The Grid-to-Grid Model for nationwide flood forecasting and its use of weather radar

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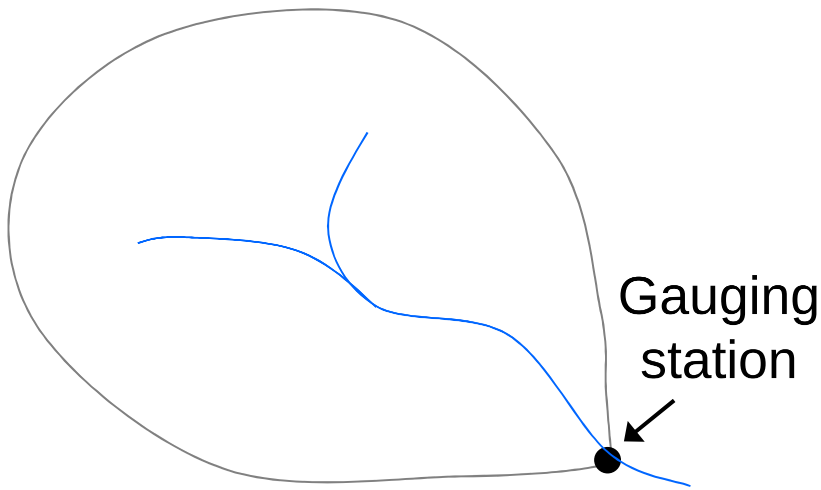
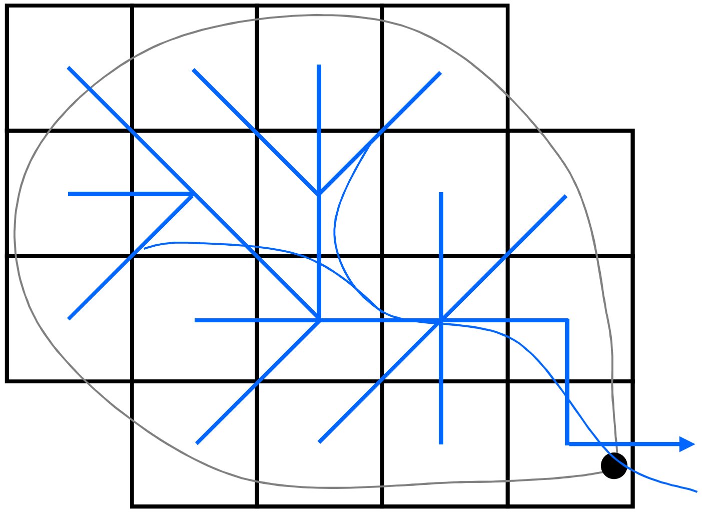
Lumped and Distributed hydrological modelling

Lumped Model



- One model for each gauging station
- Many parameters calibrated to observed flow location
- Flow estimates for one location only
- Uses catchment average rainfall

Distributed Model (G2G)



- One model for large regions (UK)
- Small set of regional parameters, strong support from digital datasets
- Flow estimates in each grid ($1km^2$)
- Uses gridded rainfall estimates

Need for distributed models of flood response

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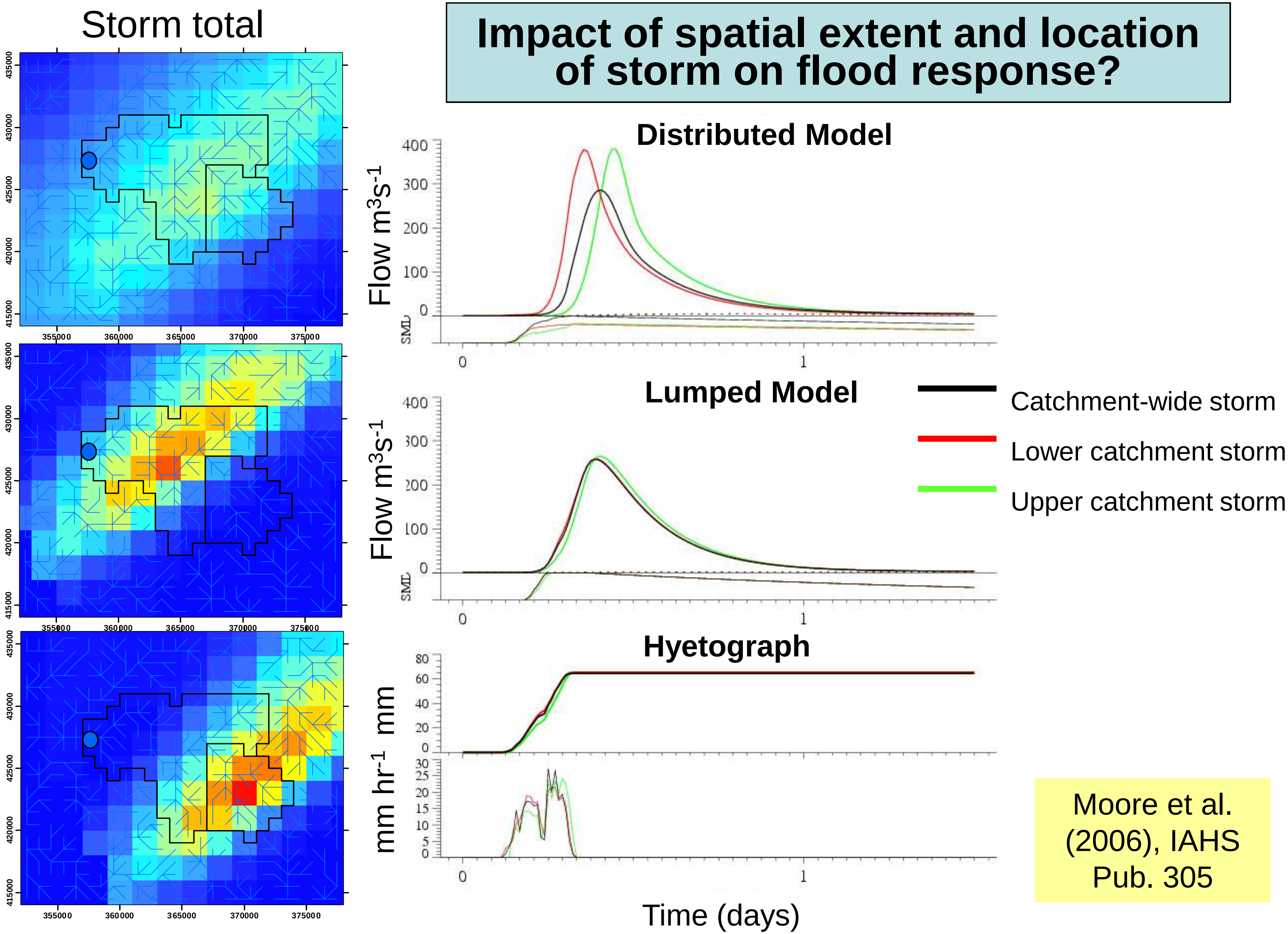
Impact of spatial extent and location of storm on flood response?



Moore et al. (2006), IAHS Pub. 305

Motivation

- Distributed hydrological models used with radar rainfall estimates offer a natural approach to area-wide flood forecasting

BUT:

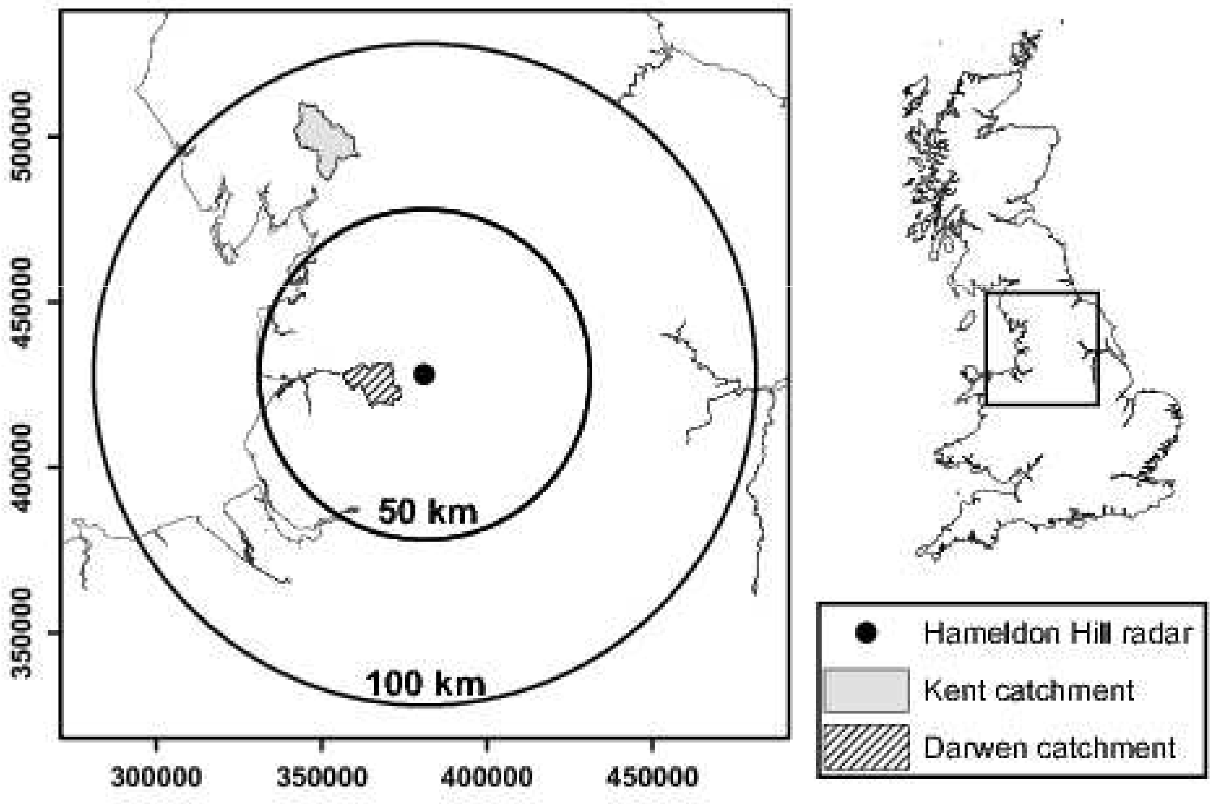
- Radar rainfall estimates can lack consistent, quantitative accuracy
- Distributed models can be difficult to formulate and configure due to process complexity and scaling issues

Science Questions

- How to obtain consistent gridded rainfall estimators, using radar and/or raingauge data, for use in distributed flood modelling?
- How to formulate area-wide distributed models for operational use in flood forecasting?
- How do these area-wide models perform at gauged and ungauged locations?
- Use two G2G modelling case studies:
  - River Kent (North-west England)
  - National application for the Flood Forecasting Centre

