Regionalising the hydrologic response of ungauged catchments using the SIMHYD, IHACRES, and Sacramento rainfall-runoff models

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EXTENDED ABSTRACT:

The SIMHYD, IHACRES, and Sacramento rainfall-runoff models were applied to six gauged catchments of the Campaspe River Basin in Victoria, Australia. Good calibration results were achieved for all three models in all six catchments.

These calibrated models were then evaluated in terms of their ability to predict the daily streamflow of the other five catchments in the basin through regionalisation (treating them as if they were ungauged). Two regionalisation procedures were used – firstly the models from the nearest catchment were used, and secondly the catchments were assessed in terms of their similarity and the models from the most similar catchment were used. Results from the 'best' regionalised model for each catchment were also compared to the models from the nearest and most similar catchments. The results of these model simulations are shown in Table 1.

For four of the six catchments, the nearest catchment was also the most similar. This made it difficult to determine whether the similarity index was a better regionalisation tool than simply applying the model from the nearest catchment. The fact that proximity is a good measure of similarity is not surprising since climate and physical characteristics are likely to be similar in neighbouring catchments.

For three of the six catchments, the nearest (and also most similar catchment) gave the best regionalisation result compared to using a regionalised model from any of the other four catchments.

Models from both the nearest and most similar catchments performed very well when applied to the ungauged catchments in five out of the six occasions. The only catchment for which either approach failed was 406250 which is the smallest, wettest, and highest elevation catchment. We hypothesise that a combination of these attributes makes it difficult to regionalise the hydrologic response from the other catchments to it.

While these regionalisation results seem promising at first, it must be remembered that these six catchments are very similar and as a result, many (although not all) of the calibrated models do a reasonable job of predicting the hydrologic response of the other catchments. Despite this, the quality of the calibrated rainfall-runoff models was the most important factor influencing the quality of the regionalised results. By comparison, the quality of the regionalised results was relatively insensitive to the regionalisation technique used.

This pilot study carried out on six catchments of the Campaspe River Basin has proven to be too small to determine whether a similarity index is more useful than a nearest neighbour approach in regionalising hydrologic response. A larger study encompassing more catchments is required for this task. The results of an extended study should provide an indication as to whether a similarity index is more useful than a nearest neighbour approach to regionalisation, as well as what similarity index is best suited for this task.

Table 1: Results of the regionalisation of daily streamflow from the nearest, most similar and best performing catchment models to each of the six 'ungauged' catchments. Numbers in brackets are the *E* values of the regionalised streamflow from the SIMHYD, IHACRES and Sacramento rainfall-runoff models respectively

Catchment	*Nearest*	*Most similar*	*Best result*
406213	406235 (.71,.74,.76)	406235 (.71,.74,.76)	406226 (.77,.77,.81)
406214	406224 (.72,.64,.68)	406226 (.67,.72,.75)	406235 (.74,.75,.81)
406224	406214 (.43,.58,.60)	406214 (.43,.58,.60)	406214 (.43,.58,.60)
406226	406235 (.68,.70,.73)	406235 (.68,.70,.73)	406235 (.68,.70,.73)
406235	406226 (.66,.68,.72)	406226 (.66,.68,.72)	406226 (.66,.68,.72)
406250	406213 (.38,-.17,.57)	406226 (.19,-.18,.50)	406235 (-.12,-.63,.8)

1. INTRODUCTION

1.1. The Campaspe Basin

The Campaspe is a 3,900 km^2 drainage basin located in Victoria, Australia (AWRC Basin #406). It drains to the Murray River and is within the Murray-Darling Basin which is an important irrigation and agricultural region in south-eastern Australia.

Mean annual precipitation in the Campaspe ranges from 430 mm in the north to 1,050 mm in the south. Rainfall for the entire basin was derived from ~ 5x5 km SILO data (www.nrm.qld.gov.au/silo) over the entire catchment.

Within the Campaspe there are six gauged catchments suitable for rainfall-runoff model calibration. The stations have at least 10 years of runoff data, and are largely unimpacted by irrigation and other water diversions. Selected attributes of these catchments are given in Table 2 and their locations are shown in Figure 1.

