OPERATIONAL USE OF RAIN RADAR IN AUCKLAND

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ABSTRACT

Accurate estimation of the spatial and time variation of rainfall across urban catchments is essential for accurate sewer and stormwater modelling and operations activities.

The Auckland region is served by an extensive rain gauge network operated by Auckland Council Healthy Waters Department. In light of the difficulties in achieving even the minimum desirable density of 1 gauge / 1-4 km^2 across the entire region (the land area of the Auckland region is some 5000 km^2 and experiences highly variable rainfall) the authors have been working collaboratively towards enabling use of rain-radar derived accumulations to support decision making in real time during flooding events, immediately post event for reporting to stakeholders and in long term planning.

To date, use of rain radar derived quantitative precipitation estimates in the engineering field has been hampered by the large data volumes which need to be handled and the high level of specialised expertise required to quality control and calibrate raw radar observations. In order to remove this barrier and foster more widespread use of radar data, data quality control from the Auckland MetService radar has been automated, operationalising real-time calibration of the radar precipitation estimates using the Auckland Council rain gauge network. The high quality radar derived accumulations (1 minute time step, 500m resolution rasters) are then fed into a cloud-based GIS platform and can be interacted with by council staff, for example to extract a catchment averaged accumulation or raster stack for model input.

KEYWORDS

Rain Radar, intensity-duration, stormwater modelling, flooding, ARI

PRESENTER PROFILE

Luke Sutherland-Stacey is an independent water 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.

1 INTRODUCTION

Accurate estimation of the spatial and temporal variation of rainfall across urban catchments is essential for accurate sewer and stormwater modelling, and operations activities. Sampling the true areal rainfall with rain gauges is difficult, because rainfall varies on spatial scales much smaller than the typical separation between gauges (Morrissey et al. 1995, Steiner 1996, Nystuen 1998, Villarini et al. 2008).

The implications of spatial under sampling for stormwater and sewer modelling activities are well documented (e.g. Berne et al. 2004, Cooper and Fernando 2009). Too sparse gauge spacing may lead to significant under and over estimation of rainfall over short time periods and therefore guidelines about minimum gauge spacing have been developed (e.g. ARC 1999, WaPUG 2002). However, even if it were possible to meet deployment and running cost of the hundreds of gauges which would be required to adequately instrument the Auckland region, adherence to minimum gauge density requirements can be difficult in urban settings because of the limited availability of sites compliant with World Meteorological Society guidelines for rain gauge deployment (WMO 2008). Deployment of rain gauges too close to buildings may cause shadowing, while deployment above ground level (e.g. on rooftops) can result in significant low biases.

Rain radar is a well-established technology for addressing the spatial sampling problem. Rain radar has been used in a variety of stormwater (Löwe et al. 2014), runoff (Shaw et al. 2010) and sewer system modelling (Sempere-Torres et al. 1999, Heinonen et al. 2013) applications internationally. Auckland Council Healthy Waters and Watercare Services Limited are actively exploring the use of rain radar in sewer modelling (Joseph et al. 2014) and stormwater (Sutherland-Stacey et al. 2016) settings.

New Zealand has been covered by the network of weather radars run by the Meteorological Service of New Zealand Limited (MetService) for many years (for a review, see Crouch 2003). However, until recently there have been only limited attempts to make use of radar data in stormwater and wastewater engineering applications. Limited use of rain radar measurements in the engineering modelling community in New Zealand may be attributed to the technical barriers which exist in making use of complex radar data compared to simpler rain gauge measurements (for a discussion, see Milsom 2007). In order to remove at least some of these barriers and foster more widespread use of radar data, we have automated data quality control from the Auckland MetService C-band radar, and operationalised real-time calibration of the radar precipitation estimates using the Auckland Council rain gauge network. The high quality radar derived accumulations are prepared at spatial and time resolutions suitable for urban hydrology (1 minute time step, 500x500m pixel resolution rasters) and are then fed into a cloud-based GIS platform and can be interacted with by council staff and consultants, for example to extract a catchment averaged accumulation for reporting or a raster stack for model input.

2 METHODOLOGY

2.1 RAIN MEASUREMENTS IN AUCKLAND

The Auckland region is served by an extensive rainfall observation network (Figure 1) comprising of telemetered tipping bucket rain gauges run by Auckland Council and a single polarisation, and Doppler C-band weather radar run by MetService.

Auckland Council and Watercare have been actively exploring the use of local radar systems to improve rainfall estimates. Current experimental monitoring with local weather radar includes a vertically pointing radar at Orewa and scanning X-band radar based at Ardmore.

The optimal estimate of rainfall accumulation can be obtained by making use of all the observation data types together.

