18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Evaluation of regionalisation methods for predicting runoff in ungauged catchments in southeast Australia

Zhang, Y.Q. [1] **and F.H.S. Chiew** [1]

[1] *CSIRO Water for a Healthy Country National Research Flagship, CSIRO Land and Water, PO BOX 1666, Canberra ACT 2601, Australia*
Email: Yongqiang.zhang@csiro.au

Abstract: Runoff predictions in ungauged basins or catchments are regarded as one of the most challenging tasks in surface hydrology. To develop practical runoff prediction methods is important for assessing water resources in an ungauged or poorly gauged catchment which is usually located in headwater regions.

Regionalisation is typically used for runoff predictions in ungauged catchments. This can be defined as the process of transferring parameter values from a gauged catchment to the target ungauged catchment. This study evaluates three commonly used methods for selecting donor catchments whose entire set of parameter values are used to model runoff in a target ungauged catchment: spatial proximity, physical similarity and integrated similarity. In the physical similarity method, the catchment with the most similar physical characteristics to the target ungauged catchment is chosen as the donor catchment. In the spatial proximity method, the geographically closest gauged catchment to the target ungauged catchment is chosen as the donor catchment. In the integrated similarity method, the spatial proximity and physical similarity measures are considered together to choose the donor catchment. The modelling results are also compared to results from a randomly selected donor catchment. The study also compares results from the use of a single donor catchment versus the output averaging of results from multiple donor catchments.

The regionalisation methods are assessed using the conceptual Xinanjiang daily rainfall-runoff model. This model is applied to 210 relatively unimpacted catchments in south-east Australia. To assess the model predictions of daily runoff in 'ungauged' catchments, each of the 210 catchments is left out in turn and considered as an 'ungauged' catchment, and the entire set(s) of parameter values from the donor catchment(s) are used to model runoff in the 'ungauged' catchments.

The results show that the biggest benefit comes from an educated selection of donor catchments and output averaging of results from multiple donor catchments. The Nash-Sutcliffe Efficiency (NSE) values from an educated selection of donor catchments are on average about 0.2 higher than the NSE values from a random selection of donor catchments. The output averaging of simulations from multiple donor catchments generally gives better daily runoff simulations than the use of a single donor catchment because it averages out the effect of choosing a poor donor catchment. The NSE values from the output averaging of results from multiple donor catchments are on average about 0.1 higher than the NSE values from the use of a single donor catchment. Compared to the differences between single donor and multiple donor output average and between random selection and an educated selection of donor catchments, the difference between the three commonly used methods for selecting donor catchments is on average relatively small. However, in the poorer modelled catchments, the integrated similarity method gives better results than the spatial proximity method which in turn gives better results than the physical similarity method.

Keywords: *rainfall-runoff modelling, ungauged catchments, regionalisation*

1. INTRODUCTION

Predictions in Ungauged Basins or catchments (PUB) are regarded as one of the most challenging tasks in surface hydrology. The International Association of Hydrological Sciences (IAHS) launched an initiative, the IAHS Decade on PUB (2003-2012), focusing on " *formulating and implementing appropriate science programmes to engage and energize the scientific community, in a coordinated manner, towards achieving major advances in the capacity to make reliable predictions in ungauged basins*" (Sivapalan, 2003). To develop practical PUB methods is important for assessing water resources in an ungauged or poorly gauged catchment which is usually located in headwater regions.

Regionalisation is typically used for water quantity studies in PUB, which is referred to as the process of transferring parameter values from a gauged catchment to the target ungauged catchment (Bloschl and Sivapalan, 1995). Three regionalisation methods have been widely used to choose the donor gauged catchment whose optimised parameter values are used to model runoff for the target ungauged catchment: regression; spatial proximity; and physical similarity. The regression method establishes a relationship between optimised parameter values from gauged catchments and catchment climatic and physical attributes, and the parameter values for the ungauged catchments are estimated from its attributes and the established relationship. The spatial proximity method uses the parameter values from the geographically closest gauged catchment because neighbouring catchments are expected to behave similarly owing to similar physical and climatic characteristics. The physical similarity method transfers the entire set of parameter values from a physically similar catchment.

