Long-term streamflow projections: A summary of recent results from the Millennium Drought

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• Why do them?
  – Climate Change impact assessments
    • Water resources system planning & management
      – Urban
      – Agricultural

• Uncertainties & Assumptions
  – Uncertainty in Climate Change inputs
    • Between GCMs
    • Within GCMs (Peel et al., 2015; Barria et al., 2015)
  – Catchment modelling Assumptions
    • Catchment rainfall-runoff relationship remains stable
    • Calibrated model parameters apply into the future
Testing catchment modelling assumptions

• Climate Change
  – Possibly wetter, similar or drier future conditions

• Catchment rainfall-runoff relationship
  – Does it remain stable under prolonged changed conditions?

• Calibrated model parameters
  – How well do model parameters apply into the future under changed conditions?

• Millennium Drought provides a real world example of prolonged dry conditions
Fig. 1. Australian rainfall deciles for the 13 years 1997 to 2009, calculated using the Bureau of Meteorology's operational 0.05° resolution analyses.
### TABLE 2. SEA seasonal rainfall anomalies expressed as percentages relative to the long-term average for selected driest 11-yr and 13-yr periods associated with three major historical droughts.

<table>
<thead>
<tr>
<th>Period (either 13 or 11 years)</th>
<th>Annual (%)</th>
<th>Autumn (%)</th>
<th>Winter (%)</th>
<th>Spring (%)</th>
<th>Summer (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federation Drought</td>
<td>1895–1907</td>
<td>-7.7</td>
<td>-1.9</td>
<td>1.3</td>
<td>-19.5</td>
</tr>
<tr>
<td></td>
<td>1895–1905</td>
<td>-8.8</td>
<td>-3.9</td>
<td>1.3</td>
<td>-23.5</td>
</tr>
<tr>
<td>WWII Drought</td>
<td>1933–45</td>
<td>-8.8</td>
<td>-15.1</td>
<td>-9.1</td>
<td>-9.2</td>
</tr>
<tr>
<td></td>
<td>1935–45</td>
<td>-11.7</td>
<td>-14.4</td>
<td>-10.7</td>
<td>-15.9</td>
</tr>
<tr>
<td><strong>Millennium Drought</strong></td>
<td>1997–2009</td>
<td><strong>-12.8</strong></td>
<td><strong>-23.4</strong></td>
<td><strong>-9.9</strong></td>
<td><strong>-7.8</strong></td>
</tr>
<tr>
<td></td>
<td>1999–2009</td>
<td>-12.8</td>
<td>-23.7</td>
<td>-9.8</td>
<td>-10.0</td>
</tr>
</tbody>
</table>

From Timbal & Fawcett (2013) J. Climate, 26, 1112-1129
The influence of multiyear drought on the annual rainfall-runoff relationship: An Australian perspective

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Abstract Most current long-term (decadal and longer) hydrological predictions implicitly assume that hydrological processes are stationary even under changing climate. However, in practice, we suspect that changing climatic conditions may affect runoff generation processes and cause changes in the rainfall-runoff relationship. In this article, we investigate whether temporary but prolonged (i.e., of the order of a decade) shifts in rainfall result in changes in rainfall-runoff relationships at the catchment scale. Annual rainfall and runoff records from south-eastern Australia are used to examine whether interdecadal climate variability induces changes in hydrological behavior. We test statistically whether annual rainfall-runoff relationships are significantly different during extended dry periods, compared with the historical norm. The results demonstrate that protracted drought led to a significant shift in the rainfall-runoff relationship in ~46% of the catchment-dry periods studied. The shift led to less annual runoff for a given annual rainfall,
• **Dry period definition based on rainfall**
  – Length ≥ 7 consecutive years
  – Mean dry period rainfall anomaly < -5% of MAP
• **Millennium Drought (MD) dry period**
  – 124 catchments with a dry period during MD in SE Aust
  – Rainfall–runoff relationships changes in 56% of catchments
Rainfall-Runoff relationship stability during the Millennium Drought (Saft et al., 2015a)

Figure 5. Map of catchments with and without significant change in rainfall-runoff relationship during the Millennium drought.
• Features **not** associated with catchments that changed rainfall-runoff relationship
  – Drought severity or length
  – PET, rainfall intensity
  – Autumn rainfall reductions
Rainfall-Runoff relationship stability during the Millennium Drought (Saft et al., 2015a)

• Features associated with catchments that changed rainfall-runoff relationship
  – Drier (less MAP), Lower slope, Less woody vegetation

• What does it all mean?
  – Rainfall-runoff relationships can change over time due to changed climatic conditions
  – Whether a catchment changes appears to be due to
    • Features of the catchment; not features of the drought
    • Something changed within some catchments, but not others
  – How can we predict which catchments will change in future?
Rainfall-runoff relationships can change during prolonged dry conditions.

