THE USE OF RAIN RADAR MEASUREMENTS FOR HYDRAULIC MODELLING

Tom Joseph [1], Luke Sutherland-Stacey [2], Nathan Donald [1], Geoff Austin [3]
1. Mott MacDonald, Auckland, New Zealand
2. www.weatheradar.co.nz, Auckland, New Zealand
3. Physics Department, University of Auckland, New Zealand

ABSTRACT

It is nearly impossible to accurately quantify rainfall variability across a stormwater or sewer catchment using discrete point rainfall measurements. The variability across the catchment can be significant depending on the catchment location and surrounding terrain. For many hydrological applications, such as sewer inflow and infiltration modelling, extrapolation of point rainfall measurements is standard practice and is one of largest unknowns in the model. Decisions about the techniques used for extrapolation, as well as the adequacy of the conclusions drawn from the modelling results, depend heavily on the magnitude and the nature of the uncertainty involved.

In this paper we will outline our recent investigation using accurate short range radar in an attempt to quantify how standard point rainfall measurement and extrapolation techniques effect sewer model calibration and eventually options resulting from the model. In the highlighted case study we completed a detailed sewer model calibration using current industry best practice. As a second work stream we obtained radar data from the University of Auckland's short range mobile radar unit for the entire monitoring period. We then tested the model calibration using the "true" rainfall distribution over each sewer-catchment as identified from the radar and commented on the variation in model calibration parameters and how the different rainfall distribution effects the perceived system performance and potential options analysis.

INTRODUCTION

It is common across New Zealand and other parts of the world to build hydrologic and hydraulic models of sewer and storm water infrastructure for planning purposes. The models are typically used to develop comprehensive master plans across the catchment which drive large capital expenditures for mitigating current system performance issues (e.g. combined sewer overflows, flooding) and planning for future growth. Having a robust calibrated hydrologic and hydraulic model is critical to planning cost effective and focused solutions.

Accurate rainfall accumulations are therefore an essential boundary condition for all these models. Too often rainfall data quality is taken for granted and the spatial variability in the data is often not well understood. In the case of New Zealand storms generally show high spatial and temporal variability which is difficult to capture using typical discrete point rainfall measurements. The traditional engineering approach to obtaining rainfall boundary conditions is to make use of tipping bucket rain gauges at a density of approximately 1 every 2 to 4 km^2 depending upon the catchment terrain. However, this standard is often not adhered too due to cost and over large regions this is not always practical.

An additional concern with using rain gauges is that a collection of sparse point measurements may not be able to properly characterise the extreme spatial gradients which are known to exist in precipitation fields (Morrissey et al., 1995, Steiner, 1996, Nystuen, 1998, Villarini et al., 2008).

Essentially, hydrologically significant rainfall may either "fit between" rain gauges, in which case it is not sampled, or it may be incident on members of a gauge network but not present in unmeasured areas, in which case oversampling occurs. Either scenario will bias the rainfall boundary conditions in sewer models, leading to poorer model predictive skill.

A complimentary source of rainfall information is available from weather radar measurements. Weather radar generate spatial maps of rain location and infer instantaneous rainfall rate by measuring the intensity of reflection (backscatter) of electromagnetic radiation off falling raindrops (after Marshal 1953 and Marshal and Palmer, 1948). Careful processing of radar data is necessary to retrieve surface rainfall rate from radar reflectivity measurements made aloft (for a recent review, see Villarini and Krajewski, 2010). Some of the sources of error in the estimation process are the uncertainty in the observed rainfall's drop size distribution (Twomey, 1953, Battan, 1973, Atlas et al., 1999), beam blocking (Harrold et al., 1974, Andrieu et al., 1997) and uncertainty in the knowledge of the vertical distribution of rain (Fabry et al., 1992, Kitchen et al., 1994, Joss and Lee, 1995). The resulting effects on the estimation of rainfall rate have been researched extensively over the past decades. Comparison of radar retrieved estimates of rainfall with point rain gauge measurements can indicate how well these errors have been accounted for and corrected.