Recent studies suggest the regression method performs worse than the spatial proximity and physical similarity methods (Bardossy, 2007; McIntyre, et al., 2005; Oudin, et al., 2008; Parajka, et al., 2007). This is because the cross-correlation between parameters are seldom taken into account and because model calibrations can produce vastly different sets of parameter values that give similar model performance (equifinality problem, (Beven and Freer, 2001)). A potential way to use the regression method is to establish relationships between catchment response characteristics and catchment attributes in gauged catchments and then to constrain model parameters by using the resulting estimated response characteristics in ungauged catchments (Croke and Norton, 2004). The spatial proximity and physical similarity methods are very common in many recent regionalisation studies (Bardossy, 2007; McIntyre, et al., 2005; Merz and Bloschl, 2004; Oudin, et al., 2008; Parajka, et al., 2005; Chiew et al., 2008). Merz and Bloshl (2004) and Parajka et al. (2005) compare the three regionalisation methods in over 300 Austrian catchments using an 11-parameter HBV model and show that the spatial proximity method performs best followed by the physical similarity method with the regression method performing worst. *Oudin et al.* (2008) draw the same conclusion using two rainfall-runoff models, GR4J and TOPMO, in 913 French catchments. As the spatial proximity method does not systematically outperform the physical similarity method (Oudin, et al., 2008), combining the two to select a donor catchment may improve the modelling results.

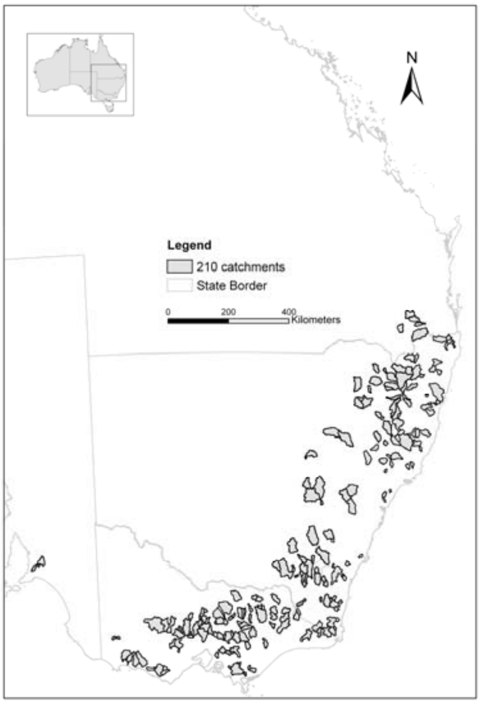


Figure 1. Location of 210 gauged catchments used in this study

Various studies, particularly those by McIntyre et al. (2005) and Oudin et al. (2008) have shown that output averaging can reduce the uncertainty in runoff predictions in ungauged catchments. In output averaging, the target catchment is modelled using parameter values from many donor catchments, rather than one donor catchment, and results from the modelling using the different sets of parameter values from the different donor catchments, are averaged to provide the runoff estimate for the target catchment. The use of output averaging is also be explored in this paper.

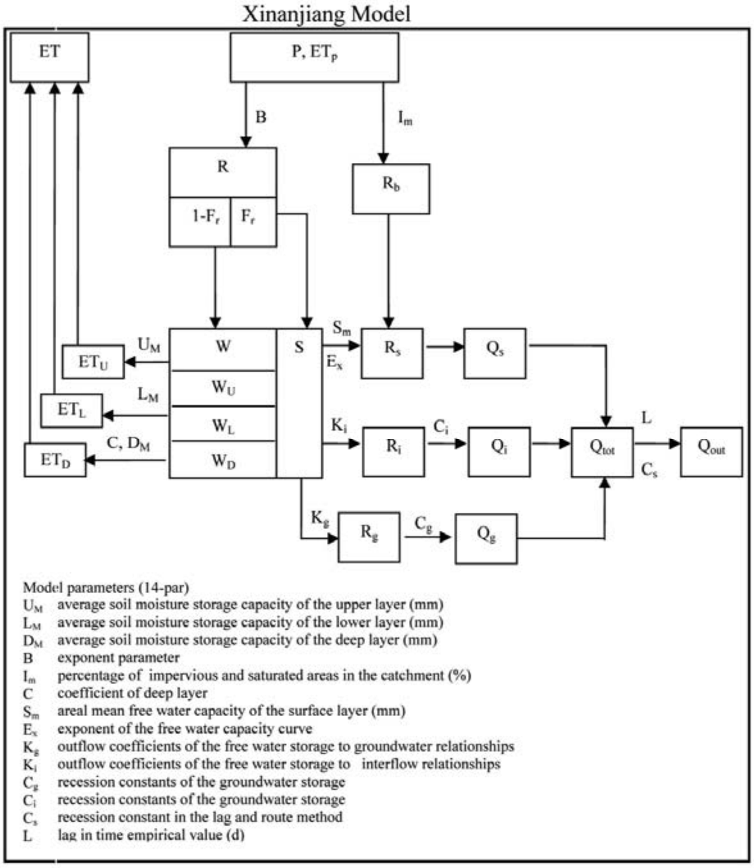
The main focus of this paper is to investigate three regionalisation methods for selecting the donor catchments: spatial proximity, physical similarity and integrated similarity (combination of spatial proximity and physical similarity). A lumped conceptual daily rainfall-runoff model, Xinanjiang model, is used in this study. The model is applied to 210 relatively unimpacted catchments in south-east Australia using data from 2000 to 2006 (Figure 1).

