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Climate-Informed Stochastic Hydrological Modelling

A thesis submitted for the degree of Doctor of Philosophy at The University of Newcastle

by

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I hereby certify that the work embodied in this thesis
is the result of original research and has not been
submitted for a higher degree at any other institution.

Benjamin J. Henley

To Shelley,
Mark, Sharon, Nic and Luke

"Science is the poetry of reality."
Richard Dawkins

"One can have no smaller or greater mastery than mastery of oneself."
Leonardo da Vinci

"We still do not know one thousandth of one percent of what nature has revealed to us."
Albert Einstein

Abstract

Several large scale ocean-atmosphere climate mechanisms are known to influence the Australasian climate, including the El Niño Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO) and the closely related Pacific Decadal Oscillation (PDO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM). The variability explained by these mechanisms presents a valuable means for improving the ability of stochastic models to characterise temporal and spatial hydrological behaviour. Whilst there is significant interannual (and higher frequency) hydrological variability due to ENSO, the IOD and SAM, water supply reservoirs typically have sufficient carry-over storage to maintain supply through shorter (e.g. El Niņo) drought spells with run-lengths up to 12-18 months. Reservoir systems are usually not designed however to cope with decadal-scale dry periods. The evidence of low frequency hydrological variability due to the IPO-PDO and the vulnerability of water supply systems to prolonged drought sequences prompt the need for a better understanding of this variability. If poorly understood, the IPO-PDO phenomenon could present a significant threat to the security of water resources.

This study develops a new combined palaeoclimate IPO (CPIPO) index using multiple sources of palaeoclimate data from around the Pacific basin, in order to better characterise low frequency Pacific Ocean variability (IPO-PDO) going back around 440 years. The resulting distribution of IPO-PDO run-lengths has a mean of 16.7 years, a mode of 10-15 years, a standard deviation of 10.6 years and 90% probability limits of 5 and 36 years. The CPIPO was found to be an improvement in representing IPO-PDO variability during the instrumental period in comparison to previous IPO-PDO palaeoclimate reconstructions. The index therefore provides the best available estimate of Pacific decadal climate variability for the last four centuries. Despite this, significant uncertainty still exists in relation to the underlying physical mechanisms and impacts of the IPO-PDO. Further work remains to understand the proportion of the variability in the IPO-PDO run-length distribution that can be attributed to multi-decadal persistence or uncertainty in the multi-decadal persistence. This study does not discount the possibility that an improved understanding of the physical mechanisms of the IPO-PDO, in particular its relation to the El Niño Southern Oscillation, could result in different estimates of the IPO-PDO persistence structure.

This study assesses a range of candidate stochastic models for the IPO-PDO. Formal model selection identifies the gamma distribution as a suitable stochastic model for the simulation of IPO-PDO run-lengths. In doing so, this study shows that the widely-used Hidden State Markov (HSM) model and related Markov family models with their monotonically decreasing run-length probability density and mode at one are structurally inappropriate for the simulation of quasi-periodic data such as the run-lengths of the IPO-PDO.

This study then develops a general framework for incorporating modes of climate variability into stochastic hydrological models. The framework, termed the climate-informed multi-time scale stochastic (CIMSS) framework, utilises Bayesian hierarchical methods to simulate multiple scales of climate mechanisms and their impacts on hydrological data. The physical phenomena operating at multiple time scales are simulated with stochastic models. A stochastic model for seasonal rainfall is then developed that incorporates the decadal-scale climate variability of the IPO-PDO. Spatial and temporal characteristics of the impacts of the IPO-PDO are investigated in detail using a range of statistics based on Australia-wide gridded data and site data from 22 stations on the east coast of Australia. A Bayesian methodology is used to infer the joint posterior distribution of the CIMSS framework parameters and therefore provide a reliable estimate of parameter uncertainty. The CIMSS approach is compared to the non-climate-informed annual AR(1)-BC stochastic model. The AR(1)-BC model is unable to adequately capture the observed rainfall distribution within separate IPO-PDO states. Therefore, due to the CIMSS model's ability to capture decadal-scale climate variability, the climate-informed approach is shown to be an advance over non-climate-informed stochastic rainfall models.