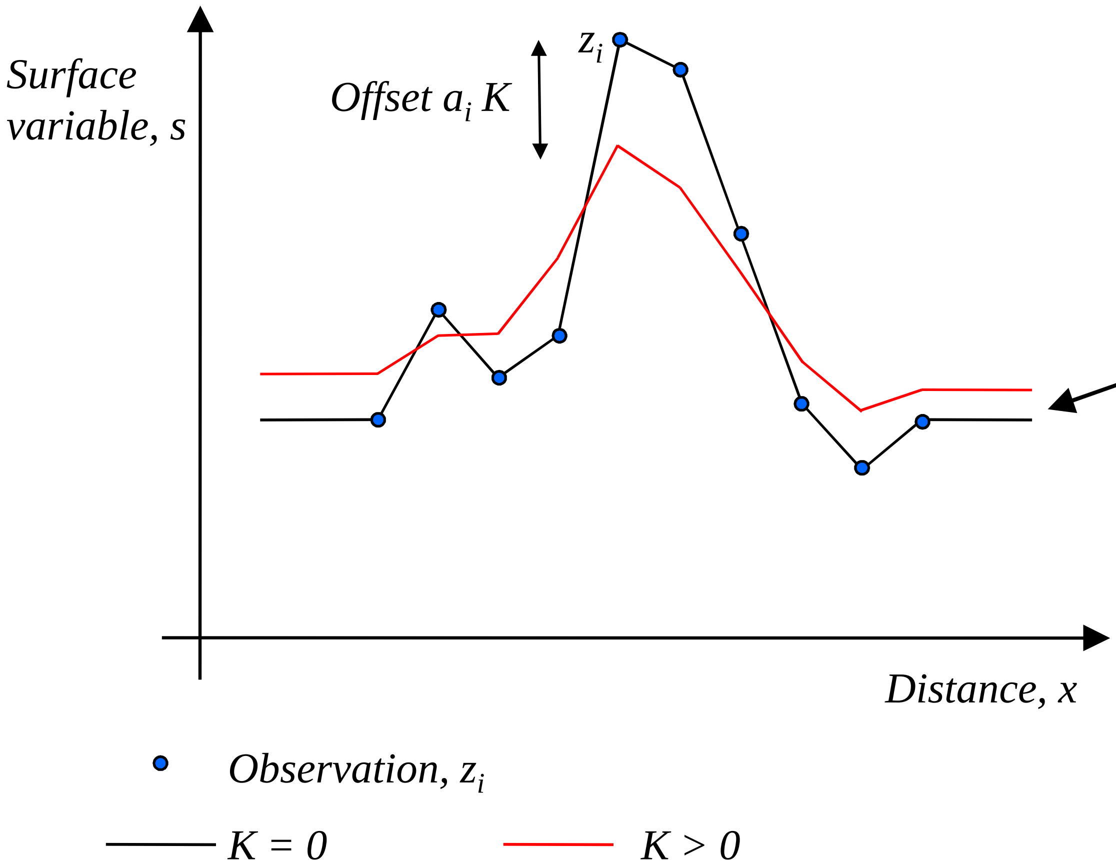
Gridded rainfall estimators: examples

- Using Hameldon Hill radar in North-West England
- Two relatively steep upland catchments (for the UK)
- Strong topographic control on flow response



Cole and Moore (2009), AWR

Multiquadric surface fitting – a 2D example



Aim: construct a multiquadric surface *s(x)* using observations z_i

Euclidean distance measure used (hence straight lines)

'Flatness at large distances' boundary condition used

Introduce an 'offset parameter', *K.*

Setting $K>0$ only requires the surface to pass ***near*** data points

Multiquadric rainfall estimation: Application

C-band radar data, from the Met Office (1 or 2km resolution)

- **Raw radar data**
- **Nimrod radar data**, a post-processed radar product including physically-based corrections

Raingauge-adjusted radar

- Let R_g^i be the **rainfall rate** of the i'th **raingauge**

  R_r^i be the **radar pixel rainfall rate** coincident with the i'th raingauge
- Then z_i is defined to be a modified ratio

$$z_i = \frac{R_g^i + \varepsilon_g}{R_r^i + \varepsilon_r}$$

where ε_g and ε_r (mm h^{-1}) are positive incidental parameters

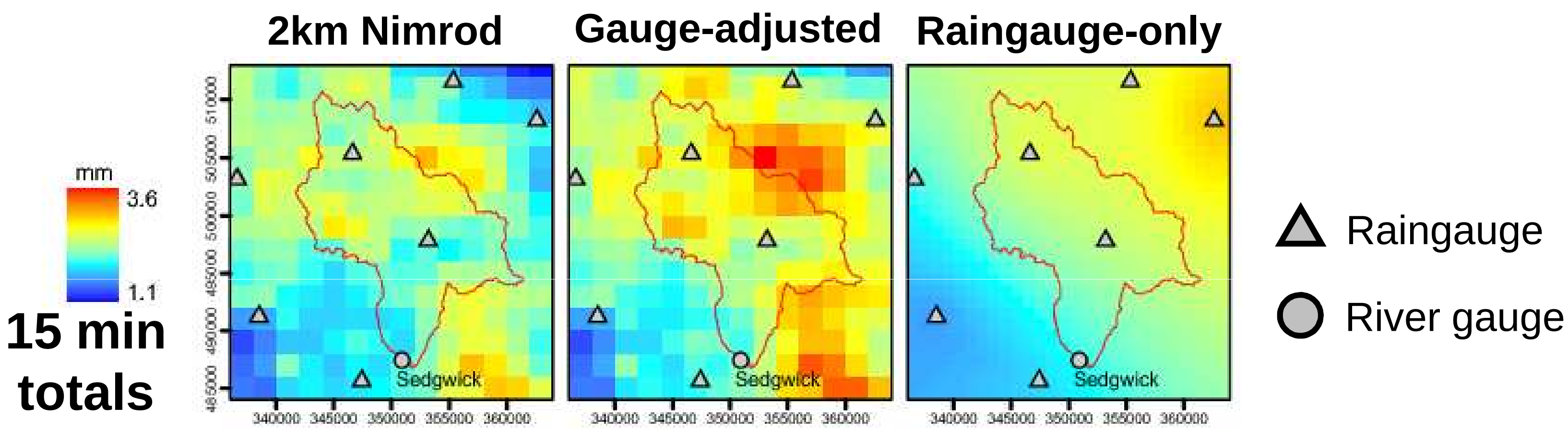
- An **offset parameter** is invoked ($K>0$)
- The **spatial surface** of adjustment factors is calculated at **15 minute intervals**

Raingauge-only estimator

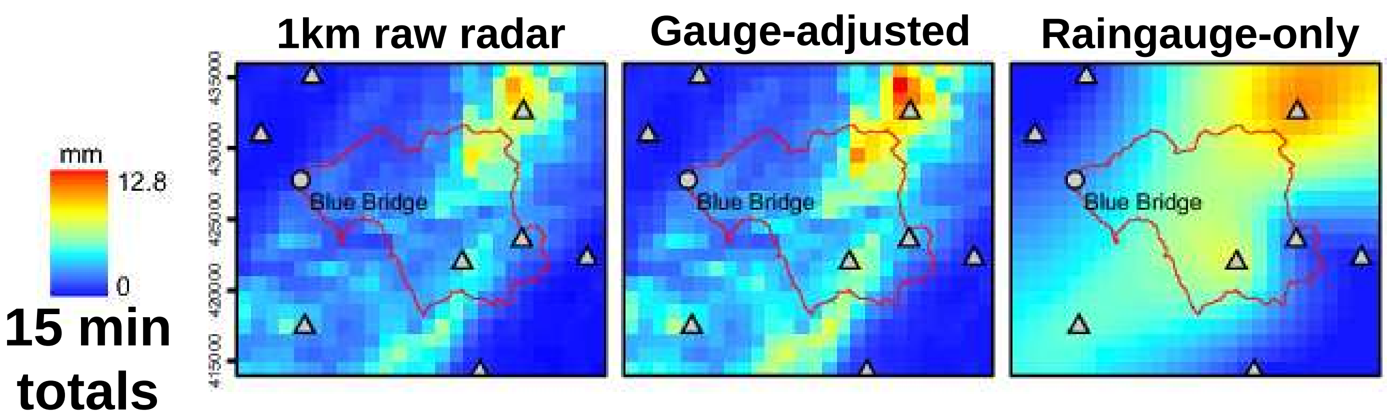
- Here z_i is defined to be the **15 minute raingauge totals**
- **No offset parameter** was used, i.e. $K = 0$

Gridded rainfall estimators: examples

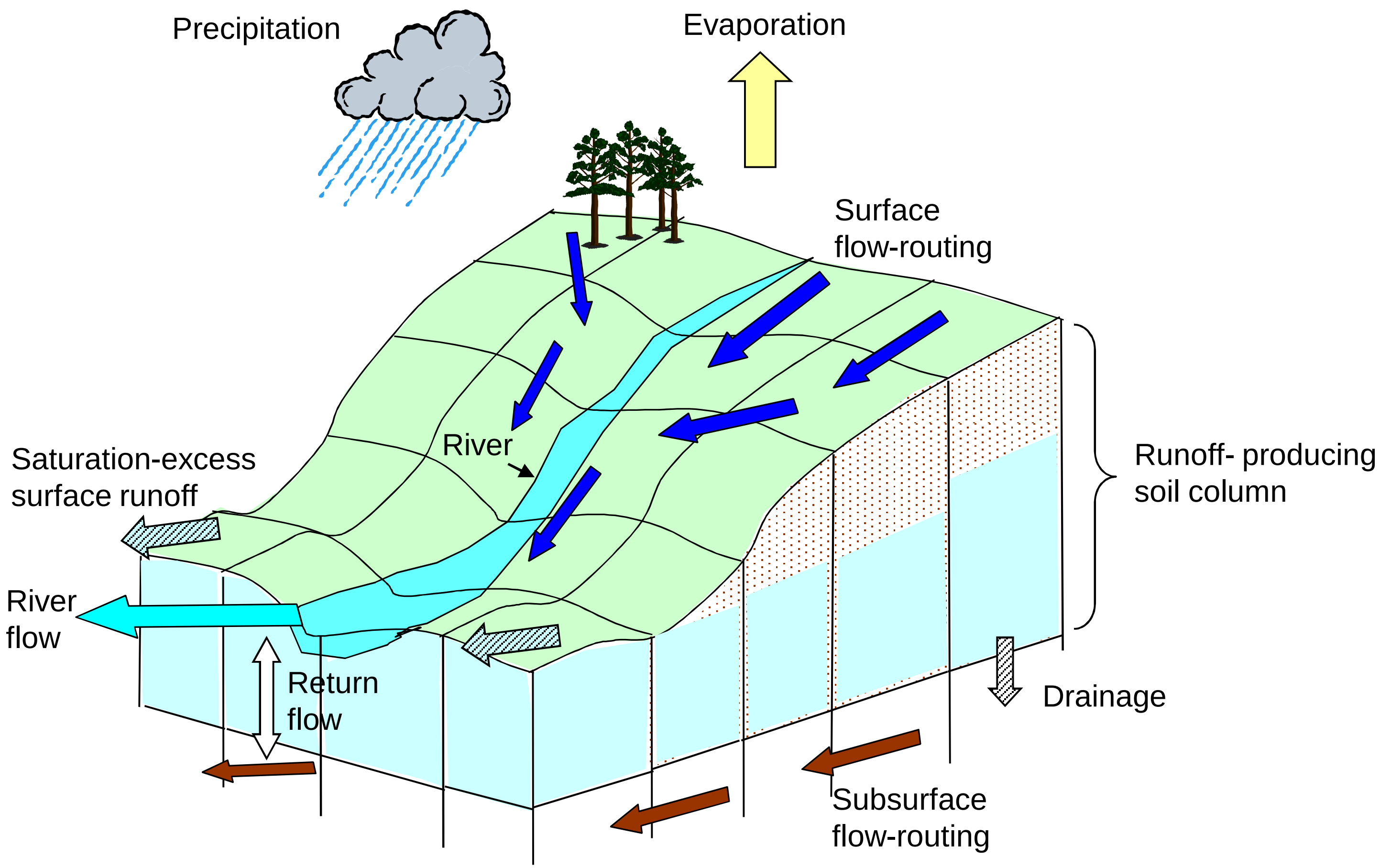
- River Kent catchment, orographic event, 3 Feb 2004



