Parameterisation of a statistical hydrology model for impact assessment of land-use change

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Abstract A comparison was made between a lumped catchment application of the statistical VIC hydrology model and a version of the same model applied separately to different land uses. The 1260 km^2 Williams River Catchment in the lower Hunter Valley, NSW, was divided into three uniform climatic regions, and each of these was further subdivided by land cover classification using Landsat images. The VIC model was calibrated separately to each land cover using both single and multiple streamflow records. The final hydrographs were compared to those obtained using the model on the catchment as a whole. It was found that internal streamflow predictions using the land cover parameterisation gave goodness-of-fit statistics that are better than the lumped catchment approach. The land class dependent parameter values were found consistent with the physical variations in the hydrological regime expected in the region. Relating the parameter values to land cover characteristics provides a method of investigating land use changes and allows the model to be more easily transferred to other catchments.

1. INTRODUCTION

Regional-scale catchments are important integrators of the effects of many forces, including land use and climate. Their natural boundaries and hierarchical structure represent an appropriate structure for hydrological analysis and modelling. Such catchments however often display substantial heterogeneity both in terms of land surface characteristics and meteorological conditions. Adequately capturing this spatial heterogeneity has long been considered as a prerequisite for improving water and energy flux predictions.

Limited spatial input data and computational constraints often result in the modelling of regional-scale catchments with conceptual lumping or averaging of process descriptions, forcing inputs, state conditions and land surface properties (see for example Chiew et al. 1993). Such models may reproduce the dynamics of the total catchment hydrograph well, but as a consequence of the averaging, the physical soundness of the process description is lost and model parameters behave only as 'tuning variables'. This has important implications in forecasting change in hydrological behaviour for periods outside the calibration conditions (e.g. due to land use or climate change).

To overcome the problems associated with the lumped catchment approach, spatially distributed hydrologic models have been developed that adopt a grid-cell arrangement to represent a catchment structure (e.g. Wigmosta et al. 1994). With such a cell-based approach, each grid cell is associated with individual forcing inputs, state conditions and land surface properties. Although such cell-based representations are able to explicitly account for the spatial variability of catchment process characteristics, the computation time and data demands are inconsistent with regional-scale applications.

A compromise between the lumped and cell based methods is the mosaic-modelling approach. With this approach land surfaces with high contrast in hydrological behaviour, such as wet-dry, bare-vegetated, non-forested-forested, plains-hillslopes, are subdivided into land surface units of equal or similar 'hydrotopes', and are modelled separately. The different hydrotypes need not be contiguous, meaning that the real distribution of individual hydrotypes within the catchment and their interaction with neighbouring hydrotypes (e.g. advection effects etc.) are neglected. Concerns have been raised however that the hydrotype aggregation method sidesteps the question of scale by ignoring the natural heterogeneity of processes/response *within* the individual hydrotypes (Band and Moore 1995). Recent research (e.g. Entekhabi and Eagleson 1989; Wood et al. 1992) however has demonstrated that this so called 'intra-patch' variability is more or less random in its distribution and can be efficiently modelled using a 'statistical-dynamical' approach. With this approach vegetation and land surface characteristics vary according to distributions that can be approximated by analytical functions, or probability density functions.

In this paper the 'statistical-dynamical' VIC hydrologic model (Wood et al. 1992) is used to investigate how streamflow predictions can be improved by computing the rainfall-runoff processes separately for different land cover classes within uniform climatic regions (where a class consists of an area of hydrologically significant land cover that may or may not be contiguous). The study aims to demonstrate how a simple statistical model, with a limited number of parameters, can be calibrated to the physical catchment, to provide meaningful parameterisations for unique land cover classes.

2. STUDY REGION

2.1 Williams River Catchment

The region investigated in this study is the 1260 km^2 Williams River catchment, located in the lower Hunter Valley Region, N.S.W. (Figure 1).

For the present study the catchment was subdivided into four main subcatchments on the basis of the river gauge network (Figure 1). The Tilligra and Chichester Dam subcatchments are characterised predominately by steep vegetated slopes, rising to 1500 m (m.s.l.) in the Barrington Tops. The lower subcatchments draining to Glen Martin and Seaham Weir on the other hand are characterised by undulating and rolling hills, with the majority of the vegetation cleared for cattle grazing.