2. MODEL AND DATA

2.1. Model

A lumped conceptual daily rainfall-runoff model, Xinanjiang model, is used for modelling daily runoff. The inputs into the model are daily rainfall and daily potential ET (ET_p), and the model estimate daily runoff.

The 14-parameter Xinanjiang model has been widely used, particularly in humid and semi-humid regions in China (Zhao, 1992). The structure of the Xinanjiang model and the model parameters are shown in Figure 2. The Xinanjiang model has three submodels, ET submodel (3-par: Um, Lm and C), runoff generation submodel (3-par: D_m, B and I_m) and routing submodel (8-par: S_m, E_x, K_g, K_i, C_g, C_i, C_s, L).



Model parameters (14-par)

U_M	average soil moisture storage capacity of the upper layer (mm)
L_M	average soil moisture storage capacity of the lower layer (mm)
D_M	average soil moisture storage capacity of the deep layer (mm)
B	exponent parameter
I_m	percentage of impervious and saturated areas in the catchment (%)
C	coefficient of deep layer
S_m	areal mean free water capacity of the surface layer (mm)
E_x	exponent of the free water capacity curve
K_g	outflow coefficients of the free water storage to groundwater relationships
K_i	outflow coefficients of the free water storage to interflow relationships
C_g	recession constants of the groundwater storage
C_i	recession constants of the groundwater storage
C_s	recession constant in the lag and route method
L	lag in time empirical value (d)

Figure 2. Model structure of Xinanjiang

2.2. Data

Daily runoff data from 210 relatively unimpacted catchments (50 to 2000 km^2) in south-east Australia (Peel et al., 2000) are used. The region includes the most populated and important agricultural areas of Australia. Data from 2000 to 2006 are used in this study.

Daily time series of maximum temperature, minimum temperature, incoming solar radiation, actual vapour pressure and precipitation from 2000 to 2006 at 0.05º × 0.05 º (~ 5 km × 5 km) grid cells from the SILO Data Drill of the Queensland Department of Natural Resources and Water (www.nrw.gov.au/silo) (Jeffrey et al., 2001) are used. The SILO Data Drill provides surfaces of daily rainfall and other climate data interpolated from point measurements made by the Australian Bureau of Meteorology. The rainfall data is required as input to the rainfall-runoff model. The other meteorological data are used to calculate potential ET (ET_p) using the Priestley-Taylor potential ET model.

2.3. Model calibration

A widely used optimization method, the partial swarm optimization, is used to calibrate the Xinanjiang model by maximizing the Nash-Sutcliffe Efficiency (NSE) of daily runoff (Nash and Sutcliffe, 1970). This model is calibrated against daily runoff data from 2001 to 2006, with the 2000 data used for model warm up.

3. PREDICTING RUNOFF IN UNGAGUED CATCHMENTS

To assess the model predictions of daily runoff in ‘ungauged’ catchments, each of the 210 catchments is left out in turn and considered as an ‘ungauged’ catchment, and the entire set(s) of parameter values from the donor catchment(s) are used to model runoff in these ‘ungauged’ catchments.

Four regionalisation methods for selecting donor gauged catchments whose entire sets of optimised/calibrated parameter values are used to model runoff in the target ungauged catchment are considered: a random selection of donor catchments as a baseline to compare the modelling results, and the three educated selection of donor catchments based on the spatial proximity, physical similarity and integrated similarity methods.

