The Importance of Rainfall Models in Catchment Simulation

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Abstract: Catchment management is a complex task that, over the past decade, has become increasingly important to the community. Information for this management increasingly is being obtained from implementation of catchment modelling systems. Implementation of a catchment modelling system requires three steps, which are the calibration of the system, the validation of the calibration, and the extrapolation of the system to different hydrologic events and catchment conditions. The robustness of the simulations when this extrapolation is undertaken is related to the calibration and validation of the catchment modelling system, which in turn are impacted by the quality and reliability of the input data. A catchment modelling system for simulation of catchment processes can be considered to consist of four conceptual components. Within each of these components, there are many alternative transformations available with each of these transformations being the result of different combinations of process models. The concept of system calibration is to select the appropriate transformations and input information that best represents the catchment being simulated. Within the generation component an important aspect is the model used to transform the point rainfall measurements into a spatially distributed rainfall over the catchment. There have been many alternative models proposed for this transformation. Presented herein is an analysis of the influence of alternative rainfall models on the simulated hydrograph and hence the influence on the system calibration. This analysis will be based on real events recorded at the outlets of the Centennial Park catchment (1.3km^2) and the Upper Parramatta River catchment (110km^2) in Sydney, Australia. It was found that an increase in the robustness of the predictions obtained was related directly to the storm variability as defined by the spatial and temporal semi-variograms developed during the study.

Keywords: *Rainfall, Hydroinformatics, Runoff, Catchment*

1 INTRODUCTION

Management of the quantity and quality of water in urban drainage systems is a complex task which has become increasingly important to the community over the last few decades. This community awareness has increased the need for managers of these systems to obtain information relevant to the response of the systems invested in their control. Two methodologies by which the desired system information can be obtained are, firstly, through monitoring of the system for stormwater quantity and quality, and, secondly, by mathematical simulation through application of catchment modelling systems. Where management changes to the drainage system are proposed and it is desired that the impacts of these changes be predicted, it is necessary to use the second methodology; the first methodology can only provide historical information after implementation of the proposed management changes.

Following a reductionist philosophy, catchment modelling systems comprise numerous process models which simulate pertinent hydrologic and hydraulic processes influencing the quantity and quality of runoff from a catchment. In general, these process models are formulated as a mathematical system which is amenable to either analytical or numerical evaluation. In reviewing a system of this kind, it is convenient to arbitrarily subdivide the total modelling system into a number of conceptual components with each of these conceptual components consisting of process models simulating pertinent catchment processes. One conceptual subdivision is that shown in Figure 1 which was first presented by Ball (1992) and consists of the following four components

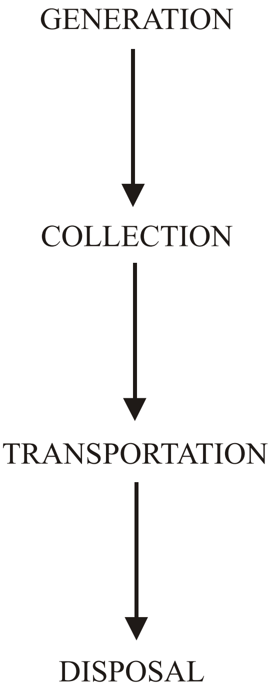

Figure 1 - Catchment Modelling System Conceptual Components

- *Generation* - the primary concern is the estimation of the available quantity of water and pollutant constituents;
- *Collection* - the primary concern is the prediction of the quantity and quality of flow at the entry point to the transport component - the hydrologic component of the system;
- *Transport* - primary concern is the motion of the water and constituents along the channels - the hydraulic component of the system; and
- *Disposal* - primary concern is how the runoff and constituents are discharged into receiving

waters.

One of the concerns of the *Generation* component is the rainfall model necessary to estimate the spatial and temporal distribution of rainfall over the catchment. The influence of the selected rainfall model on the predictions obtained from a catchment modelling system applied to an urban catchment is the focus herein. Furthermore, this influence and its relationship to the spatial and temporal variability of storm events will be investigated.