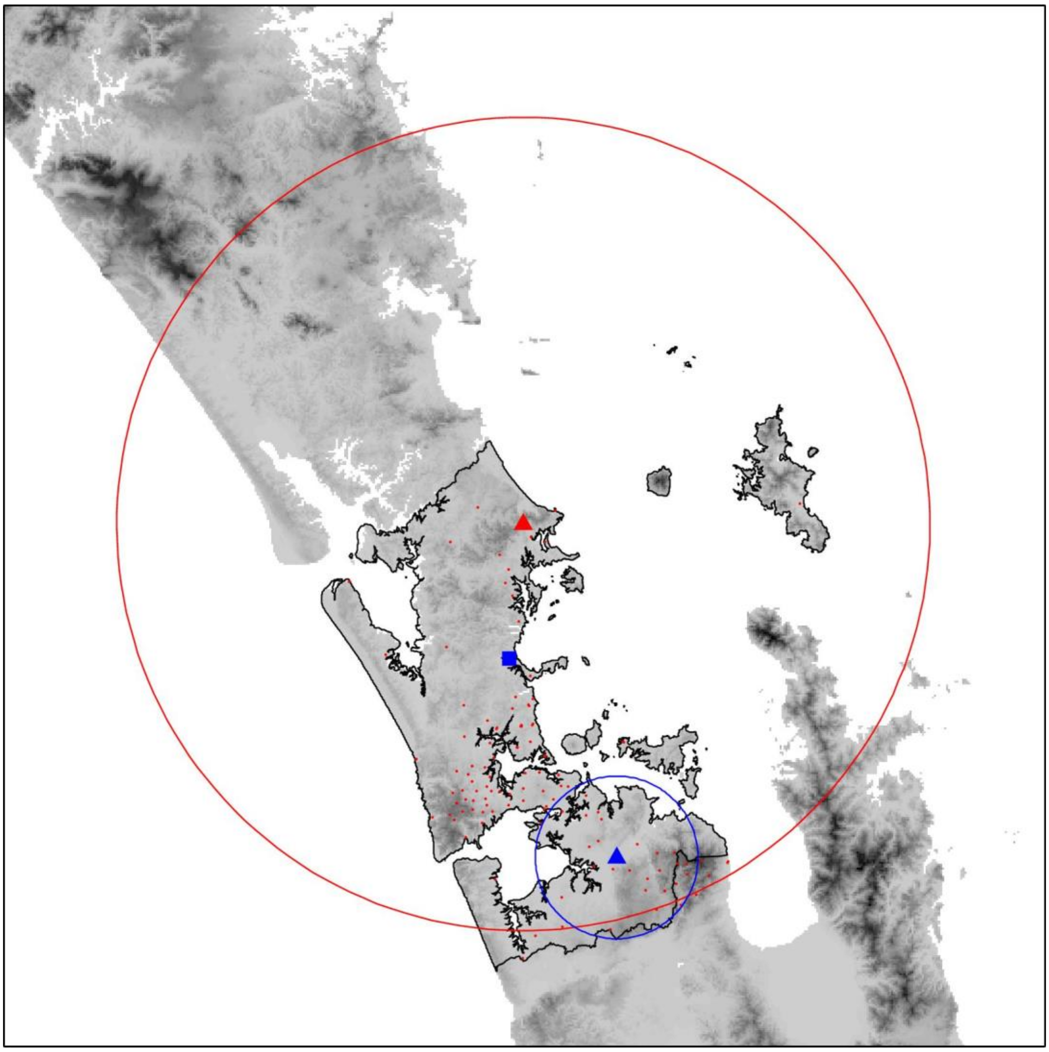


Figure 1: Map of the Auckland Region depicting the location of the MetService C-band weather radar (red triangle and 100 km range circle), tipping bucket rain gauges (red points), vertically pointing radar (blue square) and X-band radar (blue triangle and 20km range circle). The boundaries of the Auckland Region are also indicated with a black outline.

2.1.1 RAIN GAUGE NETWORK

Auckland Council Research, Investigation and Monitoring Unit (RIMU) run over 60 permanent telemetered tipping bucket rain gauge sites. The rain gauges are with a few exceptions mounted at ground level or in trenches and equipped with either 0.5 or 0.2mm buckets.

2.1.2 C-BAND AND X-BAND SCANNING RADAR MEASUREMENTS

MetService operate a single-polarisation, C-band scanning rain radar located on Mount Tamahunga near Warkworth (for description of the radar and photograph of the radar tower, see Crouch 2003). The radar performs a scan cycle every 7.5 minutes, measuring radar reflectivity at increasing altitudes and at up to 250 km in range. The radar is well positioned to provide meteorological observations for both Auckland and the Northland regions. The most southern parts of the Auckland region are up to 100km away from the C-band radar, so beam spreading and climbing effects mean radar measurements in South Auckland are made between 1.5 and 3km above the ground. To investigate the impact of range limitations on radar-derived accumulations, Weather Radar New Zealand are currently operating an X-band radar (described in Sutherland-Stacey et. al. 2011) out of the University of Auckland Ardmore field site, although data from the X-band radar is not currently part of the operational analysis described in this paper.

2.1.3 VERTICALLY POINTING RADAR MEASUREMENTS

A vertically pointing radar (VPR) (“MRR2”, Metek GMbH) has been deployed in Orewa since September 2017 (Photograph 1). In comparison to the MetService C-band radar, the VPR dish does not move but rather points directly upwards and continuously measures the vertical Doppler velocity spectra and radar reflectivity in a vertical column directly over the radar site at 100-m height resolution and 10-second intervals. The VPR The deployment location is approximately 30km to the south of the C-band radar site, allowing inter-comparison of the two radar measurements and direct calibration of the C-band radar.

Photograph 1: The vertically pointing radar.

2.2 ESTIMATING RAINFALL FROM RADAR MEASUREMENTS

Radar is an active sensing technology which illuminates targets with electromagnetic energy and measures the properties of the reflected (or “back-scattered”) radiation in order to elucidate some physical property of the targets. In the case of meteorological radars, repetitive pulses of electromagnetic energy are focused into the distance by a parabolic dish, by scanning the dish and recording the bearing and time taken for pulses of energy to return, a map of precipitation location and intensity can be constructed. Radars are typically differentiated according to the operating wavelength and we adopt this approach here - referring the MetService radars which emit 5.4 cm wavelength radiation as “C-band”.

