REAL TIME CALIBRATED RADAR RAINFALL DATA FOR IMPROVED OPERATIONAL WATER MANAGEMENT AND WSUD

Brian Jackson[1], Leanne Reichard[2], Richard Connell[1]

[1] Water Technology, 15 Business Park Drive, Notting Hill, Victoria, Australia

[2] HydroLogic Systems BV, P.O. Box 2177, 3800 CD, Amersfoort, Netherlands

ABSTRACT: *The frequent occurrence of excessive rainfall in urbanised areas and river catchments is an important reason for water managers to require access to the best available precipitation data for effective planning, design, operation and maintenance of their water systems and related assets. The ever-increasing frequency of excessive rainfall events provides further incentive for water managers to have easy access to such data, which is recognised as the most important data source required for effective water management. In this paper we compare the various sources of precipitation data available and explore the benefits of calibrated radar rainfall data by reviewing the outcomes of several studies. We conclude that calibrated radar rainfall can be a significantly improved rainfall data source for water management activities and models, that exceeds rain gauge network density recommendations for all urban water management needs, including WSUD, and that is significantly cheaper to implement than further expanding existing rain gauge networks. Acknowledging the advantages that online Software as a Service (SaaS) solutions can provide, we also highlight the ever increasing availability of online access to this information through SaaS platforms.*

KEYWORDS: Calibrated radar rainfall data, Radar, Rainfall, Real-time,

1 RAINFALL INFORMATION FOR WATER MANAGEMENT

The location, timing, duration and intensity of precipitation plays an important role in the functioning of water systems, both urban and rural. Accurate and timely quantitative precipitation information is vitally important for water managers to effectively plan, design, operate and maintain their water systems and is the most important data input into most hydrologic and hydraulic models.

Most water management activities require accurate and timely precipitation data. Such activities can include, inter alia:

- Water Sensitive Urban Design (WSUD) and monitoring, including:
    - Green roofs, roof gardens, and vertical gardens;
    - Storm water management;
    - Storm water harvesting, including reuse, storage and infiltration;
    - Rainwater harvesting,
    - Smart, real-time, operational rainwater tank and/or other asset management;
    - Green streets;
    - Urban wetlands for retention and bio retention;
    - Localised wastewater treatment and reuse systems;
    - Ponds and lakes;
    - Sediment basins;
    - Groundwater aquifer recharge and recovery;
- Sewer System Design;
- Calibration of sewer system models;
- Optimisation of the use of storage in sewer systems;
- Calibration of hydrology and hydraulic models;
- Real-time operational use of hydrology and hydraulic models;
- Predictive real-time control of infrastructure and assets;
- Operational use of rainfall data for flood prevention and management of flood situations;
- Water damage claims assessments;
- Staff mobilisation and deployment before and during events;
- Maintenance scheduling of water affected infrastructure;
- Application of spatial rainfall distribution in real-time control algorithms;
- Flood modelling and the assessment of the risks of flooding;
- Detention, recharge, and infiltration control;

- Etc.

For the purposes of this paper, accurate and timely quantitative precipitation information means the accurate determination of both the absolute rainfall amount as well as the spatial and temporal distribution over contributing areas at a sufficient resolution for the intended purposes. Timely also implies that this data should be easily accessible at an appropriate time step and within a suitable time for the intended purposes. This is especially relevant if it is to be suitable for real-time or near real-time operational water management activities.

1.1.1 The further need for easy and timely online access to accurate rainfall data

One of the key requirements of suitable rainfall data is easy and timely access. The ever-increasing frequency of occurrence of excessive rainfall events is providing a further and increasing incentive for water managers to look for easy online access to such data in real time[15][14], as the modern advances in ICT now allow us to better meet decision-makers needs for real time, simple, robust, customised and easily accessible information through cloud based software as a service (SaaS) solutions.

