Conclusions

This thesis has detailed the development of a stochastic model framework that identifies significant monthly-scale hydrological persistence across a range of different variables, provides an unbiased method to estimate the magnitude of persistence within observed data, simulates hydrologically-persistent time series accurately and offers a potentially superior approach to modelling hydrologic data than standard linear ARMA models. Moreover the results presented in this work have established spatially-coherent relationships for monthly hydrological persistence across Australia.

Hydrological persistence has only rarely been the objective of scientific research, although it is a prevalent feature of global hydrology. Where this has been investigated, the focus has regularly been upon identifying evidence for the Hurst phenomenon within hydrologic data, although this is an asymptotic feature that is difficult to identify within short rainfall time series. This thesis has shown that by interpreting persistence in terms of the clustering of data of similar magnitude allows a large body of knowledge on the behaviour of spells within time series to be utilised for detecting hydrological persistence. In particular, a number of statistical tests that are constructed from the theory of spells can identify significant clustering of values across a range of hydrologic variables. Statistical analyses such as these have been described previously to detect both the severity and the timing of drought conditions. This thesis has demonstrated that rainfall and streamflow data from across Australia show a tendency towards persistence that is more compelling at a monthly scale than compared with an annual scale. The widespread evidence for persistence, across numerous rainfall regimes, implies that this hydroclimatic feature has significant implications upon the planning and management of water resources.

Persistence within rainfall and streamflow data is a consequence of interactions between persistent global climate modes and the hydrological cycle. Although persistence should ideally be replicated in simulations from hydrological time series models, relationships between hydrologic data and climate variability should also be maintained. Climate indices are time series that are designed to relate temporal changes in key variables that describe broad-scale ocean-atmospheric interactions. One way to describe the hydroclimatic processes underlying hydrological persistence is to observe the relationships (such as the correlations) between time series of rainfall observations and climate indices. Such examinations are an attempt to explain persistence in one series solely in terms of persistence in another. However the observed relationships between these series indicate that although the most influential climate indices (those describing circulation phenomena such as ENSO) reveal significant persistence, and hydrological time series also reveal persistence over numerous time scales, climate indices cannot explain much of the persistence in the latter.

The difficulty in capturing observed patterns of persistence through models such as the linear regression of rainfall data upon climate indices can be explained in part by the role of climatic factors that are different from those described in climate indices. As an example, although ENSO variability influences rainfall across much of eastern Australia, the persistence observed in the hydrology of this region does not correspond directly with transitions between the opposite phases of this climatic phenomenon. Furthermore ENSO indices describe changes in ocean-atmospheric variables that are not necessarily measured in close proximity to the rainfall data. Accordingly time series models that provide a coherent description of hydrological persistence, rather than relying upon the influence of separate time series are favourable.

Hidden Markov models (HMMs) offer a strong conceptual basis for hydrological persistence in terms of temporal persistence within states of the climate, as well as transitions between such states. The HMM framework is therefore consistent with the theory of spells analysis that was used in statistical tests to identify persistence within hydrologic observations. Moreover HMMs are parsimonious and are calibrated through well-defined statistical approaches. Their description of climate states reflects distinct regimes observed across numerous climatic variables, even at an atmospheric scale. In this way, HMMs are consistent with the views of Salas and Smith (1981) who discussed the need for physical characteristics of the hydrological system to guide the development of stochastic models for hydrologic variables. Importantly the use of HMMs to model hydrological persistence is also justified from a statistical perspective. Hydrological persistence is interpreted in a different manner from long-term persistence, which is variously described as long memory or more accurately mathematical persistence, a feature that is revealed through a slow decay in the correlogram of a sample time series. This latter characteristic is appropriately modelled through fARIMA-style models, however hydrological persistence is more correctly termed short-term persistence, and is revealed through quick correlogram decays. This feature is accurately preserved through simulations from models such as the widely-used ARMA models, but also HMMs.

