Sensitivity of Simulated Catchment Response to the Spatial Resolution of Rainfall

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Abstract: The effect of the spatial resolution of rainfall on catchment hydrologic response was assessed by employing a distributed continuous model and radar rainfall data. The study was based on the field-data set provided by the MARVEX program in the Mahurangi, a 46km^2 catchment on the North Island of New Zealand. The model structure arose from the analysis of an intensive field study, including rainfall, runoff and spatial and temporal soil moisture patterns, conducted in a small sub-cachment (~1km^2). The model was tested against 28 internal flowgauges over a total period of two years. The long-term simulation provided the simulated antecedent catchment conditions for an event-based sensitivity analysis. This was conducted for four events employing radar rainfields with 150m grid-resolution and two-minute time resolution. Rainfields at different spatial resolutions served as model input and the deviations in catchment response were analysed for each sub-catchment identified by the flowgauge network, ranging in area from 0.3km^2 to 46km^2. Differences in simulated catchment response are highly correlated to differences in rainfall volume. Good estimates of rainfall volume can be achieved with 1.2km grid-resolution for the whole range of scales. No significant differences occur in the simulated catchment response when the rainfields of different spatial resolutions are scaled to the same basin-average values. At the analysed scales, rainfall spatial gradients are not strong enough to overcome the smoothing effects induced by models having saturation-excess as the dominant runoff generation mechanism.

Keywords: Rainfall spatial variability; Distributed hydrological modelling; Weather radar

1. INTRODUCTION

Remotely sensed rainfall observations from radars and satellites, and studies in rainfall modelling, estimation and forecasting, have demonstrated rainfall to be highly variable in space and time. The spatial variability is highly dependent on the scale of the measurement [e.g. Foufoula-Georgiou and Krajewski, 1995]. The scales at which the rainfall variability has a significant impact on the catchment response are not known. Previous studies investigating this issue have tested the sensitivity of hydrological models to different kinds of rainfall patterns. The studies differed in the kind of the catchment model and rainfall data applied. The spatial scale of analysis ranged from the hillslope to the large catchment scale (~1000km^2). The input rainfields were either measured or synthetic. Measured rainfields were derived either from raingauge networks or from meteorological radar images. The minimum radar grid-resolution employed was 400m [Pessoa et al., 1993]. Catchments were normally represented as semi-distributed or distributed, with a minimum spatial resolution ~100m [Ogden and Julien, 1994]. Only a few of the previous studies used rainfall data observed in the study area and hydrological models tested against observed data. Among these, radar data were applied only in one case [Winchell et al., 1998]. Where synthetic rainfall was used, the rainfall and hydrological models were not usually both tested against local data [Shah et al., 1996]. All the numerical experiments were event based and the model initial conditions, where explicitly discussed, were fixed on the basis of simplified assumptions. In only a few cases were the catchment initial conditions considered a source of variability [e.g. Shah et al., 1996]. The results of the previous studies are strongly affected by the specific characteristics of the experimental framework. In particular they are affected by the relative importance of dominant processes in the modelled catchment response. Models with infiltration excess as the only runoff generation mechanism were mainly applied. For these, runoff increases as the heterogeneity of the rainfall field is better represented [e.g Ogden and Julien, 1994; Winchell et al., 1998]. Runoff sensitivity is generally lower when saturation excess is dominant [Obled et al., 1994; Shah et al., 1996].

This study examined the sensitivity of a distributed model to the spatial resolution of radar rainfall data. The experimental framework was designed on the basis of field data collected in the Mahurangi catchment, a 46km^2 catchment in the North Island of New Zealand, during two years (1998-1999) of the MARVEX program [Woods et al., 2000]. Atkinson et al. [2001] made use of the MARVEX data set to investigate the minimum model complexity required for accurate flow predictions at different space and time scales. In particular, employing a semi-distributed model, they showed that accounting for rainfall variability is important for accurate predictions of the catchment internal variability of storm flow volumes.

In this study, a continuous distributed model was developed to simulate the catchment response during a two year period of field monitoring. This long-term simulation was used to define the catchment initial conditions for four storms, for which radar images with 150m-grid resolution and two-minute accumulation were available. The sensitivity of the modelled catchment response was evaluated for these four storms, applying rainfields with different spatial resolutions.