The principle radar measurement is reflectivity (Z, mm^6m^{-3}), which for meteorological applications is the scattering cross section of all the targets in the radar beam at a particular range bin:

$Z = \int_0^\infty D^6 N_v(D) dD$ (*Equation 1*) where D is the drop diameter, N_v is the number of drops with that diameter. Reflectivity is usually expressed in decibel units, and values typically range from 20 dBZ for light rain to 55 dBZ for very heavy rain. Values over 55 dBZ are likely to indicate solid precipitation (hail).

The scattering cross section, and hence reflectivity, depends on the usually unknown raindrop size distribution, and must be converted to rainfall rate (R, mm hr^{-1}) to be useful. Other factors influencing the estimation of rainfall which must also be taken into account are attenuation, ground clutter, beam blocking, uncertainty in the vertical profile of reflectivity, spatial smoothing and time intermittency of the radar measurement.

For hydrological applications, detailed quality control and processing is required to generate useable rainfall estimates. For Auckland Council's requirements, precipitation estimates were required at sub hourly frequency, sub kilometre resolution and with minimum systematic bias and error. This level of detail and accuracy was not available from the 1 hour accumulation product generated by the C-band radar's bundled software, so raw radar data in polar format (range, bearing and reflectivity) were sourced directly from the C-band radar output files and ingested in the cloud based GIS system through a customised post processing system.

2.2.1 C-BAND RADAR CALIBRATION BIAS CORRECTION

As a first step, the C-band radar measurements were compared to coincident vertically pointing radar measurements of rain above Orewa to check for any systematic bias. The much smaller size of the vertically pointing radar affords the luxury of direct end-to-end calibration in a laboratory setting, and it was assumed that any systematic difference in measurements between the radars is due to electrical calibration bias or unquantified physical losses in the C-band radar. To exclude differences arising from attenuation, the comparison (Figure 2) was only made when there was little precipitation obstructing direct line of sight between the VPR and the C-band radar sites.

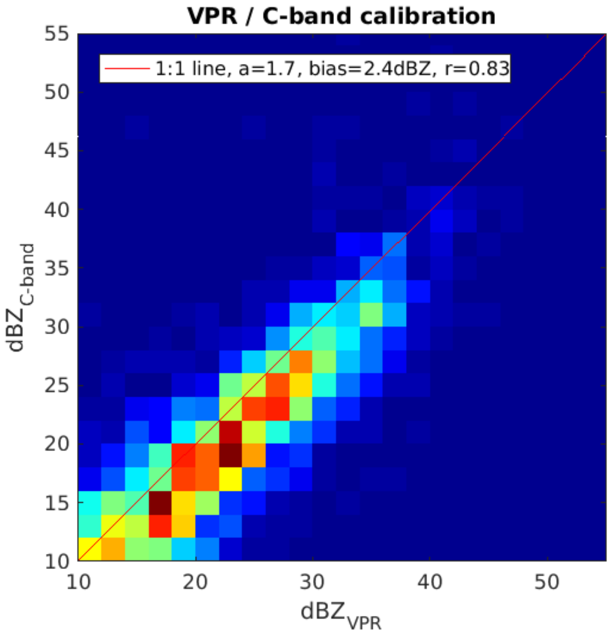


Figure 2: Comparison of reflectivity estimates for the C-band and VPR radars.

The comparison identified a low bias of approximately 2.4 dBZ in the C-band radar measurements. Because the conversion from reflectivity to rainfall is non-linear, this corresponds to a significant error in rainfall estimates, about 30% low bias. Previously, a low bias had been observed in comparison between C-band rainfall estimates and rain-gauge measurements, so the C-band / VPR comparison helps to identify the cause of the low bias as being a characteristic of the C-band radar calibration, rather than a deficiency in assumptions made in subsequent steps when processing of the radar data itself.

2.2.2 GROUND CLUTTER REMOVAL

Following correction of the low bias, radar data was treated to identify and suppress ground and sea clutter. The MetService C-band radar is equipped by the manufacturer with an automatic clutter suppression system, which is intended to remove any "extra" contribution to the reflectivity measurement from targets with zero relative velocity- e.g. hills and buildings. In practice, the non-zero dish velocity and random motion from trees and leaves means the filter often only partially suppresses ground clutter (Uddstrom and Gray 1996). Suppression of residual clutter is achieved by comparing the reflectivity measurements with a terrain elevation map. In regions where the terrain elevation is flagged as high enough to intersect with the radar beam, the radar data is treated according to a filter which checks for sharp drops in reflectivity in scans of increasing dish angle and low relative wind speed. If a large negative gradient (much stronger signal near the ground) is detected it is assumed that the radar signal is due to ground clutter and the measurement is set to zero (Figure 3). Spurious returns from ripples on the sea surface are also suppressed in a similar manner.

