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

The use of GIS to derive distributed unit hydrographs for streamflow prediction

Gibbs, M.S.[1], Maier, H.R. [1], Dandy, G.C. [1]

[1] *School of Civil, Environmental and Mining Engineering, The University of Adelaide, SA, 5005, Australia*
Email: mgibbs@civeng.adelaide.edu.au

Abstract: In many regions where rainfall-runoff models are required, there is a lack of streamflow data available to calibrate the model parameters. This can restrict the use of commonly used lumped parameter models, such as AWBM, SimHyd or the Sacramento model. Some studies suggest that the parameters of these models have limited physical basis, and do not regionalise reliably. An alternative approach to determining the timing of runoff involves the use of unit hydrographs, provided an estimate of excess rainfall can be obtained using a suitable approach (of which many are available).

A great deal of data relevant to hydrologic modelling, such as catchment topology, soil type and land use, are now stored in Geographical Information Systems (GIS). Much of these data are readily available, or can be obtained in a reasonable time frame through remote sensing methods, for example. Analysis of these data allows estimates of travel times over the catchment to be obtained, and hence the unit hydrograph to be derived, without any historical record of streamflow.

In order to derive the unit hydrograph, estimates of the flow velocities throughout the catchment are required. A number of methods have been developed to allow the velocity to be calculated on a grid cell basis over the catchment, allowing the velocity to change based on the flow type (hillslope flow or channel flow) and local catchment characteristics, such as slope and roughness. A number of uncertainties are involved in the determination of these velocities, such as the flow accumulation required before channel flow commences, Manning's n values, and the approach used to account for the hydraulic radius of flow.

The purpose of this paper is to investigate the influence of the parameters involved in the velocity estimates on the unit hydrograph produced, and to determine if these parameters can be calibrated to provide an accurate representation of the observed unit hydrograph. Estimates of travel times and velocities have been obtained by using Visual Basic ArcObjects in ArcGIS® 9.2. The SimLab package (Saltelli et al., 2000) with extended Fourier Amplitude Sensitivity Testing (FAST) method was used to investigate the importance and relationships between parameters involved on the unit hydrographs produced.

The results indicate that the threshold for channel flow and the Manning's n value had little impact on the hydrographs produced, while the maximum channel velocity and velocity when flow transition from hillslope to channel flow occurs had the most significant effect on the shape of the hydrograph. These two velocities can be used to produce the desired shape of the hydrograph, altering the peak flow and timing of the peak flow, while the minimum hillslope velocity can be used to fine tune the length of the recession limb. The results suggest that using only remotely sensed elevation data in a GIS framework is a feasible approach to approximate the expected unit hydrograph for a given catchment. Further work will investigate if values for the velocity parameters can be derived from catchment characteristics, such as the channel cross-sectional area or catchment slope, to enable the approach to be applied to ungauged catchments. This would allow streamflow to be estimated for ungauged catchments, where a lack of streamflow data prohibits the calibration of more traditional models, but where suitable GIS data are available.

Keywords: *Geographic Information Systems; Hydrologic Modelling; Unit Hydrograph; Remote Sensing; Calibration; Sensitivity Analysis.*

1. INTRODUCTION

In many cases, streamflow records are unavailable to calibrate rainfall-runoff model parameters. A great deal of research has been dedicated to regionalization of conceptual rainfall-runoff models for prediction in ungauged basins, however recent studies suggest that the parameters have little physical meaning (Post et al., 2008), and are unlikely to produce reliable results when extrapolated to ungauged catchments.

Unit hydrograph (UH) methods are another approach commonly used to model the rainfall-runoff process. The excess rainfall must be determined from a loss model, then the UH is used to determine the timing and magnitude of the runoff. This method is limited by the assumption that the catchment responds linearly to rainfall input, which is open to criticism. Despite this criticism, unit hydrographs are used to estimate streamflow from relatively small basins, typically for engineering purposes and often produce reasonable results (Cleveland et al., 2008). Generally, the UH is derived from streamflow records, however a number of studies have estimated the UH based on expected travel times in the catchment. With remotely sensed topographic information about catchments becoming increasingly readily available, this is an attractive approach for runoff prediction in ungauged catchments.