2. STUDY CATCHMENT AND DATA DESCRIPTION

The Mahurangi catchment extends for 12 km in the north-south direction, with a maximum width of 5km in the west-east direction. Two ranges of hills at the north and south extremes bound a wide central valley. The drainage network divides into two main branches near the outlet at the centre of valley. These spread into the northern and the southern sub-cathments (Figure 1). The elevation ranges from the sea level to approximately 360m above sea level. The catchment soils are mainly clay loam, not more than 1.1 m deep, developed above deeply weathered sandstone. The local climate is warm and humid, with typical annual rainfall of 1600mm. Thirteen raingauges well distributed in space and in elevation and 28 flowgauges (Figure 1 and Table 1) operated during 1998 and 1999. Other climatic data, such as minimum, maximum and average daily temperature and global solar daily radiation were also available from a local weather station.

Table 1. Mahurangi sub-catchments.

N.	Area (km^2)	N.	Area (km^2)	N.	Area (km^2)	N.	Area (km^2)
1	0.27	8	0.67	15	2.60	22	5.01
2	0.34	9	0.73	16	2.75	23	5.09
3	0.42	10	1.03	17	2.95	24	6.04
4	0.49	11	1.18	18	2.99	25	13.65
5	0.53	12	2.02	19	3.25	26	15.04
6	0.56	13	2.30	20	3.28	27	25.26
7	0.65	14	2.35	21	3.66	28	46.74

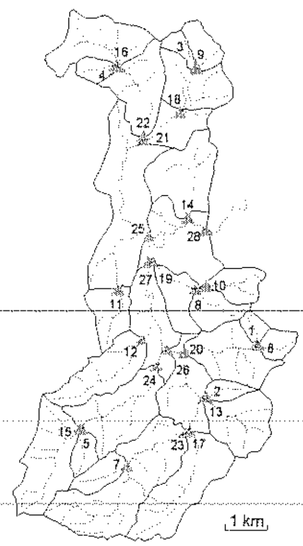

Figure 1. Mahurangi catchment: river network, flowgauge network and sub-catchment boundaries.

The radar data set used in this study was obtained using a small portable scanning X-band radar operated by the Physics Department of University of Auckland, New Zealand, as part of the MARVEX project [Woods et al., 2000]. The radar was sited in the south-west corner of the Mahurangi, at an altitude of 320m a.s.l.. The radar images were resolved into reflectivity images accumulated to 2 minutes, with a spatial resolution of 150m x 150m, on a grid of 50 x 150 pixels covering a domain 7.5km in the west-east direction and 22.5km in the north-south direction. Only four of the observed storms were suitable for model sensitivity analysis.

The transformation of the radar reflectivity images into rainfall maps represents a large source of uncertainty. Errors in precipitation data due to the transformation of reflectivity to rainfall can result in equal or larger-sized errors in simulated runoff-generation. Calibrating the reflectivity-rainfall transformation law for each storm is important to produce reliable hydrologic forecasts with radar estimated precipitation [Pessoa et al., 1993; Winchell et al., 1998].

In this study the Marshal and Palmer [1948] formula was employed to produce an initial estimation of the rainfield and then a simple bias adjustment with the raingauge data was performed following the method suggested by Collinge [1991]. Winchell et al. [1998] showed that more complete calibration procedures do not give significant improvements in runoff simulation. Radar images of one of the four events (the 9th of August 1998) were specifically corrected for radar signal attenuation effect. Radar images of two other events (the 27th of August 1998 and the 10th of November 1999) also present some attenuation effect, but this is limited to a very short period of higher rainfall intensity. These were not corrected.

Table 2. Basin-averages of radar rainfields.

Event	hours	μ_s (mm)	μ_a (mm/h)		μ_m (mm/h)	
		storm	2 min	10 min	2 min	10 min
09/08/98	38	107.6	3.34	3.34	21.52	19.58
18/08/98	18	26.3	1.70	1.70	4.34	3.80
27/08/98	13	31.0	2.40	2.41	10.01	8.66
10/11/99	13	21.8	1.89	1.92	9.60	7.81

Table 3. Coefficients of variation of the radar rainfields at the catchment scale.

Event	cv_s (mm)	cv_a (mm/h)		cv_m (mm/h)	
		2 min	10 min	2 min	10 min
09/08/98	1.00	1.37	1.24	1.12	1.04
18/08/98	1.00	1.13	1.09	1.02	1.01
27/08/98	1.03	1.91	1.69	1.08	1.06
10/11/99	1.01	2.17	1.88	1.04	1.07

The characteristic correlation length of the 2-minute accumulated rainfields is ~2.2km. Tables 2 and 3 report averages (μ) and coefficients of variation (cv) for the radar rainfields at the catchment scale. μ_s and cv_s refer to the storm accumulated rainfield; μ_a and cv_a are average values of all the rainfields with basin-average rainfall rate above 0.5mm/h, accumulated at 2 and at 10 minutes; μ_m and cv_m are the estimated values for the rainfield with highest basin-average rainfall intensity. There is limited change in the spatial structure of the rainfall from 2-minute to 10-minute accumulation, especially during the periods of high-intensity rainfall.

