New approaches to flood risk management for a changing climate: climate downscaling, continuous simulation modeling and vulnerability analysis

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Prairie Floods 2011

Saskatoon Summer Precipitation 1900-2010

Hydrologic year (Oct 1-Sept 30)

Precipitation [mm]

Summer (April-Sept)

www.usask.ca/water
Annual Flows, Souris River 1912-2011
Motivation

- Extreme floods in the prairies can have a long memory of antecedent conditions, as seen in 2010/2011
- Conventional event-based design methods will struggle to reproduce this response and have other limitations
- Continuous simulation modelling overcomes these problems, but requires appropriate representation of precipitation inputs
- This presentation reviews methods for precipitation modelling, with application to flood risk estimation under current and future climate
Classical design storm profile
(e.g. UK FSR 1975, FEH 1999)
Conventional flood design methods are commonly based on design events, but this approach has limitations.

a) Design rainfall profiles do not represent real rainfall time-series, and thus have limitations for many applications

b) Antecedent conditions are of critical importance to flood generation - it is difficult to define the probability of run-off associated with a design storm

c) For climate change studies we need to understand how antecedent conditions may change and represent those effects on flood generation
RAINFALL MODELLING

Single site modelling

Spatial-temporal modelling

Modelling climate change
Stochastic Modelling using Poisson processes

• Represent the main observable features of rainfall processes;
• Simple stochastic assumptions (e.g. Storms arriving in a Poisson process (PP));
• Small number of physical interpretable parameters
• Model constructed in continuous time and space
• Fits between
  – Deterministic models of dynamic meteorology;
  – Empirical statistical models (e.g. generalised linear models, scaling models)
Single site models

- \( \lambda \): rate of arrival of storms
- \( \mu_x \): mean cell intensity
- \( \alpha, \nu \): gamma distribution parameters for mean cell duration
- \( \kappa \): cell arrival parameter
- \( \varphi \): storm duration parameter
Different types of single site models

• Original
  – cell mean duration: exp dist. with param. ($\eta$)
  – cell intensity: exp dist. ($\mu_x$)

• Modified
  – $\eta$ varies randomly, gamma dist. ($\alpha, \nu$)
  – GAMMA: cell intensity, gamma dist. ($\rho, \delta$)

• Multiple cell types (generalised)
  – Threshold ($u$): high/low intensity cells
    • High intensity cells resampled from a GPD
  – Parameter ($a$): proportion of heavy cells in each storm
    • Two sets of cell parameters

• Dependent duration – intensity
Other modifications of the basic models

- Modification of cell shape
- Modification of cell arrival rate
- Modification of cell intensity distribution
- Combining a gamma intensity with a multi-cell representation
Hourly Extreme Values
Elmdon (Data & BLRPDDDM)

Historical Maxima
EV-II (simulated)

Return period (yrs) 2 5 10 20 100 200

Gumbel reduced variate
Conclusion

Single site models are well tested and widely used in Europe for flood estimation, temporal downscaling and climate change weather generators.
Extension to Spatial-temporal modelling

<table>
<thead>
<tr>
<th>Rainfall Element</th>
<th>Size /km²</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain cell</td>
<td>10-30</td>
<td>≤ 30 mins</td>
</tr>
<tr>
<td>SMSA</td>
<td>10²-10³</td>
<td>a few hours</td>
</tr>
<tr>
<td>LMSA</td>
<td>10³ – 10⁴</td>
<td>several hours</td>
</tr>
<tr>
<td>Synoptic area</td>
<td>≥ 10⁴</td>
<td>days</td>
</tr>
</tbody>
</table>

SMSA = small mesoscale area
LMSA = large mesoscale area
Storm 1

\[ \Theta_1 \]

\{ \lambda, \mu_A, \mu_S, \mu_D, \mu_L, \mu_C, \mu_X \}

Storm 2

\[ \Theta_2 \]

eccentricity \( e_1 \)

eccentricity \( e_2 \)
Threshold analysis of intensity field

Temporal autocorrelation

Spatial autocorrelation

Performance analysis example
Observed rainfall, SW England
Frontal precipitation

Warden Hill Radar

1021994

2200

data

Simulated data

2321995

2300

simulation
Convective precipitation

Wardon Hill Radar

3-6-1994 0700

Simulated data

206-1996 1:00

data simulation
Simplified forms of spatial temporal models are being used. However to define the full structure of these models, radar data are needed for model training, and more research is needed to represent spatial heterogeneity and storm movement.
Spatial-temporal modelling

Generalised Linear Models

These can be used to simulate daily rainfall occurrence and amounts for single site or spatial modelling. In an extension of regression modelling, independent variables can include climate variables and circulation indices.

Originally developed by Chandler and Wheater for a flood study in W Ireland, these are being widely applied to rainfall modelling in UK, Africa, Middle East.

A key recent development is their use in disaggregation of GCM and RCM outputs.
GLM simulation of winter rainfall frequencies incorporating climate variability and NAO dependence
Improved weather generators for climate change scenarios and exploring climate change impacts on floods and droughts

Simulated annual rainfall at Heathrow, 2071-2100

4 GCMs

3 RCMS + merged distributions
Downscaling global and regional climate models
Heathrow rainfall – 1990 and 2071
Prairie GLM Simulations, 1948-2000

Calgary

Saskatoon
Daily Extremes (Banff)

Simulated precipitation against observed precipitation

Simulated annual precipitation maximum (mm)

Observed annual precipitation maximum (mm)
Saskatoon drought simulations

Saskatoon (LAR-WG)

Saskatoon (GLM)

Year
Continues simulation of rainfall and potential evaporation can be used to drive hydrological models to predict flood and water resource systems under current climate and under future climate scenarios.
UK flood frequency changes 2080s

Medway, SE England

Flood Frequency curves for 63006

Weaver, NW England

Flood Frequency curves for 40007

Hadley Centre RCM GLM disaggregation
Red-current Blue-2080s
S England chalk groundwater 2050s

River Lavant flows

Groundwater levels

after Butler, 2009
Continuous simulation methods are currently being used in the UK for vulnerability analysis of future flood risk
From sensitivity analysis to vulnerability analysis - UK precipitation change

GCM/RCM scenario classification-
change in
a) mean
b) seasonal variability

After Reynard, 2009
20 year flood vulnerability

Three types of catchment vulnerability

Vertical axis - Change in mean precipitation
Horizontal axis - Change in seasonality

Colours represent 10% changes
Dots represent GCM/RCM scenarios
Conclusions

- Flood risk management in the prairies creates particular challenges for hydrological modelling.
- Conventional design storm methods have limitations.
- Continuous simulation methods offer some new ways forward for flood risk management and for estimation of the potential impacts of climate change.
Selected References

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