USING RAIN RADAR TO ESTIMATE THE SIZE OF FLOOD EVENTS

Luke Sutherland-Stacey (Sutherland-Stacey Consultants Ltd.), Tom Joseph (Mott MacDonald Ltd.), Prof. Geoff Austin (University of Auckland), Nick Brown (Auckland Council)

ABSTRACT (300 WORDS MAXIMUM)

Understanding the timing and location of extreme rainfall is one of the most important parts of Stormwater Flood Management. In most urban settings in New Zealand, city authorities make use of rain gauges to understand rain events. Often, understanding rain events is accomplished by classifying rainfall according to an Average Recurrence Interval (ARI). Rain gauge networks take point samples of the continuous spatially varying rain field and it is difficult to know if the heaviest rain has fallen on a rain gauge or fallen elsewhere in a catchment. This rainfall variability can lead to large biases in determining ARI statistics for individual events when using rain gauge data, which in turn makes it difficult to assess the performance of infrastructure which may have been designed with a particular recurrence interval in mind.

This paper presents a methodology for preparing rain radar data from the Auckland Metservice radar to allow generation of spatially continuous ARI maps, and demonstrates how the data can be used to gain understanding of the cause of flooding events for a test case.

KEYWORDS

Radar, ARI, AEP, rain gauge, spatial sampling

PRESENTER PROFILE

Luke Sutherland-Stacey is an independent environmental scientist specialising in measurement and quantification of changes in rapidly varying systems. Current work focuses on quantification of rainfall with radar for sewer and stormwater modelling applications.

Tom Joseph is a technical director at Mott Macdonald providing technical support and strategic guidance to a team of computational modellers, data scientists, and software developers. His current focus is the innovative delivery of technical content to non-technical users through web based technology.

1 INTRODUCTION

Auckland Council (AC) has recently established a standard procedure to initiate post event reporting for major events that result in customer Request for Service (RFS). This process was largely initiated to inform stakeholders and continually asses the performance of the network. Along with informing stakeholders on current network performance post event reporting, combined with better operational and public engagement, could become an essential data set for future planning and design of stormwater infrastructure and could help align hydraulic models with actual customer experiences.

Average Recurrence Interval (ARI) and Annual Exceedance Probability (AEP) are both a measure of the rarity of a rainfall event. The two metrics are directly related and are popular statistical methods used to determine the frequency or probability of a measured rainfall or flow event. Although there is an industry shift towards AEP the two metrics are interchangeable and for the remainder of this paper we will refer to ARI.

ARI is a particularly convenient statistic to quantify the magnitude of rainfall events as it incorporates both duration and intensity into a single quantifiable unit. ARI is almost exclusively used as the primary design criteria in infrastructure design for both stormwater and wastewater networks throughout New Zealand and internationally but post event analysis is difficult using discrete rain gauges and is almost always anecdotal.

The difficulties in measuring extreme rainfalls is a well understood sampling problem (Villarini *et al.*, 2008) which arises because hydrologically significant rainfall may either "fit between" rain gauges, in which case it is not sampled, or it may fall on individual gauges but not be present in unmeasured areas, in which case over estimation occurs. Simple spatial interpolation between rain gauges can lead to large and difficult to predict discrepancies between the customer experience and desktop analytics.

Rain radar is a well-established technology for addressing this sampling problem. 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 radar data better reproduced observed flow, 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).

Milsom (2007) recognised the potential of NZ Metservice radar for understanding spatial variability of rain fields in Auckland during project Strom 2, however radar data was not able to be used directly as model input due to the technical challenges in the absence of a readily available quality controlled data product suitable for urban hydrology applications. More recently, high resolution radars run by the University of Auckland have been used to provide input data for sewer modelling applications and show promise for introduction of information about rainfall which is missed even in dense temporary rain gauge networks (Joseph *et al.*, 2014).

In this paper we have revisited use of the NZ Metservice rainfall radar for urban hydrology. Here, we report on the use of the data to develop spatially continuous regional ARI statistics that can be used for post event reporting.

Radar provides many advantages but most notably the radar provides a continuous rainfall field that is not reliant on interpolation between rainfall gauges with little to no correlation. The radar field also allows us to capture areas of convective rainfall that are not well represented or simply not captured by the gauge network. The advantages of radar methodology is highlighted in this paper using a recent event that was analysed using both methods.

2 ANALYSIS METHODOLOGY

2.1 EVENT DESCRIPTION

For this work we considered a severe rainfall event which occurred overnight on the 15th July 2015

In advance of the event, the Auckland Civil Defence and Emergency Management centre received a Metservice forecast for a rain event that did not reach the warning criteria (20mm/hr). When the weather system arrived it brought with it much higher rainfall accumulations than anticipated (up to 30mm/hr recorded by rain gauges in West Auckland) and resulted in 117 Requests for Service (RFS) orientated along a band over West and South Auckland.