- River Darwen catchment, convective event, 14 June 2002



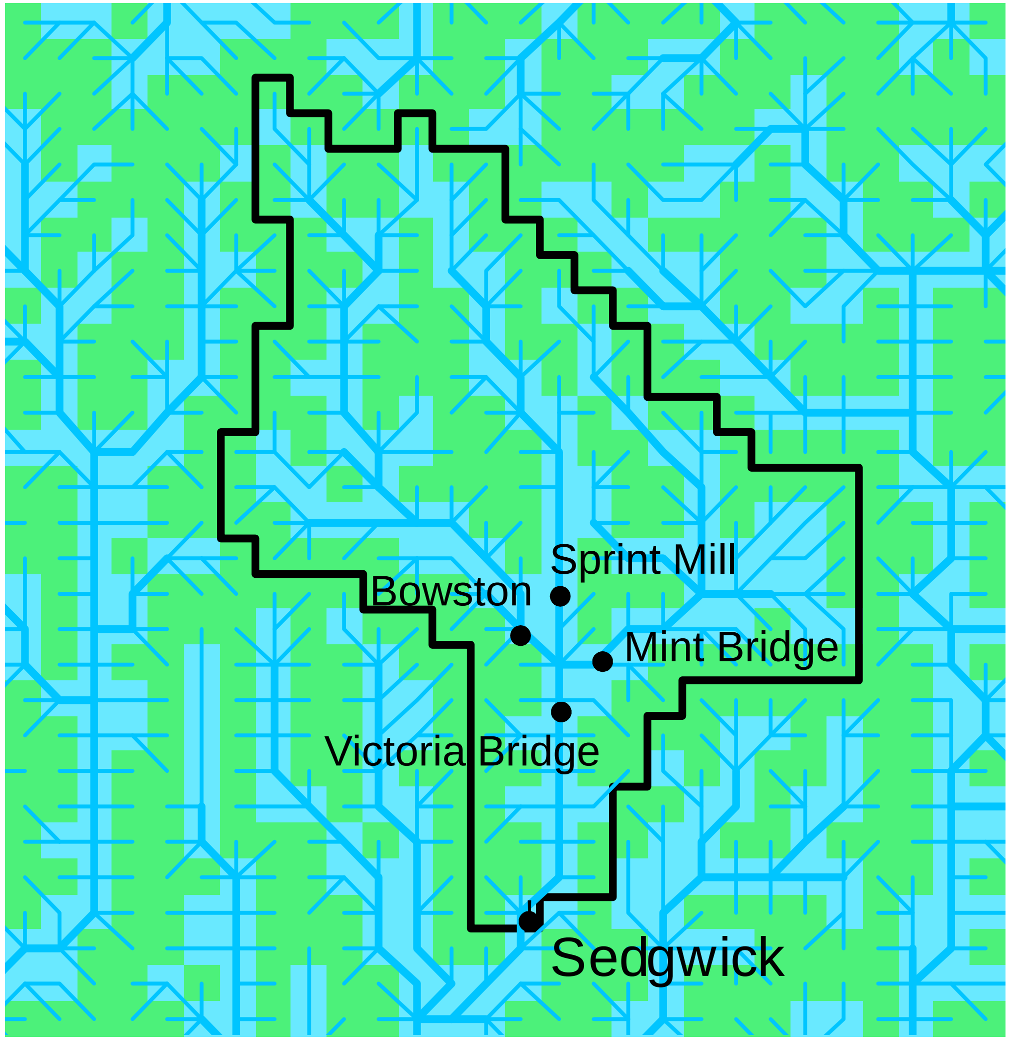
Grid-to-Grid distributed model (G2G)



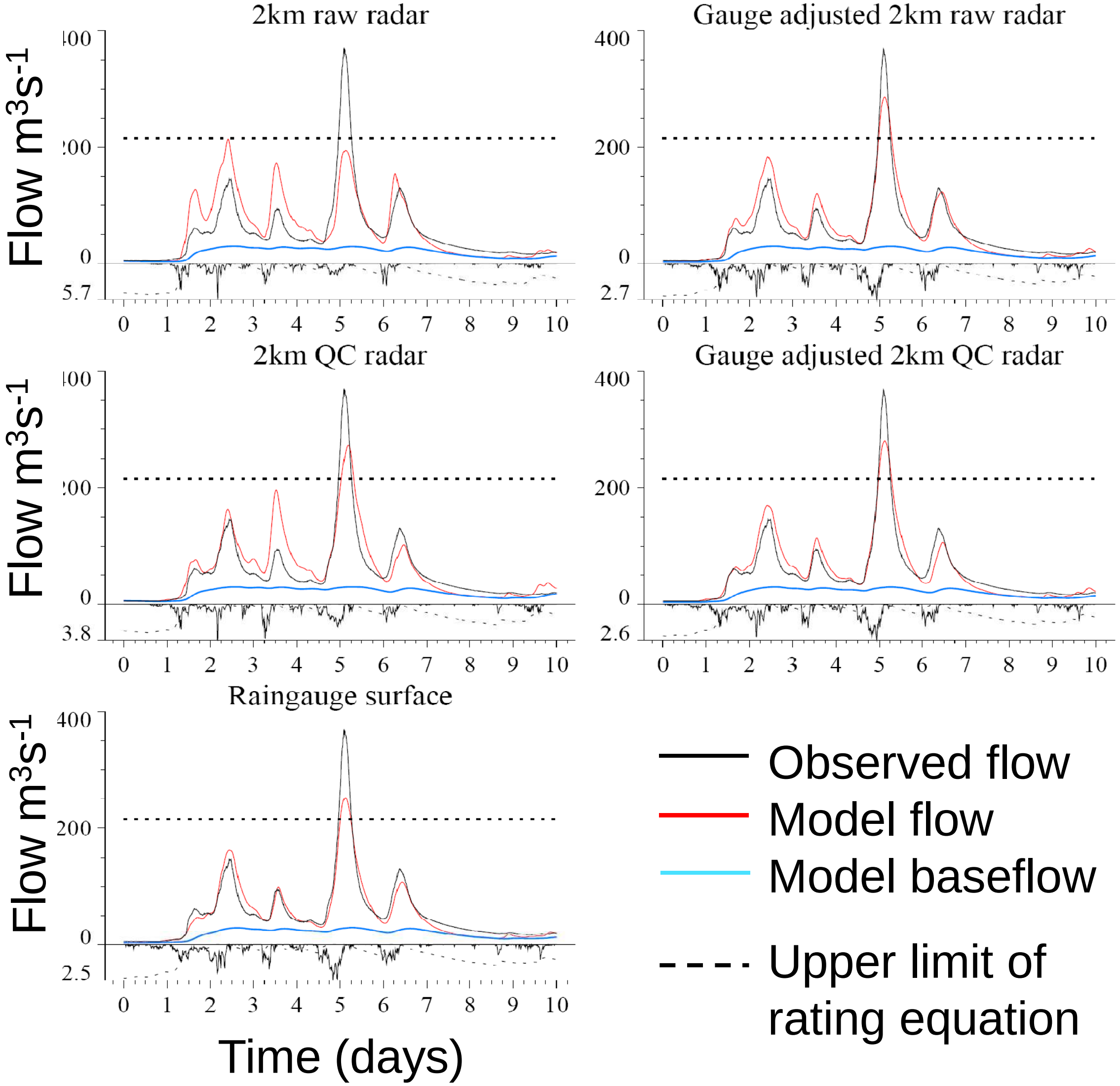
- Uses digital spatial datasets (e.g. terrain)
- Responds to spatial variation of rainfall input
- Grid-to-Grid routing using Kinematic Wave scheme

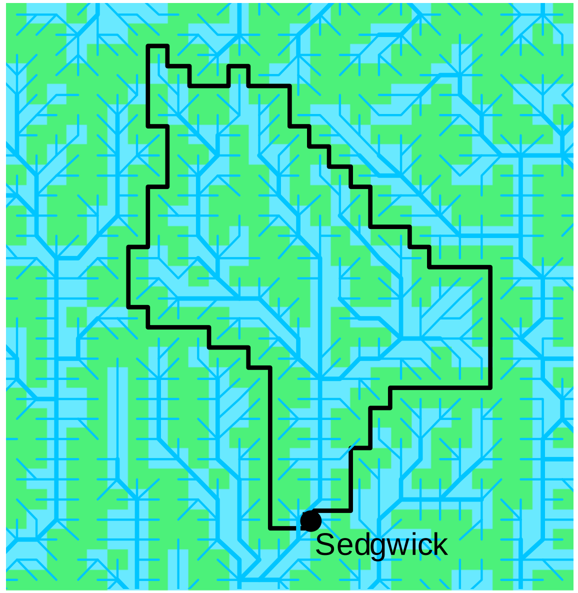
G2G routing: use of terrain data

1. **Flow directions**: apply automated method to 50m DTM to infer 1km flow-paths
2. **Catchment boundary delineation**: inferred from flow-path directions
3. **Land/river designation:** drainage area + river length threshold
4. **Select forecast locations:** gauged or ungauged



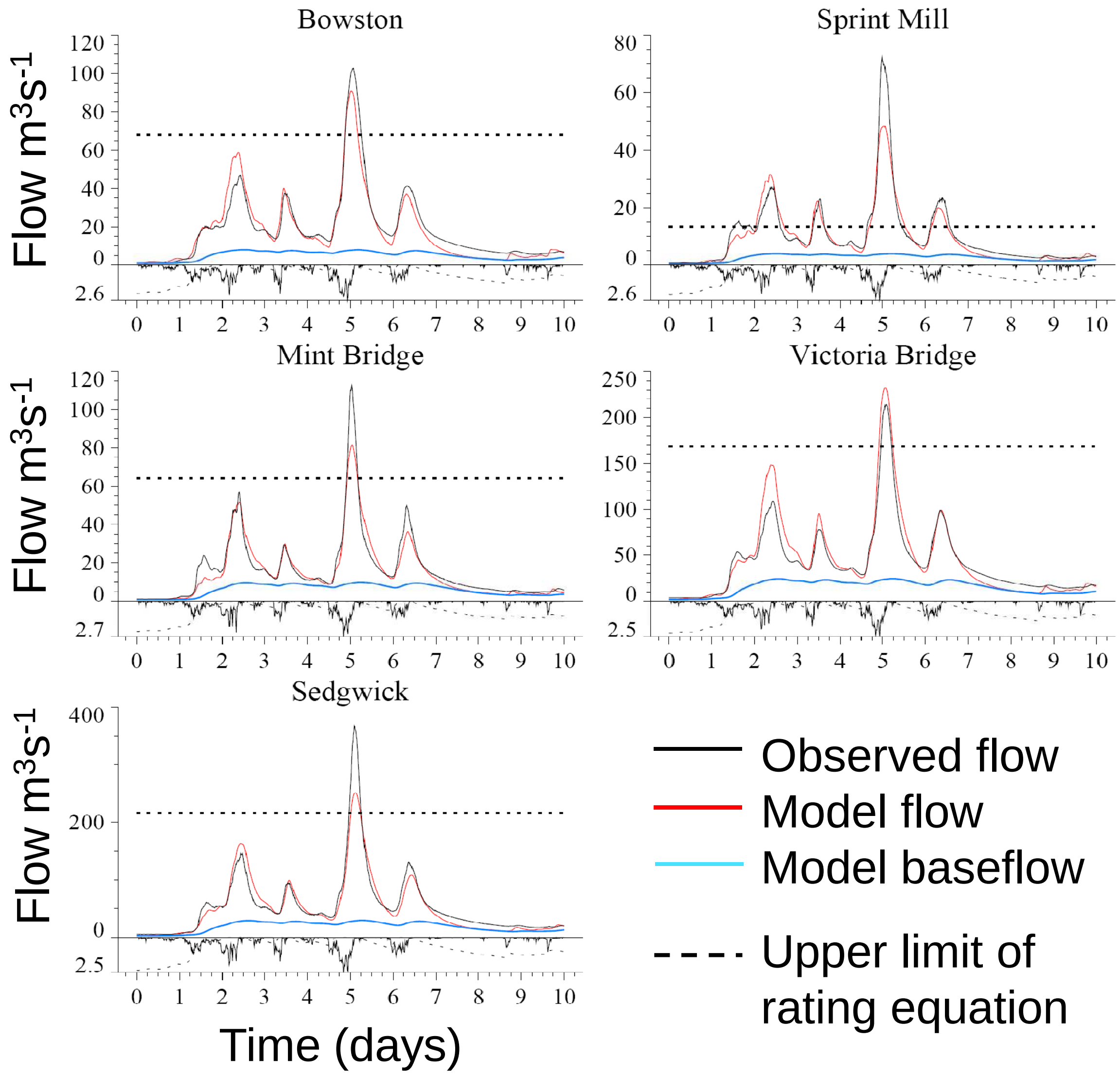
G2G model assessment of rainfall estimators

