TRANSFERABILITY OF CONCEPTUAL MODEL PARAMETERS IN MOUNTAINOUS RAINFALL-DRIVEN CATCHMENTS

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Abstract

The IHACRES model has been widely shown to be successful in modelling rainfall-runoff processes in a variety of environments. The objective of this paper is to examine the utility of physical catchment descriptors (PCDs) to predict model parameters a priori. In this paper, we report results where calibrated model parameters from a variety of catchments in mountainous pluvial regimes are compared to basin area, drainage density and other attributes derived from digital elevations models. These results indicate that some model parameters are significantly correlated to PCDs. However, significant correlations between model parameters and PCDs may not provide good predictive power at ungauged locations. Further work is necessary to determine if the correlations prove useful for transferring the model to ungauged locations.

Introduction

Accurate estimation of streamflow is essential for engineering design and water resources management. In the case of ungauged basins such direct measurements of streamflow are never available and prediction in those basins requires alternative approaches. A major difficulty in predicting hydrology of ungauged basins is the fact that watershed response is uniquely governed by interactions of climate, topography, geology, and vegetation. One approach is to use information from models derived at gauged locations as a basis for such modelling based upon watershed attributes. Statistical relations between calibrated model parameters and watershed characteristics may capture information about the governing hydrologic processes and serve to develop a classification system useful for reducing predictive uncertainty at ungauged locations.

In this work we have chosen to use IHACRES to model pluvial watersheds in mountainous regions. IHACRES is a relatively simple form of model based upon excess precipitation (Jakeman et al., 1990, Littlewood and Jakeman, 1994; Littlewood et al., 1997). Despite the simple formulation IHACRES has been shown to be suitable in a wide range of rainfall-runoff catchments (Wagener and Wheater, 2002). Regionalization approaches to daily streamflow predictions using the IHACRES model have been previously reported (Kokkonen et al., 2003) for the Coweeta watershed and Sefton and Howarth (1998) for the United Kingdom. Kokkonen et al. (2003) considered 13 catchments within a 16 km^2 watershed, while we consider 31 watersheds ranging in size from 2.88 to 9500 km^2.

The objective of this paper is to explore transferability of model parameters between catchments, based upon catchment characteristics. The ultimate goal is to provide guidance to water resource practitioners to reduce predictive uncertainty at ungauged locations (Whitfield et al., 2006).

Methodology

IHACRES Model Description

A detailed description of the IHACRES model can be obtained from a number of sources (Jakeman et al., 1990; Kokkonen et al., 2003). The IHACRES model applies a transfer function/unit hydrograph approach to relate total rainfall to total discharge in two stages (Figure 1). In the first stage, a non-linear loss model computes the amount of rainfall which does not contribute to direct runoff (i.e., lost due to evapotranspiration or held in soil storage) through continuous update of an index representing catchment soil moisture. Rainfall excess is computed as a direct function of the soil moisture index and is routed to the catchment outlet via two parallel linear reservoirs representing quick and slow streamflow response. Table 1 summarizes the six parameters describing the IHACRES model.