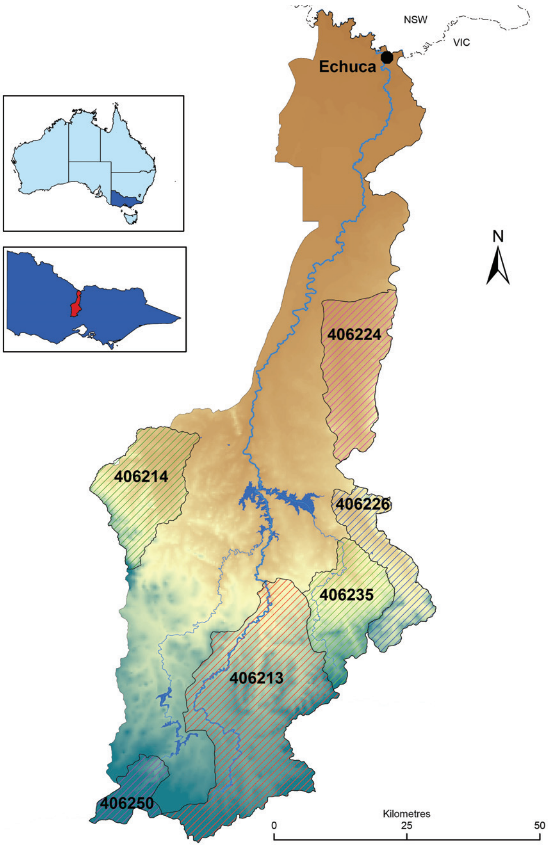

Figure 1: Calibration catchments in the Campaspe.

The aim of this study is to estimate discharge across the entire Campaspe catchment. To do this, rainfall-runoff models need to be calibrated on the gauged catchments and then regionalised to the remainder of the catchment in some way. The only way to test the adequacy of these regionalised models is through comparison with observed streamflow. As a result, this paper will focus on the regionalisation of hydrologic response from one gauged catchment to another, treating it as if it were ungauged. The models used to do this and the regionalisation procedures employed are presented in Sections 1.2 and 1.3.

1.2. The Rainfall-Runoff Models

Three rainfall-runoff models were chosen for use in this comparison. They are the SIMHYD, IHACRES and Sacramento rainfall-runoff models. These models have all been applied in numerous studies both within Australia and internationally (Boughton, 2005). They have also all been used in regionalisation studies with various degrees of success. See for example Chiew and Siriwardena, 1995 (SIMHYD); Post and Jakeman, 1999 (IHACRES); and Gan and Burges, 2006 (Sacramento). The models are described briefly in the following sections, focussing on a description of the model parameters. For more detailed model descriptions, the reader is referred to appropriate publications in the text.

SIMHYD

SIMHYD is a relatively simple, lumped conceptual rainfall-runoff model (Chiew and Siriwardena, 2006). The model structure is shown in Figure 2. For the purposes of the current study the seven parameter model shown in Figure 2 has been simplified to a five parameter model by setting the value of COEFF to 150 mm and SQ to 2 across all catchments.

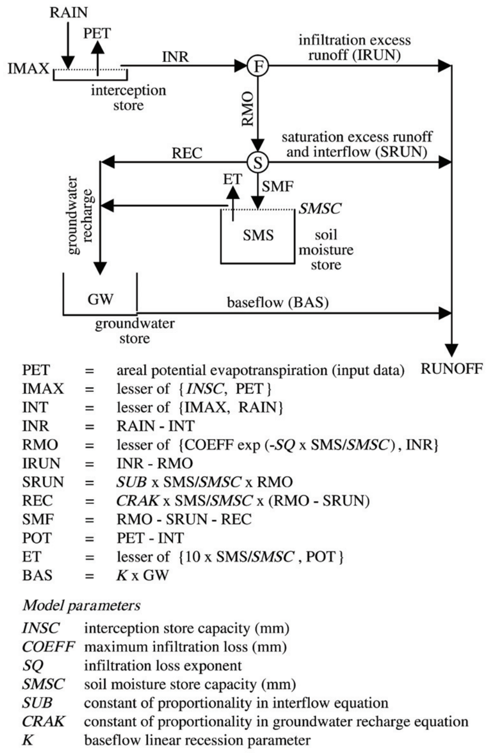

Figure 2: Structure of the SIMHYD model (from Jones et al., 2006).