2 STUDY CATCHMENTS

Two urban catchments, which are different in size and with entirely different configurations of pluviometers were used in this study; these catchments were the Upper Parramatta River Catchment and the Centennial Park Catchment. These two urban catchments are located within the metropolitan area of Sydney as shown in Figure 2. For consistency, the catchment simulation model used for bot catchments was the Stormwater Management Model (SWMM) while the observed flows at the catchment outlet were utilized in assessing the influence of the rainfall model on the catchment simulation.

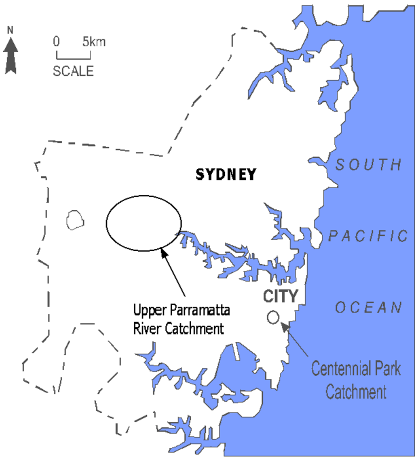

Figure 2 - Study Catchments

2.1 Upper Parramatta River Catchment

As shown in Figure 2, the Upper Parramatta River Catchment is located in the western suburbs of Sydney, Australia. Covering an area of 110km^2, it contains a population of more than 220,000 and is bounded by Prospect Reservoir to the southwest, Blacktown to the northwest, Castle Hill to the north and Carlingford to the east. The stormwater system within the catchment consists of a series of pipes, box culverts, open channels and creeks which ultimately discharge into the Parramatta River .

There are fourteen telemetered pluviometers within the Upper Parramatta River Catchment; locations of these gauges are shown in Figure 3. All of these gauges are 0.2mm tipping bucket pluviometers and have have been installed and maintained by the Upper Parramatta River Catchment Trust since its formation in 1989. Records from these fourteen pluviometers were obtained for the years from 1996 to 1999. During this period, 26 storm events where the event total rainfall was greater than 10mm were extracted for use in the study.

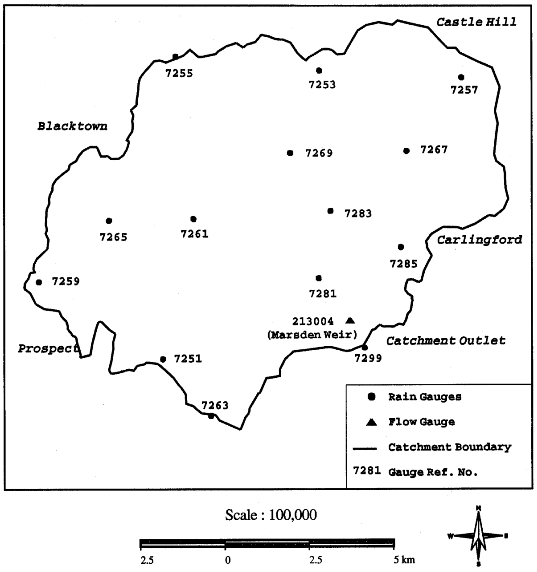

Figure 3 - Upper Parramatta River Catchment

2.2 Centennial Park Catchment

The 132 ha (1.32km^2) Centennial Park Catchment is located approximately 4km south of the Central Business District of Sydney and 1km to the north-west of the University of New South Wales. The stormwater system within the catchment consists of a series of pipes, box culverts and open channels which ultimately discharge into Musgrave Pond in Centennial Park.

For this catchment, the four pluviometers around the outskirts of the Centennial Park Catchment were among the six pluviometers considered. These four pluviometers are located within a radius of 7km from the study area and were used to supplement the pluviometers located within the catchment. The locations of these pluviometers are shown in Figure 3. All of these gauges are digitally logged 0.2mm tipping bucket pluviometers except for the Paddington gauge which has a 0.5mm bucket. The rainfall data used for this study were extracted from the HYDSYS database in the School of Civil and Environmental Engineering at UNSW. Events with more than 10mm in total were used in this study and based on this approach, 13 events from 1997 to 1999 were extracted for analysis.

2.3 Catchment Modelling System

For consideration of the importance of the rainfall model in a catchment modelling system, both catchments were simulated using the Stormwater Management Model (Huber and Dickinson, 1988). In the case of the Upper Parramatta River catchment was subdivided into 29 subcatchments after Downes

(1998) while the Centennial Park Catchment was subdivided into 42 subcatchments, after Abustan (1997), with the size of the individual subcatchments ranging from 0.5ha to 27ha.