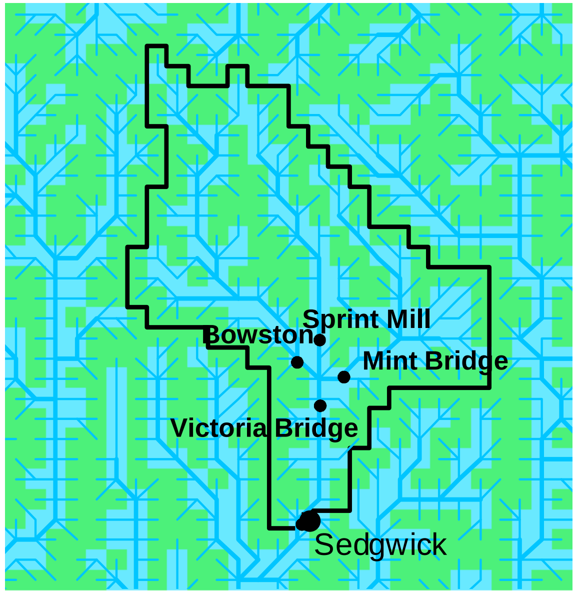




- G2G model calibrated at Sedgwick only
- Combining radar and raingauge gives comparable results to raingauge-only surface

G2G model assessment at ‘ungauged’ sites





- G2G model calibrated at Sedgwick only
- 15-min raingauge data used
- Comparable results at unguaged sites

River Kent Case Study: conclusions

- ***Radar Based Rainfall Estimation***
  - Raw and Nimrod radar products suffer from transient errors which propagate through to hydrological modelling
  - Frequent (15 min) and spatially-varying gauge-adjustment provides "hydrologically useful" gridded rainfall estimates
- ***Distributed modelling***
  - Simple physical-conceptual distributed models have real value for flood modelling at gauged and ungauged areas
  - Grid-to-Grid models provide area-wide forecasts of good quality in upland areas

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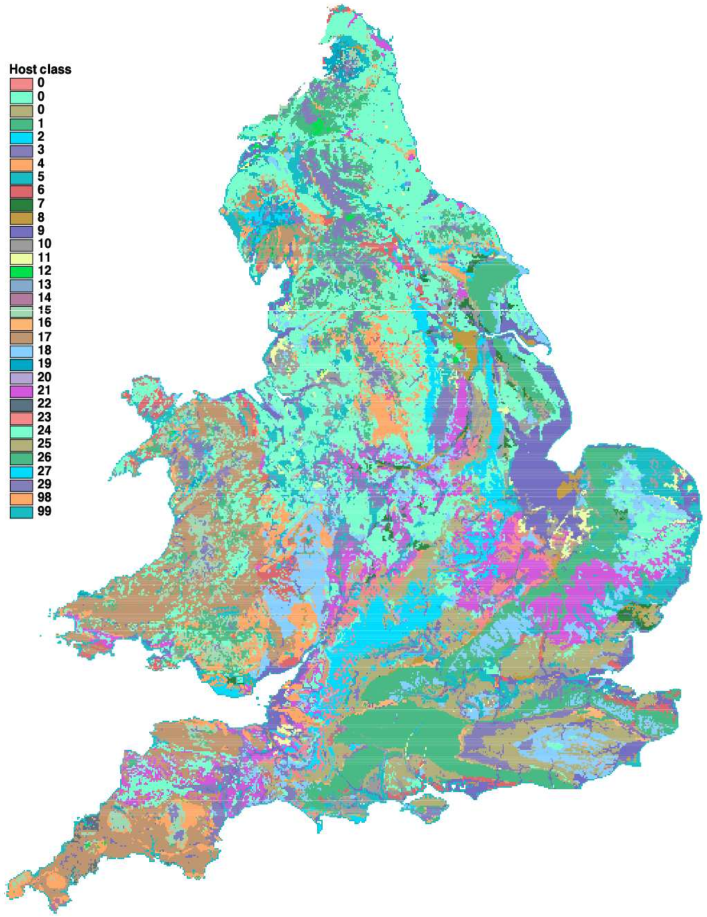
National application of G2G

- ***Several EA/Defra R&D projects recommended nationwide operational trial of G2G for flood forecasting***
  - 2004-06: Extreme Event Recognition Phase 2 (FD2208)
  - 2005-07: Rainfall-runoff and other modelling for ungauged/low-benefit locations (SC030227)
  - 2007-10: Hydrological modelling using convective scale rainfall modelling (SC060087)
- ***Pitt Review of the Summer 2007 floods***
  - Recommended joint Environment Agency/Met Office Flood Forecasting Centre (FFC) for England & Wales
  - FFC opened 1 April 2009 and commissioned operational implementation of G2G

FLOODFORECASTINGCENTRE
a working partnership between Environment Agency | Met Office

Deltares

G2G runoff production: use of soil property associations



Runoff production key element – needs to reflect heterogeneous soil properties

Use of Soil Survey data (HOST, Seismic, other…) to obtain 1km grids of:

- water content at field capacity
- residual soil water content
- porosity
- saturation hydraulic conductivity
- horizon depth

Issues:

Scale
Effective values
Lateral properties

Association table links HOST soil classes to soil properties

Runoff production scheme

Mass balance of soil water:

$$\frac{\partial V}{\partial t} = (p - E)\Delta x^2 + q_I - q_L - q_p - q_s$$

Soil column depth:	L
Soil water content:	θ (residual, θ_r)
'Available' water depth:	$S = (\theta - \theta_r) L$
'Available' soil water volume:	$V = \Delta x^2 S$

Inputs:

$(p - E)\,\Delta x^2$ **Rainfall less evaporation**

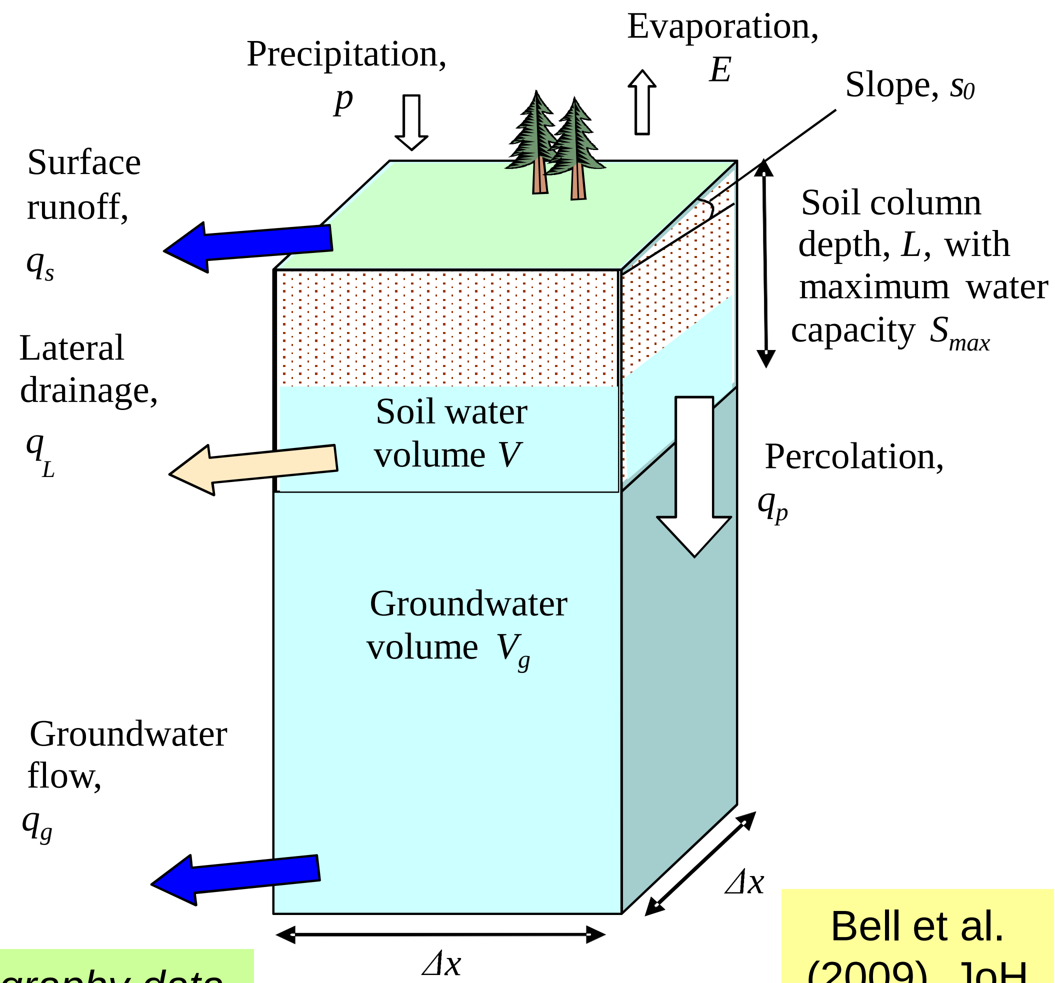
q_I **Inflow from upstream cells**

Outputs:

q_L **Lateral drainage (interflow)**
horizontal saturated hydraulic conductivity
terrain slope
pore size distribution factor

q_p **Downward percolation**
vertical saturated hydraulic conductivity

q_s **Surface runoff**
max. total soil water storage & shape parameter



Makes use of basic soil property and topography data

Bell et al. (2009), JoH

How to calibrate the national G2G model?

- **Which river gauging stations do we use?**
  – In excess of 1000 available in the National Flood Forecasting System (NFFS)
- **Calibration and assessment approach?**
  – Length of period to use, run-time and warm-up time of model
  – Split sample testing in time and/or space
- **Source of hydrometric (river and raingauge) data?**
  – NFFS real-time telemetry archive or EA archives?
- **Consistent national rainfall input?**
  – Radar, raingauge or combination?