SaaS platforms that endeavour to meet these need for forecast, observed and historic rainfall data, such as the HydroNET platform used by the authors of the studies discussed in sections 2.3.1 to 2.3.3, are thus a burgeoning method of accessing this data, as they provide the benefits of inter alia, much reduced initial capital investment costs, no further hidden hardware or software costs, reduced maintenance and support costs, cost sharing amongst all subscribers, and automatic software updates.

However, this burgeoning online access is not the focus of this paper and is only highlighted here as an important factor to note regarding the availability of rainfall data into the future. The main focus of this paper is to examine the use and suitability for water management of two sources of rainfall data, being rain gauge and radar-based rainfall data. The paper further explores the benefits of calibrated radar rainfall data, which blends rain gauge and radar rainfall data.

2 SOURCES OF RAINFALL DATA

Rainfall data comes from three basic sources; rain gauges, radar and satellite. This paper focuses on the first two.

2.1 RAIN GAUGES

The standard historical method of measuring rainfall has been with rain gauges. The World Meteorological Organisation (WMO) sets the standards required for the installation and maintenance of rain gauges, and a gauge installed and maintained to these standards is considered to be the most accurate point rainfall measurement method available. In order to be timely, automatic rain gauges that provide near-real time access to the data at small time steps are pretty much standard these days and any reference to rain gauges in this paper means an automated rain gauge.

Unfortunately, many rain gauges are not installed to these WMO standards. It is thus important to always assess the suitability of any rain gauge against an acceptable standard before using it in any water management activities or as an indicator of truth when validating other data sources, such as radar rainfall data, as only a properly installed and maintained automatic rain gauge can be considered to provide accurate and timely information. However, it is important to acknowledge that random errors in rain gauge accumulations do exist, through the influence of factors such as wind effects, rain shadows (trees etc.) and heavy rainfall. Further sources of error can be introduced during the delivery mechanism set up to transfer the data from the gauge to the end user, especially when the rain gauge data is required for operational use in near real time. For example, data gaps due to delivery failure were found to be around 2% of the total timeseries in Australian Bureau of Meteorology (BoM) automatic METAR stations surveyed [10].

It is also important to note that a rain gauge only provides information at the location of measurement, yet an understanding of the spatial and temporal distribution of rainfall is also needed. Research is showing that an improved understanding of the spatial and temporal distribution of rainfall can be equally, if not more critical to accurate hydrology than the absolute accuracy of the rainfall amount [2] [6].

2.1.1 Rain Gauge Networks

There has consequently been a lot of research into the number and densities of rain gauge networks required for various water management activities, since the highly variable rainfall patterns and their spatial distribution cannot be represented effectively without having a network of enough spatial density [16].

Unfortunately, there is little consensus and a lot of uncertainty as to what constitutes a sufficient density for a rain gauge network, and recommendations for rain gauge network density standards are highly varied. In general, as the area increases, so does the variability of the rainfall and the number of gauges required to achieve a given degree of accuracy and confidence level.

For example, the WMO recommends a minimum density of 1 gauge per 20km^2 in urban areas, whereas the U.S. Army Corps of Engineers use the formula $Ng = A^{0.33}$, where Ng is the number of gauges and A is the catchment area in miles^2 [22]. This equates to 5km^2 per gauge for a 10km^2 catchment common in an urban area, which is significantly denser than the WMO standard.

Interestingly, several studies have also shown that the number of gauges required to achieve a required level of accuracy increases dramatically as the desired spatial accuracy increases. It is not a linear relationship. For example, the U.S. Army Corps study [22] revealed that reducing the standard error of measurement from just 15% to 10% required four times the number of gauges and the study of Vieux & Vieux, 2005 [24] found that the number of gauges required to achieve a given level of accuracy increased dramatically when confidence levels were increased from 95.5% to 99.7%.

Unfortunately, rain gauge networks have widely varying levels of density and reliability [11] and are often incapable of providing adequate rainfall estimates necessary for effective hydrological analysis, areal rainfall estimations and/or point rainfall estimations at unsampled locations, etc.