Rain gauge analysis of the event indicated a maximum ARI across all durations in exceedance of 20 years in some locations (Figure 1) which was reflected in the RFS logs with some habitable floor flooding (not shown).

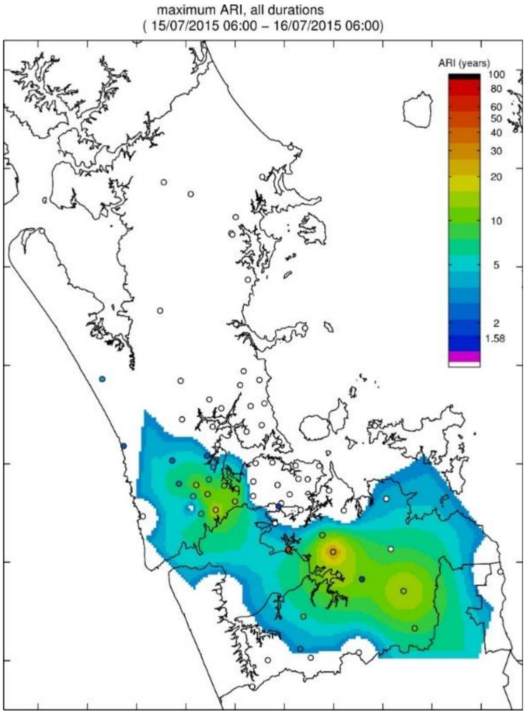

Figure 1: maximum ARI recorded across all durations by the rain gauge network (coloured points). The rain gauge estimates are interpolated with an inverse r-squared weighting to generate a spatial estimate.

The Auckland Region is geographically large, so several events with intensity-durations in exceedance of 20 year ARI can be expected each year in some part of the region. The 15th July event is a good case study as events of comparable severity will be encountered regularly and understanding what radar data can add to the analysis is therefore operationally useful.

2.2 RADAR DATA

Weather radar generate spatial maps of rain location and infer instantaneous rainfall rate by measuring the intensity of reflection (backscatter) of microwave electromagnetic radiation from falling raindrops (after Marshall 1953 and Marshall and Palmer, 1948).

There are many uncertainties in the radar rainfall estimation process. Some of the most important are the uncertainty in the observed rainfall's drop size distribution, beam blocking, uncertainty in the knowledge of the vertical distribution of rain and smoothing errors caused by low resolution (Fabry *et al.*, 1994; Shucksmith, Sutherland-Stacey and Austin, 2011). Careful processing of radar data is therefore necessary to retrieve accurate surface rainfall rate from radar reflectivity measurements made aloft (for a recent review, see Villarini and Krajewski, 2010).

Auckland is well serviced by a variety of weather radar observing platforms. The nearest permanently operated radar to Auckland is run by the New Zealand Meteorological Service and is sited about 60 km to the north of the Auckland CBD and data from this radar is used in this work. Research radars are also run out of the University of Auckland have been used recently to explore sewer modelling application in Auckland.

2.2.1 DATA PROCESSING METHODOLOGY

Radar observations from the Auckland Radar were obtained from MetService for the period 15 to 16th July 2015. Significant data treatment is required to convert from the radar measurement (reflectivity Z, in mm^6m^{-3}) to high temporal resolution surface rainfall accumulations suitable for Auckland Stormwater use.

Automated pre-processing of radar observations is required to: account for and remove the influence of non-meteorological signals such as return from hills (ground clutter) and measurement artefacts such as second trip echoes and spurious signals from other wireless transmitters and to perform a transformation from the radar measurement (reflectivity) to accumulation.

MetService radars complete a scan cycle every 7.5 minutes and the lowest elevation scan is most useful for quantitative hydrology applications. Because intense rain cells can move 10 km or more in this time, a very important step in the data processing is properly accounting for the motion of the rain field between radar scans (Thorndahl *et al.* 2014).

Figure 2 illustrates this sampling frequency problem. The left raster is generated by multiplication of the instantaneous rain rate estimated from each radar scan by 7.5 minutes. In the 24 hour period represented in Figure 2 most of the accumulation was delivered by an intense band of precipitation which crossed the domain in about 30 minutes, and was therefore measured just 6 times by the radar. The low (7.5 minute) sampling rate results in a structure of linear striations with a spacing equal to the distance the band moved between measurements. The right hand plot accounts for this motion with an advection interpolation scheme which translates each scan according to the motion of the rain field during the accumulation process.

