Integrating models, methods and measurements for prediction in ungauged basins

STEWART W. FRANKS
School of Engineering, University of Newcastle, Callaghan 2308, New South Wales, Australia
stewart.franks@newcastle.edu.au

Abstract The PUB initiative aims to integrate knowledge of hydrological processes to provide the best hydrological characterization of ungauged basins. This requires the integration of models and methods to achieve those objectives. In this paper, recent modelling activities are reviewed, with the aim of demonstrating potential application to ungauged basins. First, the development and testing of process-oriented hydrological models is presented. Examples are shown of the utility of remote sensing in conditioning hydrological model parameters at the catchment scale. Subsequently, a Bayesian error-sensitive model calibration scheme (BATEA) is presented. This scheme acknowledges that rainfall errors propagate and persist in hydrological models, corrupting the parameter estimates. It is shown that BATEA offers parameter estimates unbiased by error in rainfall data. BATEA will be applied to multiple models across a range of basins using MOPEX and Australian data. As regionalization relationships will be derived through unbiased model parameter estimates, it is hoped that stronger relationships between catchment characteristics and model parameter values may be identified, permitting improved model performance in ungauged basins. Finally, multi-decadal climate variability across New South Wales is demonstrated and an ENSO-based mechanism is elucidated. Such understanding of climate/hydrology interfaces offers a greater insight into hydrological risk assessment at different temporal scales and may easily be coupled to regionalized models for ungauged basins at continental scales.

Key words calibration; climate variability; ENSO; IPO; PDO; rainfall–runoff models; regionalization

INTRODUCTION

The development of hydrological modelling systems has to date largely been achieved in specific case studies where a need for such a system has been identified. In this paper, a methodology for developing an Australia-wide hydrological model is propos–ed, based on the integration of recent advances in model identification and parameter estimation. This necessitates the development of hydrological schemes for prediction in ungauged basins. The broad aim of the proposed modelling system is to provide robust simulation of hydrological flow regimes, but with an emphasis on the extremes induced through climate variability observed at a range of temporal and spatial scales.

MODEL IDENTIFICATION AND PARAMETER ESTIMATION

Land surface hydrological models simulate water balance dynamics at a range of spatial scales. Because of the significance of water in terrestrial ecosystems, such models are an integral part of virtually all environmental models formulated at the catchment scale. There are many potential applications of land surface hydrological models, including the estimation of extreme flow characteristics through continuous simulation, streamflow/flood forecasting, estimating the hydrological impacts of changes in land use and climate, and simulating the exchange of water and energy for climate and eco-hydrological models.

However, the problems of natural variability and data scarcity have meant that the development of a single hydrological model based upon a fundamental "physics" of hydrology is thought unattainable (Beven, 1989, 1993). As a consequence, hydrological models are largely "conceptual", in that they are constituted by simplified representations of the mechanisms perceived to dominate the hydrological problem at hand. This means that a whole range of different hydrological models exist to achieve specific tasks at specific space–time scales.

In typical applications, such models require calibration and validation against observed flows given meteorological input data. Numerous schemes have been developed toward this task, including MOCOM (Gupta *et al.*, 1998), GLUE (Beven & Binley, 1992; Franks *et al.*, 1998) and NLFIT (Kuczera, 1994). A key limitation in this regard is the usual reliance on rainfall–runoff data alone—it has long been recognized that such information can only support a limited degree of model complexity in terms of the number of parameters that require estimation.

In an attempt to better constrain the uncertainty associated with model calibration to rainfall–runoff data alone, Franks *et al.* (1998) developed a simple methodology to estimate the extent of runoff-producing saturated areas based on single frequency microwave remote sensing. Estimates of the saturation extent could then be used as an additional modelling objective with which alternative parameterizations could be assessed. Figure 1 shows a derived map of saturation extent whilst Fig. 2 shows the reduction in predictive uncertainty following the dual conditioning to both rainfall–runoff data and the saturation extent.

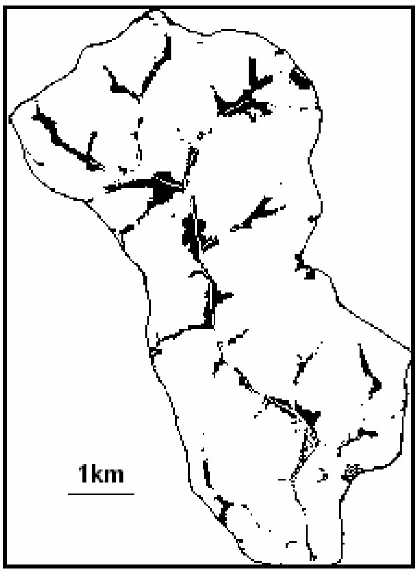

Fig. 1 Estimated extent of saturation.