A good example of the consequences of using an insufficiently dense network can be found in the not uncommon phenomenon of observing flow responses in streams before any rain event is recorded, when using rain gauges as the sole means for characterising the rainfall over a watershed [23]. This counterintuitive result is due to the rainfall having already occurred over the contributing area before reaching the gauge.

2.1.2 The cost of rain gauge networks

Rain Gauges are costly to install and maintain to WMO standards. It can thus become prohibitively expensive to install and maintain a rain gauge network of sufficient density and recommendations on minimum densities thus often attempt to minimise the cost and operational burden while maximising the spatial coverage, and are thus a compromise of mutually exclusive factors.

The Performance Review of Flood Warning Gauge Network in Queensland [12] indicates that a single automatic WMO compliant rain gauge can cost between $5,000 and $20,000 to install, plus a further $1000 to $1,500 per annum to operate and maintain. The study further indicated the need for 134 new medium and high priority automated rain gauges across Queensland at an estimated cost of $5,040,000 plus a further 98 gauges to be upgraded to automatic stations at an estimated cost of $1,470,000. In the case of Brisbane, the report indicated the need to install a further 81 rain gauges to meet the local rain gauge density criteria for flash flood risk, even though Brisbane already has one of the highest density of rain gauges at 1/19km^2, better than the WMO standard.

There is thus clearly space for water managers to consider alternative rainfall data sources that are as accurate, yet cheaper, when planning any expansions to their existing rain gauge networks. Calibrated radar rainfall data is one such option discussed in this paper.

2.2 RADAR RAINFALL DATA

Gridded radar rainfall data is a burgeoning and innovative operational data source available in Australia for hydrological modelling and WSUD applications, which can be an alternative to the purchase, installation and maintenance of further rainfall gauges.

Interest in using radar estimates of rainfall comes from the desire to reduce the existing errors and imprecise knowledge of rainfall distribution in time and space that are associated with rain gauge only networks, and the prohibitive cost and difficulties associated with installing and maintaining sufficiently accurate, dense and timely rain gauge networks.

While quantitative radar rainfall estimates have been possible for some time, recent advances in calibrated radar rainfall data are of specific interest (Figure 1) in improving our understanding of catchment rainfall patterns [24], opening the door for much improved application within WSUD and other fields.

The potential for radar to inform catchment studies is perhaps best summarised in the following quote by Ashton [2]: - “No discussion of studies on areal rainfall for hydrometeorological purposes is complete without reference to the potential of radar scanning. Application of radar to the problem of estimating area and intensity of rainfall in a series of observations is only at a rudimentary stage in Australia. The potential value is so great, however, that all improvements, as soon as available, should be applied in the field on a continuing basis. Here we have something so obviously useful that neglect of it is unthinkable”.

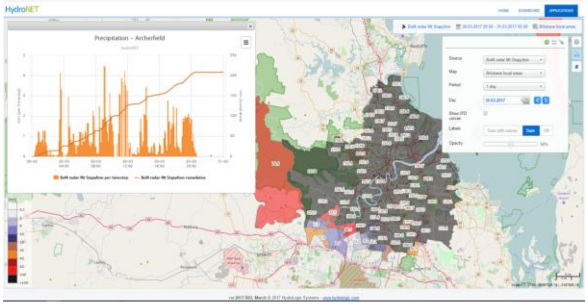

Figure 1: *24-hour rainfall totals from radar, aggregated to riverine catchment boundaries for the March 31, 2016 event around Brisbane, in HydroNET*

2.2.1 Quantitative Precipitation Estimation using Radar

Radar Rainfall data is a Quantitative Precipitation Estimate (QPE), calculated from weather or other radar reflectivity data, which are indirect, instantaneous measurements at a certain height.

The procedure for estimating radar rainfall in real time consists of three main steps: 1) the measurement of reflectivity and removal of known sources of errors, 2) the conversion of the reflectivity to a rainfall rate (Z–R conversion), and 3) the adjustment of the mean field bias as assessed using a rain gauge network [5].