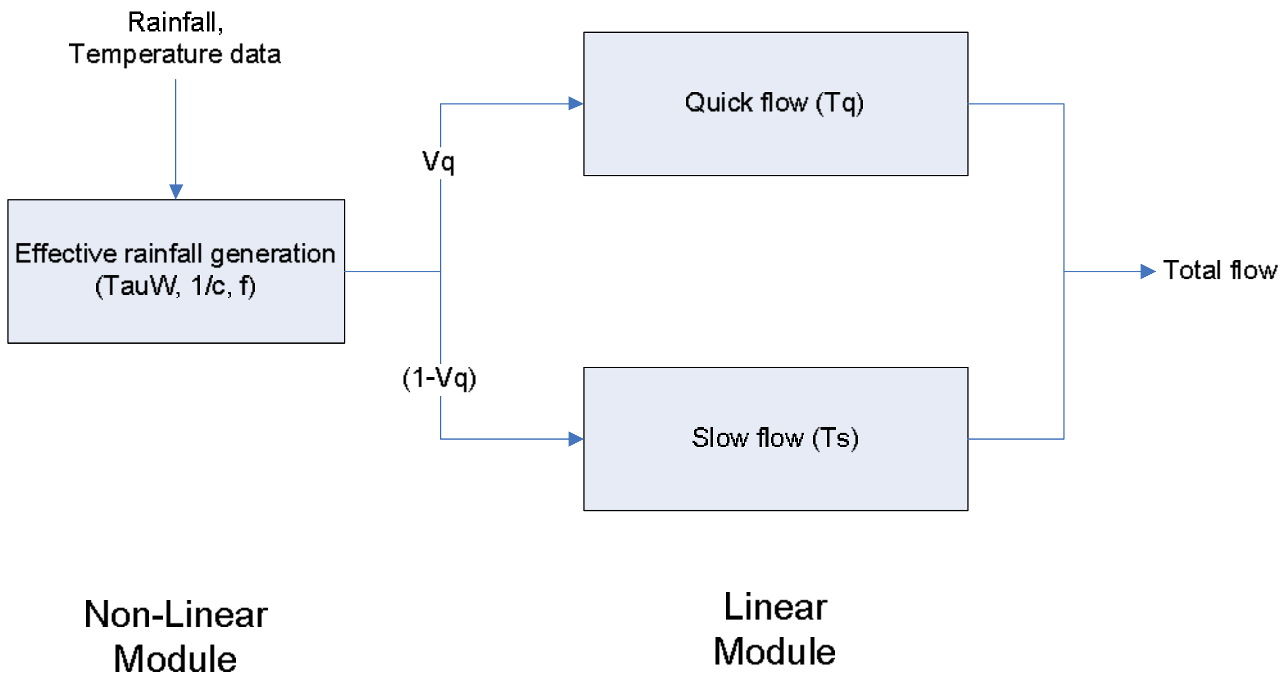

Figure 1. IHACRES model schematic (taken from Kokkonnen et al., 1993)

Table 1. Definition of IHACRES model parameters

Parameter	Description	Units
f	Temperature modulation factor	1/^{o}C
Vq	Proportion of effective rainfall which becomes quickflow	-
Ts	Quick flow reservoir time constant	days
Tq	Slow flow reservoir time constant	days
1/c	Catchment storage index/Volume-forcing constant	1/mm
TauW	Catchment drying time constant	days

Data Sources

Daily temperature and precipitation from nearby climate observing stations were used as input to the IHACRES model. Daily climate in the United States were derived from the United States Historical Climatology Network (USHCN, www.ncdc.gov/oa/climate/research/ushcn/daily.html). Streamflow gauges from the United States Geological Survey and Water Survey of Canada were selected on the basis of proximity (< 50 km radius) to nearby USHCN stations. A total of 31 watersheds were selected representing a range of scales from 2 – 9 500 km^2 (Figure 2).

Physical catchment descriptors were derived from available digital elevation models at a grid resolution of approximately 25 m (BC TRIM, USGS 1 arc second elevation model). We used an automated GIS procedure developed at the Dipartimento di Idraulica, Politecnico di Torino (Torino, Italy) to estimate basin attributes from digital elevation models [Viglione at al., 2006]. These attributes include estimated basin area, drainage density, average basin slope, average hillslope length, median basin elevation, length of main channel, and longest drainage path. We did not consider other relevant landscape-based catchment descriptors, such as percentage of open lakes or wetlands, in the present analysis.