The impacts of decadal-scale hydrological variability on water supply drought risk are then investigated. A nonparametric k-nearest neighbour (kNN) sampling approach is used to transform simulated rainfall into reservoir inflows. The design storage capacity of a fictional reservoir in the Hunter region of NSW is determined using a traditional long-term mean drought risk approach based on typical drought security and reliability criteria. A new method for assessing short-term conditional water supply drought risk is developed. This approach represents an advance on previous position analysis approaches as it explicitly incorporates the influence of a climate mechanism in the drought risk estimates, in this case the IPO-PDO. A time-based drought risk threshold equal to the annual demand is advocated over absolute levels, since this is considered to be more amenable to planning decisions which can be time-limited. When the drought risk simulations are conditioned to enter an IPO-PDO positive phase, the CIMSS-modelled short-term risks are significantly higher than those for the annual AR(1)-BC model, with higher risk persisting for up to 20-25 years for the CIMSS model. The AR(1)-BC model, with no explicit mechanism to incorporate climate information, does not capture this hydrological variability. The CIMSS model better depicts the hydrological impacts of Pacific decadal-scale climate variability. Since current drought risk evaluation approaches do not explicitly incorporate knowledge of climate mechanisms they could be significantly underestimating the risks of water supply system failure. This result could be of serious concern to water resource planners seeking to provide adequate drought security to growing populations.

This study illustrates the value of stochastic rainfall models that are informed by climate data in addition to the hydrological record, as well as the value of the short-term conditional drought risk approach. The CPIPO index, CIMSS model and short-term drought risk approach introduced in this study together provide a new opportunity for better understanding the risks to water supply systems from large-scale climate mechanisms.

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Contents

List of Publications

The following publications arose from this research:

Journal Articles

1. Henley, B. J., M. A. Thyer, G. Kuczera, & S. W. Franks (2011), Climate-informed stochastic hydrological modeling: Incorporating decadal-scale variability using paleo data, *Water Resour. Res.*, 47, W11509, doi:10.1029/2010WR010034.

Conference Articles

2. Henley, B. J., M. A. Thyer, G. Kuczera & S. W. Franks (2009), How long do phases of the Interdecadal Pacific Oscillation (IPO) persist? Utilising palaeoclimate data in stochastic hydrology, *32nd Hydrology and Water Resources Symposium*, Newcastle, Australia*.

3. Henley, B. J., M. A. Thyer, G. Kuczera & S. W. Franks (2008), Evaluating drought risk dynamics: Comparison of a Climate-Informed Multi-time Scale Stochastic (CIMSS) framework to the AR(1) model, *Water Down Under 2008: 31st Hydrology and Water Resources Symposium and the 4th International Conference on Water Resources and Environment Research*, Adelaide, Australia*.

4. Henley, B. J., M. A. Thyer, G. Kuczera & S. W. Franks (2008), Short-Term Drought Risk Dynamics: The Impact of Multi-decadal Climate Variability and Water Supply Properties, *World Environmental & Water Resources Congress*, Honolulu, USA.

5. Henley, B. J., M. A. Thyer & G. Kuczera, G. (2007), Seasonal Stochastic Rainfall Modelling Using Climate Indices: A Bayesian Hierarchical Model, *International Congress on Modelling and Simulation*, Christchurch, New Zealand*.

6. Henley, B. J., M. A. Thyer & G. Kuczera & S. W. Franks (2006), Incorporating Long-Term Climate Information into Stochastic Models of Annual Hydrological Data: A Bayesian Hierarchical Approach, 30th Hydrology and Water Resources Symposium, Launceston, Australia*.

*peer-reviewed conference articles