For most engineering applications the best estimates of surface rainfall accumulation depth can be made by combining both radar and rain-gauge measurements (Wright et al, 2014). Composite fields contain both point rain rate information from direct in-situ rain gauge measurements and information about the spatial distribution of rainfall from radar measurements and can be prepared in raster formats suitable for ingestion into distributed models.

International work has highlighted the modelling improvements made possible by these composite measurements. Lowe et al (2014) reported improvements in urban runoff modelling when using composite radar-gauge fields over the same rain gauge only measurements. The improvement in spatial sampling afforded by radar measurements can offset radar uncertainties and result in improvements in model response. Sempere-Tores et al (1999) compared radar only and rain gauge only data for driving combined sewer system (CSS) flow models and found that radar data better reproduced observed flow, despite some point wise disagreements with rain gauge measurements. The extra spatial information contained in radar measurements of rainfall has also been put to use modelling pollution buildup and runoff (Shaw et al 2010) and forecasting sewer overflow risk (Heinonen et al 2013).

In this work we investigate the impact of high resolution rain radar and rain-gauge fields on a network sewer model of the Onehunga catchment in Auckland New Zealand. In the analysis we utilized a traditionally calibrated hydrologic/hydraulic model to make an assessment on how discrete rainfall measurements might skew calibration parameters when spatial rainfall variation is persistent.

<u>METHODOLOGY</u>

Study Catchment
The study area is located on the south east of the Auckland Isthmus (Figures 1 and 2). The total contributing area is approximately 2,107 Ha (from Project Storm 2) and accommodates a total population of 46,776 (2006). Approximately half of the catchment is residential, while industrial and open space covers nearly 20% each and the remaining 5% area is commercial activities.

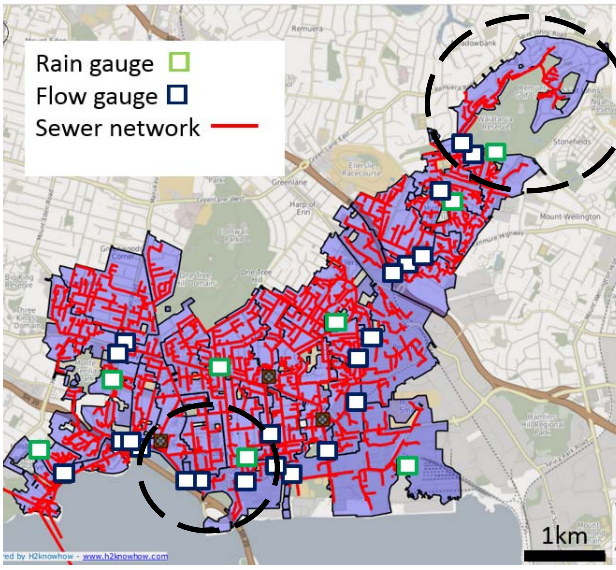

Figure 1: GIS output indicating the catchment boundary, sewer network flow monitoring and rain gauge locations. The locations of two test sub-catchments is indicated with dashed circles

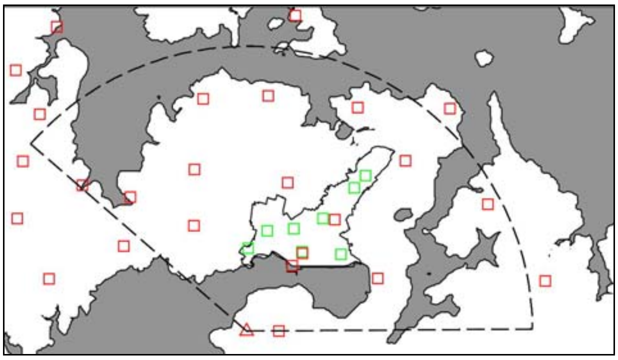

Figure 2: Location of the catchment and project rain gauges within the Auckland Isthmus. The radar location (red triangle), measurement arc (dashed line) and locations of permanent rain gauges (red squares) are also indicated.