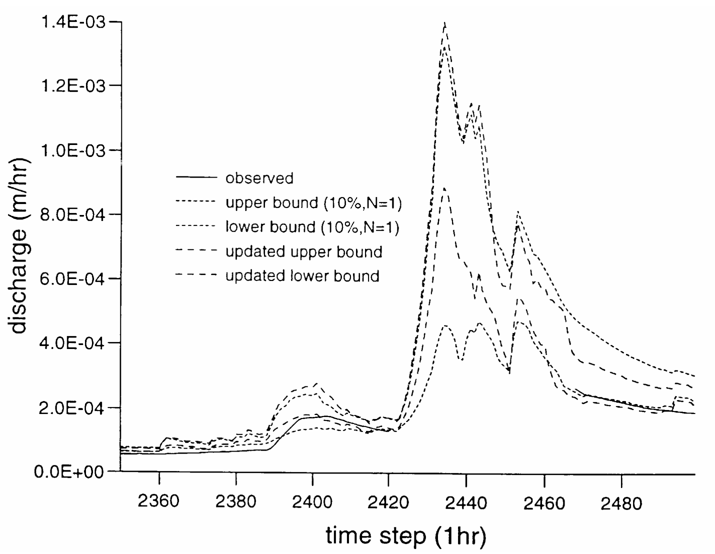

Fig. 2 Reduction in uncertainty updated by estimates of saturated area.

As can be seen, the resultant uncertainty is reduced by approximately 70%, whilst estimates of the key hydraulic conductivity parameter were constrained within an order of magnitude (comparable to field measurement precision). It is therefore clear that the additional information provided by uncertain estimates of saturation extent may be of practical use in refining model parameter estimates.

BIAS IN PARAMETER ESTIMATES

Whilst we must continue to seek new ways to constrain models through additional data, it should also be recognized that substantial uncertainty also exists in the identification of the most appropriate model. Where observations are available, calibration may yield well identified parameter values but the uncertainty associated with the model structure itself, and the role of errors in the rainfall observations, mean that significant bias exists in derived parameter values.

Kuczera & Franks (2002) show that all contemporary approaches (MOCOM, NLFIT, GLUE) oversimplify the uncertainty associated with the appropriateness of the model to the study area and the measurement of both meteorological forcing and runoff. By ignoring these key sources of error and uncertainty, typical calibration schemes have been shown to produce biased estimates of parameters, which may not have any real physical meaning (Beven, 1989; Kuczera & Franks, 2002).

In contrast, the BATEA (BAyesian Total Error Analysis) methodology (Kavetski *et al.*, 2002), recently developed in light of the problems of existing schemes, is based on a “total-error” approach using rigorous Bayesian methods. Results to date indicate that the methodology is robust and yields unbiased parameter inference. The BATEA scheme has been tested against both real and synthetic data to verify the procedure (Kavetski *et al.*, 2000, 2002). To illustrate the degree of bias that arises as a function of ignoring rainfall forcing error, Fig. 3 shows the probability distributions of a key model parameter following traditional standard least-squares (SLS) identification and the BATEA methodology.

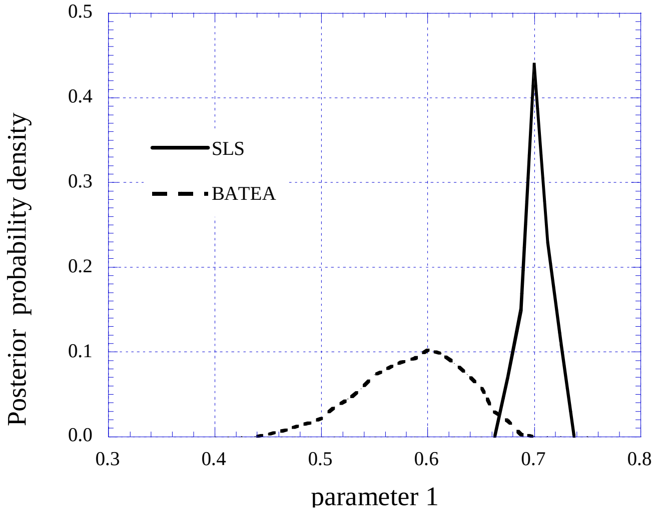

Fig. 3 Parameter inference using SLS and BATEA.