The study also compares results from the use of one donor catchment versus results from the use of eight donor catchments. Where eight donor catchments are used, the parameter values from each donor catchment are used to independently model runoff in the ungauged catchment. Each of the daily runoff time series modelled using parameter sets from each of the donor catchments are then averaged to obtain the daily runoff time series for the ungauged catchment, which is called as the output averaging method as described by McIntyre et al. (2005) and Oudin et al. (2008). Eight donor catchments are used here because the analysis (not presented here) indicates that the best results for the application here generally come from the use of six to ten donor catchments.

In the spatial proximity method the geographically closest gauged catchment(s) to the target catchment is (are) chosen as the donor catchment(s). In the physical similarity method, the catchment(s) with the most similar physical characteristic to the target ungauged catchment is (are) chosen as the donor catchment(s). Eight catchment attributes are considered here: catchment area; aridity index (the ratio of mean annual ET_p to mean annual rainfall); mean catchment elevation; catchment slope; stream length; median solum thickness; plant available water holding capacity in solum; and mean woody vegetation fraction (Table 1). The rank-accumulated similarity is used to select the donor catchment (Oudin et al., 2008). For each attribute, the catchment with the most similar attribute to the target catchment is considered rank 1, the catchment with the second most similar attribute is considered rank 2, and so on. The total rank is the arithmetic total of the rank numbers for each of the eight attributes. The catchment with the smallest total rank is chosen as the target catchment. Each attribute used for regionalisation is therefore given equal weight in the ranking system.

Table 1. Summary of catchment attributes in the 210 unregulated catchments

Catchment Characteristics	Min	25%	Median	75%	Max
Catchment area	51	160	333	633	2000
Aridity index	0.76	1.22	1.55	1.89	2.98
Mean catchment elevation	57	307	519	814	1445
Mean slope in degree	0.42	2.75	4.55	7.78	13.85
Stream length	27	121	246	475	1753
Mean solum Thick	0.44	0.86	0.96	1.20	2.00
Plant available water holding capacity	50.0	82.3	110.8	158.3	265.8
Mean woody vegetation Fraction	0.00	0.23	0.52	0.83	1.00

In the integrated similarity method, the spatial proximity and physical similarity measures are considered together. The geographic distance is used as an attribute together with two of the best catchment attributes (mean woody vegetation fraction and aridity index). Like the physical similarity method, this method also uses the rank-accumulated similarity to select the donor catchment.

4. RESULTS AND DISCUSSION

4.1. Calibration results

The model calibration results are summarised in Figure 3. The calibration is satisfactory with NSE values greater than 0.6 in about 80 percent of the 210 catchments. The calibration results are similar to most rainfall-runoff modelling studies for Australian catchments (Boughton and Chiew, 2004; Viney et al., 2008; Chiew et al., 2008).