Orographic enhancement results in the highest rainfall totals occurring in the northern Barrington range with annual rainfall totals of approximately 1600 mm. The lowest annual rainfall occurs over the central part of the catchment. Further south, maritime influences reverse the rainfall gradient and annual rainfall increases to approximately 1100 mm at Seaham.

2.2 Data Sources

Daily-accumulated rainfall records for the period 1966-1995 were available from 28 recording gauges within the catchment. For the corresponding period climatic information was available from four stations, that enabled estimation of potential evaporation using the Penman-Monteith equation (Smith et al. 1990). Streamflow measurements were available at three locations within the catchment. The Tilligra and Glen Martin sub-catchments contained daily flow gauge estimates. The Chichester Dam subcatchment despite not having a flow gauge could be estimated by undertaking a water balance on daily inflows, outflows and reservoir levels

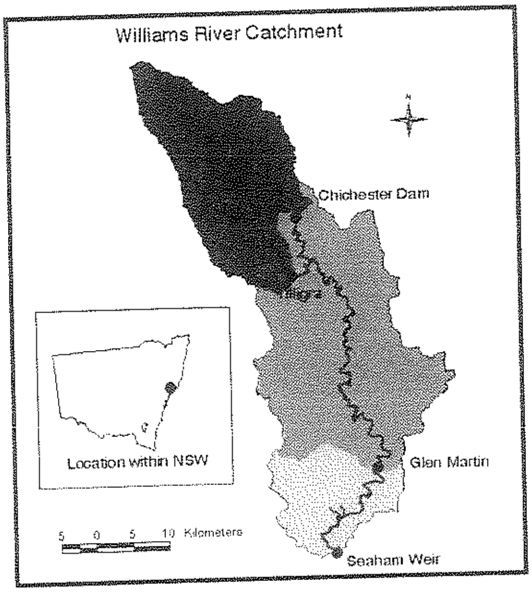


Figure 1. Williams River Catchment showing the four main subcatchments

3. VIC MODEL

The VIC (Variable Infiltration Capacity) model of Wood et al. (1992) is a quasi-distributed hydrologic model that utilises a statistical distribution of storage capacities across the catchment to characterise the spatial variation in soil moisture storage. It assumes that storage capacities and therefore runoff generation and evaporation will vary with topography, soils and vegetation. To account for this natural variation, the scaled storage capacity, s, defined as the maximum amount of water that can be stored in the soil column, is a random variable with cumulative distribution:

$$F_s(s) = 1 - [(1-s)/(1-s_{\min})]^{\beta} \qquad (1)$$

where s_{min} is the minimum scaled storage for overland flow, and β is an empirical parameter. Kalma et al. (1995) specified all the functional relationships between a scaled storage level v (equals s at saturation), the catchment average storage level w, and the fraction of saturated area α. The model assumes that any rain falling on the saturated area generates surface runoff immediately (within the model time step), while the remaining rainfall infiltrates and fills some of the available storage under the s curve.

Evaporation in the VIC model is calculated with a point-scale model of evaporation following Sivapalan and Woods (1995), in which the ratio of actual to potential evapotranspiration is computed with a distribution function of the same form as the storage capacity. Baseflow is a linear function of the scaled total soil-water storage, w.

4. GIS / MODEL INTEGRATION

4.1 Catchment Delineation

The catchment boundaries and channel network were delineated from a 100 m depressionless DEM (Krause et al. 1997) for the region using ARC/INFO GIS hydrologic modelling functions.

4.2 Uniform Climatic Zones

To account for spatial gradients in model inputs a catchment-disaggregation strategy based on climatic regions was adopted. The strategy involved subdividing the catchment into uniform climatic zones for which within-zone variability of daily rainfall and potential evaporation was negligible compared to the variability that exists between neigbouring climatic zones

Thin plate smoothing splines (Hutchinson 1995) based on annual records were utilised to define 3 rainfall zones in which spatial variability of daily rainfall measurements was substantially reduced. Within each rainfall zone, daily rainfall totals were calculated as the areal average of stations falling within each zone. It was initially proposed to further subdivide the three rainfall regions, into sub-zones of uniform rainfall and potential evaporation combinations. Investigation of monthly estimates of average daily potential evaporation (Wooldridge and Kalma 1999) indicated only minor spatial variation within the rainfall regions. Potential evaporation inputs were therefore based on nearest station information, and assumed uniform within the rainfall zones.