3. CATCHMENT MODEL

The model applied in this study is fully distributed and continuous. The choice to develop a continuous rather than a simpler event based model stemmed from the need to reduce the uncertainty in the definition of the catchment initial conditions for each of the events analysed. The catchment initial conditions were set on the basis of the long-term simulation using the tested model and they are considered a structural part of the "realistic" experimental framework, as important as any other component of the applied model.

The model structure arose from a detailed study of field-data collected in the parallel sub-catchments of Satellite Station Left (6 in Figure 1) and Satellite Station Right (1 in Figure 1) [Chirico et al., 2001]. The Satellite Station data set consists of flow and rainfall data integrated with six soil moisture patterns measured on six occasions, almost once every three months in 1998 and 1999 and six soil moisture monitoring stations.

The model includes a non-linear kinematic subsurface module, a non-linear kinematic surface module and a root-zone storage module. Only saturation-excess overland flow is simulated, as this is understood to be the dominant runoff generation mechanism in the Mahurangi catchment [Atkinson et al., 2001]. The model employs a computational network with a defined pattern of one-dimensional flow-paths. The computational network can be either contour-based or grid-based. The computational network for the Mahurangi was defined on a 25m-grid DEM employing a multiple-flow-direction algorithm and preserving the actual river network. The model was run on the whole Mahurangi catchment with 10-min time-step from the 1st January 1998 to the 31st of December 2000. The rainfields applied as input to the model were obtained by interpolating in space the raingauge hourly measurements with the Thiessen method. Spatial patterns of daily potential evapotranspiration depth were also applied. These patterns accounted only for topographic effects, while no attempts were made to simulate the effect of different vegetation covers. Soil depth, saturated moisture content and field capacity were defined for different soil classes, on the basis of the best information available. The residual soil moisture content and all the other sub-surface flow parameters were set equal to the values defined for the colluvial area of Satellite Station [Chirico et al., 2001]. No attempts were made to assess different root zone depths for different vegetation covers. Overland flow parameters were chosen equal to the average values suggested in literature. The catchment initial conditions for the 1st of January 1998 were set to those simulated for the 1st of January 1999, these being practically independent from the 1st of January 1998.

Table 4 reports the coefficients of efficiency [Nash and Sutcliffe, 1970] of the simulated flow for each sub-catchment. This study was not primarily concerned with assessing the performance of the hydrological model. However, testing the model against a representative field-data set supports the assumption that the processes occurring within the catchment are correctly described at least with respect to the space-time variability of fluxes and state variables at sub-catchment scale. This gives more confidence in extending the experimental results to contexts different from the original experimental conditions.

Table 4. Coefficients of efficiency for the 28 sub-catchments.

N.	COE	N.	COE	N.	COE	N.	COE
1	0.82	8	0.55	15	0.75	22	0.78
2	0.76	9	0.85	16	0.88	23	0.75
3	0.83	10	0.66	17	0.63	24	0.89
4	0.71	11	0.85	18	0.86	25	0.89
5	0.71	12	0.74	19	0.78	26	0.60
6	0.82	13	0.82	20	0.91	27	0.79
7	0.83	14	0.73	21	0.87	28	0.96

4. RADAR RESOLUTION ANALYSIS

Ogden and Julien [1994] observed that the effects of radar rainfall resolution on surface runoff modelling are originated both by storm and catchment smearing. Storm smearing occurs as rainfall resolution (L_R) approaches the characteristic spatial correlation length of the rainfall. Near this scale the rainfall gradients effectively reduce as grid sizes increase, with rain rates increasing in low-intensity regions and decreasing in high-intensity regions. Catchment smearing occurs when L_R approaches the characteristic dimension of the catchment. In this case the uncertainty of the location of the rainfall across catchment boundary increases, producing biased estimates of the total rainfall volume within the catchment. Catchment smearing is dominant in smaller catchments, while storm smearing is dominant in larger catchments.