At the end of the processing stream, a data product suitable for direct use in modelling or qualitative post-event analysis is available at customisable resolution and time spacing (for this work, 500m grid resolution and 1 minute output frequency were chosen).

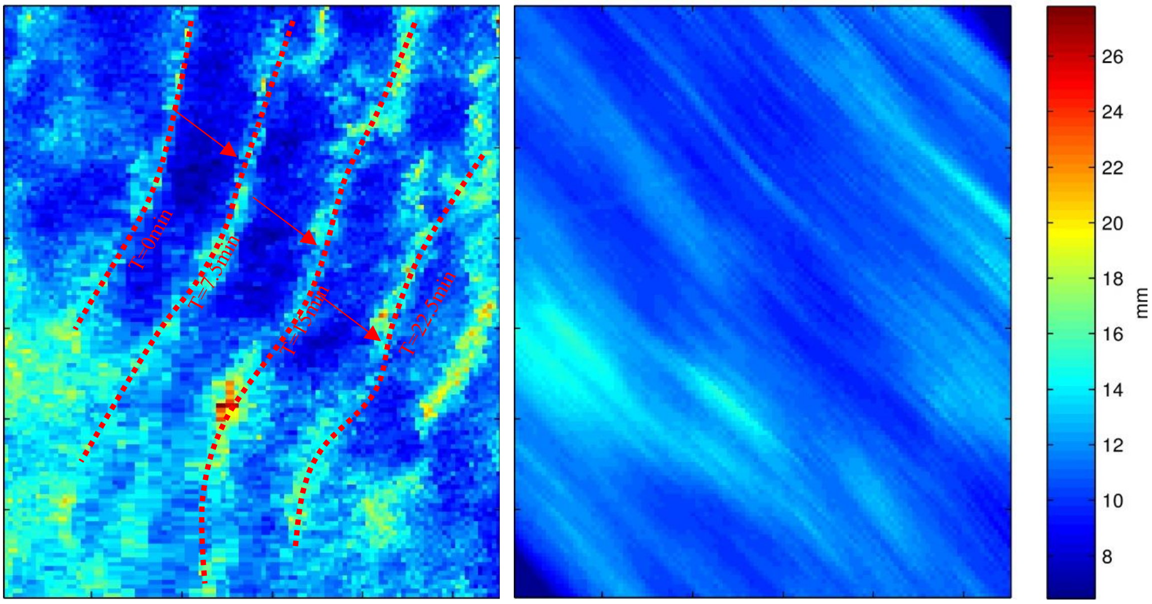

Figure 2: 24 hour accumulation maps without gauge correction for 17/07/2015 12:00 to 18/07/2015 12:00 NZST without (left) and with (right) an advection accumulation scheme.

2.3 ARI ANALYSIS METHOD

In the Auckland Region rainfall ARI can be assessed using one of two methods:

1. Auckland Council Technical Publication (TP)108 (1999) and,
2. The regional High Intensity Rainfall Distribution System (HIRDS) database administered and supported by New Zealand Institute of Water and Atmospheric Research (NIWA) (Thompson, 2010).

For this analysis the maximum ARI statistics for the event were calculated from HIRDS tables in the usual way.

Given a time series of rainfall intensities (generated from 1-minute radar mm/hr estimates at a raster pixel or gauge tips) the maximum intensity for a given duration is first determined by summation of sections of the data with a moving window to find the maximum accumulation in that time window duration for the entire event. Values immediately above and below this intensity-duration are then located on the HIRDS table, and interpolation between table entries in log-log space yields an estimate of the maximum ARI statistic for that duration. The process is repeated for all durations (increasing time window lengths) and the maximum ARI obtained is then reported at the maximum ARI across all durations. The process can be iterated across all radar pixels to generate one 2-d spatial raster for the event, suitable for post event reporting.

3 RESULTS

Figure 3 gives the 24 hours accumulation depth yielded from the processed radar data for the study event. The map highlights the spatial localization of the event with the highest total accumulations forming two bands orientated North West to South East crossing West and South Auckland.