Do changes impact conceptual rainfall-runoff model performance?
Rainfall-Runoff relationship changes & model performance (Saft et al., 2015b in prep)

• 139 catchments from SE Aust with “dry periods” defined by Saft et al (2015a)

• Test 6 conceptual rainfall-runoff models
  – Sacramento
  – GR4J
  – SIMHYD
  – SMARG
  – AWBM
  – IHACRES
• Split sample test

• Calibrate over non-dry period
  – Shuffled Complex Evolution
    • Maximise NSE
    • Minimise relative bias
  – Identify “optimal” parameter set

• Evaluate over the dry period
  – Calculate daily NSE & relative bias
Rainfall-Runoff relationship changes & model performance (Saft et al., 2015b in prep)
Rainfall-Runoff relationship changes & model performance (Saft et al., 2015b in prep)
• Catchments with no change in rainfall-runoff relationship
  – Model performance = good

• Catchments with a change in rainfall-runoff relationship
  – Model performance = very poor
    • Over-estimate runoff ~90%
    • Some models better than others, but all are poor

• Results are model independent
• **Implications for long-term streamflow projections**
  - Will rainfall-runoff relationships change in future?
    • If yes
      - Current conceptual rainfall-runoff models will significantly overestimate streamflow
        » Planning and management decision makers will have an overly optimistic assessment of future streamflow availability
    • If no
      - Streamflow projections as good as expected from a split sample test
  
  - Changes in catchment rainfall-runoff relationship
    • Can we predict which catchments will experience one?
      - Not yet
    • Can our conceptual rainfall-runoff models cope with one?
      - Not yet
|   | Predicting runoff under changing climatic conditions:  
 2  | revisiting an apparent deficiency of conceptual rainfall-runoff models |

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- Under revision at WRR

- Is poor conceptual model performance during prolonged dry periods due to:
  - Poor model structure?
  - Poor selection of parameter sets?
Poor model performance during prolonged dry periods (Fowler et al., 2015)

- Look for parameter sets that perform well during non-dry and dry periods
  - Dry period = driest 7 consecutive years of streamflow
  - 86 catchments from the BoM Hydrologic Reference Stations
    - South of the Tropic of Capricorn
  - Daily precipitation (AWAP)
  - Daily PET
    - Morton areal potential (SILO)
  - Five conceptual rainfall-runoff models
    - GR4J, SIMHYD, IHACRES, GR4JMOD, Sacramento
Poor model performance during prolonged dry periods (Fowler et al., 2015)
Poor model performance during prolonged dry periods (Fowler et al., 2015)

- Pareto approach
  - AMALGAM (Vrugt and Robinson, 2007)
    - Objective function = Kling-Gupta Efficiency (daily)
Poor model performance during prolonged dry periods (Fowler et al., 2015)

Rocky River upstream of Gorge Falls (A5130501)
Poor model performance during prolonged dry periods (Fowler et al., 2015)

Rocky River upstream of Gorge Falls (A5130501)
• Is poor conceptual model performance during prolonged dry periods due to:
  – Poor model structure?
    • True if
      – DSST and Pareto approach can’t identify a robust parameter set
    • False if
      – DSST and/or Pareto approach can identify a robust parameter set
  – Poor selection of parameter sets?
    • True if
      – Pareto approach identifies a robust parameter set, while DSST cannot
    • False if
      – DSST identifies a robust parameter set
Poor model performance during prolonged dry periods (Fowler et al., 2015)
Poor model performance during prolonged dry periods (Fowler et al., 2015)

- Where DSST failed to find a robust parameter set
  - Standard 1 (KGE>0.7) → 282 (66%) cases out of 430
    - AMALGAM found a set in 155 (55%) cases out of 282
  - Standard 2 (KGE>0.8) → 347 (81%) cases out of 430
    - AMALGAM found a set in 120 (35%) cases out of 347

- **Implications for long-term projections**
  - Robust parameter sets exist
    - Current calibration techniques don’t always find them
      - AMALGAM is not appropriate for DSST as it uses all the record
  - Some catchments are not well modelled by any of the model structures under changing conditions
    - Some models are more robust to changing conditions than others
Overall lessons learnt

• Prolonged dry periods can shift the rainfall-runoff relationship
  – We don’t know which catchments will shift

• Conceptual rainfall-runoff models perform very poorly when projecting runoff for catchments with a shift in rainfall-runoff relationship
  – They perform as expected without a shift

• Not all poor model performance is due to model structure errors
  – Robust parameter sets exist
  – Current calibration methods don’t always find them
Australian Research Council Future Fellowship (FT120100130)


