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

The effect of the raingauge distribution on stormwater models

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Abstract: It is well known that the accurate representation of spatial variation of rainfall within a catchment is important in achieving reliable outcomes from stormwater models. Various guidelines recommend different densities of raingauge distribution to sufficiently capture and represent the rainfall variation within catchments. The cost of installing a rain-gauge may be insignificant compared to the benefit to be gained from more accurate modelling outcomes. To observe and quantify the effect of raingauge distribution and to understand the limitations of guidelines, a modelling study was undertaken. The study involved collection of data from a network of raingauges and a flow gauge in a small stormwater catchment, development and calibration of a stormwater model for the catchment, and the evaluation of the sensitivity of the model to spatially distribution of rainfall data.

Three methods of rainfall data assimilation were tested with varying raingauge densities. The outcome of this modelling study confirms that the difference between the actual and the model-simulated peak flow from the catchment increased with decreasing raingauge density. The paper summarises the quantitative results obtained in this modelling study and concludes that the most robust stormwater model will be that calibrated using rainfall data gathered from within the catchment being modelled. Using a dense network of raingauges and assigning rainfall data from the nearest gauge, rather than station averaged and/or Thiesson polygon weighted sum, from a network of gauges emerges as the best approach for accurately estimating runoff peak from this small urban catchment. It is proposed that much greater emphasis should be placed on gathering adequate rainfall data to achieve specific modelling objectives given that the installation and operation of a raingauge is relatively inexpensive.

Keywords: *Rainfall-runoff models, MOUSE®, Raingauge density*

1. INTRODUCTION

The accurate representation of the rainfall data is paramount in obtaining close-to-reality runoff forecasts from hydrological/hydraulic models. Rainfall is the primary entity behind stormwater runoff and its spatial variability is a significant source of uncertainty for hydraulic modelling (Berne et al., 2004). A published study on a high intensity rainfall event that occurred in July 1997 near Fort Collins, Colorado found that in urbanised catchments rainfall estimation errors give rise to significant errors in runoff predictions and that uncertainty in (catchment) characteristics has a considerably smaller effect on runoff predictions than uncertainty in the space/time distribution of rainfall (Ogden et. al., 2000, pg82).

Rainfall regimes with strong spatial and temporal variation are characteristic of coastal areas around Auckland, New Zealand. Various guidelines make different recommendations as to the optimum density of raingauge distribution to enable the capture of all the spatial variations (WaPUG, 2002; ARC, 1999). From a cost point of view the installation of an additional raingauge is inexpensive. As such, it was considered worthwhile to quantify the improvement to the model predictions, if any, that can be achieved by increasing the density of raingauge distribution and to demonstrate the importance of variations in the spatial and temporal pattern of rainfall to both the expected accuracy of the model in predicting accurate peak flows and to produce appropriate calibration of the rainfall-runoff routing model parameters.

2. METHODOLOGY

2.1 Monitoring Network

To enable this study, a network of 10 raingauges and a flow gauge was deployed for a period of 2 weeks. The gauges were distributed in a manner that enabled the same rainfall event to be represented using several rainfall data composition methods. Figure 1 adjacent depicts the layout of the rain and flow gauges.