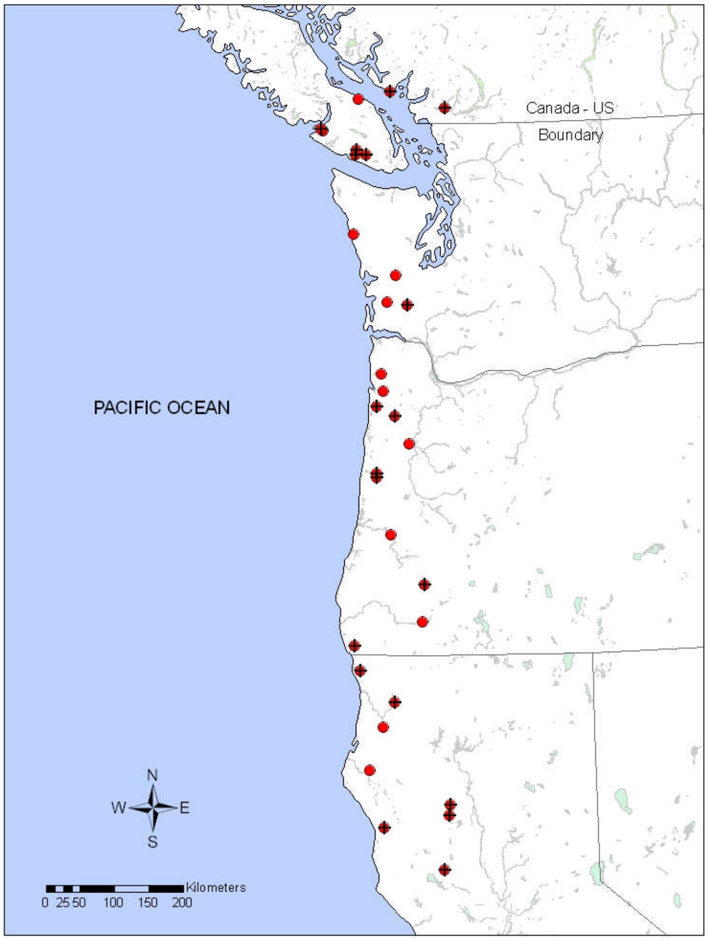

Figure 2. Locations of the 31 watersheds selected for model calibration in red circles. Stations marked with plus symbol ("+") indicate locations of successful model calibration and computation of physical catchment descriptors.

Model Calibration

In calibrating the IHACRES model, values for the catchment drying time constant (TauW) and the temperature modulation factor (f) governing the non-linear module were selected manually. Parameter values in the linear routing module and the parameter 1/c (catchment storage index/volume-forcing constant) in the non-linear module were calculated automatically by the program. The coefficient of determination (R^2) and a percentage 'average relative parameter error' (%ARPE) for the parameters in the linear module are program outputs. We used the criteria that a good model is one that has a high value for R^2 and a low value for %ARPE.

We calibrated the model using selected ranges for the parameters (TauW and f) in the non-linear loss module. In a single run of the program, R^2 and %ARPE are then tabulated by the program for each pair TauW-f to enable the operator to scan the results in search of the best pair. Ideally the maximum R^2 and the minimum for %ARPE would occur for a single pair; in practice the maximum R^2 and minimum %ARPE will define ranges of the catchment drying time constant and the temperature modulation factor. It is necessary, therefore, for the operator to make a subjective trade-off between a high R^2 and low %ARPE when selecting the optimal pair.

Results

Calibration of the IHACRES model was successful at 23 of the 31 watersheds selected for analysis. Resulting calibrations had an average coefficient of determination of 0.60, with a range from 0.45 to 0.80 (Figure 3). Lack of success in calibrating the model at the eight watersheds may be due lack of representativeness of climate input. The threshold criteria used for selecting hydrometric stations (i.e., within 50 km of a USHCN station) is likely too forgiving in mountain regions. Computational problems were encountered in processing DEMs to generate PCDs at four watersheds. Thus a total of 19 watersheds were used in the subsequent analysis (Figure 2).

Table 2 illustrates the correlation matrix between calibrated model parameters and PCDs. Significant correlations at the 5% level were found between several of the PCDs and IHACRES model parameters. Strongest correlations were found with the quickflow proportion (Vq), catchment storage index (1/c) and catchment drying constant (TauW). No significant correlations were found between the temperature modulation factor (f) and PCDs. Figure 4 illustrates correlations obtained between the quickflow proportion and PCDs. Correlations of model parameters with length of main channel, longest drainage path, and drainage area were very similar indicating that no ‘new’ information may be obtained from computing catchment descriptors beyond catchment area.