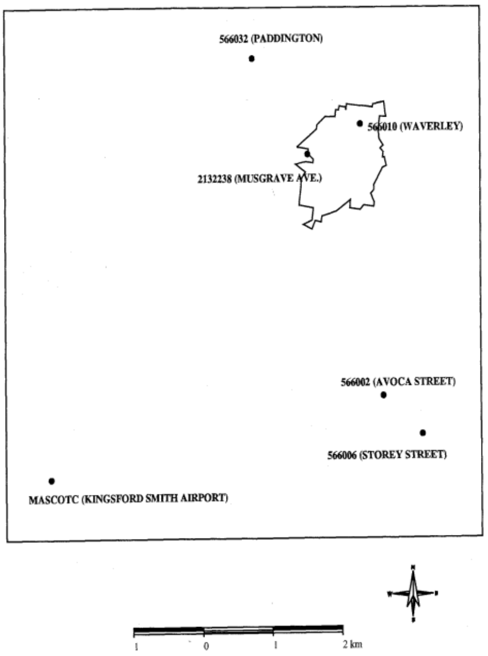

Figure 4 - Centennial Park Catchment

3 RAINFALL HETEROGENEITY

3.1 Classification of Storm Events

Prior to discussing the importance of the rainfall model on the catchment simulation, it is necessary to define the temporal and spatial variability of storm events. Using the estimators proposed by Umakhanthan (2002), it is possible to classify different events into one of the following four categories

- High Spatial and High Temporal heterogeneity
- High Spatial and Low Temporal heterogeneity
- Low Spatial and High Temporal heterogeneity
- Low Spatial and Low Temporal heterogeneity

An event classified as having a high spatial variability will show a minimum or no dependency between instantaneous rainfall data obtained from different gauges. In a similar manner, an event classified as having a high temporal variability will show no uniformity in the time dimension.

3.2 Rainfall Semi-Variograms

The basis of the categorisation is the determination of spatial and temporal semi-variograms for each event. Previous studies such as those by Bastin et al. (1984) and Storm et al. (1989) have shown the utility of the semi-variogram approach in estimating the average annual, monthly and daily precipitation values respectively for catchments. Despite the fact that these studies in the past considered the seasonal trend when producing the yearly and monthly variograms (temporal dimension), the potential spatial variability of different events within the periods considered was not incorporated in their analyses.

In general, rainfall data are available only at a limited number of locations which, usually, are located randomly across a catchment. The resultant scarcity of the data requires the use of analytic semi-variogram models. Gaussian, exponential and spherical models have been offered as acceptable models to represent stationary semi-variograms. In a similar manner, power, linear and logarithmic models have been proposed as acceptable models to represent non-stationary semi-variograms. While the range of parametric experimental semi-variogram models is extensive, previous hydrologic applications, see for example Bastin et al. (1984), and Storm et al. (1989), suggest that fairly simple power function models can be used with reliability. Consequently, power function models were used in developing the semi-variograms for the Upper Parramatta River and Centennial Park catchments. As described by Umakhanthan and Ball (2002a), the spatial semi-variogram function was computed for the complete event using every pair of pluviometers within the hydrometric networks used for the two catchments considered. The semi-variogram obtained was plotted against the separation distance of the corresponding gauge pairs in order to form a scatter plot known as a raw variogram for that event. Typical raw variograms computed for events which occurred on 27th July 1996 and 2nd May 1998 over the Upper Parramatta River Catchment are shown as Figure 5.