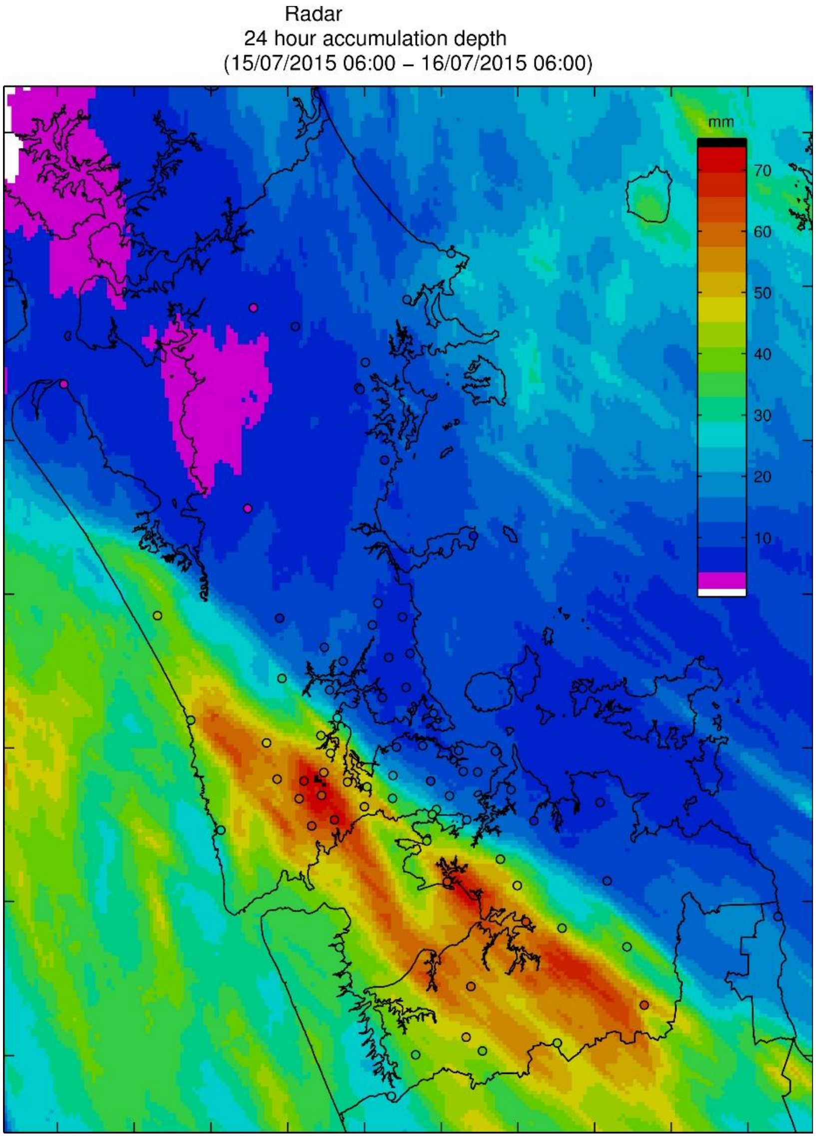

Figure 3: Total accumulation determined from the rain radar rasters. The rain gauge locations are plotted (coloured circles) for comparison.

Detailed analysis if the 1 minute rasters indicate the heaviest rainfall was caused by the passage of a series of strong convective cells (probably thunderstorms) over the city (Figure 4).

The highest ARI values were caused by these convective cells and can be located in Figure 5 along the North West border of the high ARI band. The highest ARI's also occurred at very short durations (10/20 minutes)..

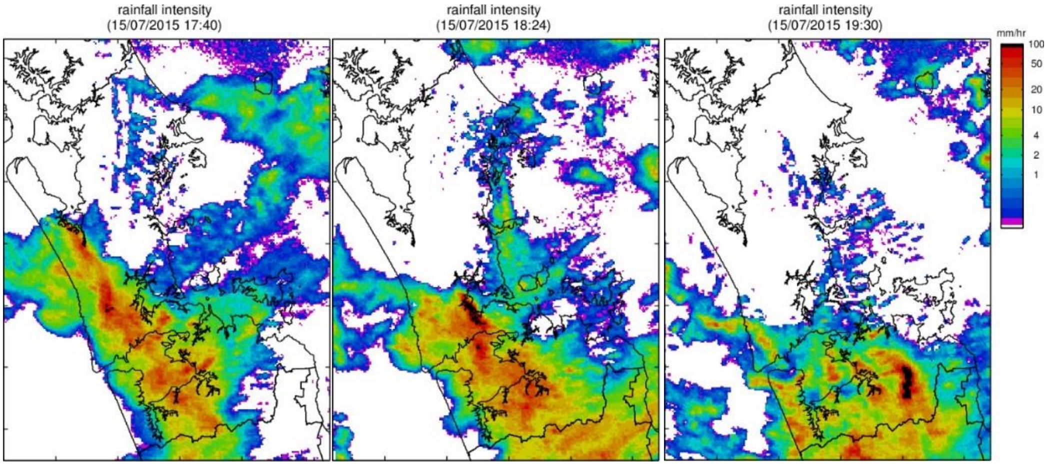

Figure 4: Selected instantaneous rain rate estimates from the radar data for the event. A series of intently precipitating convective cells move from the North West during the two hours covered by the frames.