There are two main approaches used to derive a UH from topological information: Geomorphologic Instantaneous Unit Hydrograph (GIUH) methods are based on the work of Rodriquez-Iturbe and Valdes (1979); and Spatially Distributed Unit Hydrograph methods, based on a time-area relationship for the catchment (Maidment, 1993). A number of approaches have been developed based on these two initial studies, but essentially they all involve using measurements of distance, velocity and time to derive to physical characteristics of the watershed to parameterize a unit hydrograph in the absence of observed runoff and rainfall data (Cleveland et al., 2008).

All approaches to derive UHs from topographic information require at least one parameter to describe the timing of flow across the catchment, often in the form of average velocities. These parameters are then used to derive the final UH using travel distances through the catchment. It is useful to quantify the influence the parameters have on the results produced, to understand the uncertainty involved, and determine which parameters are most important. A number of sensitivity analysis methods have been develop to address such problems, such as the Fourier Amplitude Sensitivity Test (FAST) (Cukier et al., 1978), extended FAST (Saltelli et al., 1999), the Sobol' method (Sobol', 1993) and the Morris method (Morris, 1991). An advantage of the Sobol' and extended FAST methods is that they can provide information about both first order effects between the each parameter and the output of interest and also total order effects incorporating the combined effect of more than one parameter on the result. The extended FAST method is more computationally efficient than the Sobol' method, due to the fact that a sample of parameter values can be used in more than one sensitivity analysis calculation (Saltelli et al., 1999), and hence generally provides more robust solutions from fewer samples.

This paper investigates the use of a spatial distributed time-area method for estimating the unit hydrograph for two gauged catchments in South Eastern Australia. Specifically, the aim of the paper is to investigate the influence of the parameters involved on different aspects of the UH produced, to identify which are the most significant, and if certain parameters can be used to determine certain aspects of the UH, such as the time to peak and time of concentration. Using this information, the parameters are then adjusted to investigate if the derived UH can provide a reasonable estimate of the observed UH for the catchments considered.

2. METHODOLOGY

A spatially-distributed time-area method has been used to generate the UH. The approach has the advantage that no assumptions about the functional form of the UH are required (unlike GIUH methods which commonly assume an exponential distribution). The approach of Noto and La Loggia (2007) has been used to derive the UHs, as it provides a distinction between the velocity fields over the hillslope and in the channel network, and also allows for an increase in velocity with drainage area. For the implementation used in this work, there are five parameters that must be determined in order to apply this method: the minimum velocity when flow commences on the hillslope, $V(\text{Hillslope})_{\text{min}}$; the velocity when flow transitions from the hillslope to channel flow, $V_{\text{Transition}}$; the maximum velocity in the channel, $V(\text{Channel})_{\text{max}}$; a threshold flow accumulation area for flow to transition into channel flow, $A_{\text{Threshold}}$; and a Manning’s n value. The required flow direction, flow accumulation and slope grids have been derived from 10-m × 10-m LiDAR elevation observations, commissioned by the South Australian Department for Water, Land and Biodiversity Conservation, using the Hydrology tools in the Spatial Analyst Toolbox for ArcGIS® 9.2.

Table 1. Parameter Ranges Used for the Sensitivity Analysis

Parameter	Minimum	Maximum
Flow Accumulation Threshold, $A_{Threshold}$	1,000 m^2	1,000,000 m^2
Manning's n	0.02	0.08
Minimum Hillslope Velocity, $V(Hillslope)_{min}$	0.001 m/s	0.05 m/s
Transition Velocity, $V_{Transition}$	0.05 m/s	0.5 m/s
Maximum Channel Velocity, $V(Channel)_{max}$	0.5 m/s	5 m/s

The extended Fourier Analysis Sensitivity Test (FAST) (Saltelli et al., 1999) available in the SimLab Sensitivity Analysis software (Saltelli et al., 2000) has been used to investigate the sensitivity of the hydrographs produced to the parameters involved in the UH generation method used. The main advantages of the extended FAST method are its robustness, especially at low sample size, and its computational efficiency (Saltelli et al., 1999). Ravalico et al. (2005) found that, of the methods tested available in SimLab, the extended FAST method performed the best. Each parameter has been considered as a uniform distribution over the range given in Table 1. The sensitivity analysis used 965 samples and both the first and total order influence of each parameter have been calculated. The peak flow, Q_P, the time to peak flow, T_P, and the total flow duration, T_D, have been used to characterize the hydrographs produced.