Radar Data Collection
Radar observations were provided by the University of Auckland High Resolution “Trailer Radar”. The “Trailer Radar” consists of a fully articulated 1.8m diameter radar dish mounted on a short tower, coupled by flexible waveguide to a 25kW masthead transceiver, the outputs of which are in turn fed, along with information regarding the dish direction, into a PC housed in a small operator’s cab. The radar system is entirely self-contained on a tandem axle trailer. The total mass is about 2.5 tonnes, allowing it to be towed by a light four wheel drive vehicle; provided that the trailer’s hydraulic breaking system is used. The radar mast is folded down onto the trailer for transport. A complete description of the radar system and discussion of its suitability for small catchment monitoring may be found in Sutherland-Stacey et. al. (2011).

Figure 3: The University of Auckland high resolution rain radar overlooking the study catchment.

The Trailer Radar was deployed to the harbour outfall in the Mangere Waste Water Treatment Plant (Figure 3). The site affords an uninterrupted field of view over the upper reaches of the Manukau harbour to the study catchment. The study catchment's orientation relative to the field site is such that the catchment's major axis (12km) coincides with the down-range direction.

The radar was configured to obtain a reflectivity scan of the catchment every 30 seconds during rain events. Raw radar observations spanning 3 months (2013.08.29 to 2013.10.25) were collected. The main source of error in the radar estimates of rainfall is the uncertainty in radar calibration, rainfall drop size distribution and variation in rainfall in the vertical. The radar dish angle was set to 6 degrees so the radar beam climbs from about 200m to 2000m elevation over the length of the catchment so the height at which rainfall is sampled varies over the catchment introducing a range dependent bias which depends on the weather type (depth of rain).

Radar Data Processing

The radar estimates of rainfall accumulation were processed onto a grid with 250 m X 250 m pixels and 2 minute intervals. Rain events were automatically detected by grouping periods of continuous rainfall and radar bias was reduced by correcting data by applying a radially weighted correction depending on the difference between records from the permanent rain gauges operated by the Auckland Council and their corresponding radar pixels. A correction window of 6 hours was applied, allowing the bias correction to change with time compensates for variations in rain type between different weather systems- for example large scale condensation has a very different vertical profile and drop size distribution to convectively driven rain storms.

Following the automatic correction (calibration) process, the bias corrected radar accumulations were output into a standard ERSI ASCII raster format for each time 2 min time interval. All of the rasters were loaded into the master geospatial database and standard database tools were used query and aggregate each raster into 5 minute rainfall accumulation time series for each grid cell that intersected the catchment. In all 337 (2,107 Ha / 250 m2) unique time series were generated. This allowed the full utilisation of the radar data in its most un-aggregated form.

Hydraulic Model

In this analysis a previously calibrated Innovyze InfoWorks CS model of the catchment was used to compare traditional rainfall measurements and radar measurements. The model is considered a detailed catchment model and contains nearly all of the available pipes in the network and has been calibrated using industry best practice. The calibration data was collected over the winter of 2013 with 25 flow monitoring points and 8 rainfall gauge locations.

The time series generated from the radar was directly imported into the hydraulic model. Each time series was assigned to its intersecting sub-catchment in the model (2,337 sub-catchments in total). Each sub catchment was only assigned a single grid cell from the radar raster with no splitting. As the average catchment size in the model is 0.75 Ha vs the 6.2 Ha radar grid cell size it the single cell to catchment match was considered appropriate. The radar data was supplemented by gauge rainfall data for the seeding period in the model. This provided the antecedent conditions in the model and assured that the model was producing the realistic flows from each catchment prior to the introduction of the radar rainfall.

The rainfall-runoff transformation for each sub-catchment is comprised of two separate and unrelated hydrological processes: a fast response model and slow response model. Each model (fast and slow response) is split into a volume model and a routing model. The volume model is used to complete a general mass balance between total rainfall and losses (e.g. initial losses, evaporation, and infiltration) and the routing model transforms the excess rainfall into a runoff rate. The two volume models used in for the fast response component was the Fixed PR model (for impervious surfaces) and the New UK model (for pervious surfaces) and the large catchment model was used for routing for fast response. The ground water infiltration model was utilised for the slow response component. Characteristic lag times between rainfall and a local flow model response are minuets and hours to days for the fast and slow models respectively. The runoff generated from the hydrological model at each sub-catchment is directed to a single manhole and is routed through the network using the Saint Venant equations. More information on the models can be found in the InfoWorks user manual.

