National scale flood forecasting in the world of data, models, HPC and AI—shaping a more resilient tomorrow

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Climate, Freshwater & Ocean Science
Water plays a key socio-economic role in New Zealand

**Insurance Costs** & ex-cyclones:
Between 1996-2014: $442 Million (NZD)

2017-2019: >$350 Million (NZD), 6 ex-cyclones

**Responsibilities for floods:**
Local authorities are the primary agents responsible for civil defence emergency management (CDEM)

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1Reference: Insurance Council of New Zealand (ICNZ)
There are many types of flooding, which can sometimes occur at the same time

- **River flooding**
  - Karamea, WCRC photo Jan 2017

- **Surface flooding**
  - Alan Blacklock, NIWA Wellington 2008

- **Coastal flooding**
  - Dave Allen, NIWA, Eastbourne 2016

- **Groundwater flooding**
  - [https://www.floodguidance.co.uk/what-is-resilience/types-flooding/#Groundwater%20flooding](https://www.floodguidance.co.uk/what-is-resilience/types-flooding/#Groundwater%20flooding)
Long records of historical data (and statistics of extreme distributions) are typically used to provide flood return periods

Return period = average time between flood events

- A **100-year flood** is a flood event that has a 1 in 100 chance (1% probability) of being equalled or exceeded in any given year.
- A **50-year** flood has a 0.02 or 2% chance of being exceeded in any one year.
- A **10-year** flood has a 0.1 or 10% chance of being exceeded in any one year.
12 months’ worth of rain in 2 days: flood event 08-09 Nov 2018

Goat Creek Bridge on State Highway 73 collapsed

West Coast deluge: Road to bridge wiped out, person missing in river

Heavy rain in the South Island today has wiped out a road to an Arthur’s Pass bridge, and a search is underway for a person missing in Haupiri River.

Reference image: A bridge to Arthur’s Pass collapsed after heavy rainfall lashed the West Coast region. Photo: Facebook / Greymouth i-SITE

12 months’ worth of rain in 2 days: flood event 08-09 Nov 2018
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12 months’ worth of rain in 2 days: flood event 08-09 Nov 2018
Overseas, major flood events became a catalyst for change with the establishment of national flood/flow forecasting centres.

**UK Flood Guidance statement from the UK MetOffice Flood forecasting centre**

The forecasting to decision-making pathway is complex and requires interdisciplinary science.

Weather forecasting
Hydrological forecasting
Hydrodynamics
Flood maps
Impact forecasting
Decision-making
Emergency services

Key challenges
Data
Models/computational resources
Uncertainty quantification
Forecast and impact communication
Weather is predictable (deterministic) but only for finite times as initial and model errors amplify.

Lorenz’s experiment with dynamical systems (1960s)

The difference between the initial conditions of these two curves is only 0.000127.

The atmosphere is a chaotic dynamical system.
Forecast uncertainty needs to be quantified, ensemble forecasting provides a probabilistic approach.
There are several types of ensembles, generating “good” statistical and dynamical ensembles is an active area of research.

- Lagged ensemble = consecutive forecasts
- Statistical ensemble = e.g. precipitation post-processing
- Dynamical ensemble = multiple weather realization
NIWA’s operational flow forecasting system brings together computer models, real-time and long term data.

Weather model and forecast

Hydrological model

Flow forecast

Initial conditions

<table>
<thead>
<tr>
<th>Now</th>
<th>Short range</th>
<th>Medium range</th>
<th>Long range</th>
<th>Seasonal range</th>
</tr>
</thead>
<tbody>
<tr>
<td>48h ahead</td>
<td>72h ahead</td>
<td>15 days ahead</td>
<td>3 months ahead</td>
<td>1971-2120</td>
</tr>
</tbody>
</table>
Inundation forecasting is a critical step toward impact forecasting to inform decision-making.