Known sources of error that can be removed in step 1 include, inter alia, beam blockage by structures, reflections from known objects and ground scattering of the radar beam. However, there will always be some unpredictable random errors that cannot be removed, such as birds and planes affecting the reflectivity.

The algorithm used to convert the reflectivity data into a QPE in step 2, often referred to as the Z-R conversion, can differ significantly from region to region and between different preciptitaion types. Typically, a distinction is made between stratiform and convective precipitation regimes. This is because stratiform preciptition often exhibits non-uniform phase charateristics (frozen, melting or liquid) in the vertical profile [19] that differs significantly from that of convective preciptiation. This non-uniformity consequently affects the reflectivity and thus the Z-R algorithm. Figure 2 demonstrates these differences.

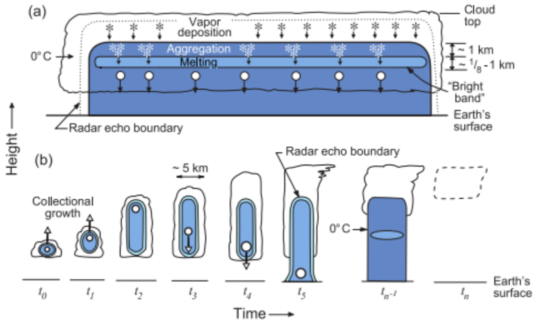

Figure 2: *Uniformity of Phase Characteristics for typical stratiform precipitation (a) and convective precipitation (b) related to quantitative Precipitation estimation from Radar (From: Houze, 1981).*

It is thus important to identify rainfall regimes to improve the accuracy of radar rainfall data, and this can be done in several ways. An example is the method of Ruiz-Leo et al. (2013) [19], which separates stratiform and convective events based on gauge data, and which has acceptable results and requires little data. This method was used in the HydroNET study in 2015 [10] (discussed in section 2.3.3), which noted that the threshold that divides stratiform and convective events can vary significantly in Australia, depending on your location. For example, the thresholds determined were 2.01 mm/6hr in Melbourne, 11.26 mm/6 hr in Sydney, 16.51 mm/6hr in Brisbane and 1.76 mm/6hr in Wimmera.

Error correction associated with these first two steps, which incorporates removing erroneous measurements and correcting biases in the Z–R conversion algorithm, is not the focus of this paper and is thus not covered any further. Step 3, the adjustment of the mean field bias as assessed using a rain gauge network, is discussed in section 2.2.3.

It is also important to note that radar rainfall data is an areal accumulation over a time step - typically 6 minutes and 1kmx1km for an S-band radar in Australia. This difference in scale between radar (areal) and gauge (point) measurements is a fundamental reason that radar will seldom agree exactly with gauge accumulations, even when sampled at the same location, due solely to this areal reduction effect [1]. However, these differences can be reduced by comparing between the two sources at longer time intervals. Daily for example, but at least hourly.

2.2.2 Radar Rainfall Data in Australia

The Australian radar network to measure precipitation consists of a mixed collection of 66 radars, ranging from high resolution Doppler radars, through dedicated weather watch radars to part-time windfinding radars. These are either S band or C band radars [3] and are unequally distributed over the country. Their distribution is shown in Figure 3. Most of the Australian cities are covered by S-Band Doppler radars with a 1-degree beam width and a typical monitoring radius of 30km, as they provide a higher resolution but are vulnerable to attenuation. C band radars, with a lower resolution, typical 2-degree beam width and monitoring radius of 100-200Km, generally serve the regional areas.

The BoM has three radar rainfall data products available in Australia. A raw radar rainfall reflectivity product (BoM product Id's IBRAPOL and IBROVOL) is available in near real time for all radars via the BoM registered user services. This product does not include any of the 3 steps of the QPE determination process mentioned in the previous section and is provided in a raw polar format that is difficult to use in models and databases. It is thus very difficult to use for water management activities and does not meet the important criteria of being easily available.