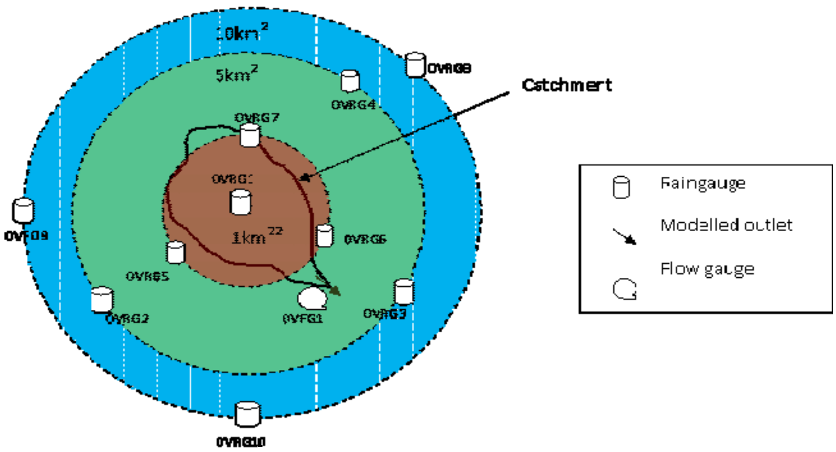

Figure 1. Schematic of the layout of the catchment and rain/flow gauges

The first raingauge (OVRG1) was located approximately at the centroid of the catchment, 3 gauges (OVRG5, OVRG6, OVRG7) were placed to represent an area of 1km², another three gauges (OVRG2, OVRG3, OVRG4) to represent an area of 5 km² and the last three gauges (OVEG8, OVRG9, OVRG10) to represent an area of 10km².

2.2 Location

A stormwater sub-catchment within North Shore City, Auckland, New Zealand was chosen for this study. The reasons for the choice included the fact that a model had already been developed for this catchment, the land use types within the catchment were a good representative mix of those found in the North Shore City, and the catchment had a single outlet that dropped some 4m into receiving waters, thereby eliminating the hydraulic complications of backwater effects.

2.3 Hydraulic Model

The original hydraulic model of the catchment (NSCC, 2006) has been developed using Danish Hydraulic Institute (DHI)'s MOUSE® 2005 hydraulic modelling software (DHI, 2007). Catchment in this study forms a part of that larger catchment and hence the appropriate part of the model was truncated to include only 51.08ha of catchment with a total pipe/channel length of 3.49km. The truncated model is made up of 33 sub-catchments, ranging in size from 0.42ha to 10.14ha, averaging at 1.55ha. The reticulation is made up of 87 circular pipes ranging in diameter from 300mm to 1780mm, two open channels and one outlet. Overall, 35.6% of the catchment is impervious.

The model used the unit hydrograph method to determine the storm runoff. The focus in this work was the peak flow rate calibration; a measure of the predictive power of the model was also compared with Nash-Sutcliffe index (NSI) values.

2.4 Hydraulic Model simulations

The model was calibrated with the rainfall data collected at the centroid of the catchment. The calibration parameters were then frozen and, using the calibrated model, simulations were carried out using as model input the rainfall time series computed in three different ways, namely, station average, Thiesson polygon weighted sum method, and actual rainfall from the nearest station. The effect of raingauge density was tested by including only those raingauges placed to represent a given zone, e.g. the 5km² zone represented by the rainfall data collected at gauges OVRG2,3 and 4.

3. DATA

Rainfall and flow data for this research was collected for a total of 22days from 20th June to 12th July 2008. Table 1 summarises the total rainfall depths recorded at the respective raingauges placed at varying distances from the centroid of the catchment to represent a uniform distribution of gauges for zones of increasing size. As can be seen from the table, data for a total of 10 gauges were collected with one gauge at the centroid of the catchment, 3 gauges to represent an area of 1km² area, another 3 to represent an area of 5km², and the last 3 to represent an area of 10km². The total rainfall depth measured at the gauges varied from a minimum of 100.6mm to 147.6mm with a standard deviation of 15.8 mm; such spatial variation is characteristic to this and other areas in Auckland.

Table 1. Total rainfall depths recorded at the raingauges

Zone	Raingauge IDs representing the zone	Total rainfall (mm) for 20/6/08 – 12/7/08
Catchment Centroid	OVRG1	143.0
$1km^2$	OVRG5	115.4
	OVRG6	145.0
	OVRG7	100.6
$5km^2$	OVRG2	132.2
	OVRG3	147.6
	OVRG4	130.6
$10km^2$	OVRG8	138.4
	OVRG9	114.4
	OVRG10	142.6