3. CATCHMENTS AND DATA

Two catchments in South Eastern Australia have been used in this study (Figure 1). LiDAR derived elevation observations were available for the area, and have been used to determine catchment boundaries, as well as flow direction, flow accumulation and local slope grids. The catchment area is 343 km^2 for the Bakers Range Catchment and 782 km^2 for the Naracoorte Creek catchment, with main channel lengths of 37 km and 78 km

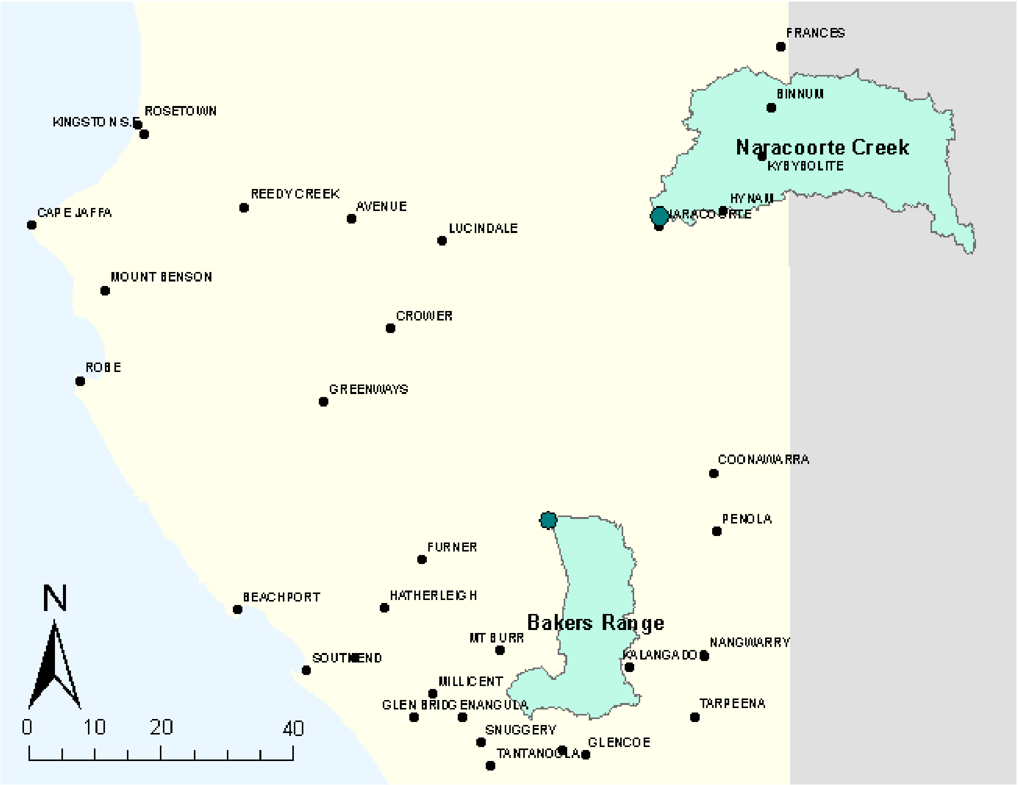


Figure 1. Study catchments in South Eastern Australia.

km

for the Bakers Range and Naracoorte Creek catchments, respectively. The dimensionless main channel slope is in the order of 0.0014 for both catchments.

Streamflow records are also required for the two catchments considered, to allow the UHs derived using the GIS data to be compared to the observed UH. Daily flow records are available at the catchment outlets, which can be seen in Figure 1. Flow has been recorded for a 22 year period between 1971 and 1993 for the Bakers Range catchment, and an ongoing 23 year period beginning in 1985 for the Narcoorte Creek catchment. In order to determine the excess rainfall, a loss model is required, along with rainfall and evaporation data inputs. The daily rainfall records from the Bureau of Meteorology have been disaggregated and interrogated using Hydrosanity (Andrews, 2007) for the R statistical package, before being interpolated using Thiessen polygons for gauges in or near each catchment. Monthly evaporation values from the nearest station have been used.