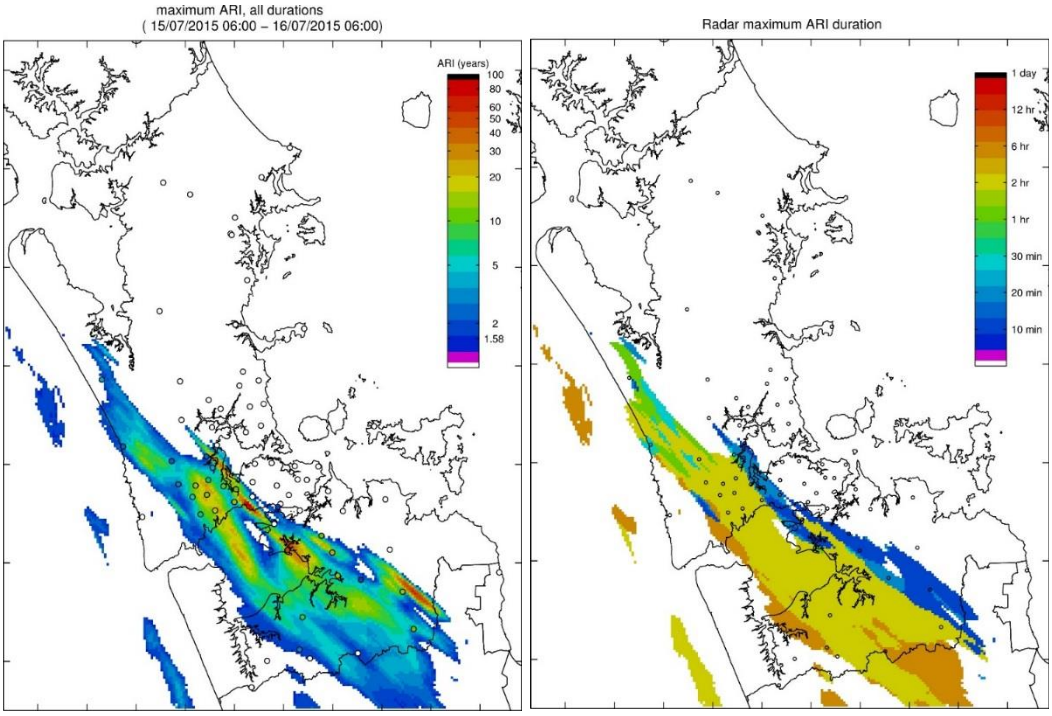

Figure 5:

Left: maximum ARI across all duration determined from the radar data. The same statistic determined from the rain gauge record is also plotted for comparison (coloured circles). Right: The duration at which the maximum ARI occurred.

The bulk of the remaining peak ARI area occurred at 120 minute duration and was at most a 30 year return period event, and generally below a 20 year return period event. The 120 minute critical duration (yellow and orange band region in Figure 5) is a result of accumulation from one very intense and several weaker convective cells within a 2 hour window.

The difference between the radar and interpolated spatial estimates based on rain gauge data is substantial in places and provided in Figure 6. The implications of the substantial disagreement between the two methods is discussed in the following section.