Frequent storms were experienced during the period of data gathering, with more than 18 rainfall events resulting in distinct peaks in the runoff hydrograph. Each event varied in intensity, frequency and duration, and correspondingly in runoff volumes. The largest event of the monitoring period had a total of 8.4mm of rainfall on the 28th June 2008 from 06:50 to 09:20 (average rate of 3.4mm/hr). The rainfall and flow data for this event are shown in Figure 2 in which the primary axis shows the flow rate observed at the catchment outlet (along with the model predicted flow after calibration) and the inverted secondary y-axis shows the rainfall depth measured at the centroid of catchment in 5min intervals. This event was selected for use in this study based on three main considerations:

1. availability of good quality recorded flow data corresponding to this rain event;
2. prevalence of a near dry weather period preceding this event; and
3. the existence of a post-event dry weather spell that allows full recession of the hydrograph to pre-event flow rates.

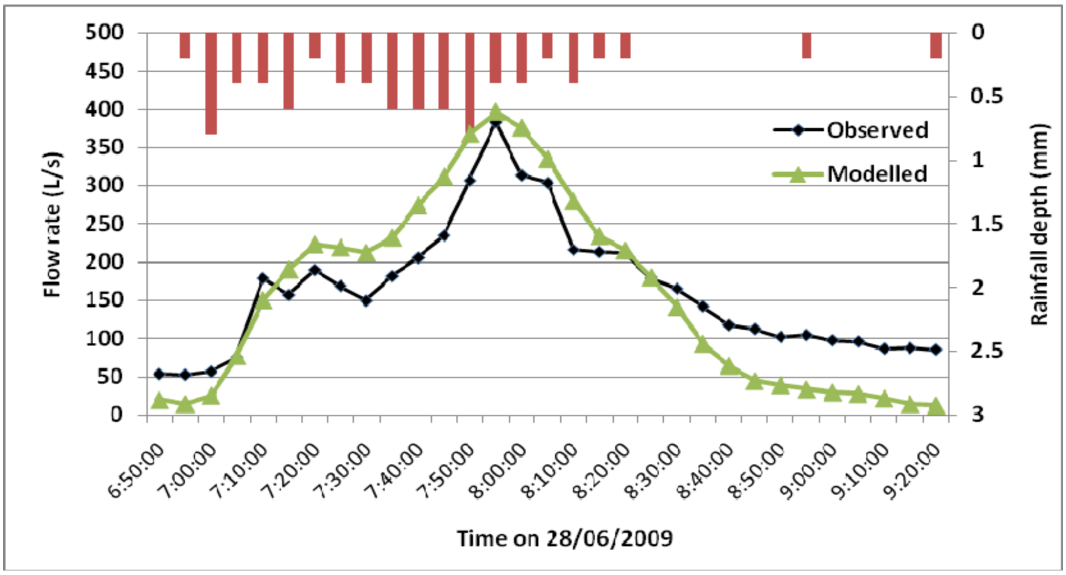

Figure 2. Storm runoff hydrographs and rainfall hyetograph for the selected event.

4. RESULTS

The MOUSE® hydraulic model was first calibrated with the rainfall data collected at the centroid. Table 2 shows the peak flow statistics indicating a high agreement (3.6% over prediction) with the observed peak flow rate at the catchment outlet. The model-predicted hydrograph fairly closely follows the observed hydrograph as can be seen in Figure 2.

Table 2. Calibration goodness-of-fit of peak flow rate

Modelled peak flow rate (L/s)	397
Observed peak flow rate (L/s)	383
Error	3.6%

The model simulations carried out with different representative rainfall time series are presented in the following sub-sections.

4.1 Station average rainfall method

The station average rainfall was calculated simply by averaging the rainfall recorded in the three gauges representing the zone to form one rainfall data time series at a single 'virtual' raingauge. Each group of raingauges (made up of three) for a zone was considered providing an indication of the potential model accuracy from decreasing raingauge density. It has been shown that averaging of temporal patterns from gauges across a region results in a reduction in the variability of rainfalls between timesteps in the event (eg. Jordan and Seed, 2002). As shown in Figure 3, the results for this small urban catchment confirm that the predicted peak is increasingly under-predicted as the raingauge density decreases.