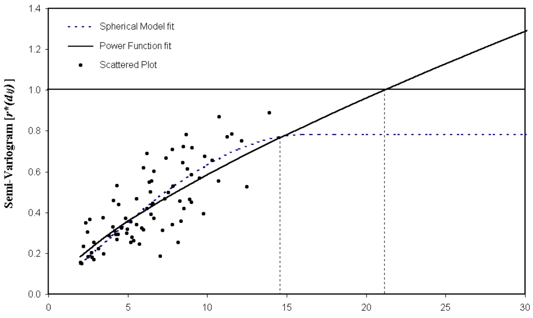

Figure 5a - Raw variogram for 27th July 1996 Storm Event on the Upper Parramatta River Catchment

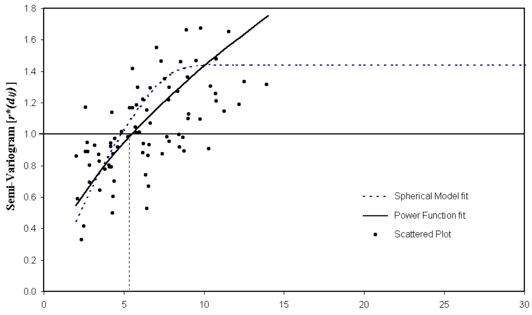

Figure 5b - Raw variogram for 2nd May 1998 Storm Event on the Upper Parramatta River Catchment

To categorise events according to their spatial variability, it is necessary to define a measure of the spatial variability. The basis of this measure was the separation distance to a semi-variogram value of 1, ie the separation distance resulting in no correlation. This separation distance can be considered as the distance by which a storm cluster holds a spatial dependence. If the raw variograms shown in Figure 5 are considered, then it can be seen that the separation distance for the 27th July 1996 event is approximately 21km while that for the 2nd May 1998 event is approximately 5km. For purposes of storm event classification, it was considered that if the separation distance was greater than the scale of the catchment, then the storm was a low spatially variable event and the reverse was the case if the separation distance was less than the scale of the catchment. As discussed by Umakhanthan (2002), for the Upper Parramatta River and the Centennial Park catchments, the selected catchment scales were 20km and 7.5km respectively.

Similar to the estimation of the spatial semi-variograms, the temporal semi-variograms were calculated for different time lags individually for all events. The semi-variogram was calculated for each gauge record and averaged over all gauges used for that catchment. The calculated average semi-variogram for a particular event was then plotted against the corresponding time lags in order to estimate the temporal semi-variogram corresponding to that event. Typical semi-variogram patterns for selected events from the Upper Parramatta River catchment and the Centennial Park catchment are shown in Figure 6.

In this case, the classification of individual storm events was based on the correlation of the time lag within of the storm event with the lag where a null correlation existed defining the extent of temporal correlation. Based on an analysis of the catchment response times, the adopted catchment temporal scales were lags of 10 and 20 for the Centennial Park and Upper Parramatta River catchments respectively. Where the extent of temporal correlation was less than the adopted catchment response time, then the storm was considered to have high temporal variability. For the reverse situation, the storm was considered to have low temporal variability.

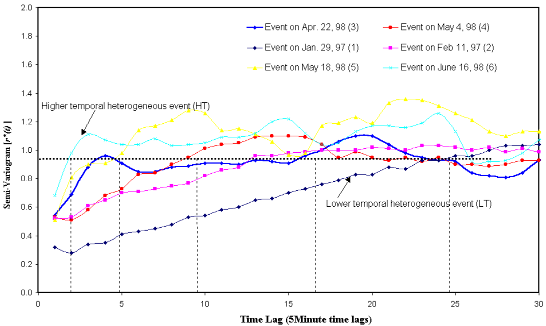

Figure 6a - Temporal Semi-variograms for the Centennial Park catchment

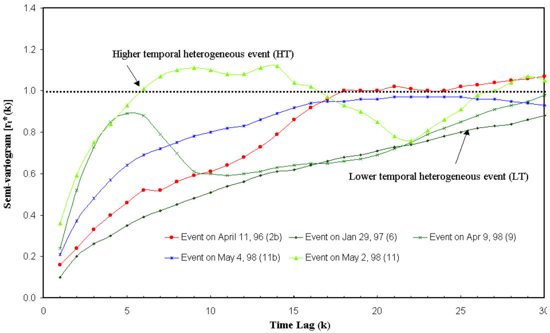

Figure 6b - Typical temporal semi-variograms for the Upper Parramatta River catchment.

Based on the developed spatial and temporal variograms, the individual storm events over the two catchments were classified into the four categories previously noted. Shown in Figure 7 is a graphical representation of the resultant storm event classification.