This thesis has demonstrated that the calibration of standard parametric HMMs, previously described as appropriate models for persistent hydrological data (eg Thyer and Kuczera, 2000; Srikanthan *et al.*, 2002d; Frost, 2003), may be impeded by certain model attributes. Their calibration is dependent upon making correct assumptions for the distribution of observations in each model state. Incorrect assumptions lead to inaccurate model calibration, with HMMs having the potential to degenerate to mixtures of distributions that lack temporal persistence within underlying model states. Such problems may hinder the use of these models to describe hydrological persistence in cases where straightforward conditional distributions are inadequate, for example with data that show significant positive skewness. Furthermore, with monthly data providing stronger evidence for persistence than is apparent with annual data, it is imperative that modelling difficulties such as these are overcome so that HMM calibrations are improved.

The development of the innovative non-parametric (NP) HMM that is detailed in this thesis has enabled a more thorough analysis of hydrological persistence, across a wide range of variables, than was previously possible. Through removing the requirement to assume the parametric forms of conditional distributions prior to model calibration, the NP HMM overcomes the major shortcoming of parametric HMMs that are revealed when attempting to identify hydrological persistence. Moreover the calibration methods utilised by NP HMMs are straightforward adaptations of the calibration approach of parametric HMMs. This thesis has demonstrated that the NP HMM can expand the areas of potential hydrological analysis through identifying persistence within various data without altering the model formulation.

The capacity for NP HMMs to model persistence in continuous and discrete data, without regard to either their magnitude of distribution, has allowed this feature to be detected within numerous hydrological variables. In fact, the detection of similar persistence within a range of monthly data provides further evidence that this is an essential component of the hydrological cycle within this country. In this thesis persistence is identified within time series of monthly rain-days in addition to records of the most intense short-duration rainfall bursts each month, results that shed light on both the origins and the impacts of monthly hydrological persistence. From analysing extreme monthly intensities from high frequency pluviograph data, it is apparent that the persistent climate states identified with NP HMMs not only modulate total rainfall amounts each month, but are associated with changes in both the number of rain events and also the amount of moisture contained within such events. The combination of these two effects subsequently impacts upon the total rainfall observed on a monthly basis.

A range of case studies in this thesis has demonstrated both the prevalence of monthly hydrological persistence and the usefulness of the HMM approach to describe and simulate this persistence. Utilising summer-dominated monthly streamflow data, catchment-scale rainfall data and spatially-averaged rainfall data from a region showing consistently high rainfall, the flexibility of HMMs to model persistent hydrologic data accurately was shown. With monthly-scale hydrological simulations being vital inputs into water resources studies, it is clear that persistence will have significant implications through affecting the timing, magnitude and spatial distribution of rainfall events. Furthermore the identification of significant persistence in the time series of residuals obtained from fitting appropriate ARMA models to monthly streamflow data indicates the importance of this feature alongside temporal dependence. This thesis has presented results that show that HMMs simulate persistent hydrological data with accuracy that at least matches and improves upon simulations obtained from ARMA models, which are the most commonly-used models for hydrological simulation at monthly and annual scales. Simulation results such as these present a new examination of the efficacy of HMMs for hydrological modelling than previously presented in the literature.

This thesis has demonstrated that persistence is a prominent feature of the hydrology of Australia, and has provided a comprehensive demonstration of the ability of HMMs to model this hydrological persistence. The standard framework of these stochastic models has been developed in a variety of ways, in the process revealing the flexibility of this approach to identify and simulate persistent data. This thesis has subsequently shown that HMMs provide an impressive addition to the field of stochastic hydrology, with results presented in this work outlining a number of future research directions, some of which are described in the following section.