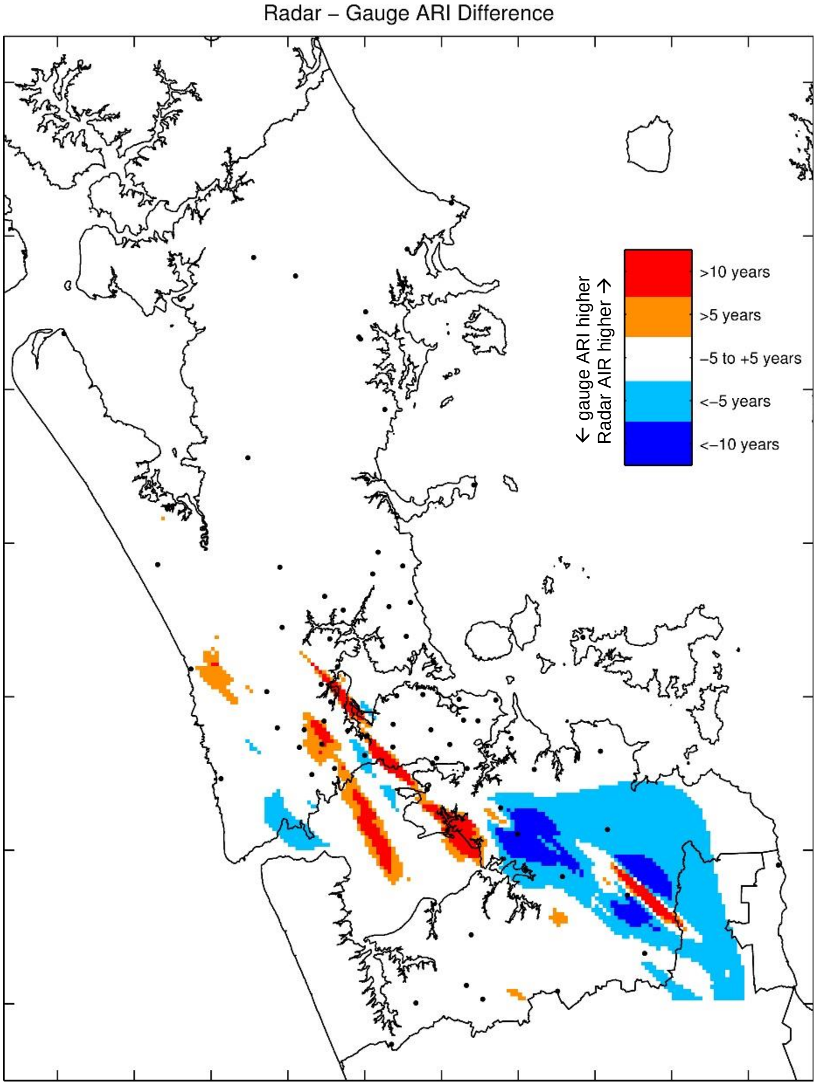

Figure 6: The difference between the rain gauge (Figure 1) and rain radar (Figure 5) ARI estimates.

4 DISCUSSION

This convective rainfall structure results in a highly variable rainfall accumulation. The rain gauge network has difficulties in adequately sampling this kind of variability because point measurements, while accurately measuring rainfall at their location, are not physically capable of inferring accumulation away from the measurement location. This difference is highlighted in the difference between the radar and gauge spatial estimates of maximum ARI across all durations, with large areas showing a difference of 10 years or more between the two methods (Figure 6), in spite of good pointwise agreement at gauge locations.

In West Auckland and near Manurewa, the rain gauge ARI contours tend to underestimate the maximum ARI at points in-between the gauge network. The underestimation appears to be because in this particular case the convective cells responsible for the maximum ARI accumulations delivered the heaviest rainfall rates between the rain gauge network.

In South-East Auckland, on the other hand, the rain gauge scheme tends to overestimate the maximum ARI. In this case the higher rainfall rates imaged by the radar are coincident with the sparse gauge network. The rain gauge contours spread the resulting higher ARI statistic into areas with no gauge observations but in which the radar measured less rainfall, resulting in a net over-estimation by the gauge network.

This is the expected mathematical behaviour of under-sampling of a variable field: By chance the sampling points will coincide with local maxima and minima and this will introduce local high bias into the resulting spatial estimates. For post event reporting this can have implications for understanding of request for service (RFS) logs and assessment of the stormwater system performance.

4.1 COMPARISON WITH RFS LOCATIONS

The locations of all the logged RFS have also been mapped on the maximum ARI across all scales determined from both rain gauge and rain radar in Figure 7.

Five clusters of habitable floor RFS are identified along the storm path and these are discussed in turn.

4.1.1 WEST AUCKLAND

West Auckland is well covered by a comparatively dense rain gauge network (about 1 gauge / 10 km^2). Addresses which suffered habitable floor flooding were all located within 2 km of a rain gauge.

In West Auckland the radar- indicated the highest ARI rainfalls fell between the rain gauge networks tracking from the North East, over the Waitakeries, the center of the Te Atutu peninsular and on to Avondale and Lynfield. Non-habitable RFS are clearly clustered along the path of the cell cores.

In this case the highest intensity rain appears to have passed between the gauge locations so the radar estimates of maximum ARI exceeded the extrapolated rain gauge estimates at many locations, including some of the RFS addresses. For the other RFS addresses with a interpolated gauge ARI estimates higher than the coincident radar pixel were within 2 pixels of high radar ARI pixels, reflecting the extreme spatial gradients associated with the event.

4.1.2 MANUKAU/MANUREWA EAST

South Auckland has comparatively few rain gauges with a characteristic gauge density of about 1 gauge / 50 km^2.

The band of RFS (marker numbers 7-11) are oriented around a high ARI area associated with a strong convective cell. The radar derived ARI field suggests all the RFS were within 2 pixels (1km) of a 20 year return period, 10 minute duration event.

The low rain gauge density in the area results in substantial spreading of information from the nearby rain gauge further to the north and east where no RFS of any type were issued.

4.1.3 MANUREWA

A cluster of habitable floor RFS (numbers 12 & 13) were associated with a cell which developed over the Auckland airport area.

The ARI spatial estimate generated from rain gauge observations indicates lower ARI than the radar estimate. This is because the gauge ARI estimate does not include any observations of the convective cell and rely on more distant rain gauge observations.