The Soil Moisture Accounting (SMA) loss model in the HEC-HMS software package (Fleming and Neary, 2004) has been used to determine the excess rainfall. Two objective functions were used to calibrate the model, both using the Nash Sutcliffe efficiency (NSE): the first based on of the daily baseflow; the second on total annual volume. The observed daily baseflow was determined from the flow records using the baseflow separation method of Eckhardt (2005) with a BFI_{max} value of 0.5 for ephemeral streams with porous aquifers, and K value derived from recession analysis of the flow data (Linsley et al., 1988). The K value has also been used to determine the groundwater coefficient and storage depth for the SMA loss model in HEC-HMS (Fleming and Neary, 2004). The ε-NSGAII multi-objective genetic algorithm (Deb et al., 2002, Kollat and Reed, 2007) was used to calibrate the 10 model parameters for the two objectives, and suitable solutions were selected from the Pareto front produced for each catchment to provide an estimate of excess rainfall. The daily baseflow derived using the Eckhardt method has also been used to estimate the direct runoff, by subtracting the predicted baseflow from the total observed flow.

4. RESULTS

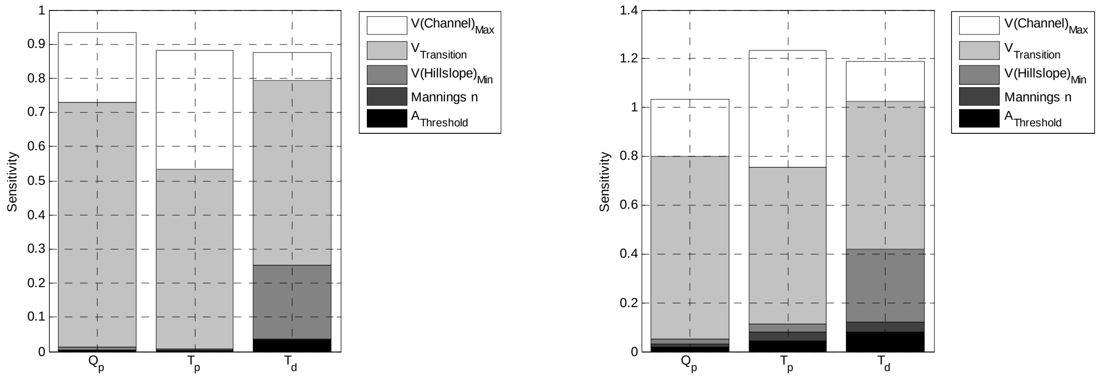
Visual Basic ArcObjects modules were used to take the parameter inputs sets, generated over the ranges given in Table 1 using SimLab, and produce the respective UH for each catchment. An hourly interval was used in the time-area method to generate the unit hydrograph, and from these results the peak flow, Q_P, time to peak flow, T_P, and total flow duration, T_D, were identified. The UH values produced were imported back into SimLab for sensitivity analysis using the extended FAST method. The sensitivity analysis results can be seen in Figure 2 for the Bakers Range catchment and Figure 3 for the Naracoorte Creek catchment.

4.1. Sensitivity Analysis Results

The first- and total-order results for the Bakers Range catchment are given in Figure 2 (a) and (b), respectively. The first order effects are those detectable between each model parameter and the respective UH characteristic (Q_P, T_P, or T_D), whereas the total-order effects include the sensitivity of the UH output to each parameter including the joint interactions with other parameters. Hence, the total order values are always equal to or greater than the first order values. However, little difference can be seen between the results in Figure 2 (a) and (b), indicating that there are only negligible interactions between the parameters used to derive the UH.