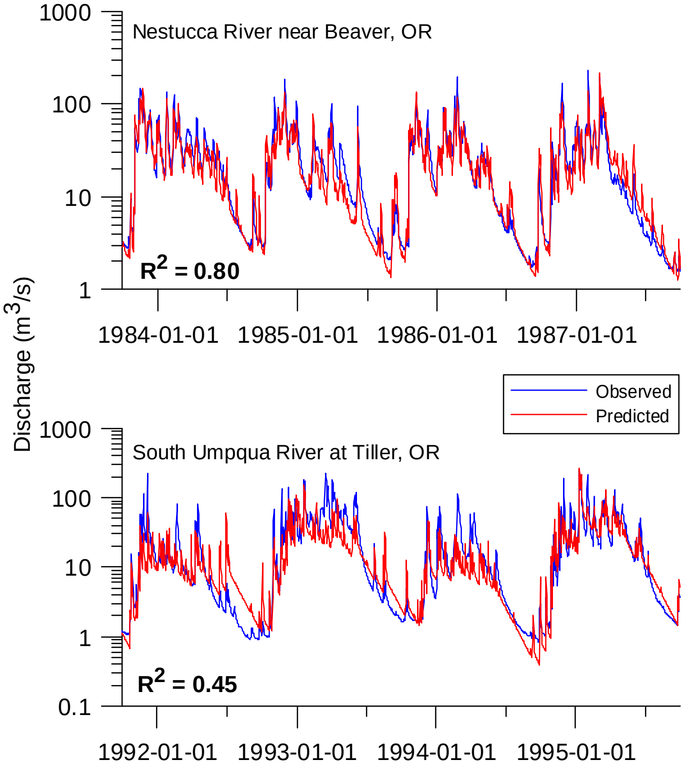

Figure 3. Example ‘best’ and ‘worst’ calibrations of the IHACRES model

Table 2. Correlation matrix for calibrated model parameters and physical catchment descriptors. Correlation coefficients significant at the 5% level are underlined.

PCD	**f**	**Vq**	**Ts**	**Tq**	**1/c**	**TauW**
Average basin slope	-0.02	0.17	-0.22	-0.30	0.23	0.05
Average hillslope length	0.45	<u>-0.63</u>	0.01	-0.05	0.19	0.43
Drainage area*	0.20	<u>-0.46</u>	-0.01	-0.31	<u>0.57</u>	<u>0.51</u>
Drainage density	-0.17	0.43	<u>0.58</u>	<u>0.51</u>	-0.39	<u>-0.60</u>
Length of main channel	0.17	<u>-0.46</u>	0.16	-0.22	<u>0.56</u>	<u>0.48</u>
Longest drainage path	0.18	<u>-0.47</u>	0.16	-0.23	<u>0.56</u>	<u>0.48</u>
Median basin elevation	0.42	-0.30	0.14	-0.13	0.15	<u>0.55</u>