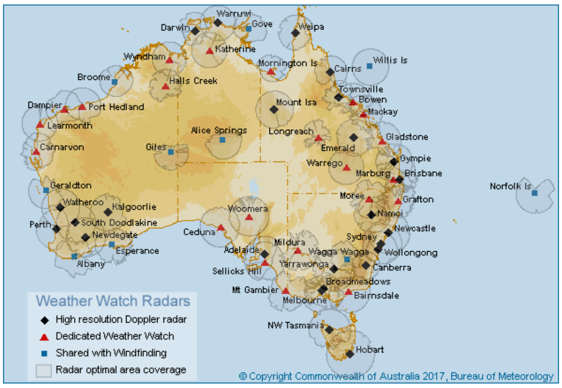

Figure 3: *Map of the Radar locations in Australia and their optimal coverage*

A Raw Rainfields radar data bundle (BoM product ID IDBRAAC) is also available for 17, mostly urban, radars. This product incorporates step 1 and 2 of the QPE determination process and is timely and easily available in near real time in a widely used format via the BoM registered user services. However, it does not include any calibration against rain gauges and is thus not a calibrated radar rainfall product.

BoM also provide a calibrated radar rainfall product for the same 17 radars as above (calibrated to their 1-minute Automatic Weather Station (AWS) data). However, this calibrated product is not available in near real-time via the BoM's registered user services, making it unsuitable for use in operational water management activities, as it does not meet the important criteria of being timely available. This is a pity, as calibrated radar rainfall data is a very relevant and desirable data source, as highlighted in section 2.3. Fortunately, there is now a means to obtain this data easily and timely in near real-time.

2.2.3 Calibrated Radar Rainfall Data

Calibrated radar rainfall data is the outcome of step 3 of the of the QPE determination process. This step entails the mean field bias adjustment, as assessed using a rain gauge network, of the initial raw, or uncalibrated, QPE resulting from steps 1 and 2.

Bias, also known as systematic error, requires correction. If not corrected, systematic error (radar bias) can have a large influence on rainfall-runoff modelling [24].

There are several methods to do this bias correction and the quality of calibrated radar products is much dependent on the procedure of calibration or bias correction[19][25]. For the purposes of this paper, the modified Brandes method as defined by Goudenhoofdt & Delobbe, 2009 [8] is described, as this provides a good compromise between required computing power and accuracy. The method is relatively fast and sufficiently accurate for application in operational water management activities.

In this method, a correction factor is calculated for each radar pixel where a rain gauge exists and the correction factors from those locations are then interpolated into a correction factor grid. The original radar rainfall data grid requiring calibration (usually the QPE resulting from steps 1 and 2 of the full QPE determination process) is then adjusted by this correction factor grid, resulting in a corrected composite, generally referred to as the calibrated radar rainfall grid data. The formula used is:

$$C = \frac{\sum_{i-1}^{N} w_i \, . \; G_i}{\sum_{i-1}^{N} w_i \, . \; R_i}, \qquad (1)$$

With Ri and Gi > 1 mm, and $w_i = \frac{1}{d_i}$,

in which:
C is the correction level,
i is a counter from 1 up to N,
w is the weighting,
R is the measured value by the radar,
G is the measured value by the rain gauge,
d is the distance from the radar pixel to the rain gauge.

The following section will compare radar rainfall and rain gauge as data sources and evaluate the benefits of calibrated radar rainfall data.

2.3 THE BENEFITS OF CALIBRATED RADAR RAINFALL DATA

Several studies into the advantages and benefits of calibrated radar rainfall data have been conducted around the world. For example, Sun et. al. (2000) [21] calculated flood hydrographs for the Finniss River Catchment in Darwin, Australia using several rainfall estimation methods. These were: (1) rain gauge data alone; (2) kriging of the rain gauge data; (3) uncalibrated radar data and (4) cokriging of both radar and rain gauge data. The results showed that rainfall estimated by cokriging considerably improved flood estimates. The outcomes of some local Australian studies are discussed in sections 2.3.1 to 2.3.3.