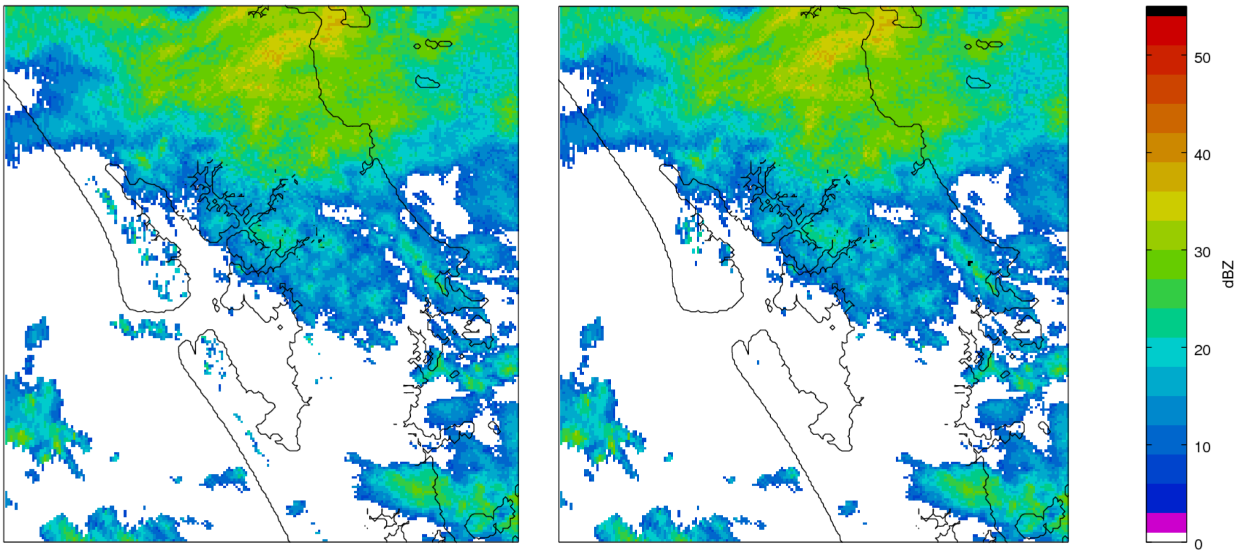


Figure 3: radar reflectivity map before (left) and after (right) ground clutter suppression. Note the removal of the returns from the ridgelines of North and South head and sea surface at the Kaipara harbour mouth.

2.2.3 ATTENUATION CORRECTION

Correction for attenuation of the radar signal by rain over the path of the radar beam is applied according to Nicol and Austin (2003), using coefficient suitable for widespread rain types. Attenuation correction is required to reduce the underestimation of rain at more distant locations from the radar site due to weakening of the radar signal by intervening hydrometeors. Figure 4 gives an example of the correction applied to a rain band approaching Auckland from the North West- the radar is located in the centre of the frame and without attenuation correction the precipitation on the far side of the rain band would be underestimated.

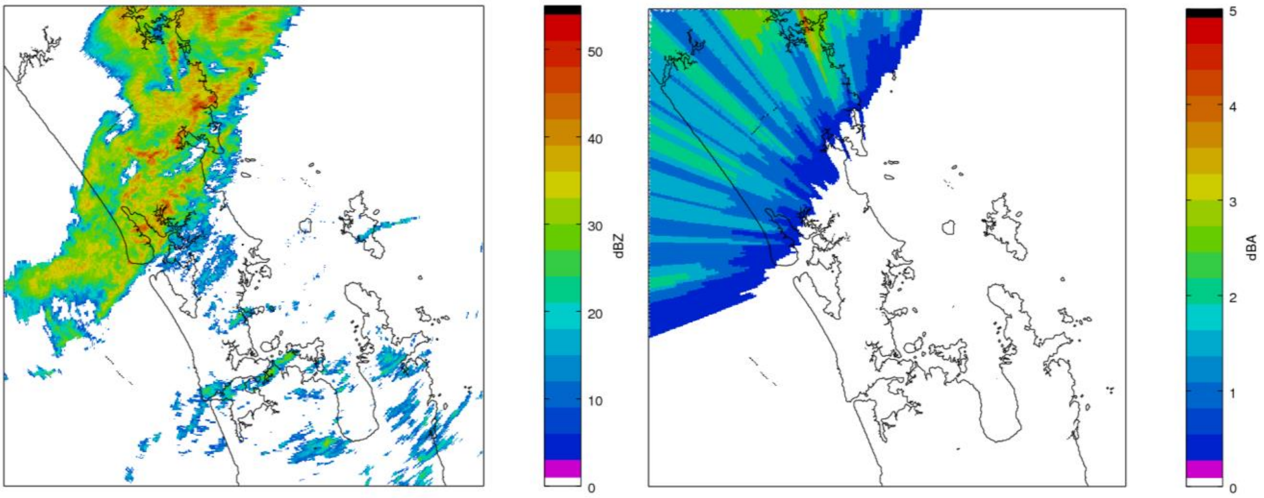


Figure 4: radar reflectivity map (left) and estimated attenuation (right), 2017/07/22 11:00

The attenuation correction method employed here is only able to partially correct the underestimation for two reasons, firstly the raindrop size distribution is unknown and therefore so to are the correct coefficients for attenuation correction equation. Therefore, in order to avoid overcorrection a conservative estimate is used. Secondly, for very strong attenuation, for example due to blocking by hail, the correction fails completely if the radar signal becomes too weak to correct. Future work with vertically pointing radars will address the uncertainty in the drop size distribution and deployment of additional small scanning X-band radars has the potential to reduce the impact of attenuation by observing rain from multiple angles.

2.2.4 ACCOUNTING FOR SAMPLING INTERMITTENCY

The C-band radar scanning strategy is optimised for meteorological forecasting and aviation hazard detection. A volume sampling strategy has been adopted whereby the radar dish rotates at a fixed rate (approximately two revolutions per minute) and after each complete rotation the dish elevation is adjusted in order to build up a three dimensional reflectivity estimate (Table 1)

Table 1: C-band radar scan procedure

Designation	Dish Elevation (deg)	Range (km)	Doppler Velocity
SURV	0.5,1.0	320	N
VOLA	0.5,0.9,1.4,2,3,4,5,6	250	Y
VOLB	7,8.5,10,12,15,20	125	Y

The time taken to perform the 16 sequential scans is 7.5 minutes. Observations from higher elevations are not particularly useful from a hydrological perspective because quantitative precipitation estimation requires the best possible measurement of rain close to the ground, rather than the details of the hydrometeor microphysics aloft.