4.2 Thiesson polygon rainfall method

The next model simulation scenario used a Thiesson polygon weighted sum method to represent the rain gauges by a single 'virtual' raingauge. Again, each group of raingauges was treated individually, providing an indication of the potential model accuracy implication of decreasing raingauge density. Figure 4 shows the predicted flow hydrographs in comparison to the observed one. The difference between the three rain-gauge densities for this approach is not significant; however, the degree of underestimate compared to the station average appears much higher.

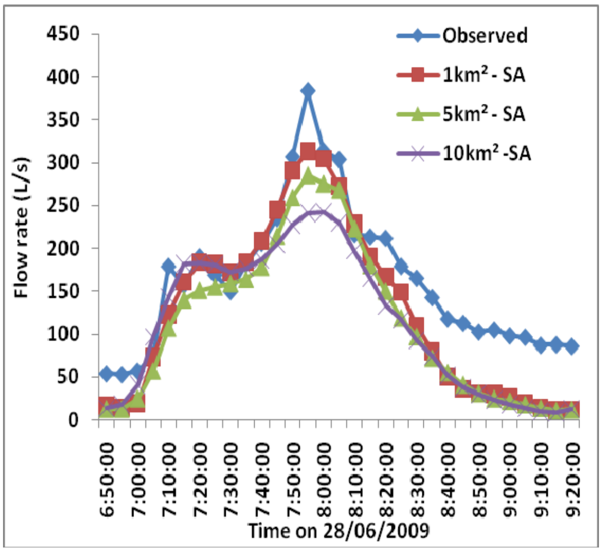

Figure 3. Simulation results using station average

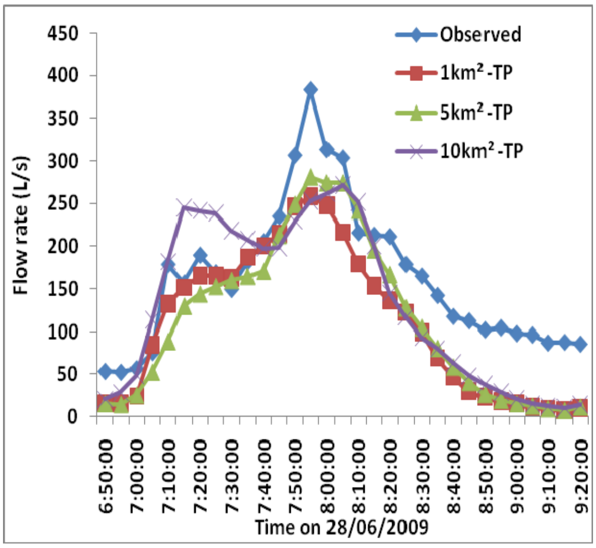

Figure 4. Simulation results from Thiesson polygon

4.3 Nearest station rainfall method

The results of the simulations carried out by assigning to each sub-catchment the rainfall data from the raingauge nearest to the centroid of that sub-catchment shows, as in Figure 5, that there is significant deterioration of model predicted peak flow as the density of raingauges increases.

