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A SYSTEMATIC APPROACH TO MODELLING THE DYNAMIC LINKAGE OF CLIMATE, PHYSICAL CATCHMENT DESCRIPTORS AND HYDROLOGIC RESPONSE COMPONENTS

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1. INTRODUCTION

There are many different types of watershed models seemingly capable of equivalent accuracy in predicting streamflow (eg [1]), although there has yet to be a convincing performance comparison of representative model types on a large range of catchments and over a lengthy period of record. Emerging environmental needs, however, require a better quantitative ability to represent the dominant hydrologic processes over a range of spatial and temporal scales. These emerging needs include the ability to predict catchment streamflow and baseflow in response to fluctuations in climate and/or to changes in land use. Progress in water quality and the representation of regional and global hydrological phenomena, including feedback processes and their effect on climate, requires a commensurate effort in catchment hydrology [2]. Improved linkage of the surface and groundwater components in watershed models is also required, for example for conjunctive use management [3].

According to [2], "future research in catchment modeling must address the problem of permissible system and model complexity, the scales over which model components are valid, and the integration of model components into an overall balanced framework. Integrated models also cannot ignore the sources of uncertainty resulting from ill-defined input and system parameter distributions."

Clearly, this research should best proceed on several fronts. Studies on heavily instrumented catchments can provide insights into and quantification of key processes and this knowledge can be tested for its applicability to other catchments (eg [4]). These experiments may also involve the use of tracers to gain improved understanding of flow paths and provenances. A brief summary of some recent work is given in [5].

Another point of attack addressed here can come from analysis of the wealth of existing time series data for precipitation,evaporation/temperature, stream discharge and, where available, groundwater levels and water chemistry. These data represent indirect observations of catchment behaviour. According to [3], "understanding catchment response over a wide

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range of basin scales and identifying easily derived measures that quantify differences and similarities of catchment behaviour remain important and active areas of research. Progress in these fields is paramount if our collective knowledge of catchments is to aid in understanding regional and global hydrologic phenomena." It is the purpose of this paper to argue how these indirect data and appropriate methodology can be used to quantify the behavioural response of catchments. If this analysis is combined with the more recent ability to obtain intensive spatial data on Physical Catchment Descriptors (PCDs) such as topography, soils, vegetation/ land use and geology, then the quantified behavioural properties can be causally linked with the catchment descriptors to obtain response properties and hence water balance separation in ungauged (streamflow) situations.

In the next section we describe some important improvements in our ability to separate water balance components at various scales and to identify concise measures of a catchment's Dynamic Response Characteristics (DRCs) from rainfall, streamflow and temperature time series data. We then go on to map out a plan for systematically addressing some of the fundamental research needs of watershed modeling.

2. IDENTIFIABLE SEPARATION OF THE WATER BALANCE

In [6], a methodology is described for parametrically characterising the response of catchments from time series data on rainfall, streamflow and temperature. The model uses a non-linear and linear module to represent the conversion of rainfall to rainfall excess (that portion of rainfall available to contribute to streamflow and not lost through evapotranspiration processes), and the subsequent transport of this to stream. It has been applied successfully to a wide spectrum of catchments in Australia, the United Kingdom and United States (eg [6-8]).

In the non-linear module, a one-parameter model is used to index catchment wetness according to antecedent conditions. Temperature can be used to modify the rainfall lost as a consequence of changes in evapotranspiration. This module yields rainfall excess once the model output is scaled to equate rainfall excess volume with measured streamflow volume.

For the transport of rainfall excess to stream, the assumptions [9,6] of unit hydrograph theory are used so that total streamflow at any point in time is equal to a linear convolution of rainfall excess and the unit hydrograph. The latter is the response of the catchment to a unit input of rainfall excess. A rational transfer function module is used to approximate the convolution operator. This is a natural representation both mathematically and conceptually. Rational functions are well known as good approximators of high order polynomials, which is what the continuous convolution operator is in discrete time. Conceptually, the transfer function can be regarded as a configuration of linear reservoirs or storages, the order of the numerator and denominator polynomials determining the specific design of the parallel-series pathway for the rainfall excess. This module is a linear generalisation of many conceptual models of the rainfall- runoff process in catchment hydrology. The main differences are: that the perceived non-linear thresholds of storages in traditional models are absent, the non-linearities being accounted for in the first (rainfall to rainfall excess) module; and, if water enters a store, it leaks continually to stream.

Crucial to the methodology in [6] is an identification exercise which determines the order of the transfer function or the number and configuration of storages. Experience (eg [6-8]) shows that the appropriate order is consistently identified as one where the specification of additional storages leads to no significant improvement in model fit to streamflow but a substantial increase (usually orders of magnitude) in the average relative parameter variance.