During the model calibration the rainfall recorded at the nearest rain gauge (8 in total) was used to general runoff from each of the 2,337 catchments. The rainfall from radar was introduced into the model as a collection of rain gauges located at the centre of each intersecting radar grid cell which comprised of 337 pseudo-rain gauges.

RESULTS AND DISCUSSION

For this analysis we have chosen to utilise a rainfall event on 12th September 2013. About 25 mm rain fell over the catchment between 6:00 and 14:00 which is considered a representative winter event for the catchment. The event was not used in the original rain-gauge driven flow model calibration or validation process which also made it attractive for the analysis.

Model Flow Prediction Comparison

The flow outputs from the model calibrated using rainfall gauge (Gauge Model- *GM*) and the comparison outputs from radar rainfall estimates (Radar Model- *RM*) were examined for a selected number of flow monitoring locations. The focus of the analysis was to determine if calibration parameters and subsequently catchment infiltration is being misrepresented using discrete point rainfall measurements. It was essential to compare only the two variations on the model to ensure consistency in the output and that the unknowns could be managed. It was also essential to ensure that the two comparative models produced an exact match during periods of no rainfall or outside of the radar data collection period.

To minimise complexity, comparison primarily focused on three sub-catchments with no upstream unmonitored flow inputs to ensure that variance in the results was not a result of rainfall variation in the upstream catchments. The approximate locations of these sub-catchments is indicated in Figure 1.

RM and RG output, along with rain gauge measurements from the catchments' rain gauge are provided for the north-east sub-catchment (Figure 4).

GM at the test flow station in this catchment shows a reasonably good match during the first portion of the event (Figure 4 a) however there is almost 25% difference in peak flow to RM during the later stages (b). It is interesting to note that there is a relatively minor point-wise increase in the radar intensity compared to the rain gauge at the rainfall gauges at this time, however it is not likely that this minor intensity spike would account for the magnitude of increase seen in the radar model.