***Correlation based on logarithm-transformed values of the PCD**

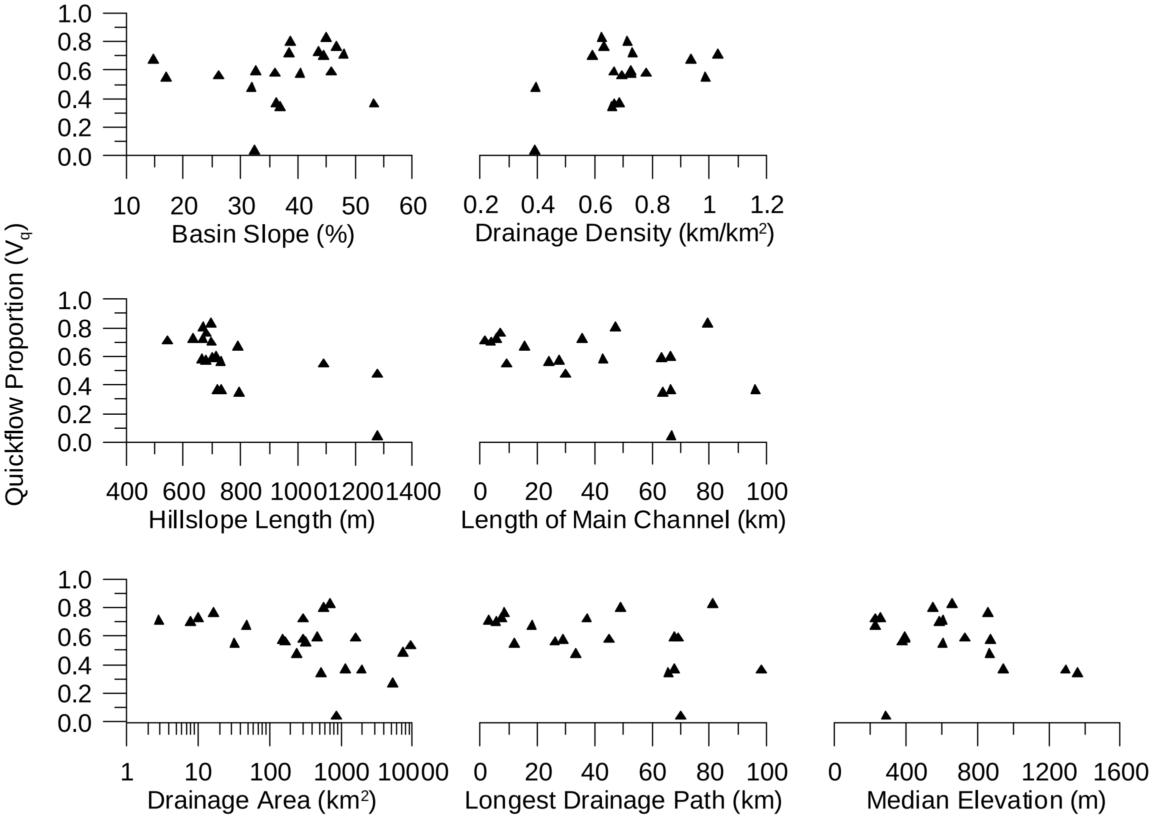

Figure 4. Relations between quickflow proportion (Vq) and physical catchment descriptors

Discussion

We have only considered a limited number of PCDs that are generally felt to be hydrologically relevant. Some of the chosen descriptors namely ‘length of main channel’ and ‘longest drainage path’ are redundant and provide essentially the same information as basin area. Our study neglected to include important landscape descriptors such as percentage of lakes, wetlands, forests, and surficial geology which can likely account some of the unexplained variance in relations.

The lack of an observed relation between PCDs and the temperature modulation factor (f) may be related to the seasonal variability in climate of these mountain/maritime regions. For example, there can be significant differences in seasonal temperature and precipitation lapse rates in mountain catchments of the Pacific Northwest. Observed climate records, typically representative of valley-bottom climates, may not be expected to represent the seasonal variability of basin-averaged temperature and precipitation assumed by the model.

The general lack of correlation between the PCDs and quick and slow reservoir coefficients may be related to the large spatial domain over which the IHACRES model was calibrated. The catchments incorporate both glacial (northern half) and non-glacial (southern half) surficial geologies which have different controls on runoff generation. In retrospect, we should have refined the sample size to glaciated catchments, to remain useful in the Canadian context. However, it would have been difficult to obtain an adequate sample size and remain within pure rainfall-runoff regimes as assumed by the IHACRES model. The significant positive correlation between drainage density and the quick and slow reservoir coefficients was unexpected. One would expect that increasing drainage density would reduce the reservoir time constants (i.e., quicker runoff response).