IHACRES

IHACRES is also a relatively simple, lumped conceptual rainfall-runoff model (Jakeman and Hornberger, 1993). The model structure is shown in Figure 3.

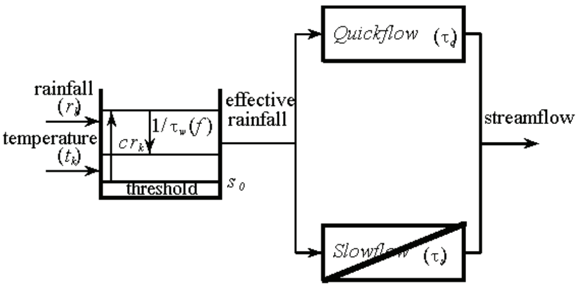

Figure 3: Structure of the IHACRES model (from Post, 2007).

The IHACRES model typically has two linear stores representing quickflow and slowflow. However, in the relatively flashy catchments of the Campaspe, the slowflow store was difficult to identify and thus removed from the model structure as shown in Figure 3. As a result, the model used in the current study can be fully defined by five parameters:

c is a mass balance parameter and therefore defines catchment water yield;
τ is the streamflow recession time constant;
τ_w is the rate of catchment drying;
f varies the rate of catchment drying based on temperature;
s_0 is the catchment wetness index below which no runoff will occur.

Sacramento

Sacramento is also a lumped conceptual rainfall-runoff model (Burnash, 1975), but it has considerably more complexity than SIMHYD and IHACRES. The model structure is shown in Figure 4. The version of Sacramento used in this study has 13 parameters as follows:

ADIMP is the impervious fraction of the catchment;
LZFPM is the free water capacity of the slower draining lower store (mm);
LZSFM is the free water capacity of the faster draining lower store (mm);
LZPK is the drainage rate from the slower draining lower store;
LZSK is the drainage rate from the faster draining lower store;
LZTWM is the tension water storage capacity of the lower store (mm);
PFREE is the proportion of percolated water transferred to the lower store;
REXP is the exponent in the percolation equation;
SARVA is the fraction of the catchment covered by water and riparian vegetation;
UZFWM is the free water capacity of the upper store (mm);
UZK is the lateral drainage rate from the upper store;
UZTWM is the tension water storage capacity of the upper store (mm);
ZPERC is the maximum percolation rate coefficient.