The VOLA scan type is best suited for quantitative precipitation estimation as the Doppler velocity measurement aids in suppression of reflection from non-meteorological targets (ground clutter). Of the VOLA scans, the 0.9 degree elevation slice is a good compromise between lowest possible elevation angle and minimal terrain blocking effects. Using just one slice of the volume scanning pattern results in an effective sampling intermittency of 7.5 minutes. Rain patterns can move markedly in short time periods so an *advection interpolation* scheme is used to estimate the position and intensity of rainfall between 7.5 minute scans. An echo tracking scheme following the COTREC method originally proposed by Li and Schmid (1995) has been implemented, whereby:

1) Sequential radar images are compared to identify discrete precipitation features
2) The motion of each precipitation feature is diagnosed and assigned an *echo motion vector*
3) All echo motion vectors are combined to generate a best guess of the overall echo motion field (Figure 5).
4) Sequential images are advected forwards and backwards according to the echo motion field to estimate the position and intensity of rain between 7.5 minute radar scans.

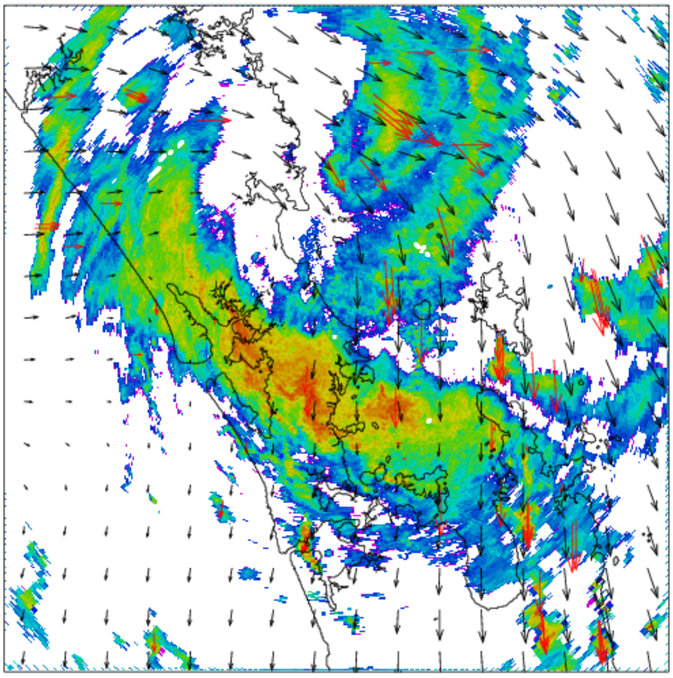


Figure 5: radar reflectivity image overlaid with individual precipitation feature echo motion vectors (red arrows) and the overall echo motion field (black arrows) for a cyclonic system 2017/03/12 09:23. The intense convection in the south west quadrant of the cyclone stalled over the suburb of New Lynn, delivering significant precipitation in a short space of time.

In this way, 1 minute reflectivity estimates can be disaggregated from the 7.5 minute measurements. Figure 6 gives an example of a synthetic radar estimate constructed by advection interpolation between two measurements. While the qualitative differences in the rainfall maps on such short time scales are subtle, accumulation measurements are significantly impacted by the rainfall motion between echoes. Figure 7 gives the difference in accumulation estimate for the same 7.5 minute period with and without advection applied. Failure to account for the motion of the storm between 7.5 minute scans results in up to ∓25mm/hr localised under-and over-estimation of rainfall rate, which would both confound comparison with rain gauge measurements and result in very different stormwater model responses.

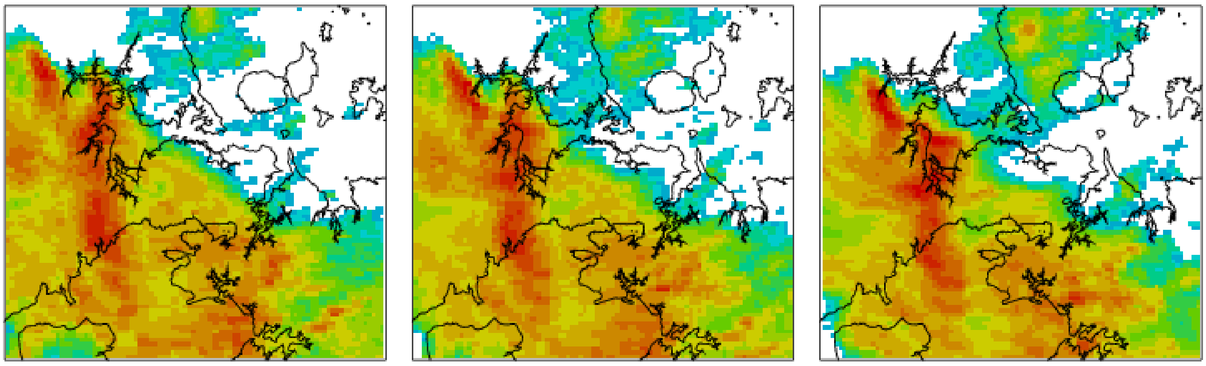


Figure 6: Radar images measured 2015/07/15 16:15:00 (left) and 2015/07/15 16:22:30 (right). The centre image is a synthetic image constructed by the advection interpolation scheme, valid at 16:18. Note the subtle movement of the intense precipitation features between frames. Flooding resulting from this short-duration yet intense precipitation resulted in habitable floor flooding in West Auckland.