Each storage can be regarded as a unit hydrograph whose response form in continuous time is an exponential function. Each storage can be completely characterised by two parameters. One is the rate of exponential decay from a peak response to unit rainfall. The other can be the area under the exponential or the peak response. The former is a measure of the relative volume passing through a store. Most often the identified configuration is two storages in parallel. In these cases, we label the one with faster response the quick flow component (with volumetric response Q_t at time step t) and the other the slow flow component(S_t).

Then we are able to partition the water balance dynamically over time t as

$$\sum_t Ap_t = \sum_t (l_t + u_t) \quad \text{and} \quad \sum_t u_t = \sum_t (Q_t + S_t)$$

where

$$Q_t = a_q Q_{t-1} + b_q u_t \quad \text{and} \quad S_t = a_s S_{t-1} + b_s u_t$$

The transfer function parameters (a_q ,a_s ,b_q ,b_s) are estimated by an instrumental variable method which can, if desired, maximise the likelihood of streamflow given rainfall excess and streamflow data. The rainfall excess term u_t over the catchment is the output of the non-linear module wherein the single parameter is also optimised in the calibration procedure to maximise streamflow predictive performance. The loss term l_t over the catchment is the difference between streamflow and rainfall volume Ap_t , A being catchment area and p_t being precipitation at a point.

The DRCs can easily be calculated from the vector of transfer function parameters. The quick and slow time constants of the storages are

$\tau_q = -\Delta/\ln(a_q)$ and $\tau_s = -\Delta/\ln(a_s)$

with Δ the time series sampling interval. The relative volumetric throughputs are

$V_q = b_q/(1-a_q)V_T$ and $V_s = b_s/(1-a_s)V_T$

with $V_T = b_q/(1-a_q) + b_s/(1-a_s)$

The relative contributions of each component to the peak of the total unit hydrograph are

$I_q = b_q/I_T$ and $I_s = b_s/I_T$

with $I_T = b_q + b_s$

3. UNCERTAINTIES AND SCALE INDEPENDENCE OF MODEL STRUCTURE

The methodology used in [6] allows the calculation of indicative confidence intervals for the DRCs. The assumptions associated with the confidence interval estimation of the directly related transfer function parameters are discussed in [10]. The uncertainty of transfer function parameters is a function of the underlying response behaviour of a catchment, the nature of the rainfall (eg variance and persistence) and the level of model and data errors. They indicate the absolute minimum amount of data required to achieve a useful accuracy.

For most of about 25 catchments analysed to date, good predictive performance of streamflow can be achieved on an hourly to daily basis. As a general rule, small catchments of the order of 1 sq km require approximately hourly data while catchments of 10 to 1000 sq km require approximately daily data, although this will depend on individual response dynamics. Model residuals are zero mean, generally have acceptably small variance (with R-squared values concentrated about 0.8), and while they can be correlated to some extent with rainfall excess, they tend to show that model output and streamflow agree very closely during hydrograph recessions. This implies that most errors arise from the unrepresentativeness of precipitation or rainfall excess for the catchment.

Results associated with [11] indicate that good predictive performance can be obtained from much smaller catchments than the above range. Data from a 500 sq m catchment in China were analysed, at six minute intervals after the catchment had wetted up. Treating rainfall as rainfall excess allowed convincing separation into a quick and slow component. It is clear that the quality of the rainfall and, to a lesser extent, streamflow, time series data can limit the ability to identify the separation at low temporal and spatial scales. However, for most intended applications, where the daily time step and associated catchment size of 10 to 1000 sq km is relevant, current data quality seems to be adequate in a sufficiently large number of catchments to make analysis for DRC values worthwhile.

The fact that only two dominant, linear components can be extracted from such time series data but that they explain most of the structure in the hydrograph response can be viewed in a positive way. If catchment response can be well described by just four parameters in a linear module plus those in the rainfall- rainfall excess module (in our case with one parameter), then it should not be too difficult to examine statistically the dependence of these parameters on physical catchment descriptors. The predominant linearity of the model structure over a wide range of scales also potentially allows simple integration of the water balance of catchments into basins and basins into grid elements of global circulation models.

But this task must be preceded by an investigation of the sensitivity of modelled streamflow to meteorological variables other than rainfall, principally temperature, and an understanding of any possible dependence of estimated model parameters on the meteorological sequence of the calibration records.

4. ON THE INVARIANCE OF DRCs

A simulation study of the Sacramento model by Gan and Burges [12] found parameter estimates to be climate sequence dependent. The latter is likely to occur to varying degrees with any model of the precipitation-streamflow process because of the need for parameter calibration. The main objective should be to minimise the dependence by understanding and quantifying the structure of it. This can best be achieved by model parameter estimation over a large number of events which encapsulate a wide spectrum of response conditions. Representative catchment and climates types must therefore be selected where good quality (daily) records of sufficient length are available. Preliminary analysis suggests at least a decade of such data are needed for this purpose.