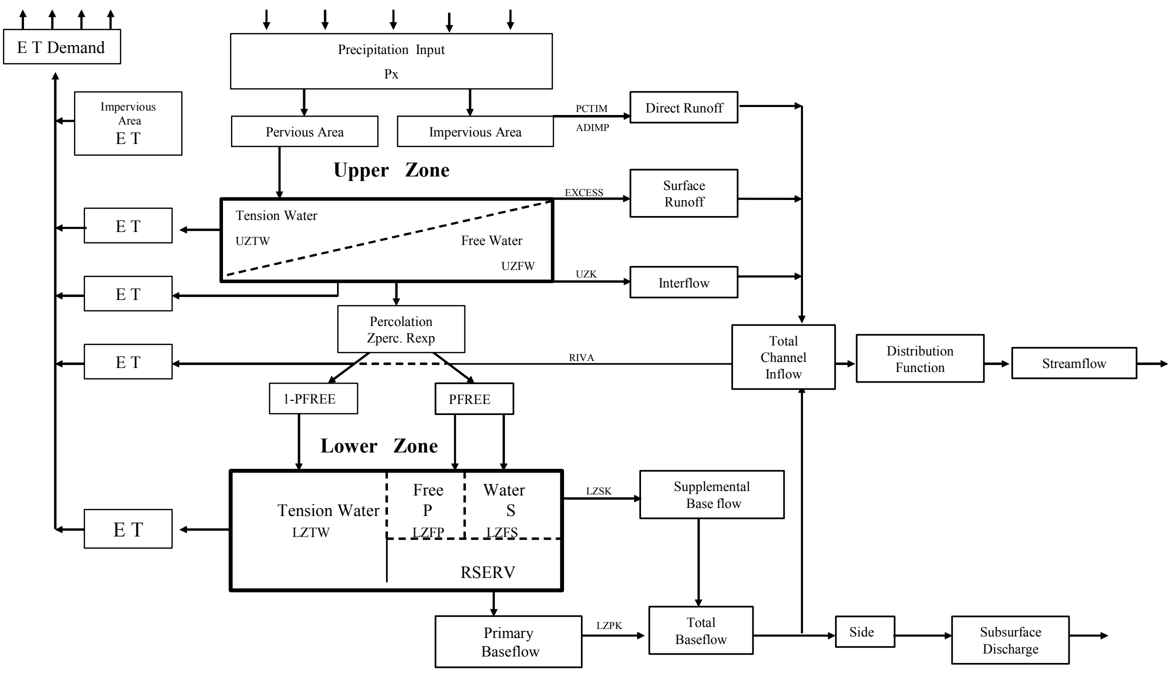

Figure 4: Structure of the Sacramento model

1.3. Regionalisation Approaches

Two different regionalisation approaches to predict the hydrologic response of ungauged catchments were assessed in this study. Firstly, model parameters from the nearest calibration catchment were applied to the ungauged catchment. Secondly, a measure of catchment similarity was developed and model parameters from the most similar calibration catchment were used in the ungauged catchment. To test the adequacy of these regionalisation approaches, models built on all five of the other catchments were applied in turn to the regionalisation catchment in order to observe which performed best.

2. METHODS

2.1. Model Calibration

All three rainfall-runoff models were calibrated on each of the 6 catchments over the period 1975 to 2006. The SIMHYD and Sacramento models were calibrated to the rainfall from each 5x5 km cell individually then summed to give a catchment-scale response. The IHACRES model was calibrated to a catchment-average rainfall derived from data from each 5x5 km cell. The difference between these two approaches is not expected to greatly influence the results.

2.2. Applying Regionalised Models

Having calibrated the SIMHYD, IHACRES and Sacramento models to each of the six calibration catchments, these models were then run in simulation mode using rainfall and temperature data from the other five catchments in turn. This resultant 'regionalised' streamflow was then compared to the observed streamflow from each of these five catchments.

3. RESULTS

3.1. Model Calibrations

The models were calibrated to optimise the Nash Sutcliffe coefficient, E on daily streamflow, with the proviso that the model bias was maintained at less than 5%. All three models produced reasonable calibration results on all 6 catchments. Calibration E values are shown in Table 3.

The efficiencies of all three models are similar, SIMHYD averaging 0.69, IHACRES 0.73 and Sacramento 0.79. All six catchments are also well represented by the models, with only catchment 406224 having a slightly lower efficiency (0.62 average) than the other catchments.

3.2. Model Simulations

Having calibrated the IHACRES, SIMHYD and Sacramento models on all six catchments, the next step was to take the calibrated model parameter values from each of the six catchments and apply them in simulation mode to the other five catchments. This was done in order to determine which of the sets of model parameters gave the best prediction of the hydrologic response of the other 'ungauged' catchments. The results of these simulations are summarised in Table 4, Table 5, and Table 6 for the SIMHYD, IHACRES, and Sacramento models respectively.

Table 2: Selected attributes of the six calibration catchments

Catchment	*Area (km^2)*	*Mean elevation (m)*	*Mean slope (°)*	*Mean annual rainfall (mm)*	*Stream density (km/km^2)*
406213	644	508	2.40	746	0.86
406214	237	275	2.29	563	0.70
406224	250	188	0.94	491	0.75
406226	175	323	3.07	624	0.95
406235	214	373	2.73	663	1.15
406250	80	680	2.13	1001	0.74

Table 3: Calibration efficiencies for all three models on all six catchments

Catchment	*406213*	*406214*	*406224*	*406226*	*406235*	*406250*	*Average*
SIMHYD	.81	.76	.48	.69	.69	.72	*.69*
IHACRES	.83	.78	.65	.71	.69	.71	*.73*
Sacramento	.87	.84	.74	.75	.73	.79	*.79*
Average	*.84*	*.79*	*.62*	*.72*	*.71*	*.74*	*.74*

Table 4: Model efficiencies when the six calibrated **SIMHYD** models were applied in simulation mode to the other five catchments. Optimal results for each catchment are shown in bold text.