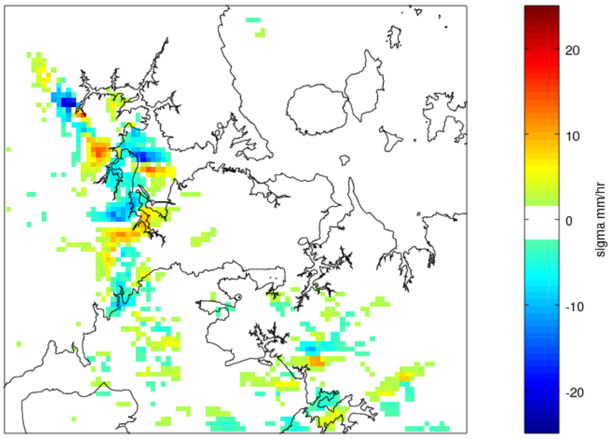


Figure 7: Difference in average rainfall rate for the 7.5 minute period starting 2015/07/15 when using estimating the accumulation with just the measured frames or including the advection interpolated data.

2.2.5 COMPARISON WITH RAIN GAUGES

The quality controlled reflectivity (*Z*) obtained by the processing steps still needs to be converted to rainfall rate to be useful. This could be achieved exactly by substitution using equation 1 if the raindrop size distribution were known, since

$$R = \int_0^\infty D^3 v(D) N_v(D) dD \qquad (\textit{Equation 2})$$

where *v(D)* is the raindrop fall speed for a drop of a given diameter. However, the raindrop size distribution can vary markedly with time and is not able to be constrained with a single polarisation radar.

A well-established method for overcoming the limitation in knowledge of the drop size distribution and for converting radar measurements to rainfall is to assume a constant form of the raindrop size distribution, resulting in a fixed power law Z-R relationship:

$$Z = aR^b \quad \text{with a=200, b=1.6} \qquad (\textit{Equation 3})$$

and then compare the resulting radar rainfall estimates with local rain gauges to derive a scaling factor. This "gauge scaling" approach which has been used in most radar hydrology work in Auckland to date (e.g. Sutherland et al. 2016, Joseph et al. 2014).

A simple "gauge scaling" approach is implemented as follows:

1) the advection interpolated reflectivity measurements are extracted from the 1 minute rasters at each (n^{th}) rain gauge location to construct a time series of the radar rainfall estimates (RR_n).
2) the available rain gauge tips are obtained at each (n^{th}) rain gauge to construct a time series of the gauge rainfall measurements (RG_n).
3) For each (n^{th}) rain gauge/ rain radar time series pair, a time window is identified which contains a minimum rain gauge accumulation threshold (e.g. 5mm).
4) For the selected time window, the gauge/radar bias is calculated according to $dBbias_n = dBRR_n - dBRG_n$ where dB indicates a logarithmic conversion $dBRG_n = 10\log_{10}(RG_n)$

5) dB*bias* is a collection of point estimate of the difference between the rain gauge and rain-radar measurements at the rain gauge locations, the point estimates are interpolated onto the full domain using an inverse distance weighting scheme to give a spatially complete estimate of the raster radar/gauge bias. In the inverse distance weighting scheme, a minimum radius at each pixel is set equal to the distance to the nearest three gauges in order prevent any one gauge from strongly influencing the local bias estimate.
6) The full raster of the radar rainfall estimates is corrected according to the interpolated bias map.

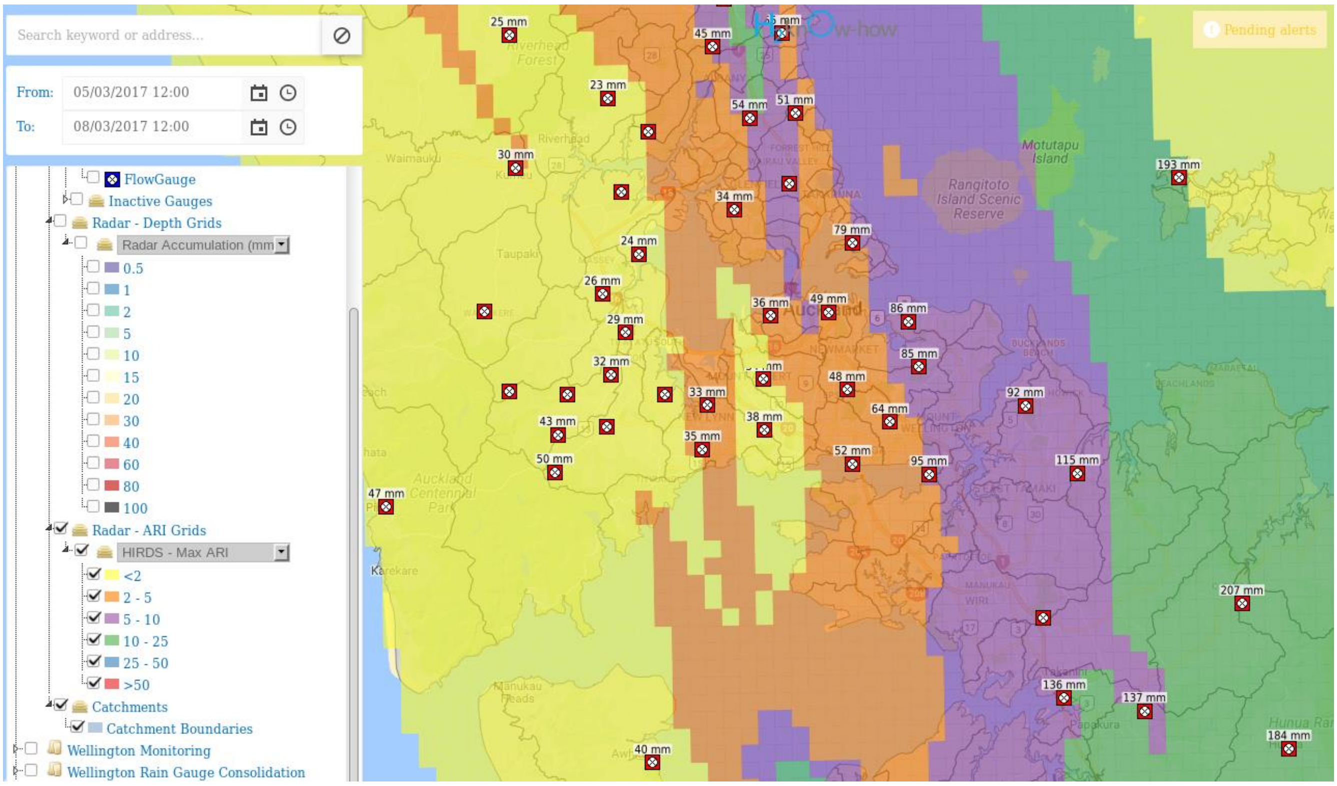
In the operational (real-time) implementation of the gauge scaling procedure, up to the last six hours of rain gauge and rain radar measurements are used to estimate the correction factor. Later, a second pass repeats the gauge scaling procedure considering a symmetric 12 hour time window centred about the analysis time.