Following is from Phase 3 of 'Hydrological modelling using convective scale rainfall modelling' (SC060087)

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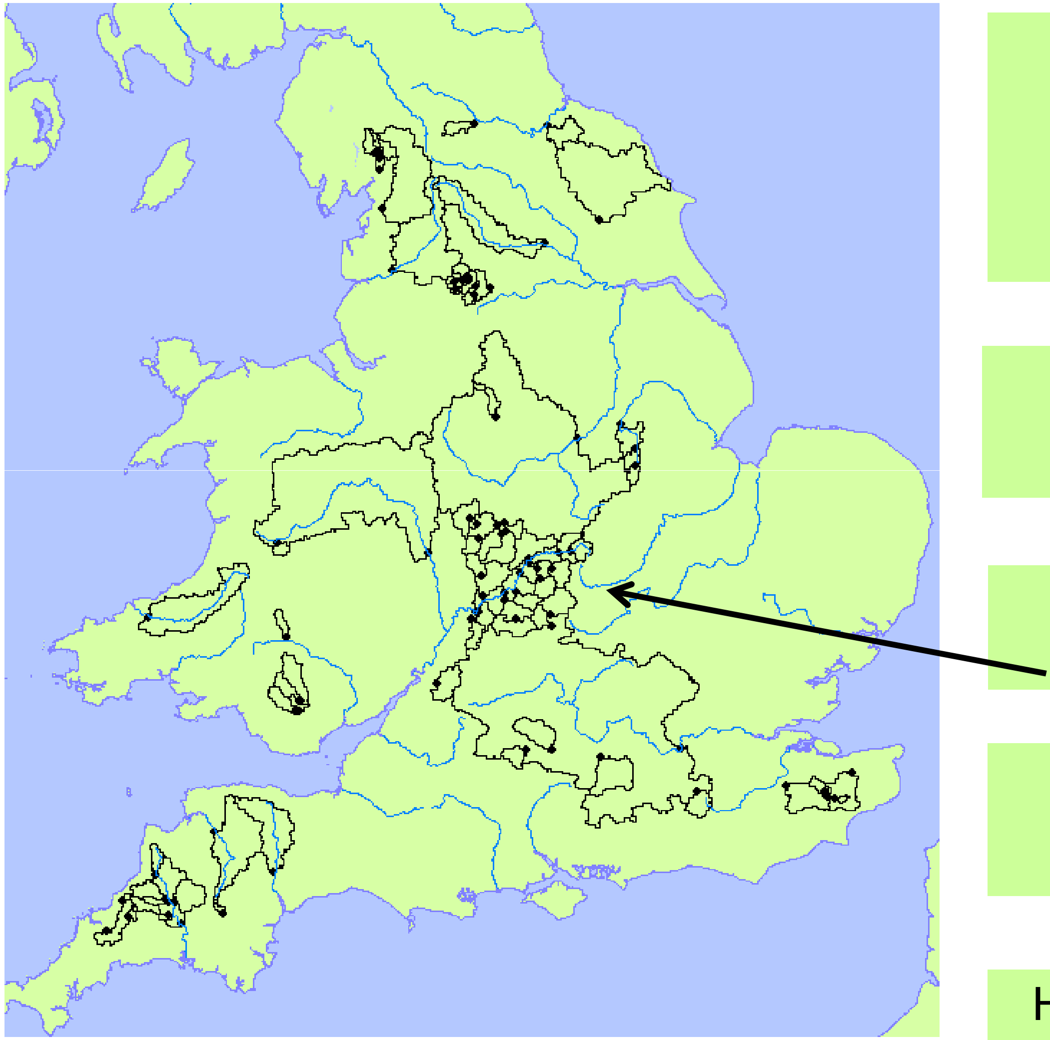
G2G model calibration and assessment



Phase 3 of project focused on **Urban/lowland** areas

Expanded to national calibration following Pitt Review

67 gauge sites for calibration

9 further sites for validation

Greater density of sites over Midlands study area

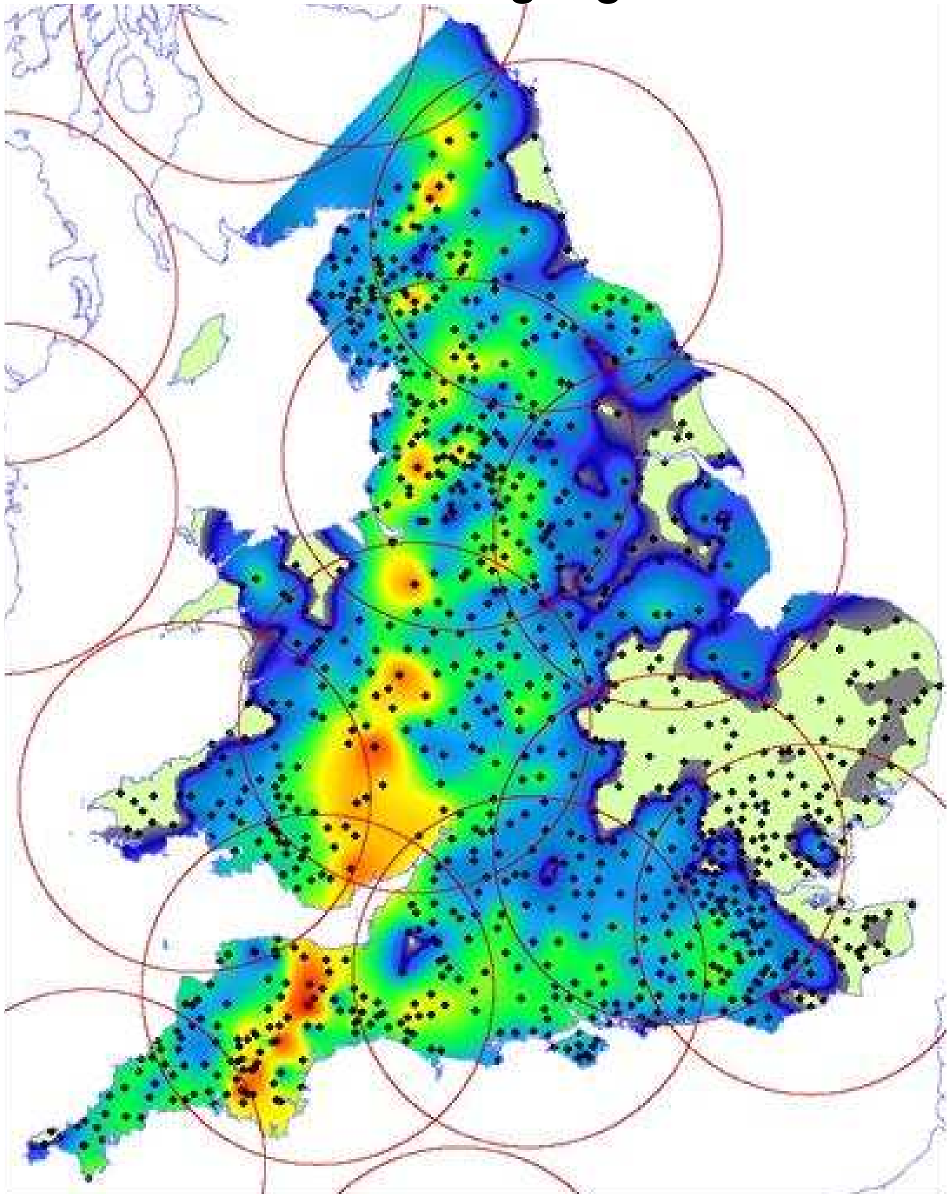
Data for Jan 2007 to Oct 2008

Focused on 2008 for calibration

Hydrometric data from NFFS real-time archives – problems!

Rainfall data

15 min total from raingauges



- Around 981 EA tipping-bucket raingauges are available
- Density of raingauges varies, high elevations under represented
- Radar coverage and performance varies in space (and time)
- Variable quality of rainfall data must be considered in assessing G2G results

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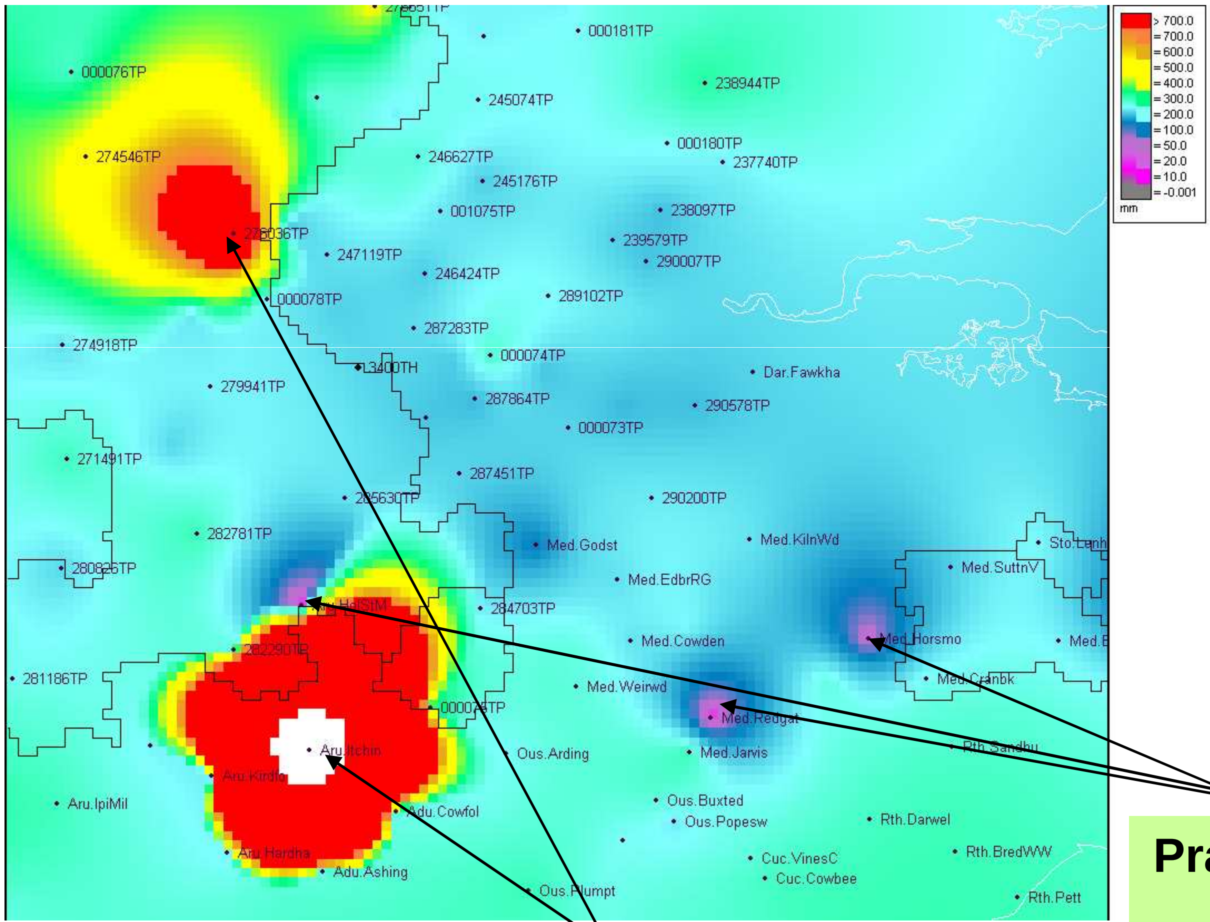
NFFS tipping-bucket raingauge data quality issues

Three month raingauge-only rainfall totals



More than 3 times the average

Practically no rainfall observed

Common issues are

- Raingauge is down but treated as zero instead of missing
- Anomalous single large values
- Systematic over-recording (e.g. double tips)