Catchment	*406213_SH*	*406214_SH*	*406224_SH*	*406226_SH*	*406235_SH*	*406250_SH*
406213		0.61	0.49	**0.77**	0.71	0.62
406214	0.62		0.72	0.67	**0.74**	0.48
406224	0.32	**0.43**		0.40	0.42	0.33
406226	0.66	0.64	0.52		**0.68**	0.53
406235	0.62	**0.68**	0.62	0.66		0.49
406250	**0.38**	-0.28	-0.57	0.19	-0.12	

Table 5: Model efficiencies when the six calibrated **IHACRES** models were applied in simulation mode to the other five catchments. Optimal results for each catchment are shown in bold text.

Catchment	*406213_IH*	*406214_IH*	*406224_IH*	*406226_IH*	*406235_IH*	*406250_IH*
406213		0.69	0.14	**0.77**	0.74	0.63
406214	0.68		0.64	0.72	**0.75**	0.50
406224	0.42	**0.58**		0.48	0.52	0.30
406226	0.70	0.67	0.26		**0.70**	0.53
406235	0.65	0.68	0.40	**0.68**		0.46
406250	**-0.17**	-0.89	-4.30	-0.18	-0.63	

Table 6: Model efficiencies when the six calibrated **Sacramento** models were applied in simulation mode to the other five catchments. Optimal results for each catchment are shown in bold text.

Catchment	*406213_Sac*	*406214_Sac*	*406224_Sac*	*406226_Sac*	*406235_Sac*	*406250_Sac*
406213		0.45	0.13	**0.81**	0.76	0.73
406214	0.67		0.68	0.75	**0.81**	0.45
406224	0.34	**0.60**		0.46	0.55	0.21
406226	0.71	0.53	0.21		**0.73**	0.56
406235	0.66	0.62	0.45	**0.72**		0.50
406250	0.57	-0.65	-0.93	0.50	**0.80**	

Table 7: Most similar catchments to each of the ungauged catchments in terms of a number of criteria.

Catchment	*Nearest*	*Area*	*Elevation*	*Slope*	*Stream density*	*Mean annual rainfall*	***Overall similarity***
406213	406235	406224	406235	406214	406235	406235	**406235**
406214	406224	406224	406226	406213	406226	406226	**406226**
406224	406214	406214	406214	406250	406226	406214	**406214**
406226	406235	406235	406214	406235	406214	406235	**406235**
406235	406226	406214	406226	406213	406224	406226	**406226**
406250	406213	406226	406213	406214	406214	406213	**406226**

In general, the results are very good, with the hydrologic response of each of the 'ungauged' catchments represented fairly well by models calibrated on at least one, and in some cases more than one of the gauged catchments.

Overall, the Sacramento model performs best, giving the best model efficiencies for all six of the 'ungauged' catchments. IHACRES performs better than SIMHYD on three, SIMHYD performs better on one, and they perform equally well on two of the 'ungauged' catchments.

However, these are just simulation results. In a truly ungauged situation the important question is how do we know which of the calibrated models should be used to predict the hydrologic response of the ungauged catchments? This is the question we will attempt to answer in the following section.

3.3. Catchment similarity

To determine which of the calibrated models we need to use to predict the hydrologic response of an ungauged catchment, we could assess which of the gauged catchments is 'most similar' to the ungauged catchment. This can be done by comparing the attributes of the catchments, or by choosing the closest catchment in the belief that it is likely to behave similarly. The most similar catchment to each of the 'ungauged' catchments in terms of seven different factors is shown in Table 7.

Obviously, the gauged catchment which is most similar to each ungauged catchment depends on which criteria one uses to assess similarity. Catchments which are most similar in terms of their area (for example) are not necessarily going to be similar in terms of their mean annual rainfall. The last column in Table 7 is an attempt to determine the most similar catchment in terms of the previous five attributes. It was derived by summing the percent differences between each pair of catchments in terms of area, elevation, slope, stream density and mean annual rainfall and then choosing the catchment which had the lowest overall score.