4.3 Land Cover Classes

Within the ARC/INFO GIS framework a detailed land cover datalayer obtained from Landsat multispectral scanner (MSS) data was classified into 100 m pixels of forested and non-forested areas (Figure 2). The non-forested areas consisted mainly of grassland, however there were isolated areas devoted to cropping, urban settlement and mining.

4.4 Modelled Units

The combined climatic/land-use disaggregation required that VIC water balance calculations be undertaken concurrently for 6 possible scenarios. To facilitate this, it was necessary to determine the fractional coverage of each land cover within each rain zone. Because variations in rainfall input result in different soil moisture status, it was also necessary to account for variations in antecedent moisture conditions within each land-cover class at the start of each model run.

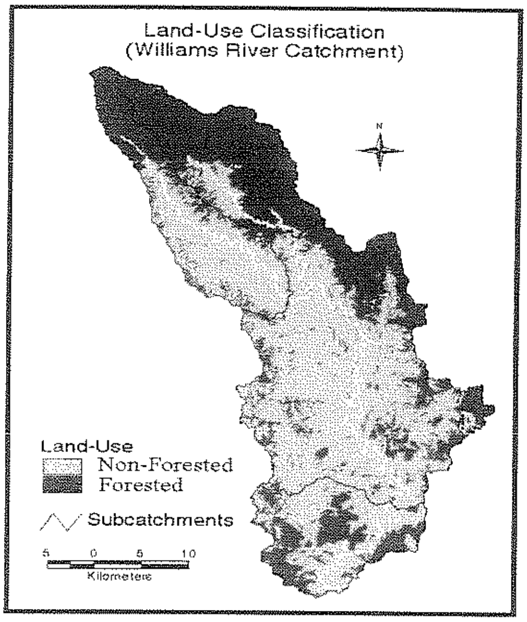


Figure 2. Land-use classification

5. VIC SIMULATIONS

5.1 Model parameters

The VIC model conceptualisation results in 4 key parameters that need to be calibrated. The parameters β and s_{min} control the effective catchment storage capacity by influencing the shape of the storage distribution curve, and thus most notably affect the high and low flow peaks respectively. The evaporation parameter (η) and baseflow coefficient (k_c) both affect the removal of water from storage, with subsequent effects on moisture levels and saturated areas.

For the present application the optimised value of k_c was shown to be relatively insensitive to the chosen disaggregation scheme. The optimisd value of 0.005 obtained for the lumped catchment represenation was therefore fixed globally for the various subareas. The value is typical of large rivers (Stamm et al. 1994).

Investigation of limited soil data (Soil Conservation Service 1995), suggested values of D_{max} = 1.5 m and $\Delta\theta$ = 0.35 for the conceptual maximum soil depth and effective porosity respectively. Without further information both parameters were set prior to calibration and were assumed spatially uniform.

Other parameters that were set prior to calibration included the initial soil water storage (W_{init} = 0.0) and the height of the capillary fringe (ψ_c) divided by D_{max} (0.005). A constrained value of ψ_c could not be achieved by calibration due to strong correlation with η, suggesting that the current evaporation routine is ill-posed with respect to streamflow data.

5.2 Optimisation of parameters using NLFIT

The β, s_{min}, and η parameters for each land cover class were optimised using the interactive optimisation package NLFIT (Kuczera 1987). NLFIT employs the shuffled complex evolution search algorithm of Duan et al. (1994).

Because the nature of the present work involved identifying parameter variations for different catchment dissagregation strategies, it was chosen to utilise the entire thirty-year streamflow record for parameter inference. The optimisation strategy was to run the model at a daily time step and aggregate the output to *monthly* totals, thus eliminating timing issues associated with the passage of runoff to the subcatchment outlets. To test the sensitivity of the model parameters to the chosen time-step a *weekly* streamflow optimisation strategy was also adopted.

The output summary from NLFIT provides information on the mean and standard deviation of fitted parameters. These two measures can be used to determine the coefficient of variation, CV. The CV indicates the precision of determination of a parameter; the lower the CV, the more precise the value determined by the optimisation. As a guide, a CV value of 0.25 or less indicates 'sensitive' parameters (Mein and Brown 1978).