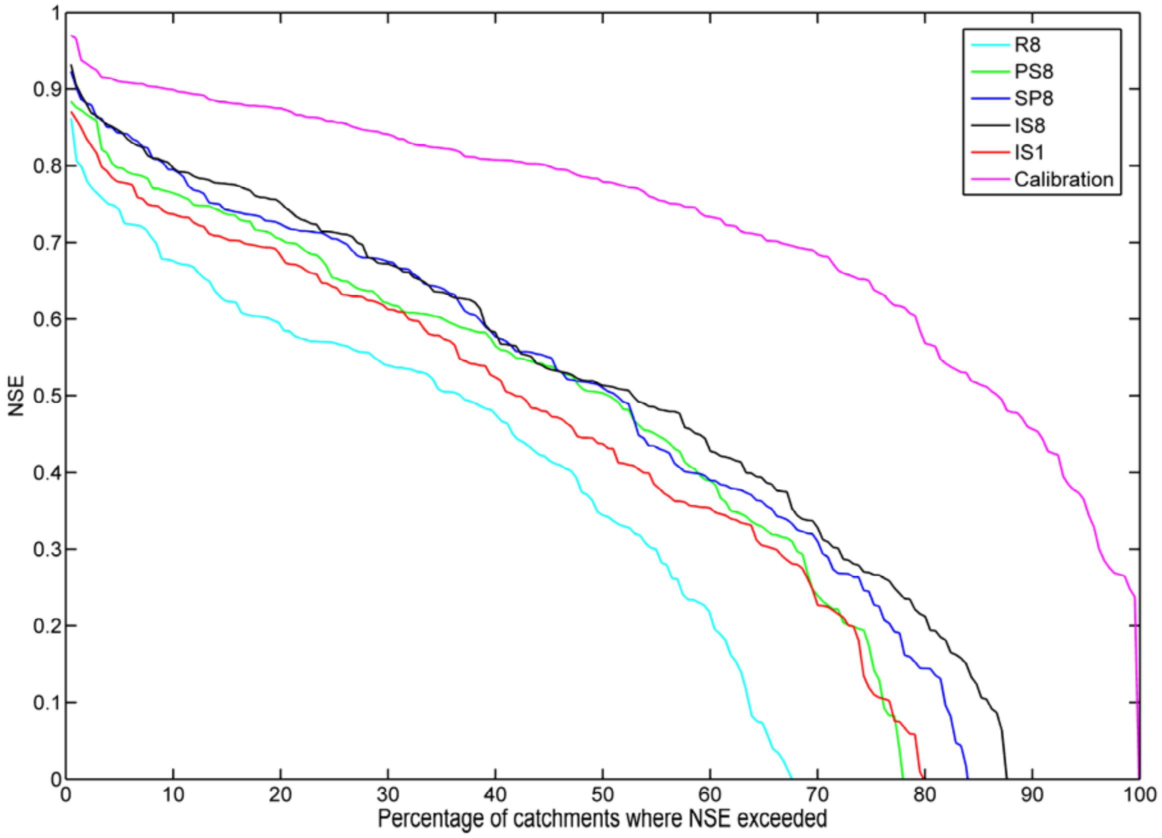


Figure 3. Accumulation curves summarising the Nash-Sutcliffe Efficiency (NSE) of daily runoff values from the 210 catchments for the model calibration and regionalisation (R8 is random selection with eight donor catchments; PS8 is physical similarity method with eight donor catchments; SP8 is spatial proximity method with eight donor catchments; IS8 is integrated similarity method with eight donor catchments; and IS1 is integrated similarity method with one donor catchment)

The NSE values for the 210 catchments from the different regionalisation methods are summarised as accumulation plots in Figure 3. The scatter plots in Figure 4 compare the NSE values between various regionalisation methods. Figure 4 also shows the number of catchments where one regionalisation method is significantly better than the other (for the purpose of this paper, a method is considered significantly better when the NSE value is 0.02 higher than the other method as suggested by Oudin et al. (2008)). The model calibration results are similar to most rainfall-runoff modelling studies, but the regionalisation results are generally poorer than other similar studies, most likely because of the higher temporal and spatial variability in Australian dataset used here and the period of analysis being a very dry period.

4.2. Single donor catchment versus multiple donor catchments

The output averaging of simulations from multiple donor catchments generally gives considerably better daily runoff simulations than the use of a single donor catchment because it averages out the effect of choosing a poor donor catchment. The NSE values for the integrated similarity method with eight donor catchments are on average about 0.1 higher than the NSE values for the integrated similarity method with a single donor catchment (IS8 and IS1 in Figure 3). The number of catchments where the NSE value for IS8 is significantly higher (more than 0.02 higher) than the NSE value for IS1 is 2–3 times more than the number of catchments where the NSE for IS1 is significantly higher than the NSE for IS8 (125 catchments versus 46 catchments, see Figure 4a). A reasonable explanation for this result is that output averaging overcomes the limitation that single donor catchment happens to give very good or very bad predictions for the target catchment and hence reduces the uncertainty in runoff predictions.

4.3. Educated selection of donor catchments versus random selection of donor catchments

The educated selection of donor catchments gives on average NSE values of about 0.2 higher than a random selection of donor catchments (IS8 and R8 in Figure 3). The number of catchments where the NSE value for IS8 is significantly higher (more than 0.02 higher) than the NSE value for R8 is about four times more than the number of catchments where the NSE for R8 is significantly higher than the NSE for IS8 (144 catchments versus 33 catchments, see Figure 4b).