Instead, the rain gauge ARI estimate is strongly influenced by the nearby observations from the Puhinui gauge which collected rain from the convective cell associated with RFS number 7-11. These extrapolated gauge results tend to imply a link between the two RFS clusters, while not adequately explaining the gap between them.

The radar map indicates the discrete and separate nature of the two sets of events so aids in understanding the spatial structure of logged RFS.

The NZ MetService rain gauge at Auckland airport, recorded a 10 minute ARI return period of just over 40 years but this data was not available when the rain gauge spatial estimate was generated.

4.1.4 PAPAKURA/TAKANINI

Three habitable floor RFS were logged in this area.

The nearby Longford park rain gauge reported a 120 minute duration ARI with a return period of over 10 years. The radar estimate of ARI was substantially lower. This lower radar bias appears to be due to attenuation of the radar measurements of rainfall which contributed to the 120 minute duration ARI. Attenuation of the radar signal is readily identifiable in the radar data set during the passage of the intense convective cell over Manukau/Manurewa East to the North. This biased the radar measurement low by up to 10 mm and resulted in the lower radar ARI.

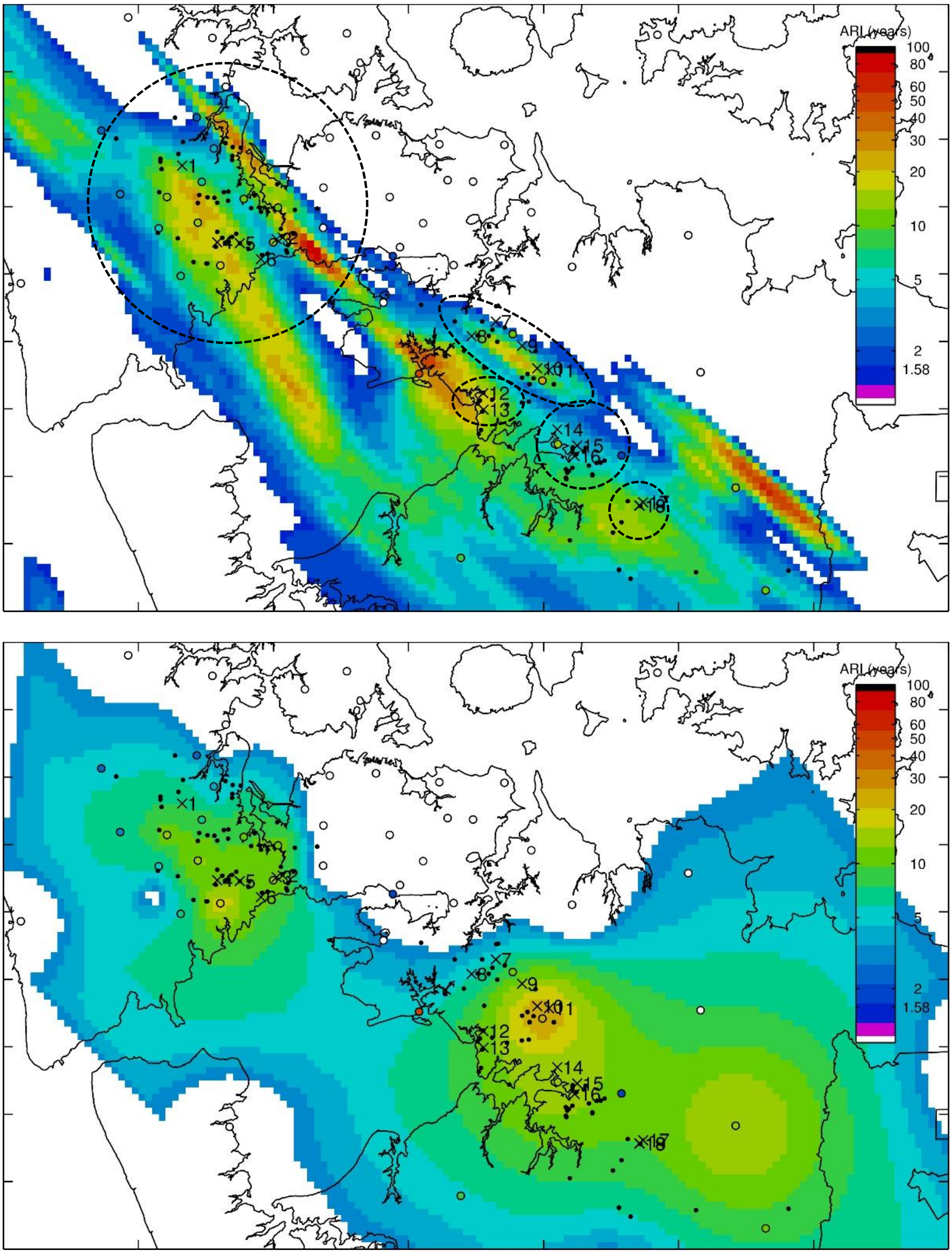

Figure 7: Location of habitable floor RFS's (indicated with x and numbers) and non-habitable RFS (dots). Spatial estimate of the maximum ARI across all durations are calculated by inverse distance weighting from the rain gauge point measurements (bottom) and merged radar-gauge product (top). Rain gauge ARIs are also indicated (filled circles)