4. DISCUSSION

4.1. Best models and most similar catchments

The three models (SIMHYD, IHACRES and Sacramento) tend to agree on which of the calibration catchments are best suited for regionalising the hydrologic response of the ungauged catchments. All three models agree that:

- catchment 406213 is best predicted by models built on 406226;
- catchment 406214 is best predicted by models built on 406235;
- **catchment 406224 is best predicted by models built on 406214;**
- **catchment 406226 is best predicted by models built on 406235;**
- **catchment 406235 is best predicted by models built on 406226** (with the exception of SIMHYD where 406214 is just slightly better than 406226;
- catchment 406250 is best predicted by models built on 406235 (by Sacramento which is the only regionalised model that represents the hydrologic response of 406250 well).

Of these six catchment-model combinations, the three in bold are also the most similar catchments, indicating perhaps that our measure of similarity is not a bad one to use in determining which model to apply to which ungauged catchment.

In addition, for two of the three catchments where the most similar catchment was not the best regionalised model, the most similar catchment did at least perform well in terms of Nash-Sutcliffe *E.* For example, the model built on the most similar catchment to 406213 (catchment 406235) performs very well when applied to 406213, giving *E* values of 0.71, 0.74 and 0.76 for SIMHYD, IHACRES, and Sacramento respectively. Results for catchment 406214 are also good with the model built on the most similar catchment (406226) giving *E* values of 0.67, 0.72, and 0.75 for SIMHYD, IHACRES and Sacramento respectively.

The only catchment where the model built on the most similar catchment failed to reproduce the hydrologic response of the ungauged catchment was catchment 406250 where the model built on the most similar catchment (406226) gave *E* values of 0.19, -0.18 and 0.50 for SIMHYD, IHACRES and Sacramento respectively. Interestingly, the calibrations for catchment 406250 were all good (*E* values of 0.72, 0.71, and 0.79 respectively), but none of the models built on other catchments could reproduce the hydrologic response of 406250 with the exception of the Sacramento model built on catchment 406235. Why this model should perform well is unknown. Catchment 406250 is the smallest, highest and wettest catchment of the six, and it is possible that a combination of these attributes makes it difficult to regionalise the hydrologic response from the other catchments to it.

4.2. Most similar versus nearest catchment

For the six catchments in the Campaspe basin, the nearest one is also the most similar for four of the six catchments. The fact that proximity is a good measure of similarity is not surprising because climate and physical characteristics are likely to be similar in neighbouring catchments.

For the other catchment where acceptable simulation results are obtained (406214), the most similar catchment outperforms the nearest catchment for the IHACRES and Sacramento models, but the nearest catchment outperforms the most similar catchment for the SIMHYD model. The nearest catchment outperforms the most similar catchment for all three models for 406250, but the simulation results are so poor as to make comparisons meaningless.

5. CONCLUSIONS

The SIMHYD, IHACRES and Sacramento models all perform reasonably well when calibrated to the six gauged catchments in the Campaspe Basin. In addition, when regionalising results from one gauged catchment to another, the most similar catchment and the nearest catchment both give reasonable results for five of the six catchments.

It should be noted however that the most similar model is also the nearest in four of those five cases indicating that proximity is a good measure of similarity. This is hardly surprising because climate and physical characteristics are likely to be similar in neighbouring catchments.

For the sixth catchment, which is significantly different to the others in terms of area, elevation and slope, regionalised models from the gauged catchments generally performed poorly.

While these regionalisation results seem promising at first, it must be remembered that these six catchments are very similar and as a result, many (although not all) of the calibrated models do a reasonable job of predicting the hydrologic response of the other catchments, treating them as ungauged.

This pilot study carried out on six catchments of the Campaspe River Basin has proven to be too small to determine whether a similarity index is more useful than a nearest neighbour approach in regionalising hydrologic response. A larger study encompassing more catchments is required for this task. The results of an extended study should provide an indication as to whether a similarity index is more useful than a nearest neighbour approach to regionalisation, as well as what similarity index is best suited for this task.

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