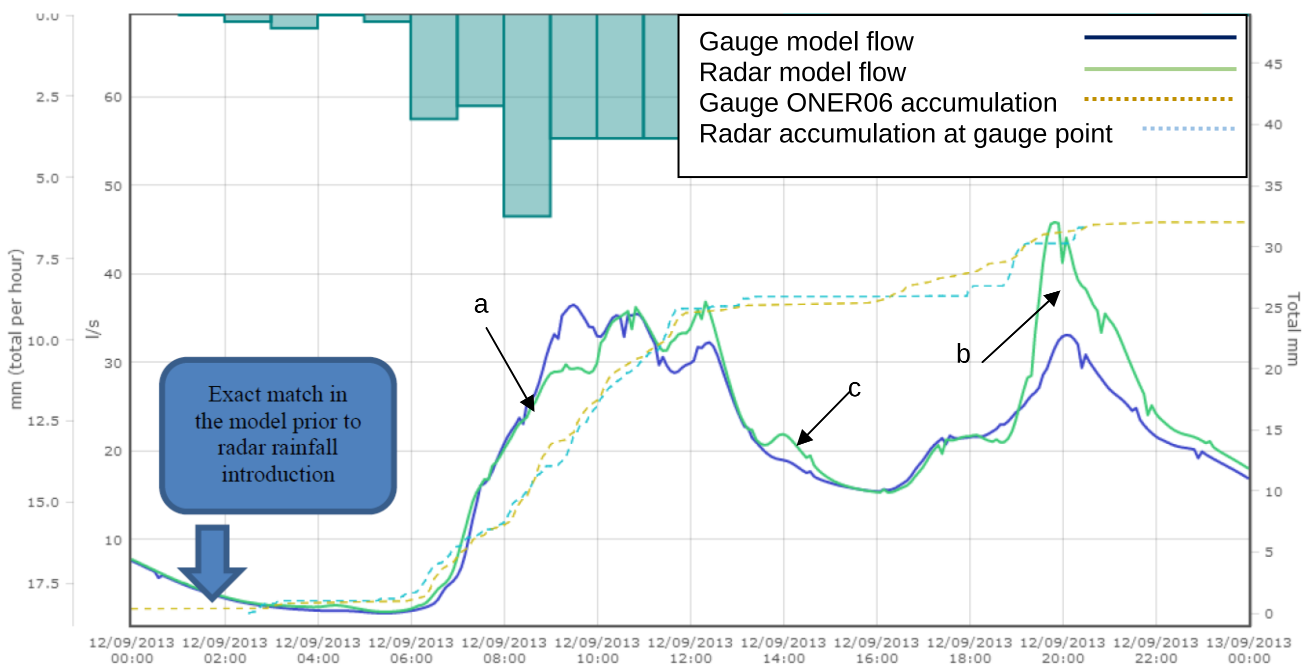

Figure 4: Radar and Gauge driven model flow output for the north-east test catchment 12/09/2013 - 12/09/2013

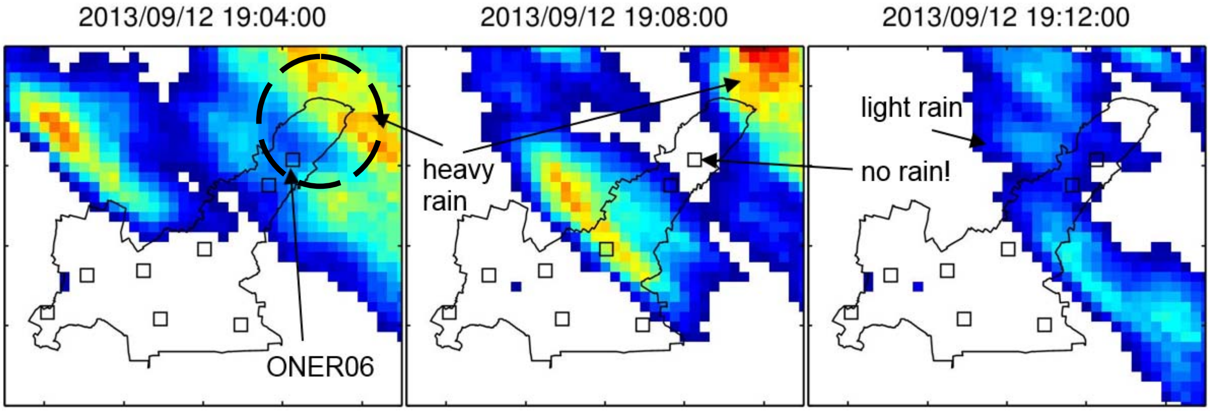

Figure 5: Radar images corosponding to the flow spike b in Figure 4. Hot colours indicate heavier rain. The approximate location of the sub-catchment is indicated with a dashed circle.

The discrepancy appears to be due to rain failing in the upper reaches of the catchment which are not adequately covered by the rain gauge network (Figure 5). At about 19:00 a convective rain band passes over the catchment. The heaviest rainfall is just to the north east of the sub-catchment, nonetheless the south western most extremity contributes accumulation to the catchment. Rain gauge ONER006 is less than 2km away from the heaviest rainfall, but receives only much lighter rain. Because the catchment is already saturated at the end of the case study event and the extra intense rainfall in the top of the catchment readily infiltrates the sewer network resulting in the higher model flow about 1 hour later.

Flow monitoring stations in the south western test catchment show a 14% and 24% difference respectively in peak flow between RM and GM during the peak of the event (Figure 6). The rain gauge and radar data is nearly identical at the rainfall gauge location. Once again, the radar rainfall revealed spatial variability in the rain field (Figure 6). The radar indicates that the rainfall distribution did not completely cover the subcatchment, however the rain gauges have trouble resolving these gaps because their observations are propagated to the edges of the catchment where there are no observations, resulting in over-estimate of rainfall. . Over time, it is also likely that the rain-gauge driven model surface becomes wetter for the same reason, resulting in a further increase in runoff and model flow later. It was also noted that the flow at one of the flow stations in the south-western catchment was consistently overstated by RM compared to the physical flow monitor at this location.