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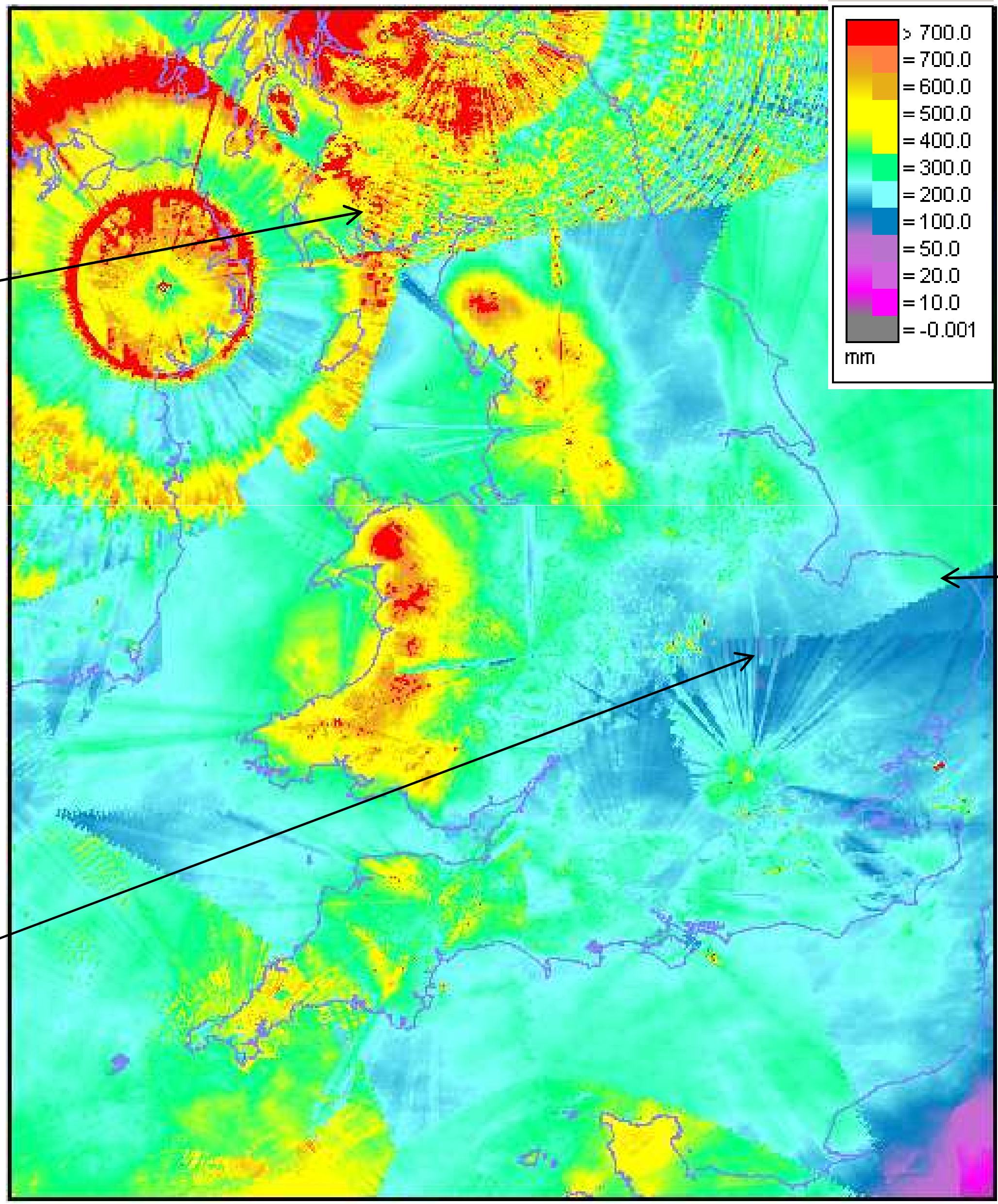
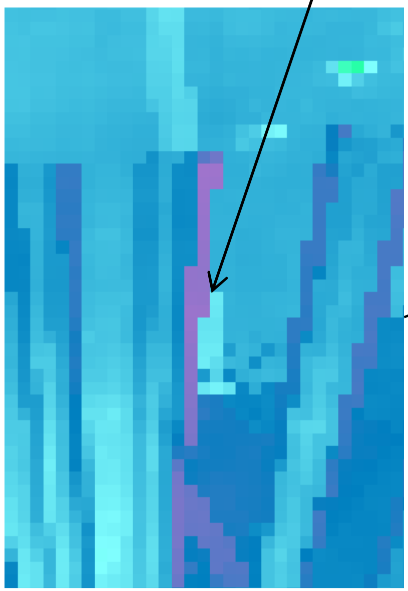
Radar data quality issues

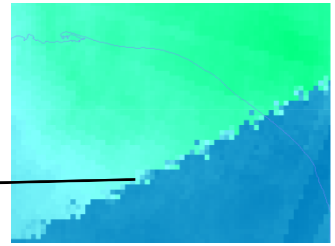
Totalled over 90 days – Mid Sep-Mid Dec 2008

Patterns from "duff" image(s)



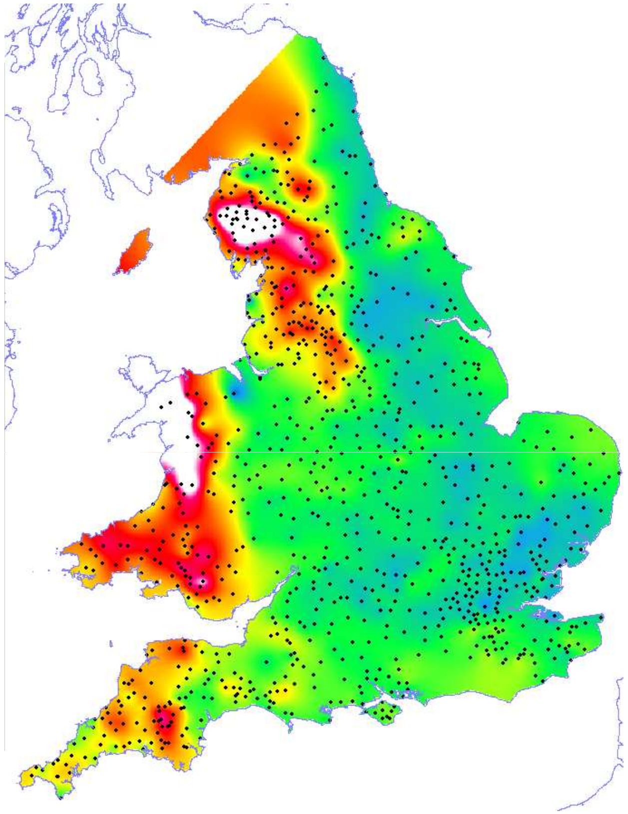
Blockages produce adjacent pixels of 60 and 180mm



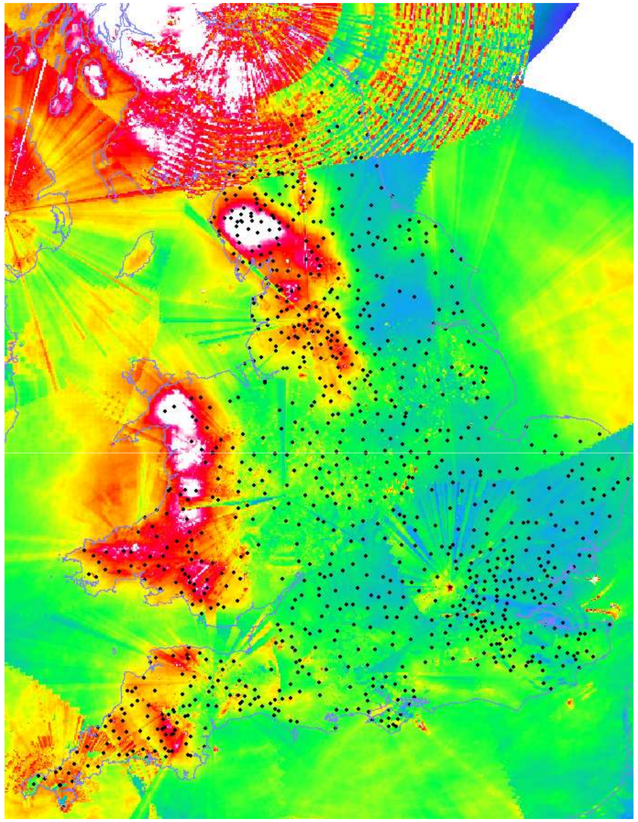


Radar boundary line produces 200-300% more rainfall to North (250mm vs 100mm)

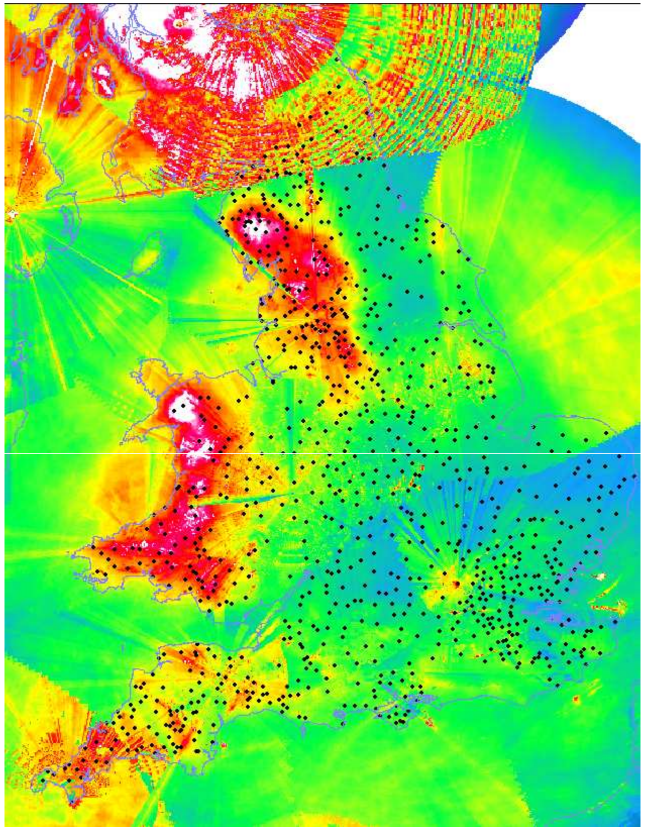
90-day rainfall totals



HyradK Raingauge-only



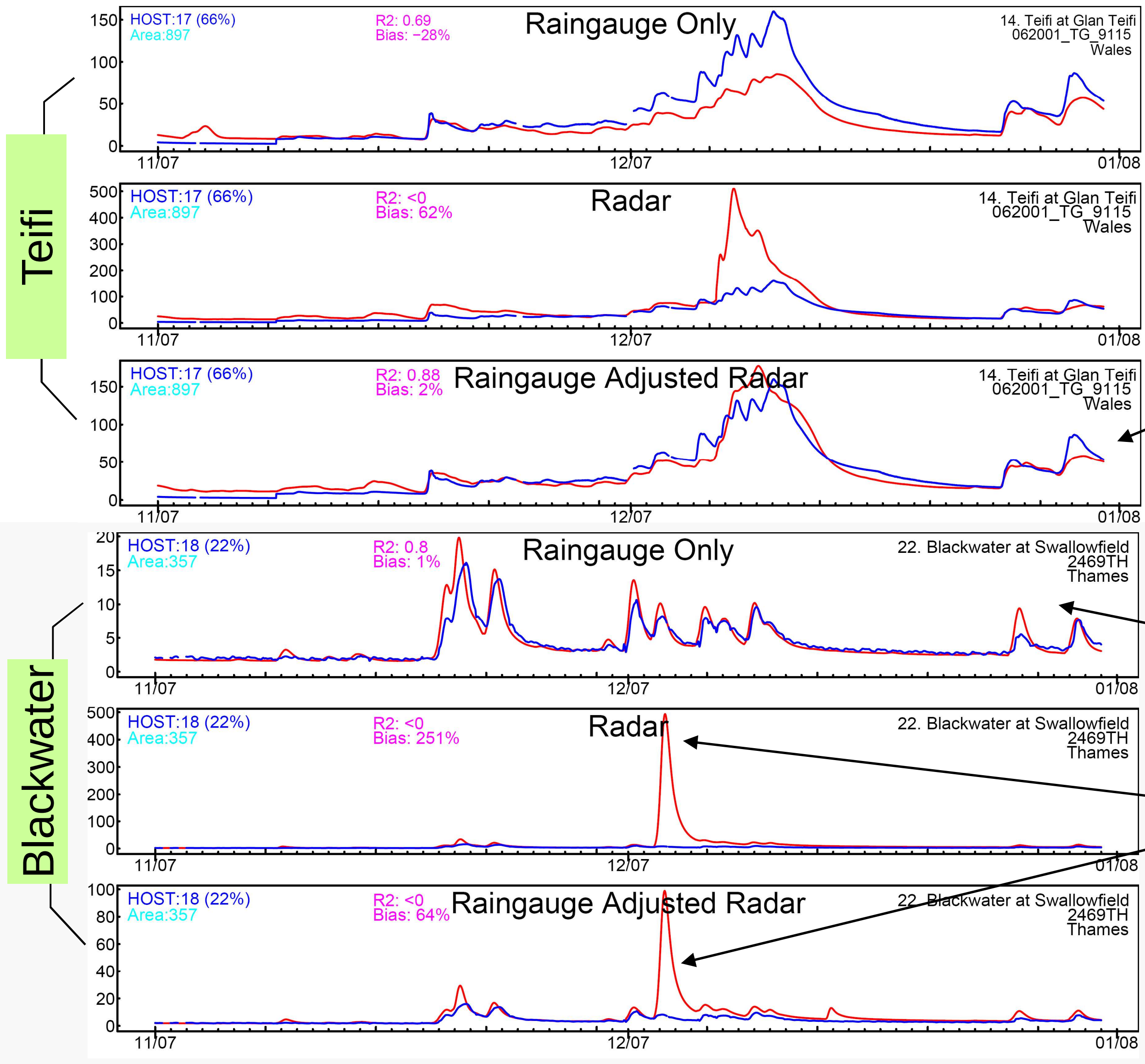
HyradK adjusted radar



Radar

Three rainfall options considered for model calibration

Choice of rainfall estimator for use with G2G?



