a model, resulting in complex error structures
- When a problem is too difficult it leaves lots of scope for arguing about alternate methodologies (statistical, fuzzy, info-gap, GLUE……)

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Still be done

1. Reducing uncertainty depends more on better observation techniques than better model structures. Better model structures might still be achieved - need more tests for both flow <u>and</u> transport
2. Will still have to accept that models of both hazard and consequences will have limited accuracy – so uncertainty estimation will remain important (better likelihood measures and need to identify disinformative data)
3. Should look more carefully at epistemic uncertainties that might lead to surprise – particularly in respect of future non-stationarities (are we looking at a wide enough range of scenarios?)
4. Need to communicate the meaning of predictions (and uncertainties) to decision makers – it may make a difference to the decision process.