It is worthwhile pointing out that the volume difference between the two models is relatively small at most other flow monitoring stations for this event (<10% in most cases). This suggests that the overall predicted excess rainfall is similar in both models. Indeed, the largest volume differences

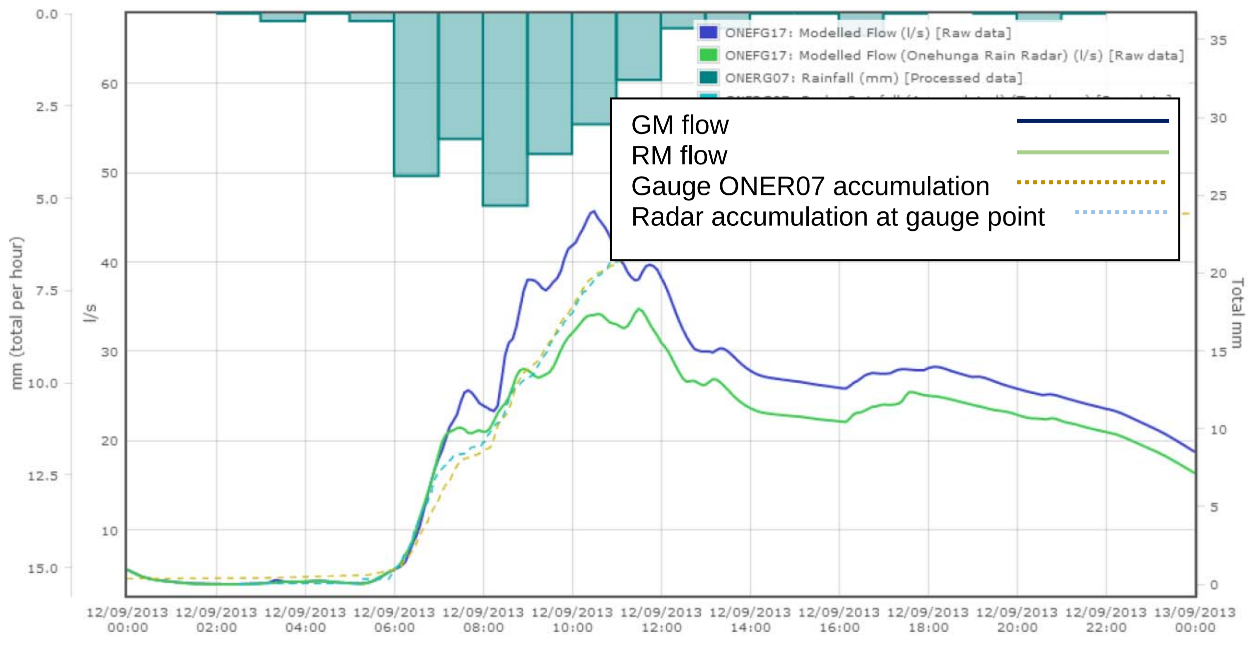

Figure 6: Radar and Gauge driven model flow output for the south-west test catchment 12/09/2013 - 12/09/2013