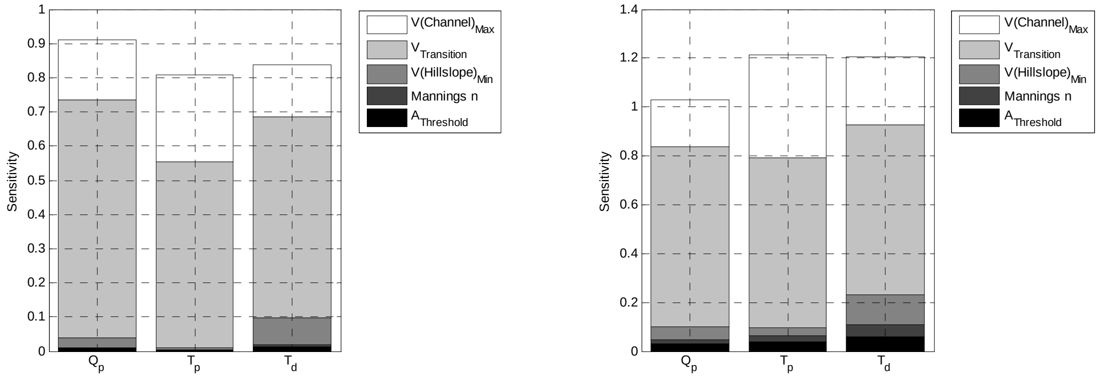
The extended FAST results indicate that the influence of Manning's n and $A_{Threshold}$ on the UH produced is minimal for the parameter ranges considered. The influence of these parameters becomes slightly more apparent in the total order results seen in Figure 2 (b), but they are still relatively small compared to the velocity parameters. From Figure 2 it can be seen that the velocity when flow transitions from hillslope to channel flow has the largest influence on all components of the hydrograph. For the peak flow and time to peak flow, $V(Channel)_{Max}$ is also significant, and for these parameters $V(Hillslope)_{Min}$ has little to no first order effect, and only a slight effect when all interactions are taken into account (Figure 2 (b)). However, $V(Hillslope)_{Min}$ has a greater impact on the total flow duration than $V(Channel)_{Max}$ suggesting that this parameter can be used to tune the flow duration, as it has little influence on the peak or timing of the peak of the UH.

Very similar results can be seen in Figure 3 for the Naracoorte Creek catchment, suggesting that the sensitivity of the UH generation method to parameters involved in estimating UH is consistent for the two catchments considered in this study. The results suggest that Manning's n and the threshold flow accumulation have little influence on the UH produced, and therefore can potentially be fixed to appropriate values. For example, Manning's n could be obtained from remotely sensed land use data. Then $V(Channel)_{Max}$ and $V_{Transition}$ can be used to obtain the UH, and $V(Hillslope)_{Min}$ used to fine tune the total flow



(a) (b)

Figure 2. Extended FAST (a) First Order and (b) Total Order results for Bakers Range Catchment.



(a) (b)

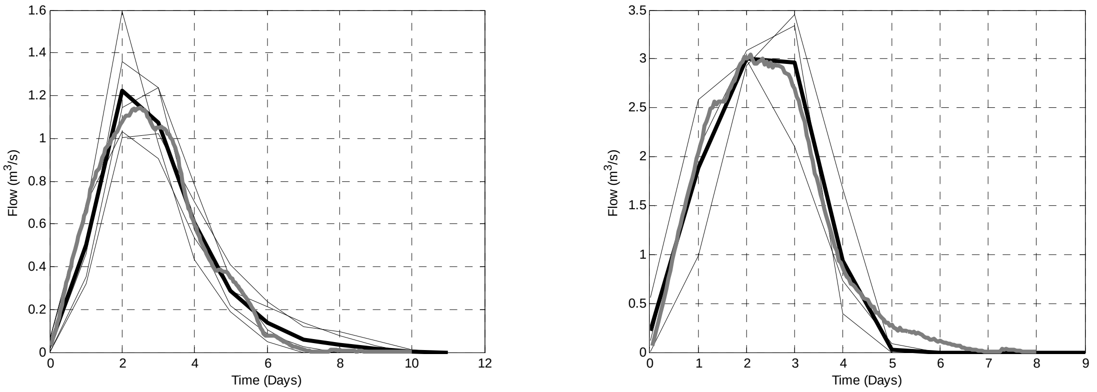
Figure 3. Extended FAST (a) First Order and (b) Total Order results for Naracoorte Creek Catchment.

duration. This approach is used in the following section to investigate if the UHs derived using only elevation data can be used to accurately approximate the UH observed from flow data from the catchment.