Operational ensemble inundation system for the Karamea catchment (West Coast)

Weather forecast → Flow forecast → Pre-computed hydrodynamics model map library → Probability of flood depth >5cm threshold
GPGPUs could speed up inundation forecasting to include 2D model complexity in real time

Dr. Cyprien Bosserelle, Dr. Wolfgang Hayek, Dr. Emily Lane

- BG code: Numerical model for simulation of shallow water hydrodynamics on the GPU using adaptive mesh refinement type grid.
- rain on grid

https://github.com/CyprienBosserelle/BG
The scientific workflow for operational forecasting is very complex

Cylc ("Silk")

Dr. Hilary Oliver, NIWA
Example: Cylc workflow for the weather forecast

NZCSM forecast (NIWA)
Example: Cylc workflow for the national flow forecast

“Group”

“Ungroup”

National flow forecast (NIWA)
Scientific provenance is critical to an operational system: models, datasets, forecasting configurations need to be version controlled.

List of model/datasets repository and tag versions

Forecasting suite configuration is also version controlled.
NIWA’s high-resolution convective-scale weather forecast (deterministic) has been operational since 2014.
High-resolution models can give more realistic orographic and convective rainfall in New Zealand topography.

August Storm Event 2014

Legend:
- Rain Stations
- Cumulative Precipitation [mm]:
  - 0.000000
  - 57.000000
- Rainfall Product Cumulative Precipitation
- 8
- 4.35
- 8.64
- 11.9

Large scale 12km (NZLAM)
- Penn Ck at McIntosh
- 328mm
- Akatarawa at Warwicks
- 137mm
- Tauherenikau at Bull Mound
- 29mm
- Whakatiki at Blue Gum Spur
- 95mm
- Hutt at Kaitoke Headworks
- 136mm
- Wallaceville
- 66mm
- Pakuratahi at Central Ridge
- 128mm
- Lower Hutt
- Hutt at Taita gorge

Convective-scale 1.5km (NZCSM)
- Penn Ck at McIntosh
- 328mm
- Akatarawa at Warwicks
- 137mm
- Tauherenikau at Bull Mound
- 29mm
- Whakatiki at Blue Gum Spur
- 95mm
- Hutt at Kaitoke Headworks
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- Wallaceville
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- Hutt at Taita gorge

Map areas and rainfall data indicate the differences in accuracy and scale between large and convective resolution models.
Weather forecasting is computationally expensive, requires parallel computing, HPC systems

Principal models for everyday forecasting at NIWA are NZLAM-12 and NZCSM. NZLAM-4 and NZENS are currently test models.

<table>
<thead>
<tr>
<th></th>
<th>NZLAM-12</th>
<th>NZLAM-4</th>
<th>NZCSM</th>
<th>NZENS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain Size</td>
<td>324 x 324 x 70 (L70_80km)</td>
<td>900 x 900 x 70 (L70_80km)</td>
<td>1200 x 1350 x 70 (L70_40km)</td>
<td>400 x 450 x 70 (L70_40km)</td>
</tr>
<tr>
<td>Dynamics timestep (Δt)</td>
<td>300 s</td>
<td>120 s</td>
<td>60 s</td>
<td>120 s</td>
</tr>
<tr>
<td>Forecast period / frequency</td>
<td>T+75 (4x daily)</td>
<td>T+75 (4x daily)</td>
<td>T+51 (4x daily)</td>
<td>T+60 (1x daily)</td>
</tr>
<tr>
<td># HPCF cores</td>
<td>272 (7 nodes)</td>
<td>1024 (26 nodes)</td>
<td>1080 (40 nodes)</td>
<td>440 (11 nodes)</td>
</tr>
<tr>
<td>Wallclock time</td>
<td>~20 mins</td>
<td>~100 mins</td>
<td>~145 mins</td>
<td>~21 mins</td>
</tr>
</tbody>
</table>
The development of a NZ Water Model is key for many applications including flood forecasting.
The GeoFabric includes a digital network to model the river network.