There may also be bias introduced into parameter values due to the choice of climate station to pair with the hydrometric station. The climate station may be an inappropriate distance away to assume it representative of basin climate conditions. An alternative would be to use either a reanalysis model approach or a regional climate model to derive basin-wide proxy climate records (Whitfield et al., 2002). Gridded daily climate products, such as DAYMET (Thornton et al., 1999), may provide better forcing inputs to hydrological models in complex terrain than individual climate stations.

Although the IHACRES model is parsimonious in structure, there are likely several alternative parameter sets which perform as nearly as well as the optimally-chosen parameter set. In retrospect, it would have been useful to plot these alternative parameter sets against the PCDs to explore the extent to which equifinality controls variability and trend in the observed relations.

Even with parsimonious hydrological models such as IHACRES, the spatial variability of climate may overwhelm parameter identifiability in mountain catchments. Even if regional parameter relations can be established, applying local climate (i.e., station) to predict hydrological response might produce incorrect results. Despite these shortcomings, at the scales we have considered there is evidence that basin attributes might be used to estimate the range of model parameters that might be applied in ungauged basins. At the very least, this range of parameters could serve as the basis for establishing estimates of streamflow with an expression of uncertainty obtained from a distribution of model parameters. However, high significance of correlation between values of PCDs and model parameters does not necessarily guarantee success in predicting parameters at ungauged locations (Kokkonen et al., 2003).

Conclusions and Recommendations

This study is presents preliminary results on transferability of IHACRES model parameters in mountainous pluvial catchments. While there is some indication of relationships between PCDs and model parameters, there is considerable variability and noise. Further work is necessary to test the strength of the observed relations against an independent set of catchments and include other hydrologically relevant catchment descriptors into the analysis.

References

Jakeman, A.J., I.G. Littlewood and P.G. Whitehead, 1990. Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. Journal of Hydrology, 117, 275-300.

Kokkonen, T.S., A.J. Jakeman, P.C. Young, and H.J. Koivusalo, 2003. Predicting daily flows in ungauged catchments: model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. Hydrological Processes 17(11), 2219-2238.

Littlewood, I.G. and A.J. Jakeman, 1994. A new method of rainfall - runoff modelling and its applications in catchment hydrology. In: P. Zannetti (ed.) Environmental Modeling (Volume II), Computational Mechanics Publications, Southampton, UK, 143-171.

Littlewood, I.G., K. Down, J.R. Parker and D.A. Post, 1997. The PC version of IHACRES for catchment-scale rainfall-streamflow modelling: User Guide. Institute of Hydrology, Wallingford, UK.

Sefton, C.E.F., and S.M. Howarth, 1998. Relationships between dynamic response characteristics and physical descriptors of catchments in England and Wales. J. Hydrol., 211, 1-16.

Thornton, P.E., S.W. Running, and M.A. White, 1997. Generating surfaces of daily meteorology variables over large regions of complex terrain. J. Hydrol. 190, 214-251.

Viglione, A., P. Claps, and F. Laio, 2006. Mean Annual Runoff Estimation in North-Western Italy, In: G. La Loggia (ed.) Water resources assessment and management under water scarcity scenarios, CDSU Publ. Milano, Italy.

Wagener, T and H.S. Wheater, 2002. On the evaluation of conceptual rainfall-runoff models using multiple objectives and dynamic identifiability analysis. In: I.G. Littlewood (ed), Continuous river flow simulation: methods, applications and uncertainties. British Hydrological Society Occasional Paper No. 13, 45-51.

Whitfield, P.H., C.J. Reynolds, and A.J. Cannon, 2002. Modelling streamflows in present and future climates -- Examples from Georgia Basin, British Columbia. Canadian Water Resources Journal, 27(4), 427-456.

Whitfield, P.H., J. Cathcart, S. Hamilton, J. Heinonen, D. Hutchinson, J.G. Lang, C. Spence, and R. White, 2006. Hydrology for the Orographically Challenged - A Commentary from the Workshop on Predictions in Ungauged Basins (PUB) in Mountainous Regions. Canadian Water Resources Journal, 31(2), iii-v.