4.2. Comparison with Observed Unit Hydrograph

The surface runoff for each catchment was calculated by subtracting the baseflow determined using the Eckhardt filter from the observed total flow. The excess rainfall was determined from the calibrated SMA loss model. The rainfall record was interrogated to identify periods where there was only one day of excess rainfall producing surface runoff, to allow the observed runoff hydrograph to be identified. Each runoff hydrograph was then converted to a unit hydrograph by scaling the observed hydrograph so that the runoff volume matched to the volume produced by 1 mm of excess rainfall on the catchment area. The observed hydrographs can be seen as thin black lines in Figure 4, with the thick black line indicating the average of the different events. It can be seen from Figure 4 that while there is some variation between the observed runoff events, generally the average hydrograph provides a reasonable representation of the expected response of the catchment to excess rainfall.

Based on the information provided by the sensitivity analysis above, values were selected to determine if the derived UH could be generated to match the observed UH. For both catchments values of $A_{Threshold} = 10{,}000\ m^2$ and a Mannings n = 0.03 have been used, as the extended FAST results indicate that these two parameters have little impact on the UH produced. Through trial-and-error experiments, $V(Channel)_{Max} = 1$ m/s and $V_{Transition} = 0.02$ m/s have been used to produce the UH in Figure 4 (a) for the Bakers Range catchment, and $V(Channel)_{Max} = 3$ m/s and $V_{Transition} = 0.05$ m/s have been used to produce the



(a) (b)

Figure 4. Observed UH for individual events (~~light~~ thin black), and average UH (~~solid~~ thick black) compared to derived UH (thick grey) for (a) Bakers Range Catchment and (b) Naracoorte Creek Catchment.

UH in Figure 4 (b) for the Naracoorte Creek catchment. V(Hillslope)$_{Min}$ = 0.005 m/s was found to produces suitable total flow durations for both catchments.

The results in Figure 4 suggest that accurate UHs may be derived from catchment elevation data alone, without the requirement of a long flow record. Relationships between remotely sensed catchment characteristics (e.g. land use or soil type) and the UH parameters may be able to be derived, for example a larger value for $V_{Transition}$ may coincide with a different land use for the Naracoorte creek catchment, and a value for V(Channel)$_{Max}$ may be able to be derived from the channel cross-sectional area. However, results from more catchments are required to investigate if such relationships can be identified. This is the focus of future work.

5. DISCUSSION AND CONCLUSIONS

This study has investigated the use of elevation data alone in deriving accurate UH for streamflow prediction. A detailed sensitivity analysis was undertaken, to investigate the effect of each of the parameters involved on different aspects of the UH produced. It was found that the velocity to represent when flow transitions from hillslope to channel flow had the largest influence on the shape of the UH, followed by the maximum velocity in the channel. The minimum velocity when flow commences on the hillslope was found to only effect the total flow duration, and hence can be used to alter this aspect of the UH, while keeping the peak flow and timing of the peak flow relatively constant.

The sensitivity analysis results indicate that the threshold flow accumulation area for flow to transition from sheet to channel flow has a negligible effect on the derived UH, along with the value of Manning's n used. A greater effect may be seen for these two parameters by considering a larger range of values in the sensitivity analysis, however, the ranges considered in this study are quite generous (Manning's n ranged from 0.02, which could be used for a straight excavated channel, to 0.08, which could be used for a heavy brush floodplain). The results suggest that these two parameters can be set to appropriate values based on the data available, for example remotely sensed land use data could be use to derive a suitable value for Manning's n. Then the velocity parameters used to produce the desired UH should be obtained, first by adjusting $V_{Transition}$, as it had the largest influence on the UH, then V(Channel)$_{Max}$, and finally V(Hillslope)$_{Min}$ to adjust the total flow duration.