4.4. Educated regionalisation methods

The difference between the three educated regionalisation methods is small compared to the improved modelling results from the use of multiple donor catchments versus a single donor catchment and an educated selection of donor catchments versus a random selection of donor catchments discussed above. The median NSE values for the three regionalisation methods are very similar, but in the poorer modelled catchments the integrated similarity method performs better than the spatial proximity method which in turn performs better than the physical similarity method (IS8, SP8 and PS8 in Figure 3). The spatial proximity method (SP8) generally performs slightly better than the physical similarity method (PS8), where the NSE value for SP8 is significantly higher than the NSE value for PS8 in 102 of the 210 catchments and the NSE value for PS8 is significantly higher than the NSE value for SP8 in 64 catchments (Figure 4c). The results for the integrated similarity method and spatial proximity method are very similar (IS8 and SP8 in Figure 3 and Figure 4d).

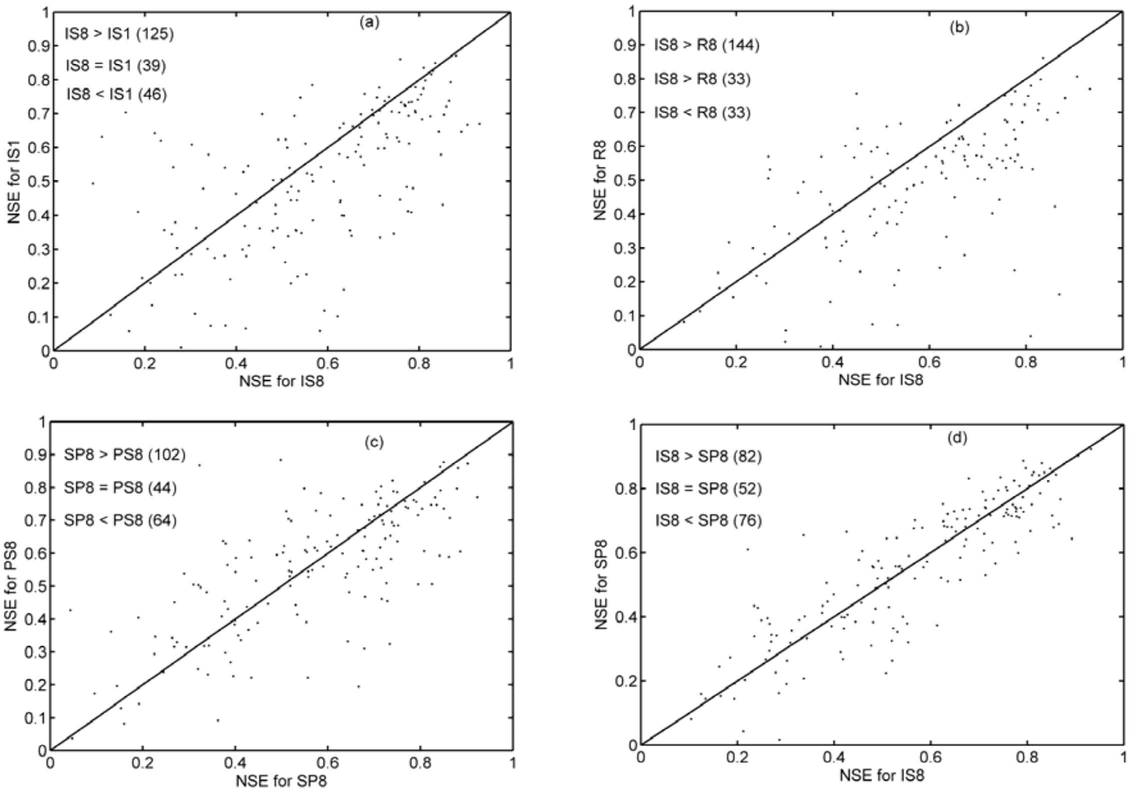


Figure 4. Comparisons of NSE values between various regionalisation methods (number of catchments where NSE for one method is significantly higher (more than 0.02 higher) than the other method are shown in the top left hand of each plot).

5. CONCLUSION

This study evaluates the relative benefits of different methods for modelling daily runoff in ungauged catchments, using the Xinanjiang conceptual daily rainfall-runoff model on 210 relatively unimpacted catchments in south-east Australia. The results show that the biggest benefit comes from an educated selection of donor catchments and output averaging of results from multiple donor catchments. The difference between the three commonly used methods for selecting donor catchments is on average relatively small. However, in the poorer modelled catchments, the integrated similarity method gives better results than the spatial proximity method which in turn gives better results than the physical similarity method.