In this study two sets of numerical experiments were designed in order to assess separately the effect of catchment and storm smearing across the range of scales defined by the 28 sub-catchments. The sensitivity of the catchment response was evaluated by applying radar rainfields with different spatial resolutions (L_R). The simulations with the finest rainfall resolution (L_{R1}=150m) were considered as the best results and used as reference values. For each sub-catchment, j, five different variables were examined in the sensitivity analysis: the rainfall volume $V_R(j,L_R)$; the flow volume $V_F(j,L_R)$; the peak discharge $Q_P(j,L_R)$; the flow peak-time with respect to the start time of the rainfall $T_P(j,L_R)$; the maximum variation of the contributing area during the storm $\Delta CA(j,L_R)$. The following indices were chosen to describe the model sensitivity:

$$VR_j = \frac{V_R(j,L_R)}{V_R(j,L_{R1})}; \qquad VF_j = \frac{V_F(j,L_R)}{V_F(j,L_{R1})}$$
$$PF_j = \frac{Q_p(j,L_R)}{Q_p(j,L_{R1})}; \qquad PT_j = \frac{T_p(j,L_R)}{T_p(j,L_{R1})}$$
$$CA_j = \frac{\Delta CA(j,L_R)}{\Delta CA(j,L_{R1})} \qquad (1)$$

Five different aggregation scales were chosen: L_R=300, 600, 1200, 2400 and 7200 m. The computational time-step was set to 10 minutes. Smaller time-steps did not produce any detectable difference in the simulated response, while increasing the computational load significantly. Moreover, as reported in section 2, there is a limited loss in spatial organisation of rainfall from 2-minute to 10-minute accumulation.

The combined effect of catchment and storm smearing was first evaluated by applying rainfields simply aggregated to the 6 different spatial scales. Figure 2 displays the results of the sensitivity analysis conducted for 27th of August 1998 as a sample case. The results of the three other storms are similar. The sensitivity indices are plotted versus the catchment areas in logarithmic scale. VR is a direct measure of the catchment smearing. It is limited for the 9th and 18th of August 1998 events and only occurs for catchment size less than 5km^2 with 0.87 <VR<1.06. It is more marked on the 27th of August 1998 (0.85 <VR < 1.4) and on the 10th of November 1999 (0.85 <VR < 1.15). This could be due to spurious spatial organisation produced by the attenuation effect in the radar rainfields of 27th of August 1998 and in the 10th of November 1999, which were not accounted for in radar calibration. In all the analysed cases, catchment smearing occurs only for grid-resolutions larger than 1200m (half the rainfall correlation length) and is significant for catchment sizes less than 10km^2. VF, PF and CA are strongly correlated with VR. Errors in basin-average rainfall estimation produce similar errors in flow volume and larger errors in peak flow. Significant errors in peak flow occur only for catchment size below $10km^2$ and except for the 27^{th} of August 1998, these errors are less than 25%. For the 27^{th} of August 1998 errors in peak flow reach a maximum value of 45%. Flow peak-time is less sensitive to spatial aggregation. Errors in peak time prediction occur only for rainfall grid size equal to 7200m and are significant only for catchment size below $1km^2$, with a maximum value of 20%. For the 9^{th} of August 1998 event, which peak flow is more marked within the hydrograph, practically no variation occurs in PT aggregating rainfall in space.

A different set of rainfields was applied in order to evaluate the effect of storm smearing alone. These rainfields were calculated by scaling the rainfields at different resolutions in order to match the same amount of rainfall volume across each sub-catchment as observed at the highest radar rainfall resolution at each time-step. In other words the index VR was forced to be equal to 1 for each sub-catchment and for each time-step. Thus 5 different rainfield series had to be calculated and applied for each sub-catchment and each event. A total of 140 model runs had to be accomplished for each event. The model sensitivity to storm smearing is extremely limited. All the indices assume values close to or equal to 1.

The model does not have any structural limit in accounting for the spatial gradients of rainfall rather the rainfall spatial gradients are not large enough to affect the sub-surface and surface flow routing. This was confirmed by two numerical experiments for the 9^{th} of August 1998 event. Uniform rainfall patterns equal to the basin-average calculated from the radar-based rainfields at highest resolution were used as input to the model. The rainfall volume across the catchment was preserved and no significant differences resulted in the response at the catchment outlet. A similar experiment was then conducted using rainfields obtained by interpolating the raingauge measurements with the Thiessen method, resulting in higher spatial gradients. These rainfields and the corresponding uniform patterns were both used as input to the model. Significant differences were observed at the catchment outlet even though the rainfall volume was preserved. The flow volume calculated with the uniform patterns is overestimated by 16%, while the flow peak by 26%. These results show that stronger rainfall gradients could affect significantly the response of a catchment as large as the Mahurangi.