6. MODELLING STATISTICS

6.1 Single Streamflow Conditioning

As a basis of comparison, the VIC model was first applied to the Williams River Catchment above Glen Martin using one land cover for the entire catchment. The semi-distributed version of the model was then applied in parallel for the forested and non-forested areas. The semi-distributed version results in parameter estimates for both the forested and non-forested areas, and hence the predicted runoff volumes from each land cover needed to be added together to represent the total outflow.

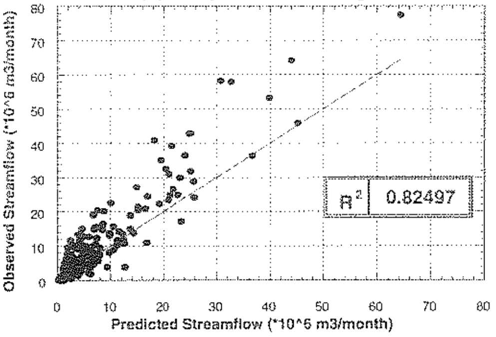
The optimised parameter combinations along with associated CVs for both the lumped and the semi-distributed models based on the single outlet optimisation are shown in Table 1. The lower CVs for the lumped version of the model highlights that the optimised parameters are more constrained from the calibration record than the semi-distributed version. Comparison to the internal streamflow record at Tilligra (Figure 3) however reveals that the semi-distributed version has much better distributed predictions. A similar result was found for the Chichester subcatchment (Lumped R^2=61%, Semi-distributed R^2=80%). The superior predictive ability of the semi-distributed model is likely to be a combination of improved rainfall inputs as well as a more 'physically' realistic parameterisation, with the correct processes being modelled, rather than the model parameters just being 'tuned' to the outflow response. The relatively high CVs associated with the semi-distributed parameterisation however suggests that the different runoff 'signals' from the forested and non-forested areas are only weakly distinguishable from a single integrated streamflow record.

Table 1. Parameter set obtained by NLFIT for single streamflow conditioning.

Par.	Lumped Model		Semi-distributed Model			
			Forest		Non-Forest	
	Ave.	CV	Ave.	CV	Ave.	CV
β	5.65	0.14	3.20	0.67	5.10	0.54
s_{min}	0.17	0.13	0.31	0.25	0.12	0.17
η	1.28	0.10	2.20	0.32	0.64	0.41

The parameterisations associated with the forested and non-forested regions may be explained in terms of the physical processes deemed active in the Williams River catchment. The larger value of s_{min} and smaller value of β for the forested regions compared to the non-forested regions confirm that the forested areas

(a) Lumped Model - Tilligra



(b) Semi-distributed Model - Tilligra

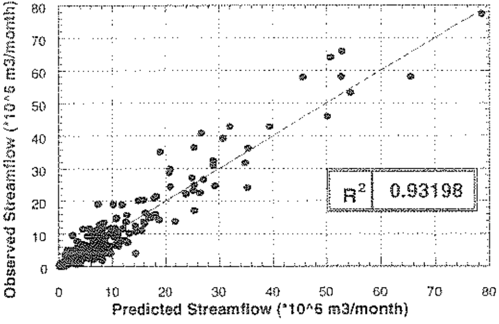


Figure 3. Internal streamflow comparison (1966-1996) at Tilligra for the (a) Lumped and (b) Semi-distributed model.

have larger water storage, and produce a much less 'peaky' runoff response, with less surface runoff and more subsurface flow. The smaller value of s_{min} and larger value of β for the non-forested areas are linked with less water storage and a more 'all-or-nothing' response to runoff, with dynamic formation and depletion of zones of saturation. The relative values of the evaporation parameter, η also suggest that when the catchment is wet, greater evaporation will occur from the non-forested surfaces, whereas the forested surfaces will start to dominate as the catchment dries out. The simplicity of the evaporation routine makes it difficult to draw conclusions about the exact nature of the evaporation variation (e.g. canopy effects etc.). The addition of a more physically based yet parsimonious evaporation routine is the subject of on-going research.

6.2 Multiple Streamflow Conditioning

In an effort to constrain the VIC parameter estimates resulting from the land-use classification it was decided to utilise the two internal streamflow estimates (Tilligra and Chichester) along with the Glen Martin outlet record to provide multiple conditioning of optimised parameters. The parameter values along with their associated CV resulting from the multiple conditioning to *monthly* streamflow are displayed in Table 2(a). The lower CV associated with the multiple conditioned parameters compared to those resulting from single conditioning to the outlet record (Table 1), highlights that the two internal streamflow records have provided additional information that allow the expected value of the parameters to be constrained. The more constrained parameters are not likely to have resulted simply because more gauges were utilised, but rather because the information content within each streamflow record is unique due to the fact that the contributing area for each streamflow gauge contains different percentages of forested and non-forested surfaces.