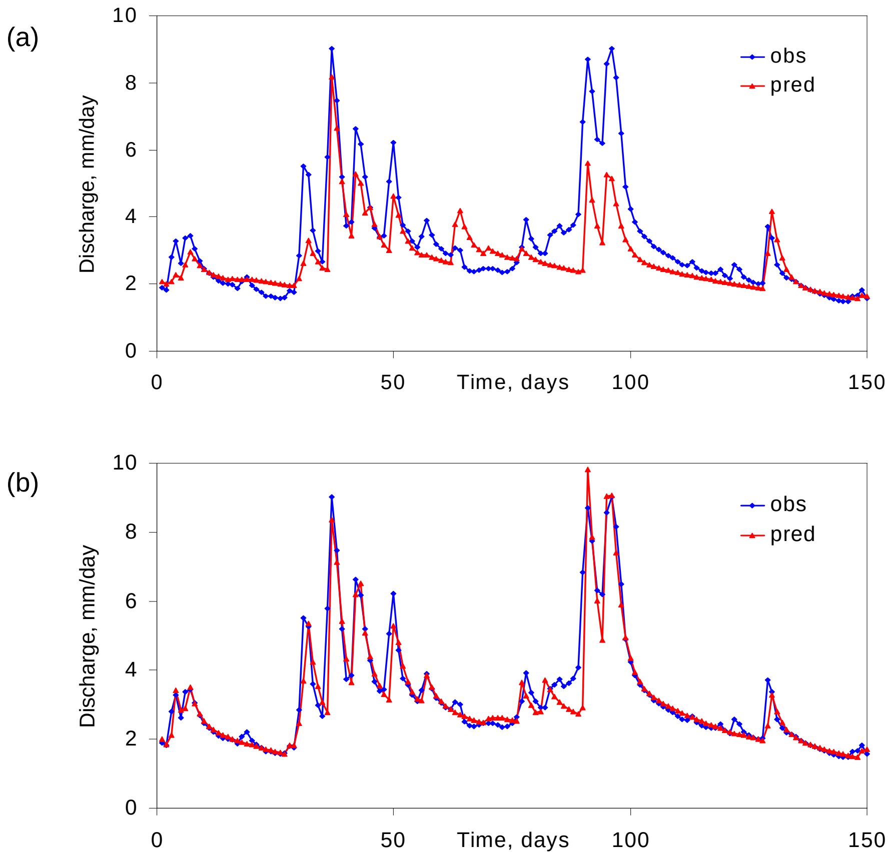

Fig. 4 A comparison of optimized model performance using: (a) Standard Least Squares and (b) Bayesian Total Error Analysis methodology.

As can be seen, the *a posteriori* parameter distributions are very different. Also important to note is the tight constraint of uncertainty following the traditional Standard Least Squares (SLS) approach indicating false confidence in the inferred parameter distribution. It is therefore clear that ignoring key aspects of data uncertainty results in marked parameter bias. Figure 4 shows a comparison of the SLS and BATEA approaches using the resultant optimal simulations for a six month calibration period. It is apparent that by ignoring errors, the SLS approach is unable to reproduce key aspects of the flow record.

BATEA is unique in that it permits the inclusion of error models for observations (both input and output) with any hydrological model. It provides a rigorous framework for dealing with data, parameter and model uncertainty. Importantly, it has revealed the key role of rainfall data error which, if ignored, will result in biased parameters.

MODEL IDENTIFICATION AND PARAMETER ESTIMATION IN UNGAUGED BASINS

To attain the full utility of hydrological modelling, hydrological models must be applicable to *all* catchments. In applying models to ungauged basins where no flow record is available, additional difficulties exist in the specification of an appropriate model with appropriate parameter values. As no flow record is available with which to calibrate or verify the model, significant uncertainty is associated with the *a priori* specification of both model and parameters. The applied catchment model is assumed to correctly represent the dominant flow generating mechanisms, whilst its specified parameters are assumed to be meaningful.