It was found that accurate estimates of observed UHs could be obtained by tuning the parameter values using information obtained from the sensitivity analysis. Values of $A_{Threshold}$ = 10,000 m^2, Mannings n = 0.03, and V(Hillslope)$_{Min}$ = 0.005 m/s were used for both catchments, while V(Channel)$_{Max}$ = 1 m/s and $V_{Transition}$ = 0.02 m/s produced a suitable UH for the Bakers Range catchment, and V(Channel)$_{Max}$ = 3 m/s and $V_{Transition}$ = 0.05 m/s for the Naracoorte Creek catchment. These results suggest that suitable unit hydrographs can be generated from only elevation observations for use in rainfall runoff modelling. Further work is required to apply a similar approach to a range of catchments, to investigate if the parameter values involved can be derived from observable catchment characteristics, such as soil types, land use, channel cross sections, or average or local slopes. This would allow streamflow to be estimated for ungauged catchments, where a lack of streamflow data prohibits the calibration of more traditional models, but where suitable GIS data are available.

ACKNOWLEDGMENTS

This work is supported by the Australian Research Council through its Linkage scheme and the South Australian Department of Water, Land and Biodiversity Conservation as industry partners. Their contribution to this work is gratefully acknowledged, especially that by Darren Willis, Mark deJong, and Chris Medlin.

REFERENCES

Andrews, F. (2007), Hydrosanity: a Starting Point for Hydrological Analysis, in Oxley, L. and Kulasiri, D. (Eds), MODSIM 2007 International Congress on Modelling and Simulation, 1540-1546.

Cleveland, T. G., Thompson, D. B., Fang, X. and He, X. (2008), Synthesis of unit hydrographs from a digital elevation model, *Journal of Irrigation and Drainage Engineering-ASCE,* 134, 212-221.

Cukier, R. I., Levine, H. B. and Shuler, K. E. (1978), Nonlinear Sensitivity Analysis of Multiparameter Model Systems, *Journal of Computational Physics,* 26, 1-42.

Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T. (2002), A fast and elitist multiobjective genetic algorithm: NSGA-II, *IEEE Transactions on Evolutionary Computation,* 6, 182-197.

Eckhardt, K. (2005), How to construct recursive digital filters for baseflow separation, *Hydrological Processes,* 19, 507-515.

Fleming, M. and Neary, V. (2004), Continuous hydrologic modeling study with the hydrologic modeling system, *Journal of Hydrologic Engineering,* 9, 175-183.

Kollat, J. B. and Reed, P. M. (2007), A computational scaling analysis of multiobjective evolutionary algorithms in long-term groundwater monitoring applications, *Advances in Water Resources,* 30, 408-419.

Linsley, R. K., Kohler, M. A. and Paulhus, J. L. H. (1988), Hydrology for engineers, McGraw-Hill, New York.

Maidment, D. R. (1993), Developing a Spatially Distributed Unit Hydrograph by Using GIS, in Kovar, K. and Nachtnebel, H. P. (Eds), Applications of GIS in hydrology and water resources management, April, 181-192.

Morris, M. D. (1991), Factorial Sampling Plans for Preliminary Computational Experiments, *Technometrics,* 33, 161-174.

Noto, L. V. and La Loggia, G. (2007), Derivation of a distributed unit hydrograph integrating GIS and remote sensing, *Journal of Hydrologic Engineering,* 12, 639-650.

Post, D., Vaze, J., Chiew, F. H. and Perraud, J. (2008), Impact of rainfall data quality on the parameter values of rainfall-runoff models: implications for regionalisation, in Lambert, M., Daniell, T. and Leonard, M. (Eds), Water Down Under, 14-17 April, 2315-2326.

Ravalico, J. K., Maier, H. R., Dandy, G. C., Norton, J. P. and Croke, B. F. W. (2005), A Comparison of Sensitivity Analysis Techniques for Complex Models for Environmental Management, in Zerger, A. and Argent, R. M. (Eds), MODSIM 2005 International Congress on Modelling and Simulation, 2533-2539.

Rodriquez-Iturbe, I. and Valdes, J. B. (1979), The geomorphologic structure of hydrologic response, *Water Resources Research,* 15, 1409–1420.

Saltelli, A., Chan, K. and Scott, E. M. (2000), Sensitivity Analysis, Wiley, New York.

Saltelli, A., Tarantola, S. and Chan, K. P. S. (1999), A quantitative model-independent method for global sensitivity analysis of model output, *Technometrics,* 41, 39-56.

Sobol', I. M. (1993), Sensitivity Analysis for Nonlinear Mathematical Models, *Mathematical Modeling & Computational Experiment,* 1, 407-414.