The parameter values resulting from the multiple streamflow calibration, while presumably being more 'realistic', show the same trends as exhibited by the estimates obtained from the single streamflow calibration. The result confirms the physical reasoning given to the parameters above.

Table 2. Parameter set obtained by NLFIT for (a) multiple *monthly*, and (b) multiple *weekly* streamflow conditioning.

Par	Forest		Non-Forest	
	Ave.	CV	Ave.	CV
(a) Multiple *Monthly* Streamflow Conditioning				
β	2.04	0.14	3.32	0.12
s_{min}	0.26	0.16	0.11	0.12
η	1.61	0.10	0.22	0.19
(b) Multiple *Weekly* Streamflow Conditioning				
β	2.07	0.07	4.60	0.06
s_{min}	0.29	0.06	0.13	0.05
η	1.77	0.07	0.44	0.08

6.3 Time-Step for Parameter Conditioning

To test the sensitivity of the forested and non-forested parameterisations to the time period utilised for calibration, the semi-distributed version of the VIC model was again calibrated to multiple streamflow records, but this time the objective function was chosen to minimise the difference between observed and predicted *weekly* streamflow. The parameter values along with their associated CV resulting from the *weekly* conditioning to multiple streamflow records are displayed in Table 2(b). The parameter values resulting from the monthly and weekly conditioning are comparable, but the parameter CVs for the weekly conditioning are far superior, with parameters having around half the variation of monthly conditioned estimates. The reason that the parameter estimates are more constrained for weekly conditioning results from timing considerations. For example if a calibration month was to have a series of storm events, by conditioning to monthly streamflow no information can be inferred regarding the speed of response. Presumably the same monthly volume could be predicted from a high volume, quick recession response as from a low volume, slow recession response. The time-step chosen on which to condition parameters obviously has greater significance in constraining parameters that affect the timing of runoff (e.g. β and s_{min}) rather than parameters that simply affect volumes such as η.

The similarity of parameter values for both the weekly and monthly conditioning is a somewhat pleasing result. It is obviously aided by the fact that the model is forced with daily data, ensuring that the predicted responses are kept on track. It would also seem reasonable to conclude that the temporal variability of rainfall within the Williams River catchment is such that the majority of storm events within a month are likely to occur over the period of a single week. It is expected that the parameter values at the daily time step would show more variability.

7. CONCLUSIONS AND FUTURE WORK

In this paper it has been demonstrated that the simple statistical VIC model is capable of reproducing the dynamics of the Williams River catchment hydrograph well. A more robust calibration of the controlling parameters was obtained when the model was applied successively to different land uses within the catchment, as compared to the lumped catchment representation. The parameters derived for the separate land-use classes were shown to initiate processes that are deemed active in the Williams River catchment. Utilisation of innovative optimisation strategies allowed the determination of unique parameter sets for randomly distributed forested and non-forested areas. The need for gauged catchments that consist of just one hydrologically homogeneous land cover for the purpose of calibration was eliminated. It was shown however that a more constrained parameterisation was achieved when the informative content of multiple streamflow records, consisting of different percentages of forested and non-forested contributing areas, was utilised to condition the model. Results showing improved parameterisation of the model when conditioning to shorter streamflow periods also highlight that the true nature of parameters controlling the timing of runoff events can only be realised from event based calibration

The results of this study are encouraging in that a simple statistical model, with a limited number of parameters, when calibrated to the physical catchment, has been able to provide meaningful parameterisations for both forested and non-forested regions. The knowledge gained is particularly useful for model transfer to ungauged catchments wherein observed data for calibration are not available, but for which spatial land surface information is known. The modelling framework also enables investigation of *what if* questions concerned with changes in land use (such as deforestation or urbanisation) and climatic variables.

From the present investigation it has been shown that within the Williams River catchment a land classification based on forested and non-forested regions can act as a surrogate for a number of climatic and physiographic variables. Ongoing research within the catchment aims at identifying other physical characteristics that can be identified from the streamflow record that significantly contribute to runoff variability, and hence warrant classification in the hydrotype-disaggregation process.

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