While gauge correction methods are comparatively simple to implement, they make the assumption that the rain gauge measurements they rely on are unbiased and representative of the same areal rainfall as the co-located radar pixel. Wind effects may result in significant gauge under catch, particular for rain gauges not mounted flush with the ground surface or well away from local flow obstructions (Rodda and Dixon 2012). Sub-pixel radar- variability in the rain field and uncertainty about the distribution of rain in in the vertical has also been shown to be significant (Shucksmith *et al.* 2010, Fabry *et al.* 1995). For this reason Auckland Council is currently investigating the potential of using vertically pointing radars (such as the unit at Orewa) to directly estimate the raindrop size distribution to allow direct calibration of the C-band radar measurements.

3 OPERATIONAL USE OF RADAR DATA

After gauge scaling, the radar rasters (500m pixels, extent 512x512 pixels centred on the Auckland radar) are ingested into a cloud based database. Radar accumulations can then be retrieved automatically through a standard application programming interface (API) or by a user through a google-maps based geographic information system (GIS) portal (H2knOwhow, Mott MacDonald).

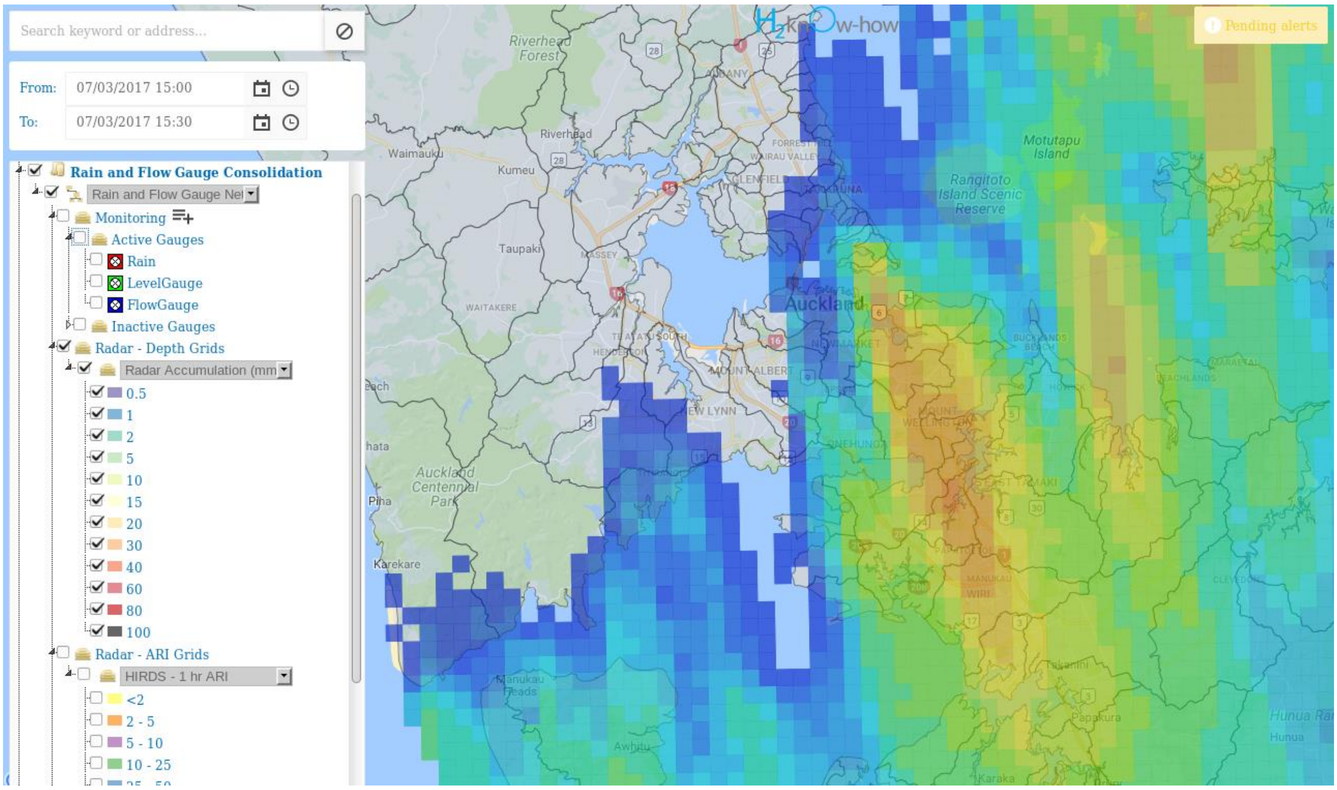
The GIS portal implementation for Auckland Council has been designed to assist in post-event reporting activities and includes functionality to automatically generate spatial maps of Average Recurrence Interval (ARI) statistics (Figure 8) as well as visualisation of the radar rainfall estimates (Figure 9).