5. CONCLUSIONS

This study has many limits and most of these are common to other similar studies conducted in the past. The interpretation of the results and their extension to general hydrological applications are limited by the uncertainty in how well the model structure and parameters represent the real system. Specifically, more investigations have to be undertaken in order to test the capability of the model in representing the actual processes distributed in space. The limited number of storms analysed represents another limitation. A larger set of cases should be analysed before drawing final conclusions. However, the experimental framework adopted in this study has some advances with respect to past studies. The event based sensitivity analysis was conducted within a continuous distributed simulation tested against flow observations at a broad range of spatial scales. This gives greater confidence in the reliability of the experimental framework, both in the description of the process and in the definition of the catchment initial conditions. The sensitivity analysis was also conducted contemporarily on a large range of spatial scales. High-resolution radar data have been applied (150m-grid size) together with a high-resolution distributed representation of the catchment (25m-grid size).

As found by Atkinson et al. [2001], accounting for spatial patterns of rainfall is important for making the correct estimate of the rainfall volume across the catchments. At Mahurangi, good estimates of rainfall volume can be achieved with rainfall data resolution of 1.2km even for catchments ~$0.5km^2$, for rainfields with a spatial correlation length of 2.2km. For catchments larger than $10km^2$ even resolutions of 7.2km give satisfactory results in rainfall volume estimates.

The simulated catchment response has however limited sensitivity to spatial gradients of rainfall within each sub-catchment. This and previous studies [e.g. Obled et al., 1994; Ogden and Julien, 1994; Shah et al., 1996] confirm that at the spatial scale analysed, rainfall spatial gradients are relevant only when rainfall is transformed by intensity-sensitive processes, such as infiltration, before being processed by the runoff routing. When saturation-excess is the dominant runoff generation mechanism, the rainfall gradients are not sufficiently organised in space to overcome the effects of smoothing induced by the model on surface runoff.

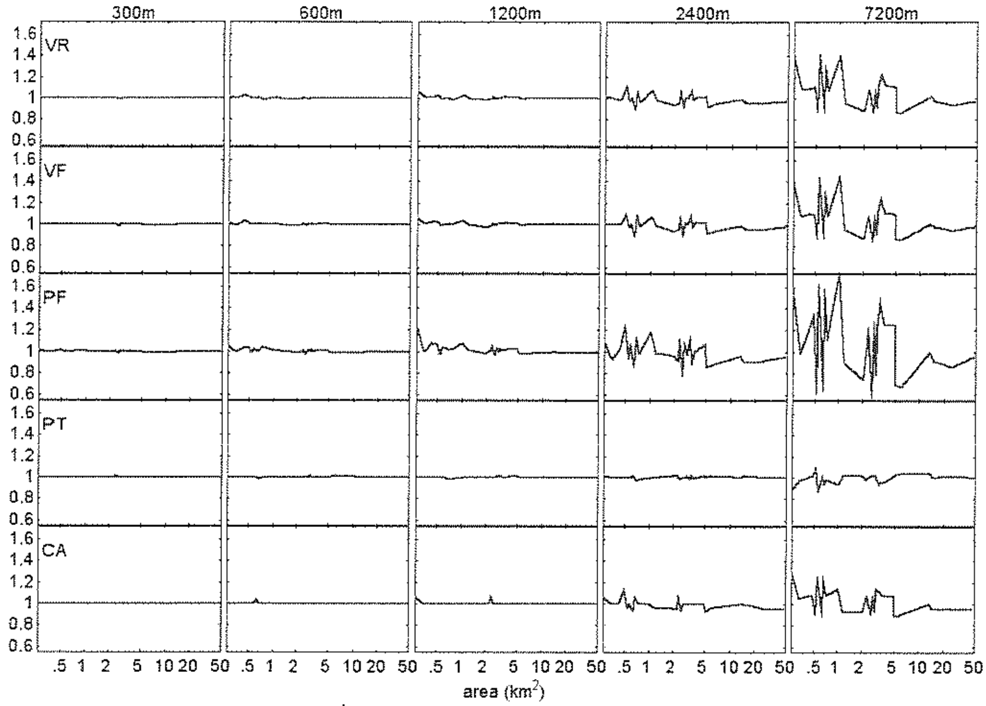

Figure 2. Sensitivity analysis for the 27th of August 1998 event. Rainfall resolutions are shown on the top.

6. ACKNOWLEDGEMENTS

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