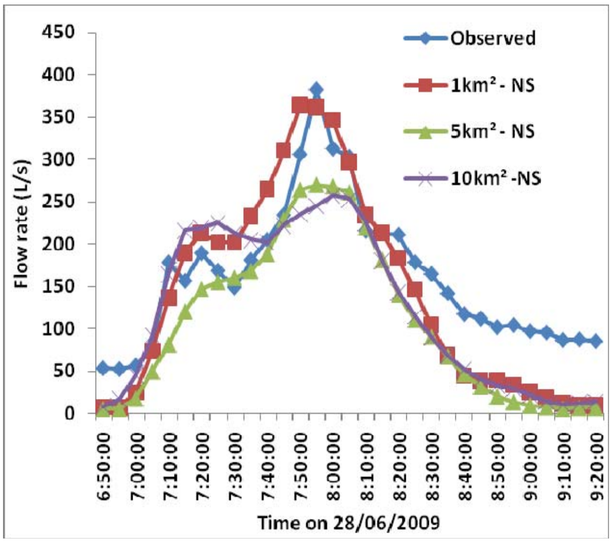

Figure 5. Simulation results using nearest gauge rainfall

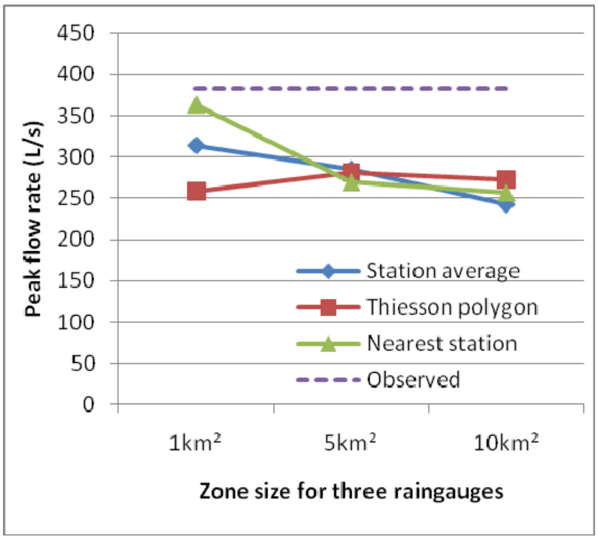

Figure 6. Simulated and observed Pak flow rates

Figure 6 shows how the predicted peak flow rates obtained from various raingauge densities and rainfall representations compare with the observed. Bearing in mind that the peak flow rate obtained from the raingauge at the centroid of the catchment (used in calibration) was a 3.6% over-estimate, it appears that using rainfall data from a network of gauges, irrespective of the raingauge density, has in general given rise to an under-estimate of the peak flow rate. Table 3 summarises the prediction errors and the general model predictability in terms of the achieved Nash-Sutcliffe index (NSI) for the simulations.

As far as the prediction of peak flow rate is concerned, the application of rainfall data from the nearest gauge when the raingauge density is high (-4.9% error) appears to be the next best to having a gauge at the centroid of this catchment (+3.6% error). However, the prediction accuracy steadily decreases with decreasing raingauge density. Using a Thiesson polygon weighted sum method to represent rainfall data with a single virtual station does not appear to be an approach with a predictable outcome with mixed signals for the prediction error for decreasing raingauge density.

Table 3. Comparison of predicted peak flow rates and Nash-Sutcliffe Indexes

Area for 3 raingauges	1km²	5km²	10km²
Peak flow prediction error			
Station average (%)	-18.0	-25.6	-36.8
Thiesson polygon (%)	-32.6	-26.6	-29.0
Nearest station (%)	-4.9	-29.5	-32.9
Nash-Sutcliffe Index (NSI)			
Station average	0.65	0.55	0.43
Thiesson polygon	0.42	0.53	0.44
Nearest station	0.58	0.41	0.44
Calibrated	0.60	0.60	0.60