4 MODELLING RAINFALL

A detailed rainfall distribution model in space and time was developed for the study catchments within a GIS framework. The basis of this model for estimating the spatial and temporal distribution of rainfall is an extension of the model developed by Ball and Luk (1998) through a temporal discretisation of the storm event as discussed by Umakhanthan and Ball (2000). Based on the rainfall recorded at pluviometers, the spatial distribution of rainfall was ascertained at five-minute increments using a thin plate spline algorithm which has been used previously to spatially interpolate hydrological phenomena by, for example, Hutchinson (1995) and Ball and Luk (1998). The method employed for estimation of the spatial distribution at five-minute increments can be summarized as

- For each rainfall gauge, rainfall data were extracted from HYDSYS.

- The extracted data were appended and converted to an Arc-Info compatible format.

- For each time step;
  - < Rainfall data were loaded into Arc-Info and spatially linked to the locations of the gauges.
  - < A rainfall grid was interpolated from the current rainfall intensities using a thin plate spline surface interpolation technique.
  - < Subcatchment grids were combined with the rainfall grid to produce the mean rainfall within subcatchment boundary.

- The subcatchment rainfall were extracted as time series hyetographs to produce the rainfall input in a compatible format for the Catchment Modelling System to be used.

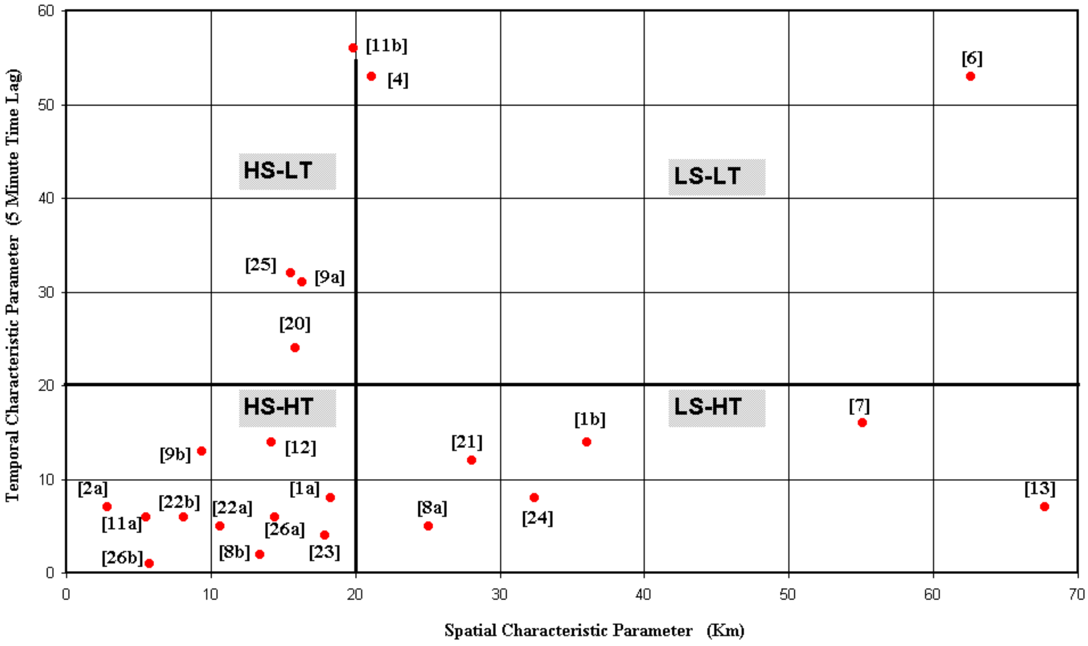

Figure 7 - Classification of Storm Events occurring over the Upper Parramatta River Catchment

5 IMPACT OF RAINFALL MODELS ON RUNOFF PREDICTION

While the techniques outlined above can be used to determine the variability of an individual storm event, it remains to determine the influence of the rainfall variability on the predictions obtained from a catchment modelling system. These impacts were ascertained by considering the prediction errors resulting from the use of two alternative rainfall models with a catchment modelling system and recorded data. These two alternative rainfall models were the detailed rainfall model described previously and a rainfall model based on Theissen polygons while the catchment modelling system used, as previously discussed, was SWMM.