This task may yield an improved model or verify the adequacy of the existing one in [6]. Either way, records can then be analysed with the model to examine the detectable signal of meteorological variables other than rainfall in streamflow. For example, what is the lower level of change in seasonal temperature that yields a detectable difference in streamflow under the same rainfall conditions? In this study the period of historical record will need to contain a sufficient amount of climatic variability.

With the potential of long term climatic change, as opposed to climatic fluctuations, biotic regimes in particular are likely to evolve under such conditions. It may be possible to find catchments with adequate long term hydrologic and meteorological records where this has occurred. In these cases it should be possible to quantify how (much) a regime has to evolve before a change in DRCs and streamflow response can be detected.

5. SPATIAL EXTRAPOLATION OF THE DYNAMIC WATER BALANCE

It has been necessary to stress the need for an evaluation of the inherent uncertainties in calibrating DRC values due to random model and data errors and systematic errors from the nature of the climatic sequence in the record. The evaluation arising from analysis of long periods of record can be compared with the indicative uncertainties provided by parameter estimation of shorter term records, since only the latter will be available in some catchments. Once this has been achieved, it will be possible to begin exploring the relationship of DRCs to Physical Catchment Descriptors. PCDs summarise the distribution of physical factors such as elevation, shape, contributing area, soil type and depth and vegetation in catchments. Already, it has been shown in [13] that topographic characteristics strongly control the dynamic response of catchments. If useful relationships can be established, then extrapolations to other areas is feasible using geographic databases being developed in many countries on PCDs. Extensive extrapolations will require the coupling of dynamic models to a Geographic Information System.

The exercise should lead to improved understanding of the major determining factors in catchment response. A good start could be achieved by first isolating the effects of land use on hydrologic response. On a worldwide basis there is now a useful number of catchment studies with hydrologic records before and after an anthropogenic land use change to derive a much better understanding of the role of land use in hydrologic response. This isolation will require that the methodology used for determining DRCs yields sufficiently small variation in DRCs due to the nature of the climatic sequence used for parameter estimation.

6. WATER QUALITY AND HYDROCHEMICAL RESPONSE

Low flow periods are often critical to water quality assessment. In the USA, the 7-day, 10-year low flow is mandated in a water quality analysis aimed at determining adherence to a standard. At least to the extent that our separation yields impressive reproduction of low flows from meteorological inputs, the model can be used to indicate the susceptibility of a catchment to water quality problems under climate and land use changes.

Partitioning of water into quick flow and slow flow has important implications for inferring the hydrochemical response of catchments as well as the purely hydrologic response. Quick flow may be composed of varying amounts of pre-event water depending on the nature of the storm event and the antecedent conditions within the catchment (e.g. [4]). If our method is used to infer quick flow response and variation in the concentration of stable isotopes in the stream is used to infer the percent of pre-event water (e.g. [14]), then the degree of mixing within the subsurface reservoir can be calculated. Thus the amount of interaction between storm waters and the rocks and soils of a catchment could be inferred under a variety of conditions which might lead to improved quantification of the effect of precipitation events on streamwater quality. This scheme would work only if the assumptions underlying the method for hydrograph separation using isotopic ratios are reasonably met. Recent evidence casts some doubt on certain of these assumptions (e.g. [15]). It may be necessary to implement a multivariate refinement of the model presented in this paper. This would entail the estimation of a transfer function for rainfall to runoff and simultaneously the estimation of a transfer function from time-varying input isotopic ratios to the time-varying output isotopic ratios. If the parameters of the transfer function are time-variable (e.g. [16]), further refinements on the scheme may be required. Regardless, the results of our quick flow-slow flow separation undoubtedly contain important information about the hydrochemical response of catchments and, if the DRCs for the chemical response can be elicited, the program outlined here for water quantity could be extended to water quality as well.

7. CONCLUSIONS

An objective tool is now available to describe the hydrologic behaviour of catchments from streamflow, rainfall and other basic meteorological data. Additional information such as chemical and groundwater level measurements may also be used in conjunction with the methodology to improve this description. Strictly, the model is not physically-based which on the one hand limits immediate generalisation. However, it is proposed that statistical relationships be developed to relate quantified dynamic hydrologic characteristics to physical catchment descriptors. This is one way of overcoming the present parametric ambiguities in physically-based models and generating new knowledge about the physical controls on catchment response.

Appealing features of the model are its efficient parameterisation, structural simplicity, predominant linearity over a wide range of useful scales, and low computational demand in simulation and calibration modes. If it ultimately provides hydrologic characteristics that are reasonably insensitive to the climate sequence of the calibration period, then a new window of opportunity is open for such applications as investigating the effects of climate and land use changes on hydrologic response, extrapolating these water balance separations spatially and quantifying the feedbacks between hydrology and climate.

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