Internationally, radar rainfall data calibrated against gauge stations is now generally assumed to be an accurate QPE of high spatial and temporal resolution, as has been found for the Dutch calibrated radar product developed by the KNMI [14].

2.3.1 RADAR Rainfall Calibration of Flood Models, A Case Study of the Stanley River Catchment in Moreton Bay, Queensland

Daly et. al. [6] conducted a study to compare the results of calibrating an existing WBNM hydrology model and TUFLOW hydraulic model in the Stanley River Catchment in Queensland using a) rain gauge interpolated data as input and b) calibrated radar rainfall data as input for 3 significant events in January 2011, January 2013 and February 2015.

The calibrated radar rainfall data for the subject events was extracted from the BoM Mt Stapylton radar and aggregated to the sub catchments using the HydroNET portal. Spatial and temporal rainfall variation of the calibrated radar rainfall data was then compared against selected rain gauges as well as against the catchment aggregated rainfall data derived from the interpolated rain gauge data alone. Similar cumulative depths were noted at the gauges, confirming the accuracy of the calibrated radar rainfall data. Significant differences were noted in catchments further away from the rain gauges, with the calibrated radar data estimating the high and low extremes far better than the rain gauge interpolated data.

For example, in the January 2011 event the study observed greater extremes in the radar rainfall data with the maximum depth being 125mm more and the minimum depth being 65mm lower than the rain gauge interpolated data, and a higher average rainfall depth across the catchment of 20mm when using the calibrated radar rainfall data, which provided a much improved indication of the spatial distribution of the rainfall across the catchment and an improved estimation of the volume of rainfall as well. See Figure 4 and Figure 5.

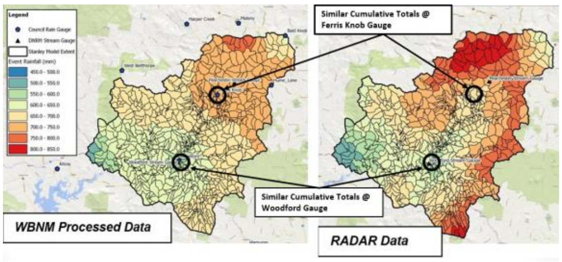

Figure 4: *Similar cumulative rainfall totals observed between rain gauges and the calibrated radar rainfall data, confirming the accuracy of the radar rainfall calibration process*

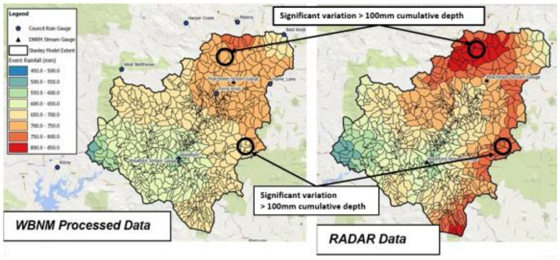

Figure 5: *Significant variations >100mm in cumulative rainfall totals observed between rain gauges and the calibrated radar rainfall data at sub catchments without a rain gauge, with the calibrated radar rainfall data the more accurate interpolation method.*

The calibrated radar rainfall data was then applied to the existing hydrology model and analysed to generate sub-catchment runoff for each of the analysed events, and compared to that derived from the interpolated rain gauge only data. The sub-catchment runoff from each data source was then applied to the hydraulic model. The Hydrology and hydraulic models were re-analysed in the absence of any other model changes in order to directly compare calibration outcomes between rain gauge data versus calibrated radar rainfall data.

The outcome was that the calibrated radar rainfall input produced larger and more accurate discharge peaks (excl. February 2015) that were a very good match to the observed flow levels and discharges for single and dual peak events as well as the overall hydrograph shape, with no further calibration effort.

