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

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

Distributed Model

Lumped Model

Hyetograph

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
**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 \( R^i_g \) be the **rainfall rate** of the \( i \)'th raingauge
- \( R^i_r \) be the **radar pixel rainfall rate** coincident with the \( i \)'th raingauge
- Then \( z_i \) is defined to be a modified ratio
  \[
  z_i = \frac{R^i_g + \varepsilon_g}{R^i_r + \varepsilon_r}
  \]
  where \( \varepsilon_g \) and \( \varepsilon_r \) (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
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
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:**
\[
\frac{\partial V}{\partial t} = (p - E) \Delta x^2 + q_I - q_L - q_p - q_s
\]

- **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

- **Available** soil water volume:
  \(V = \Delta x^2 S\)

- Soil column depth: \(L\)
- Soil water content: \(\theta\) (residual, \(\theta_r\))
- ‘Available’ water depth: \(S = (\theta - \theta_r) L\)

-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)
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

- 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
NFFS tipping-bucket raingauge data quality issues

Three month raingauge-only rainfall totals

Common issues are:

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

Practically no rainfall observed

More than 3 times the average
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)
National application of G2G

90-day rainfall totals

HyradK Raingauge-only  HyradK adjusted radar  Radar

Three rainfall options considered for model calibration
National application of G2G

Choice of rainfall estimator for use with G2G?

Raingauge-only used for calibration

Raingauge-adjusted radar does best here

Large transient radar errors untenable for calibration
Bias: 1% with rain gauges (14% with radar)

Different R² across 2007 & 2008 - indicates data problems

Summer 2007 events can dominate R²

R² Efficiency (truncated to 0)
Bias is % volume overestimation
Examples of catchments with generally good G2G performance
January & February 2008

Demonstrates modelling of different flow regimes with the G2G Model
Precipitation hierarchy in NFFS

Raingauge-only (>700 raingauges)
Gauge-adjusted radar (>10 raingauges)
Radar

QPF

Observed
Forecast
Ensemble Flood Forecasting

1km NWP pseudo-ensemble
G2G Model 1km river flow ensemble
Comparison with river flow observations

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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*

Acknowledgements:
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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