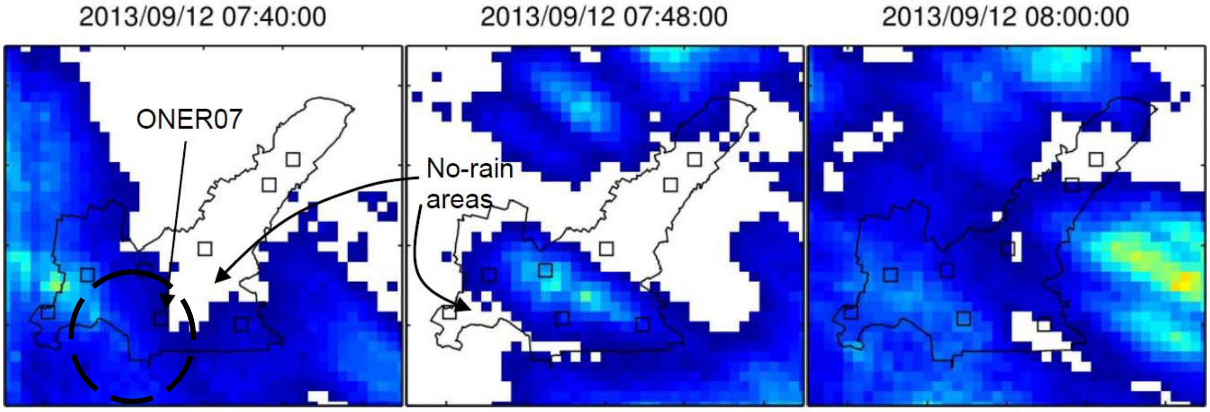

Figure 7: Radar images corosponding to the RM-GM mismatch in peak flow Figure 6. Hot colours indicate heavier rain. The approximate location of the sub-catchment is indicated with a dashed circle.

occurred in catchments for which there was a substantial discrepancy in the spatial distribution of rainfall according to the areal gauge estimate compared to radar (the examples discussed above). A larger variation between RM and GM which more closely related to the peak intensities across all of the catchments might have been expected. This difference can likely be attributed to the calibrated ground water infiltration model which stores excess rainfall in soil prior to a slower release into the system. It is possible that the averaging effects of the rain gauge measurements tend to result in more spread out estimates of rainfall and hence a bias towards the slow release model during the initial calibration phase. On the other hand, the localised intensities detected by the radar may temporarily saturate sub-catchments resulting in fast release and higher peak flows even though the overall volumes are the same.

CONCLUSIONS

In general the rainfall radar model RM and rain gauge model GM compared well. This indicates that high resolution radar data is capable of producing similar results to rainfall gauge measurements. The 8 rainfall gauges in the catchment appeared to provide ample coverage to define most of the events captured by the radar. However, as expected there are some sub-catchments that showed considerable variation between the two models which can only be attributed to spatial-temporal rainfall variability. The magnitude and number of events which varied would have no doubt increased if less rainfall monitors were deployed in the catchment.

For test event reported here the volume difference between the two models remained minor, presumably buffered by the soil store in the ground water infiltration model. Peak intensities however do vary highlighting spatial variation in short localised rainfall bursts in the radar.

The case study highlights that high resolution radar data estimates can accurately estimate rainfall across a catchment. It also supports that spatial-temporal variation highlighted within the radar data is not always well captured by discrete rainfall measurements and can have a significant impact on predicted peak flows and likely subsequent system performance and inflow and infiltration predictions. Although it is believed that the rainfall gauge density in this case study provided ample coverage it is not always possible to deploy rainfall gauges at this density, especially in larger city wide catchment models.

In conclusion rainfall radar provides a significant amount of additional information that can be confidently used to further our understanding of the rainfall to runoff phenomenon that occurs in both wastewater and storm water catchments. It is in the opinion of the authors that the use of this type of data will become critical in future modelling projects, especially in larger areas with high rainfall variability like the Auckland isthmus. The true advantage is the added confidence in model calibration, ability to better understand and investigate different catchment model responses, and ultimately the large scale capital projects driven from model outputs.

Looking Forwards

In this analysis we only examined one rainfall event in detail over the entire monitoring period. Several other events were captured and statistics were analysed in less detail with similar results witnessed. The analysis presented above highlights that there are some significant differences in the predicted peak flows between the rain and radar models. Ultimately what is most important question is will these differences skew our vision of the catchment performance and subsequent capital improvements (to manage peak flows) driven from the models. Additional analysis should be carried out to answer these questions.

ACKNOWLEDGEMENTS

The Authors would like to thank Watercare Services Limited for allowing us to utilise the base monitoring data, calibrated model, and providing access to a site for the radar unit deployment. The University of Auckland's support in providing the high resolution radar hardware is also appreciated.

REFERENCES

Andrieu, H., Creutin, J. D., Delrieu, G. & Faure, D. 1997. Use of a weather radar for the hydrology of a mountainous area. Part I: Radar measurement interpretation. Journal of Hydrology, 193, 1-25.

Atlas, D., Ulbrich, C. W., Marks Jr, F. D., Amitai, E. & Williams, C. R. 1999. Systematic variation of drop size and radar-rainfall relations. Journal of Geophysical Research D: Atmospheres, 104, 6155-6169.