Future work

Results presented in this thesis have identified a range of areas in which future research could be directed. Some of these possible research objectives are as follows:

Further development of the NP HMM

The non-parametric HMM is a valuable addition to existing parametric HMMs that have been described as being suitable for modelling hydrological persistence. This is a parsimonious development of parametric HMMs that utilises a similar approach to model calibration. The ability of this model to represent state transitions is dictated through a description of the division of a unit square. The interpretation of the NP HMM that was utilised in this thesis described a division through three contiguous lines. However it is possible that through an enhanced description of this division, the calibration of this model may be improved. As a result, further work should be directed at developing alternative descriptions for the division and analysing the calibration performance.

Other aspects of the NP HMM framework that require further analysis are methods to estimate conditional distributions following the calibration of the unit square division. Currently these distributions are estimated from the marginal distribution, with a simulated uniform random variable u_t inferred as a value from the marginal cumulative distribution function. This process has proved suitable for estimating the shape of these distributions. However the use of the NP HMM to simulate hydrologic data, such as monthly streamflows in the Burdekin River that was shown in this thesis, raises the question of whether simulations should merely duplicate the distribution of observed values. The existing approach is to simulate a state series using posterior distributions for HMM transition probabilities, then to infer values from the estimated conditional distributions. It is possible that this approach may be improved through non-parametric techniques such as kernel smoothing, through which a smoothed description for the conditional distributions can be attained. Furthermore, work needs to improve methods for simulating extreme values that have the potential to exceed the maximum value of the marginal. In the existing version of this model, simulations from the NP HMM are constrained to values below the maximum of the marginal distribution. Each of these developments of the NP HMM framework will improve this novel approach to modelling hydrological persistence.

Producing monthly hydrological forecasts with HMMs

This thesis has outlined a method to simulate hydrological time series with HMMs. Another useful application in the field of stochastic hydrology for the HMM approach would be the provision of accurate forecasts at a monthly scale, which would be of practical use across a wide range of water resource management issues. Therefore it is worth investigating whether a HMM that offers superior descriptions of a particular time series than alternative models such as ARMAs, may also produce more accurate forecasts of hydrologic data. This application of the HMM approach has not been previously described in the hydrological literature.

Using an observed time series of length T, forecasts are produced in one time-step intervals, and rely upon the simultaneous forecast of model state probabilities. The three-step iterative process that achieves a forecast of the observed series at time $(T+1)$ is described by the following:

1. Forecast of the model state probability at time $(T+1)$:

$$P(s_{T+1}^{j} \mid Y_T) = \int P(s_{T+1}^{j} \mid s_T^{i}) P(s_T^{i} \mid Y_T) ds_T$$

This forecast of the model state probability density utilises the posterior distributions for HMM transition probabilities, together with the posterior state series that describes the probability for the model to exist in each model state at the terminal time point T. This density is integrated over the state variable at time T.

2. Forecast of the observation density at time $(T+1)$:

$$P(y_{T+1} \mid Y_T) = \int p(y_{T+1} \mid s_{T+1}^{j}) P(s_{T+1}^{j} \mid Y_T) ds_{T+1}$$

The second stage of this process is to use the forecast state probability from Step 1, together with the probability density function that describes observations in each model state. In the case of a Gaussian HMM, $p(y_{T+1} \mid s_{T+1}^{j})$ represents a Gaussian pdf with parameters from state j, and in an ARHMM, will be described by a time series regression.

3. Updating the model state probability at time $(T+1)$:

$$P(s_{T+1}^{j} \mid Y_{T+1}) = \frac{p(y_{T+1} \mid s_{T+1}^{j}) P(s_{T+1}^{j} \mid Y_T)}{P(y_{T+1} \mid Y_T)}$$

The final step of this process is to update the future state probability using the observation density forecast that was evaluated at Step 2 in this process. This updated state probability then feeds back in to Step 1 in order to forecast values at time $(T+2)$ and so on. Future research could be directed at identifying the most convenient approach to estimating integrals in Steps 1 and 2, together with estimating whether models that are superior from a Bayesian model selection perspective necessarily provide the most accurate forecasts.

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