Many regionalization approaches have been developed (for example, recent works include Abdullah & Lettenmaier, 1997; Sefton & Howarth, 1998; Post & Jakeman, 1999; Siebert, 1999; Yokoo *et al.*, 2001). These techniques aim to identify common physical characteristics of catchments that may then relate to model parameters. Typically, a single conceptual hydrological model is selected and subsequently calibrated to the records of a number of gauged basins. Regression analysis is then performed to assess the consistency of individual parameter values (for instance, hydraulic conductivity, root zone store, etc.) against measured physical catchment characteristics (i.e. soil texture, vegetation, etc.). These approaches have revealed some success in finding significant relationships for approximately half of the model parameters. However, the predictive capability of models varied (e.g. Post & Jakeman, 1999; Siebert, 1999). Apparent parameter consistency or variability between different catchment characteristics and responses in previous studies will have been significantly biased due to: (a) the assumed single applicable model and (b) the calibration scheme employed providing biased parameter estimates.

In this light, we aim to take a novel approach to the regionalization problem by developing a hierarchical hydrological model and by generalizing the BATEA methodology to simultaneously test alternative model structure as well as inferring their parameters. Within this strategy, the bias induced by input data error is removed. Additionally, by permitting alternative functional descriptions of hydrological processes, instead of assuming that a single model structure is valid everywhere, the optimal identified models will be more representative of the catchment-specific controls on hydrological response. This approach will provide considerably greater opportunity to identify robust relationships and hence provide greater predictive capability for ungauged catchments.

TOTAL ERROR ANALYSIS FOR REGIONALIZATION

The first aim of the proposed methodology should be to develop a new type of hydrological model that provides functional descriptions of all dominant processes affecting rainfall–runoff transformation at a range of space–time scales. The model will represent a hierarchy of processes of varying detail, as well as different functional forms of individual processes. This range of functional descriptions of differing complexity enables the identification of an optimal catchment model structure for a particular catchment. This is expected to differ between catchments as a function of data quantity and quality, as well as potentially diverse flow generating processes dominating each individual catchment.

The hierarchical model will then be coupled with a novel extension of the BATEA methodology to simultaneously evaluate both model structure and parameters, through developing a Monte Carlo Markov Chain (MCMC) reversible jump methodology. This will be applied to numerous quality-assured data sets across Australia and also the MOPEX data sets. Resultant unbiased parameter estimates will then be analysed with regard to detailed physical catchment characteristics through regression analyses to identify underlying relationships which will then form the basis of a rigorous regionalization approach. These regionalization approaches can then be tested using cross-validation techniques to estimate the uncertainty of *a priori* parameter estimates for ungauged basins. In this way, it is hoped that stronger regionalization relationships will be developed providing the basis for large-scale hydrological model applications. The following section provides a strong example of the need for regionalized hydrological schemes.

HYDROCLIMATOLOGICAL VARIABILITY, NEW SOUTH WALES

The quantification and understanding of hydrological variability is of considerable importance for the estimation of flood and drought risk. At present, traditional methods are largely empirical in that annual maximum floods are assumed to be independently and identically distributed (Franks, 2002a). Despite the development of rigorous Bayesian frameworks to assess the uncertainty of flood risk estimates, these techniques have not acknowledged the possibility of serial correlation within periods of elevated or reduced flood risk (cf. Kuczera, 1999). However, recent research has highlighted the persistence of multi-decadal epochs of enhanced/reduced flood risk across New South Wales (Erskine & Warner, 1988; Franks, 2002a,b; Franks & Kuczera, 2002). In particular, Franks & Kuczera (2002) demonstrated that a major shift in flood frequency occurred around 1945. Previous authors have noted that the mid-1940s corresponded to a change in both sea surface temperature anomalies as well as circulation patterns (Allan *et al.*, 1995). Franks (2002a) showed that the observed change in flood frequency could be objectively identified as corresponding to this shift in climate parameters. Furthermore, it was shown through the use of a simple index of regional flood risk that the observed shift in flood frequency was statistically significant at the <1% level.

Recent climatological studies have also revealed multi-decadal variability in the modulation of the magnitude of El Niño/Southern Oscillation (ENSO) impacts. Power *et al.* (1999) have investigated marked temporal changes in ENSO correlations to Australian rainfall records. The temporal stratification was achieved according to what has been termed the Inter-decadal Pacific Oscillation (IPO). The IPO was defined by anomalous warming and cooling in the Pacific Ocean. Power *et al.* (1999) showed how ENSO correlations changed with the observed changes in persistent large-scale Pacific Ocean SST anomalies. Importantly, Power *et al.* (1999) demonstrated that individual ENSO events (i.e. El Niño, La Niña) had stronger impact across Australia during the negative phase of the IPO, implying that there exists a multi-decadal modulation of the magnitude of ENSO events.