Observed

Modelled

Raingauge-adjusted radar does best here

Raingauge-only used for calibration

Raingauge-only does best

Large transient radar errors untenable for calibration

Name	NFFS Id	Host	Region	R2 2007 (rg)	R2 2008 (rg)	R2 2008 (ra)	R2 2008 (ro)	R2 2008 (nl)	Bias 2007 (rg)	Bias 2008 (rg)	Bias 2008 (ra)	Bias 2008 (ro)
Brown Mill	Sto.BroMil	1	Southern	0	0.46	0.6	0.48	0	24	19	5	-15
29. Great Stour at Horton	Sto.Horton.Wei	1	Southern	0.63	0.83	0.84	0.63	0	-15	-1	-4	-26
28. Dun at Hungerford	2239TH	1	Thames	0.44	0	0	0	0	20	55	57	54
7. Lambourn at Shaw	2269TH	1	Thames	0.1	0.37	0.35	0.21	0	-14	-3	1	-8
Witham@Colsterworth	E1652	2	Anglian	0.47	0.24	0.29	0	0	35	79	62	127
Witham@Claypole Mill	E2901	2	Anglian	0.72	0.83	0.69	0	0	-17	-6	4	56
24. Frome at Ebley Mill	2027	2	MidlandGen	0.71	0.37	0.52	0.2	0	7	-15	-15	-31
Aylesford Stream	Sto.AylStr	3	Southern	0	0.47	0.51	0.41	0	-18	21	33	-11
27. Dove at Izaak Walton	4046	4	MidlandGen	0.04	0	0.12	0.47	0	3	3	7	1
De Lank	49129	15	SouthWest	0.54	0.48	0.46	0.38	0.59	-12	-6	-11	-23
Rhondda@Trehafod:	057006_TG_515	15	Wales	0.58	0.73	0.68	0.54	0.81	-1	-10	-19	-24
31. Dulas at Rhos-y-pentref	2025	17	MidlandGen	0.86	0.85	0.86	0.75	0.69	4	15	28	18
Sprint@Sprint Mill	730203	17	NorthWest	0.72	0.73	0.69	0.42	0.63	-16	-10	-15	-29
Kent@Bowston	730120	17	NorthWest	0.81	0.83	0.77	0.49	0.76	-9	-4	-16	-29
Kent@Victoria Bridge	730507	17	NorthWest	0.81	0.77	0.76	0.53	0.65	2	9	1	-12
Kent@Sedgwick	730511	17	NorthWest	0.71	0.64	0.62	0.43	0.58	-8	-1	-7	-18
Beales Mill	47139	17	SouthWest	0.82	0.71	0.62	0.46	0.61	-15	-17	-15	-24
Lifton Park	47116	17	SouthWest	0.7	0.64	0.56	0.57	0.33	10	6	17	-5
18. Exe at Thorverton	45118	17	SouthWest	0.65	0.36	0.52	0.5	0.55	-22	-43	-35	-34
19. Taw at Umberleigh	50140	17	SouthWest	0.69	0.58	0.59	0.53	0.5	-10	-11	3	-5
Tamar@Gunnislake	47117	17	SouthWest	0.68	0.54	0.53	0.47	0.49	-12	-10	-8	-20
14. Teifi at Glan Teifi	062001_TG_9115	17	Wales	0.8	0.74	0.81	0	0.76	-9	-26	-4	19
22. Blackwater at Swallowfield	2469TH	18	Thames	0.49	0.74	0	0	0	-18	12	54	143
Ottery@Werrington Park	47129	21	SouthWest	0.71	0.62	0.62	0.49	0.44	-24	-23	-27	-37
Badsey Brook	2023	23	Midlands	0.26	0.33	0.29	0.27	0.21	0	-18	4	-19
8. Severn at Bewdley	2001	24	MidlandGen	0.75	0.72	0.66	0.57	0.29	7	6	17	30
17. Trent at Colwick	4009	24	MidlandGen	0.74	0.8	0.67	0.61	0	1	7	19	25
Arrow at Studley	2094	24	Midlands	0.8	0.81	0.75	0.65	0.26	28	17	31	39
Tame at Bescot	4081	24	Midlands	0.09	0	0.01	0	0.04	-19	-38	-26	-13
Blythe at Castle Farm	4094	24	Midlands	0.75	0.71	0.76	0.75	0.68	-16	-20	-7	-10
Swift at Rugby	2090	24	Midlands	0.58	0.62	0	0	0.21	-23	1	93	101
Sowe at Stoneleigh	2004	24	Midlands	0.67	0.72	0.67	0.5	0.35	-30	-26	-6	-5
Arrow at Broom	2104	24	Midlands	0.74	0.68	0.73	0.69	0.26	-2	-7	7	6
Avon at Stareton	2019	24	Midlands	0.69	0.74	0.03	0	0	-19	-6	62	67
Tame at Lea Marston Lakes	4080	24	Midlands	0.64	0.35	0.24	0.09	0.46	-21	-20	-6	-1
16. Leven at Leven Bridge	LEVENB1	24	NorthEast	0.61	0.74	0.67	0.44	0.53	-12	-15	-15	-11
4. Wharfe at Flint Mill Weir	FLINTM1	24	NorthEast	0.43	0.08	0.34	0.27	0	0	-13	-20	-15
3. Derwent at Buttercrambe	BUTTCR1	24	NorthEast	0.57	0.78	0.78	0.65	0	14	-4	-6	-13
15. Lune at Caton	724629	24	NorthWest	0.51	0.38	0.39	0.38	0.45	-11	-18	-17	-16
34. Ribble at Samlesbury	713019	24	NorthWest	0.45	0.32	0.31	0.22	0.43	-4	1	6	16
Crowford Bridge	47133	24	SouthWest	0.63	0.73	0.77	0.72	0.68	-35	-14	-12	-17
Polson Bridge	47115	24	SouthWest	0.74	0.72	0.75	0.66	0.45	-17	-5	-5	-15
Dene at Wellesbourne	2048	25	Midlands	0.66	0.48	0.52	0.38	0	10	-1	-1	-22
Avon at Lilbourne	2088	25	Midlands	0.63	0.6	0.06	0	0.27	-21	9	87	90
Itchen at Southam	2613	25	Midlands	0.33	0.43	0.38	0.3	0.44	-25	-1	17	-1
Leam at Kites Hardwick	2609	25	Midlands	0.17	0.27	0	0	0.1	16	17	96	83
Stour at Shipston	2092	25	Midlands	0.79	0.42	0.72	0.61	0	1	6	10	-18
Leam at Eathorpe	2050	25	Midlands	0.71	0.54	0.39	0.25	0.23	11	13	63	45
Stour at Alscot Park	2010	25	Midlands	0.64	0.43	0.67	0.57	0	37	36	34	-1
Avon at Warwick	2091	25	Midlands	0.78	0.81	0.64	0.47	0.06	-17	-8	35	31
Avon at Stratford	2093	25	Midlands	0.72	0.72	0.79	0.62	0.37	-30	-30	-2	-7
Avon at Evesham	2002	25	Midlands	0.79	0.7	0.69	0.64	0	-3	2	27	16
1. Mole at Kinnersley Manor	3240TH	25	Thames	0	0.5	0.22	0	0.38	28	-41	-2	46
Cherwell@Banbury	1420TH	25	Thames	0.59	0.51	0	0	0	17	15	67	60
2. Thames at Kingston	3400TH	25	Thames	0	0.59	0	0	0	49	36	71	122
Taff@Fiddlers Elbow	057007_TG_504	26	Wales	0.63	0.47	0.37	0.33	0.49	14	30	32	22
25. Taff at Pontypridd	057005_TG_513	26	Wales	0.66	0.65	0.62	0.51	0.74	-1	-4	-9	-15
Walsden Water@Walsden	WALSDN1	29	NorthEast	0.53	0.29	0.15	0	0.32	17	28	32	37
Calder@Todmorden	TODMDN1	29	NorthEast	0.55	0.73	0.78	0.73	0.74	-43	-29	-17	-13
Ripponden	RIPPND1	29	NorthEast	0	0.55	0.14	0	0.17	59	44	70	82
Hebden Water@Nutclough	NTCLGH1	29	NorthEast	0.7	0.76	0.77	0.69	0.77	11	25	30	40
Hebden Bridge	HEBDBR1	29	NorthEast	0.7	0.69	0.67	0.61	0.72	-12	-8	-5	-1
26. Greta at Rutherford Bridge	RUTHBR1	29	NorthEast	0.54	0.46	0.47	0.38	0.44	-22	-34	-36	-37
Calder@Mytholmroyd	CLDENE1	29	NorthEast	0.47	0.49	0.46	0.3	0.57	82	86	87	99
Sowerby Bridge	SOWRBY1	29	NorthEast	0.56	0.53	0.53	0.49	0.64	-12	-13	-11	-7
30. East Dart at Bellever	46123	29	SouthWest	0.6	0.51	0.57	0.34	0.4	-34	-33	-29	-49
				0.5615	0.5573	0.49	0.373	0.327	-1.0597	1.3284	14.582	14.134