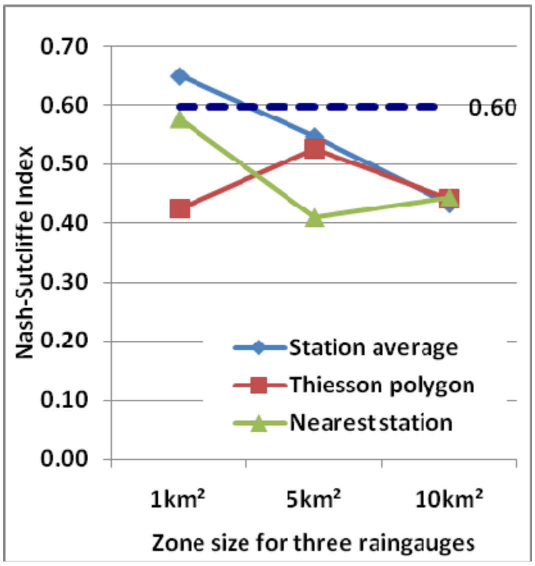

Figure 7. Variation of Nash-Sutcliffe Index

Figure 7 shows graphically the variation of the NSI values tabulated in Table 3. The NSI indicates the general goodness-of-fit of the hydrograph rather than focusing on the peak flow rate alone; a high NSI (close to 1) represents high degree of goodness-of-fit. Bearing in mind that the NSI for the calibrated flow hydrograph is 0.6, it can be seen that the station average gives a better NSI (0.65) for the highest density of raingauges. This approach however also shows the steadiest and the most marked decrease in the NSI value with decreasing raingauge density. The nearest station method gives an NSI (0.58) fairly close to that of the calibrated value (0.6) for the highest density of raingauges. As this approach gives the best estimate of the peak flow rate as well, it could be said that this approach gives the best possible outcome both in terms of peak as well as the shape of hydrograph if the raingauges are within close proximity to each other.

The Thiesson Polygon approach once again gives mixed signals for varying raingauge density.

5. CONCLUSIONS

The following conclusions can be made:

- If the raingauge density is low, confidence in the accuracy and ability of the model as a tool to predict peak storm flow rates is diminished. Decreasing raingauge density has detrimental effect on the ability of the stormwater model to predict the peak flow rate as well as the shape of the runoff hydrograph.
- To estimate the peak flow rate from a small urban stormwater catchment, applying rainfall from a gauge at the catchment centroid or from gauges situated at a high density (3 gauges per 1km2) renders the best model to predict the peak flow rate; this is the most appropriate for design purposes.
- The best method to assign rainfall to a sub-catchment in the case of a high density raingauge configuration is to use the data from the gauge at closest proximity to the centroid of that sub-catchment. Accurate stormwater model calibration is best achieved by a dense network of raingauges. Reliance on radar rainfall estimates is a possible alternative to raingauges. Successful outcomes from this approach have been reported (e.g. Jordan and Hill, 2006).
- The Thiesson polygon method gives the most inferior peak flow prediction for a high density of raingauges and an inconclusive outcome with regard to a relationship between accuracy and raingauge density.

- A reduction of model prediction accuracy associated with a reduced raingauge density was most obvious with the station average and nearest station methods. The lower the raingauge density, the greater the modelled peak flow rate differed from that calibrated to a raingauge at the catchment centroid.
- Due to insufficient data was gathered to determine an exact relationship between modelled peak runoff rates and raingauge density. A qualitative relationship however, does exist.

There are several limitations of this research work:

- The deployment of a monitoring network in an uncontrolled environment, modelling assumptions, limited data collection and study of a single catchment.
- Modelling uncertainties are present in addition to measurement uncertainties. The unit hydrograph method employed for this model is thought to be the reason that the modelled storm recession falls away dramatically on the falling limb of the hydrograph. This is the nature of the unit hydrograph used in the model; it does not adequately represent groundwater storage following rainfall. This limitation is mitigated however by the primary purpose of the model being determination of peak flow rates, which the unit hydrograph shape does adequately.
- The model calibrated for this research has not been validated using a second rainfall event. As the poor quality flow data collected did not include a sufficiently long time series, the shape of the unit hydrograph used in the model did not represent post-event infiltration very well.

The following conclusions can be made with regard to the cost:

- Improvement in the accuracy of stormwater models can come from a number of sources; high accuracy asset data, extensive flow data from a comprehensive network of flow gauges or extensive rainfall data from a high density network of raingauges. In relative terms, the costs of operating a raingauge network are significantly lower than that of a flow gauge network or collection of high accuracy asset data. This is a function of the labour intensity required for the latter two options.
- Optimal model calibration will be achieved with a network that contains a higher raingauge to flow gauge ratio for the same total cost as a network with the inverse, a higher flow gauge to raingauge ratio.

ACKNOWLEDGEMENTS

The authors are thankful to Mr Tom Joseph and Mr Peter Stephens for their technical advice and guidance and North Shore City Council for use of the GIS data, Oteha Valley model and base data. The presenter would like to thank the financial support provided by Unitec New Zealand to present this paper at MODSIM09 in Cairns, Australia in July 2009.

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