4.1.5 DRURY

Habitable floor flooding in Papakura occurred on Judge Richardson Drive, about 4 km from the nearest gauge. Given the highly spatially variable convective events which where characteristic of the day, this spatial separation tends to suggest the extrapolated radar information will contain little information about local rain intensity. By way of comparison, the extrapolated rain gauge ARI to the north east of RFS number 7-11 indicates an approximately 6 year return period, but the radar estimate in the area was relatively light and did not exceed a 1.58 year return period considered here.

For the Drury area, the radar spatial ARI indicated a longer return period than the rain gauge extrapolation for the event which may be more consistent with the reported habitable floor flooding.

5 CONCLUSIONS

Rain Radar can be useful for detailed characterisation of rainfall intensity and distribution over urban catchments where the spatial distribution of rainfall is important.

This paper presents results of disaggregating the MetService raw radar data into 1 minute, 500m accumulation maps which have been generated by post processing of radar observations from the NZ MetService radar and Auckland Council Rain gauge network.

Analysis then focused on a storm which passed over Auckland in July of 2015. For the event (15/07/2015) the line of convective cells which passed over the Western and Southern parts of the city was narrow and the core areas of these cells where the heaviest rainfall occurred was a few hundred meters wide (likely narrower even than the radar resolution).

The convective rainfall structure results in a highly variable rainfall accumulation. The rain gauge network has difficulties in adequately sampling this kind of variability because point measurements, while accurately measuring rainfall at their location, are not physically capable of inferring accumulation away from the measurement location. The measurement deficiency is apparent in the rain gauge spatial ARIs which produce smooth contours which don’t adequately explain clustering and spatial structure of RFS (or indeed, absence of RFS).

Radar measurements are more suited to characterising this extreme spatial variability as radar samples the complete horizontal extent of Auckland Stormwater catchments, albeit some distance above the ground. The downside of radar measurements are questions around sampling representation. For the NZ MetService radar the principle sampling errors are the the sample frequency (7.5 minutes), measuring rainfall aloft (up to several km above the ground), attenuation of the radar signal in heavy rain and uncertainties in the relationship between radar measurement and rain rate.

As demonstrated Rain Radar provides us with a better way to compute ARI across a variable rainfall field. Accurate post event reporting in combination with better operational and public engagement, will become an essential data set for future planning and design of stormwater infrastructure and will help better align our hydraulic models outputs with actual customer experiences.

5.1 LOOKING TO THE FUTURE

Uptake of radar data amongst potential “urban-hydrology” end users has been slow in New Zealand, and this lack of progress can probably be attributed to the high technical expertise threshold required to make proper use of the data streams available from radar systems currently available. This is a regrettable situation, as the rainfall data collected by the NZ MetService radar network is as good as any in the developed world, yet, in the authors’ view, underutilised.

The work presented here focuses on preparing a standard and familiar analysis product from radar data for just one event, however the methodology employed is able to be largely automated, allowing equivalent reporting data products to be generated for other events either retrospectively or in near real-time. Indeed, with proper implementation use of qunatitiative precipitation estimates from NZ radar need not be confined to post event reporting or retrospective modelling studies. The methodology presented here can be run in real time so is suitable for use in both real-time city optimisation modelling and emergency management use.

Radar data will be most useful if it can be disseminated in such a way as to be accessible to as large a pool of end users as possible. Modern web GIS platforms represent an opportunity to establish enhanced engagement tools with customers and operational staff to provide more on the ground data and help better align flood reports to ARI. Inclusion of radar data in these systems, and easily accessible to engineering practitioners in both visual and as model input conditions will result in better uptake of this data and eventually improved engineering outcomes.

Radar sits alongside rain gauges as an “observational” data set about rainfall collected in a centralized manner. Other examples include satellite data or microwave link estimates of rainfall. We see great potential in developing centralized GIS systems which combine these data types to arrive at optimum estimates of rainfall. The advent of these systems also has potential to allow collection and merging of crown-sourced information, for example using social media to aggregate information about flash flooding to add even more depth and context to our understanding of urban stormwater processes.

ACKNOWLEDGEMENTS

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