rg: raingauge-only R^2=0.56
ra: radar-adjusted R^2=0.49
ro: radar-only R^2=0.37

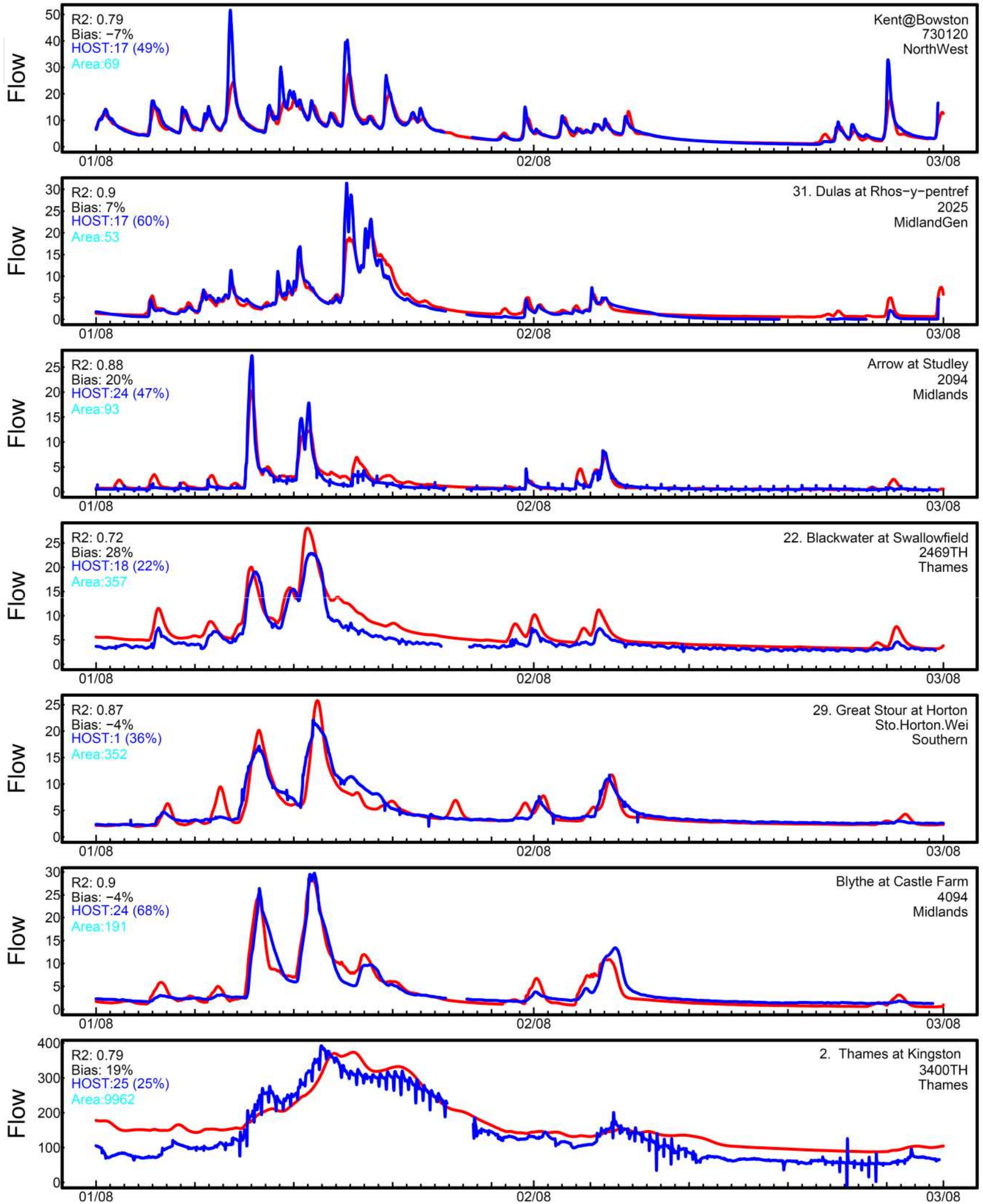
Bias : 1% with raingauges
(14% with radar)

Different R^2 across 2007 & 2008 - indicates data problems

Summer 2007 events can dominate R^2

R^2 Efficiency (truncated to 0)

Bias is % volume overestimation



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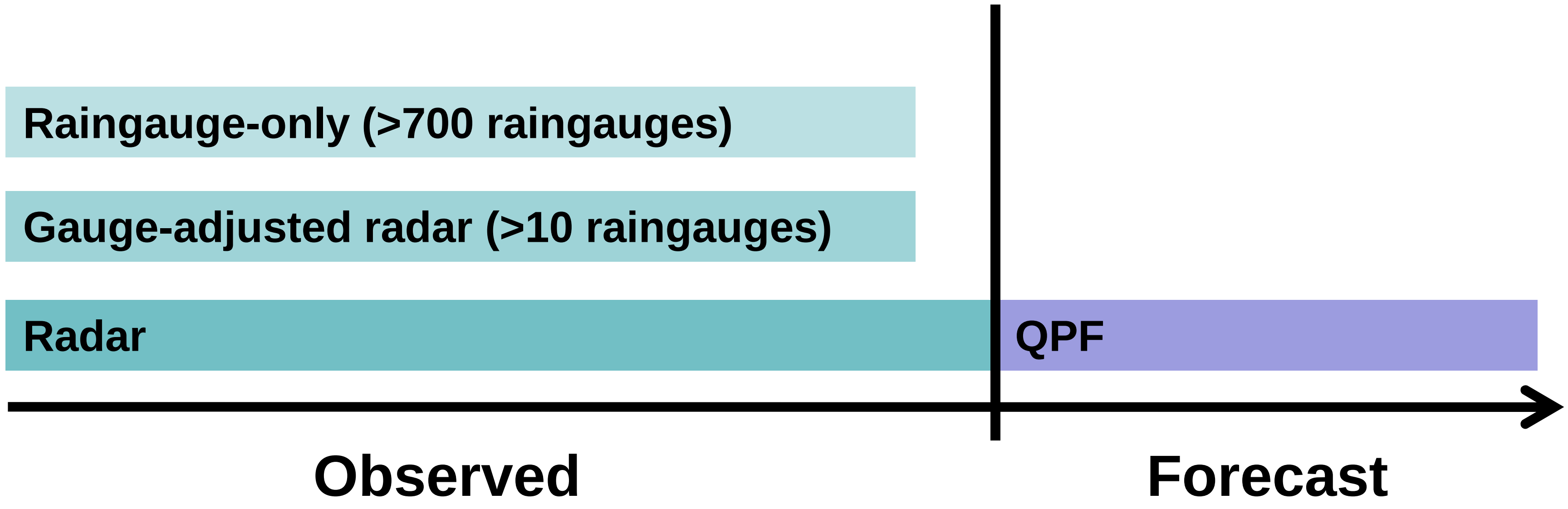
Examples of catchments with generally good G2G performance

January & February 2008

Observed
Modelled

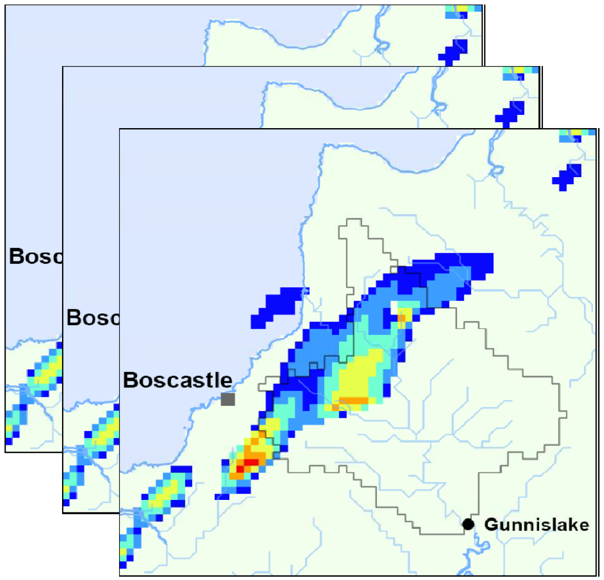
Demonstrates modelling of different flow regimes with the G2G Model

Precipitation hierarchy in NFFS

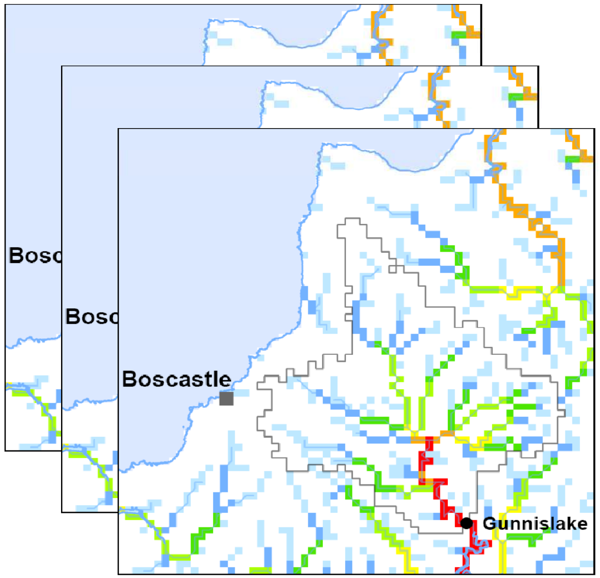


Ensemble Flood Forecasting

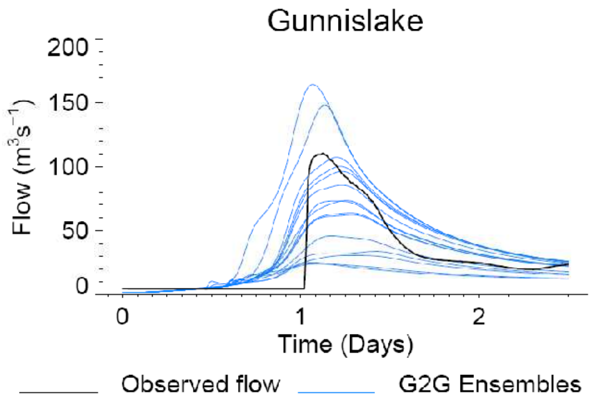
1km NWP pseudo-ensemble



G2G Model 1km river flow ensemble



Comparison with river flow observations



Acknowledgements:
Collaboration with JCMM (Met Office)

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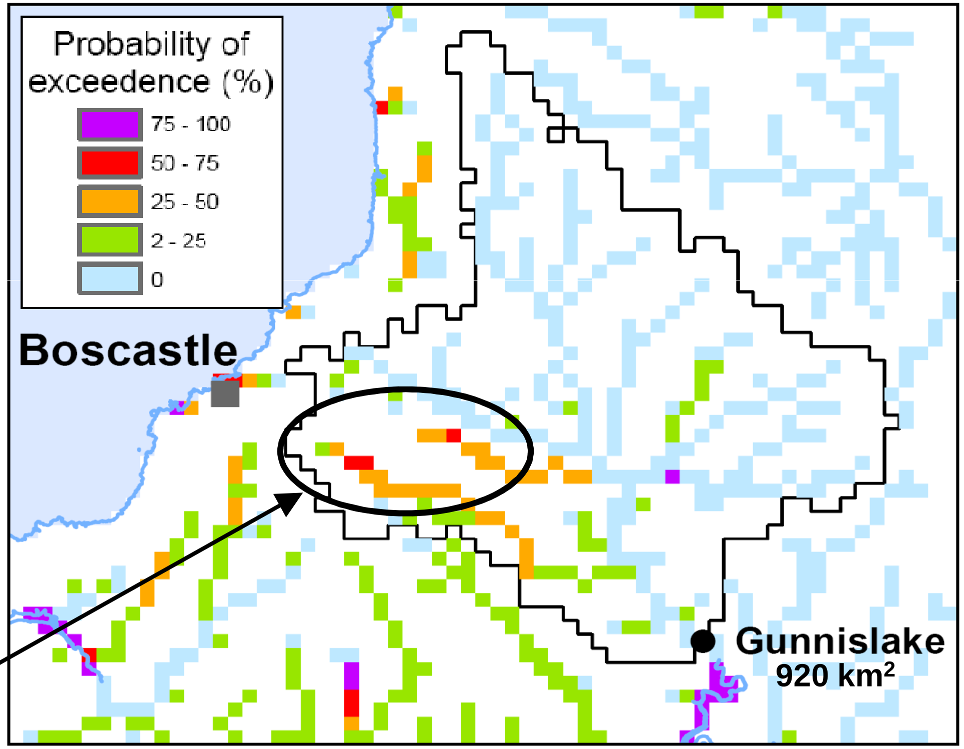
Risk Map of flood exceedance using G2G ensembles and Q(T) grids

Probability of ***exceeding*** a given ***flow threshold***, for a given ***forecast horizon***

This example employs:
NWP 1km rainfall pseudo-ensemble
10 year return period flow thresholds
24 hour forecast horizon

Potential to identify flood risk ***hotspots***



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Possible benefits to national G2G from future radar developments?

Quantitative Precipitation Estimates (QPE)

- Improved rain-rate and rain accumulation products
- Better coverage through additional radars
- Improved data quality indicator information
- Uncertainty products and ensembles
- Precipitation classification (e.g. rain or snow)

Quantitative Precipitation Forecasts (QPF)

- Improved STEPS nowcasts
- Improved NWP rainfall through data assimilation