Figure 5 shows the different flood frequency distributions for the warm El Niño and cold La Niña extremes of the Southern Oscillation. As can be seen, La Niña events are the dominant drivers of elevated flood risk. Figure 6 shows the effective enhancement of flood risk through IPO modulation of the magnitude of La Niña impacts. The marked separation of the La Niña flood distributions under different IPO states clearly demonstrates statistical significance (see Kiem *et al.*, 2002, for more details).

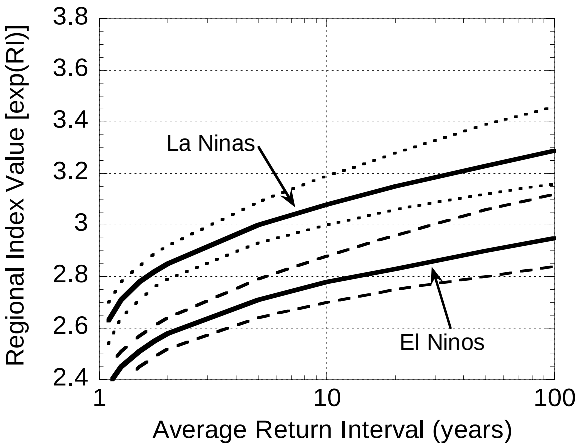

Fig. 5 NSW flood distributions stratified according to El Niño and La Niña extremes.

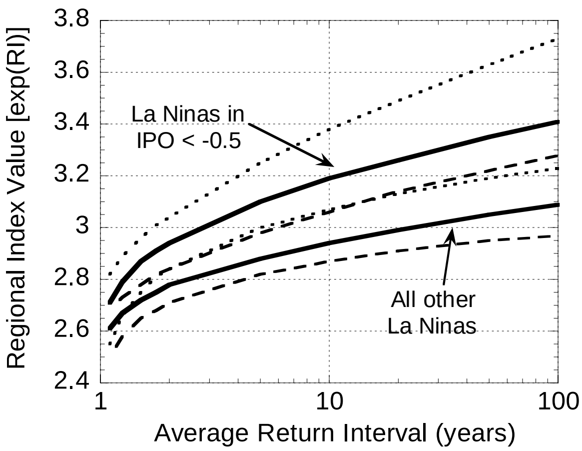

Fig. 6 Effect of IPO enhancement of La Niña flood risk.

These figures provide irrefutable evidence that flood risk in any given year does not arise from a single distribution. It is clear that flood risk is a function of the prevailing climate state. An analysis of drought frequency shows similar climatological influences (Kiem & Franks, 2002). The net effect of multi-decadal IPO modulation of ENSO is to give rise to the multi-decadal hydrological variability previously observed through non-climatological temporal analysis (Cornish, 1977; Erskine & Warner, 1988; Franks & Kuczera, 2002).

Given the predictability of individual ENSO events and the multi-decadal persistence of IPO, it may now be possible to issue forecasts of expected conditions. However, to make useful quantitative statements on hydrological flow conditions, a regional scale hydrological modelling scheme is required to account for the differences in scale and physical characteristics of different catchments across New South Wales. This will enable more robust environmental management practices under the periodic extremes of the Australian climate using simple IPO and ENSO indices.

CONCLUSIONS

It is widely acknowledged that substantial uncertainty exists in the development of appropriate hydrological models. For ungauged basins, the problem of model and parameter uncertainty is even more acute as no data are available to constrain predictive uncertainty. Regionalization approaches based on parameter calibrations, aim to reduce parameter uncertainty for ungauged basins—typically relationships are derived between calibrated parameters and catchment physical characteristics from nearby gauged basins. These relationships then form the basis for estimating parameters for ungauged basins according to their physical characteristics (e.g. area, vegetation, topography, etc.). However, significant bias exists in calibrated parameter values due to observation error and model process uncertainty that permeate the derived regionalization techniques. This must hinder the derivation of robust relationships on which ungauged basins can be confidently parameterized. This would subsequently lead to high predictive uncertainty for ungauged catchments.

BATEA offers the possibility, for the first time, to robustly distinguish between uncertainties in rainfall data, parameter and model. The new methodology permits the unbiased parameter inference and enables more rigorous testing of different model structures. It is therefore expected that efforts to provide regionalization of model parameters may benefit substantially from the improved methodology. A critical need for large-scale regionalized hydrological modelling schemes has been identified in the case of New South Wales hydroclimatological variability. It has been shown that substantial predictability of the impacts of IPO modulated ENSO events is possible. The development of a regionalized model will be of considerable importance in delivering insight into the hydrological impacts of climate variability at a range of space-time scales.

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