BATTAN, L. J. 1973. Radar Observation of the Atmosphere, Chicago, University of Chicago Press.

Fabry, F., Austin, G. L. & Tees, D. 1992. The Accuracy Of Rainfall Estimates By Radar As A Function Of Range. Quarterly Journal of the Royal Meteorological Society, 118, 435-453.

Harrold, T. W., English, E. J. & Nicholas.Ca 1974. Accuracy Of Radar-Derived Rainfall Measurements In Hilly Terrain. Quarterly Journal of the Royal Meteorological Society, 100, 331-350.

Heinonen, M., Jokelainen, M., Fred, T., Koistinen, J., Hohti, H., Improved wet weather wastewater influent modelling at Viikinmäki WWTP by on-line weather radar information. Water Science & Technology. 2013, Vol. 68 Issue 3, p499-505. 7p.

Joss, J. & Lee, R. 1995. The Application Of Radar-Gauge Comparisons To Operational Precipitation Profile Corrections. Journal of Applied Meteorology, 34, 2612-2630.

Kitchen, M., Brown, R. & Davies, A. G. 1994. Real-Time Correction Of Weather Radar Data For The Effects Of Bright Band, Range And Orographic Growth In Widespread Precipitation. Quarterly Journal of the Royal Meteorological Society, 120, 1231-1254.

Löwe R., Thorndahl, S., Mikkelsen P. S. Rasmussen M. R., Madsen H. , 2014, Probabilistic online runoff forecasting for urban catchments using inputs from rain gauges as well as statically and dynamically adjusted weather radar. Journal of Hydrology. Vol. 512, p397-407. 11p.

Marshall, J. S., 1953. Interpretation of the fluctuating echo from randomly distributed scatterers. Canadian Journal of Physics 31 (6). 12

Marshall, J. S., Palmer, W. M., 1948. The distribution of raindrops with size. Journal of Meteorology 5 (4), 165–166. 13

MORRISSEY, M. L., MALIEKAL, J. A., GREENE, J. S. & WANG, J. 1995. The uncertainty of simple spatial averages using rain gauge networks. Water Resources Research, 31, 2011-2017.

Sempere-Torres Daniel, Corral, Raso Jordi, Malgrat Pere, 1999, Use Of Weather Radar For Combined Sewer Overflows Monitoring And Control, Journal Of Environmental Engineering, Vol. 125, No. 4, 372-380

Shaw Stephen B.; Stedinger Jery R., and Walter M. Todd, 2010 Evaluating Urban Pollutant Buildup/Wash-Off Models Using a Madison, Wisconsin Catchment JOURNAL OF ENVIRONMENTAL ENGINEERING Vol. 136, No. 2, 194-203

STEINER, M. 1996. Uncertainty of estimates of monthly areal rainfall for temporally sparse remote observations. Water Resources Research, 32, 373-388.

Sutherland-Stacey, L., Austin, G., Shucksmith, P., 2011. A mobile rain radar for high resolution hydrological observations in New Zealand. New Zealand Journal of Hydrology 50 (2), 339–360. 22

Twomey, S. 1953. On The Measurement Of Precipitation Intensity By Radar. Journal of Meteorology, 10, 66-67.

NYSTUEN, J. A. 1998. Temporal sampling requirements for automatic rain gauges. Journal of Atmospheric and Oceanic Technology, 15, 1253-1260.

VILLARINI, G., MANDAPAKA, P. V., KRAJEWSKI, W. F. & MOORE, R. J. 2008. Rainfall and sampling uncertainties: A rain gauge perspective. Journal of Geophysical Research D: Atmospheres, 113.

Villarini, G., Krajewski, W. F., 2010. Review of the different sources of uncertainty in single polarization radar-based estimates of rainfall. Surveys in Geophysics 31 (1), 107–129. 14

Wright, Daniel B. Smith, James A. Villarini, Gabriele Baeck, Mary Lynn 2014 Long-Term High-Resolution Radar Rainfall Fields for Urban Hydrology Journal of the American Water Resources Association. , Vol. 50 Issue 3, p713-734. 22p.