ACKNOWLEDGMENTS

The study was supported by the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) Science Leadership Scheme and the water information research and development alliance between CSIRO and the Australian Bureau of Meteorology. We thank the Murray-Darling Basin Sustainable Yields Project in providing catchment attribute data.

REFERENCES

Bardossy, A. (2007), Calibration of hydrological model parameters for ungauged catchments. Hydrology and Earth System Sciences, 11, 703-710.

Croke, B.F.W. and Norton, J.P. (2004), Regionalisation of Rainfall-Runoff models, In Pahl, C., Schmidt, S., Rizzoli, A.E. and Jakeman, A.J. (eds.) Complexity and Integrated Resources Management, Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society, Volume 3 pp. 1201-1207. iEMSs, June 2004.

Beven, K., and Freer, J. (2001), Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. Journal of Hydrology, 249, 11-29.

Bloschl, G., and Sivapalan, M. (1995), Scale Issues in Hydrological Modeling - a Review. Hydrological Processes, 9, 251-290.

Boughton, W., and Chiew, F. (2004), Estimating runoff in ungauged catchments from rainfall, PET and the AWBM model. Paper presented at International Symposium on Environment Software System, Harrisonburg, VA, May 18-21.

Chiew F. H. S., Vaze J., Viney N., Jordan P., Perraud J. M., Zhang L., Teng J., Young W., Arancibia J., Morden R., Freebairn A., Austin J., Hill P., Wiesenfeld C., and Murphy R. (2008), Rainfall-runoff modelling across the Murray-Darling Basin. A report to the Australian government from the CSIRO Murray-Darling Basin Sustainable Yields Project. CSIRO, Australia.

Jeffrey, S. J., Carter, J. O., Moodie, K. B., and Beswick, A. R. (2001), Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling & Software, 16, 309-330.

McIntyre, N., Lee, H., Wheater, H., Young, A., and Wagener, T. (2005), Ensemble predictions of runoff in ungauged catchments. Water Resources Research, 41, W12434, doi:10.1029/2005WR004289.

Merz, R., and Bloschl, G. (2004), Regionalisation of catchment model parameters. Journal of Hydrology, 287, 95-123.

Nash, J. E., and Sutcliffe, J. V. (1970), River forecasting using conceptual models, 1. A discussion of principles. Journal of Hydrology, 10, 280-290.

Oudin, L., Andréassian, V. C., Perrin, C., Michel, C., and Le Moine, N. (2008), Spatial proximity, physical similarity, regression and ungaged catchments: A comparison of regionalization approaches based on 913 French catchments. Water Resour. Res., 44, W03413, doi:03410.01029/02007WR006240.

Parajka, J., Bloschl, G., and Merz, R. (2007), Regional calibration of catchment models: Potential for ungauged catchments. Water Resources Research, 43, 10.1029/2006WR005271.

Parajka, J., Merz, R., and Bloschl, G. (2005), A comparison of regionalisation methods for catchment model parameters. Hydrology and Earth System Sciences, 9, 157-171.

Peel, M. C., Chiew, F. H. S., Western, A. W., McMahon, T. A. (2000), Extension of unimpaired monthly stream flow data and regionalisation of parameter values to estimate stream flow in ungagued catchment, Appl. Hydrol., University of Melbourne, Parkville, Victoria, Australia.

Sivapalan, M., Takeuchi, K., Franks, S. W., Gupta, V. K., Karambiri, H., Lakshmi, V., Liang, X., McDonnell, J. J., Mendiondo, E. M., O'Connell, P. E., Oki, T., Pomeroy, J. W., Schertzer, D., Uhlenbrook, S., and Zehe, E. (2003), IAHS decade on Predictions in Ungauged Basins (PUB), 2003-2012: Shaping an exciting future for the hydrological sciences. Hydrological Sciences Journal-Journal Des Sciences Hydrologiques, 48, 857-880.

Viney, N., Vaze, J., Chiew, F., and Perraud, J. (2008), Regionalisation of runoff generation across the Murray-Darling Basin using an ensemble of two rainfall-runoff models. Paper presented at Water Down Under 2008, April 2008, Adelaide: Engineers Australia.

Zhao, R. J. (1992), The Xinanjiang Model Applied in China. Journal of Hydrology, 135, 371-381.