From: 05/03/2017 12:00

To: 08/03/2017 12:00

Figure 8: Example of automatic generation of a maximum ARI surface from the processed radar data for the flooding event 2017/03/07.



From: 07/03/2017 15:00

To: 07/03/2017 15:30

Figure 9: Extraction of radar rainfall accumulation estimates for a sub hourly time period, in this case 2017/03/07 15:00 - 15:30.

Future functionality may be to establish radar-based alarming limits in terms of total catchment accumulation or exceedance of an ARI value and addition of a radar Nowcasting layer to extend warnings by up to 2 hours into the future. This feature has been tested and appears to offer considerable future benefit for operational use.

4 CONCLUSIONS

This paper describes the first implementation of a truly GIS compatible and fully automated rain-radar analysis system in New Zealand. The notable technical improvements over previous efforts, aside from improved quality control, are the facility to access sub-hourly accumulation estimates and a simple web-API interface to retrieve data. Sub hourly disaggregation of the radar data allows both estimation of short duration ARI statistics and extraction of rainfall estimates at timescales suitable for use directly in sewer and stormwater modelling applications and catchments with short hydrological response times.

The new analysis methodology is suitable not only for the Auckland Region, but any area of New Zealand served by a local weather radar (Figure 10) and automatic telemetered rain gauges.

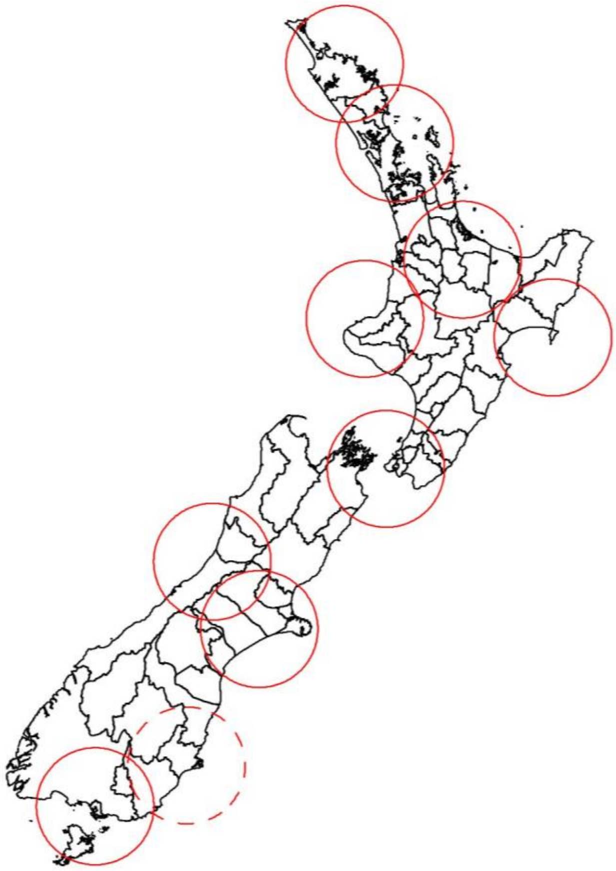


Figure 10: Coverage map for the C-band radars which comprise the national radar network. 100km range circles indicated the maximum optimal range of the radars for quantitative precipitation estimation (QPE). The approximate coverage of the planned Dunedin rain radar is also indicated (dashed circle).

Already, the Auckland Council radar processing workflow generates analyses for an area 256x256km around the Auckland radar site (Figure 1), which includes the southern half of Northland, including Whangarei and the Coromandel Peninsula. The modification to the existing system which would be required to provide radar derived rainfall estimates in these regions is limited to establishing data telemetry to the regional rain gauges. Likewise, the equivalent analysis can be extended to other radar locations. Enabling work is underway to propagate the system to the Wellington region but equivalently the analysis could be efficiently adapted to include major population centres such as the Bay of Plenty, Waikato and Christchurch which are well served by the MetService radar network.

The web based data management system established for the radar accumulations can also be used to handle other spatial data types. A natural extension to the system is ingestion of numerical weather prediction data. Current work is underway to enable ingestion and exposure of MetService forecast products to the same API to allow user interaction via the GIS portal.

Up until now, high technical barriers have prevented uptake of advanced rainfall data for water engineering applications in New Zealand. The work described in this paper is essential for realising the value of the investment in the radar network for urban hydrology. The authors hope that this new methodology will allow more engineering practitioners to begin to explore the use of radar data in their planning, modelling and operational applications.

ACKNOWLEDGEMENTS

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