Prediction accuracy, as outlined by Lettenmaier and Wood (1993), is a measure of the difference between predicted and observed values and is best assessed by retrospective comparison of the values. There are many performance measures inclusive of the Mean Square Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Variance, Bias and Absolute Errors. Each of these alternative measures has advantages and disadvantages which, in turn, are related to the problem requiring development of the model.

Shown in Figure 8 are the predicted hydrographs obtained using both rainfall models for the 18th October 1999 storm event which is typical of other storm events. The improvement in prediction of the peak discharge for the events considered in the study are summarised in Figure 9. As shown in this figure, the spline surface rainfall model consistently resulted in a better fit to the recorded event than the Thiessen rainfall model.

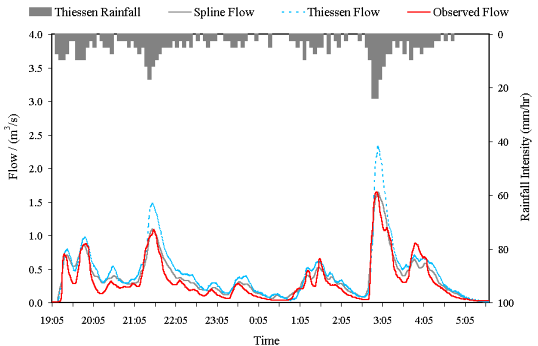

Figure 8 - Event of 18th October 1999

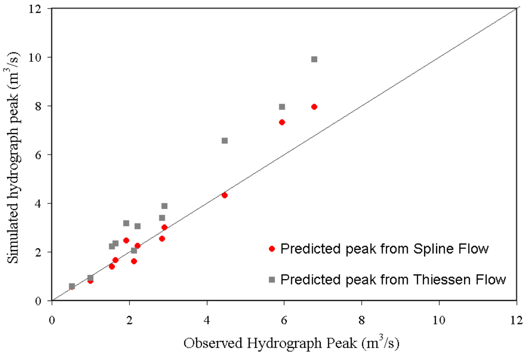

Figure 9 - Comparison of Estimated Peak Flow

An interesting issue is whether the magnitude of the improvement in the predicted hydrograph is related to the spatial variability of the storm event as measured using the variogram technique outlined earlier. Umakhanthan and Ball (2002b) present

Table 1 - Performance Statistics for Alternative Rainfall Inputs

Measure	'LS' event on 19/10/1998			'HS'Event on 09/10/1998		
	Spline	Thiessen	Imp.	Spline	Thiessen	Imp.
MSE - $(m^3/s)^2$	0.001	0.001	0	0.002	0.011	0.009
RMSE - (m^3/s)	0.032	0.032	0	0.045	0.105	0.060
MAE - (m^3/s)	0.024	0.026	0.002	0.025	0.046	0.021
Variance - $(m^3/s)^2$	0.001	0.001	0	0.002	0.010	0.008
Bias - (m3/s)	-0.005	-0.001	-0.004	-0.002	0.032	0.030
Variation in Peak (%)	6.5	14.0	7.5	-11.6	42.6	31.0

various measures of fit for two storm events which occurred on 19th October 1998 (low spatial variability) and 9th October 1998 (high spatial variability). Presented in Table 1 are the performance parameters for these two events and the improvement in the performance parameters. As indicated by an analysis of these performance parameters, the improvement in the catchment modelling system predictions arising from the changed rainfall model are a function of the spatial variability of the rainfall. Hence, it can be concluded that the more variable the rainfall, the greater the need for a rainfall model which incorporates this variability in space and time.

6 CONCLUSIONS

Reported herein have been the results of an investigation into the importance of the rainfall model for robust predictions from catchment modelling systems. Two alternate rainfall models, namely a Thiessen based rainfall model and a spline surface rainfall model, were considered. It was found that the rainfall model significantly influenced the predicted hydrographs obtained from a catchment modelling system. Furthermore, it was found that the spline surface rainfall model, which considered the spatial and temporal variability of the rainfall in greater detail than the Thiessen rainfall model resulted in predicted hydrographs that more closely duplicated the recorded hydrograph for the same parameter set. The degree of this improvement in the predicted hydrograph was found to be dependent on the spatial and temporal variability of the storm event.

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