River network

Wetness or topographic index

Hybrid of Lidar and Otago Uni 15m DEM
Increased resolution of the river network will improve forecast but increase computational resources

**River network**
- 425,000 km or river
- Independent verification by regional councils

**Network characteristics**

<table>
<thead>
<tr>
<th></th>
<th>DN2</th>
<th>DN3 (LIDAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reach length (m)</td>
<td>750</td>
<td>250</td>
</tr>
<tr>
<td>Catchment (km²)</td>
<td>0.7</td>
<td>0.07</td>
</tr>
<tr>
<td>Nb element</td>
<td>~560,000</td>
<td>&gt;3,700,000</td>
</tr>
</tbody>
</table>
The GeoFabric includes national databases of land cover and soil property information (Landcare, GNS)
The NZ water model is physically-based

Semi-distributed hydrological model based on TopModel

Full water balance simulated within each catchment

Ongoing model processes improvements:

- Groundwater
- Evapotranspiration


Once more with equations...

State equations

Canopy Storage
\[
\frac{dS_c}{dt} = p - p_t - e_c
\]

Snow Storage
\[
\frac{dS_s}{dt} = p_s - m_s
\]

Soil Storage
\[
\frac{dS_r}{dt} = i - e_r - d
\]

Aquifer Storage
\[
\frac{dS_a}{dt} = d - q_b
\]

Overland Storage
\[
\frac{dS_o}{dt} = q_{ix} + q_{sx} + q_b - q_o
\]

Weather inputs:
- Precipitation (rain snow)
- Atmospheric temperature
- Relative humidity
- Snow melt
- Surface winds, etc.
- Potential evapotranspiration
- Solar radiation
Profiling and optimisation are key to increase model complexity and efficiency
A traditional flow forecasting approach uses historical observed flow for model calibration, this approach is not applicable at national scale for ungauged catchments.
Getting enough (long historical records) and in real-time data is challenging

Rain data at NIWA

Flow data NIWA+RCs

Modelled rivers

Years of record

<1000

~60,000
Flow observations are not always a true areal integrator of rainfall over a catchment, this makes model testing more difficult.
The national scale approach produces forecast relative to a long-term modelled flow climatology at gauged and ungauged catchments.

Flow climatology
- 40 year model simulations using observed climate data (VCSN)
- Model flow statistics (FDC) at ~60,000 basins

Categorical flow forecasts
- > 99% FDC
- 90% - 99% FDC
- 66% - 90% FDC
- 33% - 66% FDC
- 10% - 33% FDC
- 0% - 10% FDC

![Flow climatology diagram](chart.png)
Machine learning could be a pathway towards forecast beyond relative values by merging physically-based with AI models.

Random Forest - hourly Flow Duration Curve (FDC)

Based on catchment characteristics and observed gauges (training set), derive FDC at ungauged basins across countries.
What constitutes a “good” ensemble forecast?

**Accuracy**
Forecasts should agree with observations, with few large errors

- Continuous Ranked Probability Score (CRPS)
- Ranked Probability Score (RPS)
- Mean Absolute Error (MAE)

**Bias**
Forecast mean should agree with observed mean

- %bias

**Reliability**
Agreement between the probability provided by the ensemble forecast and the frequency of occurrence of observation

- Reliability histogram
- Probability Integral Transform (PIT) histogram
To statistically evaluate the performance of the system and establish a baseline for future improvements, we need to first assess the flow climatology and produce enough flow forecasts

- ~710 flow gauges
- Period 1973-2015

- **Flow climatology: 1973-2015**
  - Categorical scores (correlation, misclassification, Adjusted Rand Index, ... )
  - Cross validation, leave one year out for Flow Duration Curve

- **Flow forecasts: October 2018-...** -> Several years of flow forecasts are ideal for verification scores, especially for flood. Ongoing work.
Overall the flow climatology performs well across diverse catchments, however poor geology representation, abstractions and managed rivers likely affect the performance in some regions.

Preliminary results:
- ~710 flow gauges
- Period 1973-2015
- 6 flow categories
With access to new HPCs, NIWA’s been running an 18 member convective-scale ensemble at (~4.5km) in test since March 2019

- UM10.9/RA1-M
- 40km model top
- Up to 18 members
- LBCs: MOGREPS-G
- Forecast period: T+60
- Output frequency: Hourly
- AT: 00 UTC (from T+3 dump)
Understanding and representing uncertainty in flood forecasting is critical and a complex challenge

Given computational resources available what is the most optimized flood ensemble operational configuration?

Is higher resolution with a small ensemble size better?

Is smaller ensemble size but more frequent issue times better?

How do statistical and dynamical ensembles compare?

Australian collaborators
D. Robertson (CSIRO), Q.J. Wang (U. of Melbourne), J. Bennett (CSIRO)
Post-processing methods are essential to produce bias free and reliable statistical ensembles

Post-processing method based on the Bayesian joint probability (BJP) model (Wang et al 2009)

Step 1: Correct biases and quantify uncertainty

Step 2: Instill temporal and spatial patterns

New post-processing method with daily data for national scale flow forecasting: using spatial and temporal information from high-resolution rainfall forecasts

Cattoën, C., Robertson, D.E., Wang, Q.J, Bennett J.C., Carey-Smith, T., (In preparation) “Calibrating hourly precipitation forecasts with daily observations”. J. Hydrometeorology

We need to understand dominant sources of uncertainty to get the right answer for the right reasons.

**Ensemble Flood event case studies**

- Impact of weather IC, LBC, resolution, physics, domain, Data assimilation.
- Statistical ensembles and post-processing
- Impact of flow DA, flow initial conditions

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**Buller ~ 5yr flood**

**Waimakariri ~15yr flood**

**Observed flow**
Flood forecasts seem most sensitive to lagged ensemble, initial and lateral conditions, model physics perturbations, and simple statistical perturbations

Case study: Ex-cyclone Debbie 4th April 2017, weather initial conditions vs perturbed model physics

Visualisation and communication of flow forecasts at national scale is challenging, it is being developed with GIS-based tools.
Examples of some recent experiments using ESRI
Why developing a national scale system?

Shaping a nationwide approach for New Zealand’s river flow forecasts

- Potentially a major aid to public safety, the NZ river flow forecasting project aims to support & strengthen New Zealand’s response in planning and extreme weather prediction

- A co-design approach: we seek to complement and support existing local models and work together to shape research that is designed for decision-makers’ needs and priorities
Decision-making relies on multiple sources of information, short timelines and flood manuals
Experience is heavily used in scenario testing to cope with uncertainty in decision-making: “15 years ago there was a similar event and this happened, so let’s test adding more rain here” (Participant 5).

Models can be another critical source of information for councils. “[...] if you were in a council and there’s no one there who has more than 10-years’experience, you’re quite vulnerable, [...] unless you’ve got very good documented systems and they have models” (Participant 5).
The forecasting to decision-making pathway is complex and requires interdisciplinary science.
What are the challenges for the next 5-10 years?

**Data, models and uncertainties:**
Incorporating and assimilating data into forecast models from diverse sources: remote sensing, radar images, LIDAR technology, real-time updates from social media?

**Model complexity, resolution:**
Producing accurate and reliable seamless flood forecast from hours to weeks of lead time?

**Communicating forecast impact:**
Communicating and translating probabilistic flood forecast into accurate impact based decisions?
Conclusions

Shaping a nationwide approach for New Zealand’s river flood forecasts

- First step towards NZ river flow forecasts
- Data, models, HPC, machine learning are central
- Long-term next steps, ensemble forecasting of impact
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Natural Hazards Research Platform 2017 - C05X0907 2017-NIW-03-NHRP
Enhanced probabilistic flood forecasting using optimally designed numerical weather prediction ensembles
Thank you

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Assessing the hydrological model across the country is crucial to establish a benchmarking process and test future model improvements