Their paper concluded that:

- calibrated radar rainfall data provided significant improvements in our understanding and appreciation of spatial and temporal rainfall variability throughout the catchment;
- the use of calibrated radar rainfall produced outcomes that, within the bounds of uncertainty, provided similar accuracy with no calibration effort for catchments that have relatively few or no rain gauges;
- calibrated radar rainfall data can contribute to calibration outcomes and represents a further source of information that should be used where available as part of the overall model calibration process.

2.3.2 Recognising radar rainfall as a conventional method of estimating rainfall patterns with hydraulic models – A case study of the Lockyer Valley flood event in January 2011

Delany et. al. [7] conducted a similar study to that done by Daly et. al. [6] for the January 2011 flood event in the Lockyer Valley.

The HydroNET platform was used, as was done by Daly et. al., to collect the relevant 1km gridded calibrated radar rainfall data from the BoM and then to aggregate the data to the sub catchments.

This study used the inverse distance weighting method to interpolate between the available rain gauges for input into the model sub catchments as a comparison against the calibrated radar rainfall data.

Once again, significant differences up to 60mm were found between the gridded radar rainfall surface and the rain gauge interpolated surface (Figure 6), with the calibrated radar providing a much-improved indication of the spatial distribution of the rainfall across the catchment as well as the volume of rainfall.

The rain gauge data significantly underestimated the rainfall that occurred over the Murphy's Creek Catchment, while the radar rainfall data could identify the increase in rainfall over this smaller segment of the Lockyer Catchment. Thus, in this scenario, the radar data produced a far better representation of the rainfall patterns during the storm event.

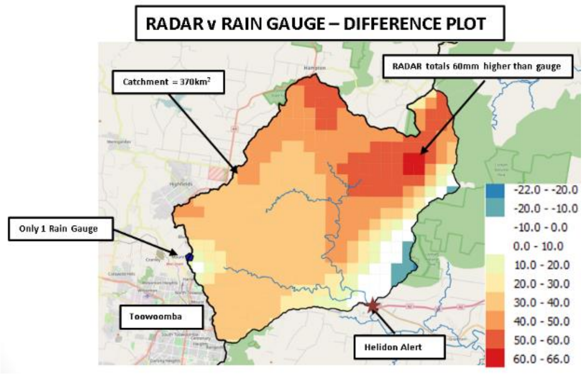

Figure 6: *Difference plot between the gridded Rainfields calibrated radar dataset obtained from HydroNET and the interpolated rain gauge rainfall data, highlighting the superior spatial distribution provided by the calibrated radar rainfall data.*

In the hydraulic model set up as part of the study, a much improved calibration against the observed flows at the Helidon River Gauge was achieved when using radar rainfall data as compared to interpolated rain gauge data alone (Figure 7).

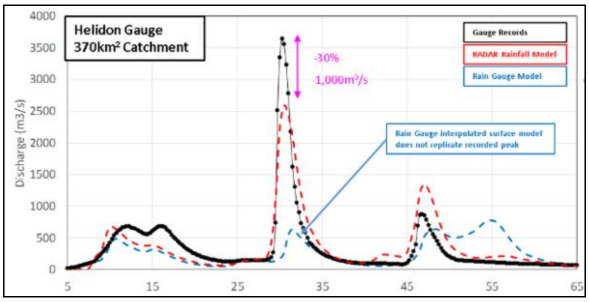

Figure 7: *Calibration of the hydraulic model for the Murphy's Creek at Helidon Gauge with rain gauge data and radar data compared to the observed flows, showing the vast improvement against the observed when using calibrated radar rainfall data.*

2.3.3 The validation of operational radar-based Quantitative Precipitation Estimation in extreme Events in Australia

HydroNET conducted an extensive exercise in 2015 to validate the accuracy of various rainfall data products in Australia, including calibrated radar rainfall data, at four locations [10]. These locations were Brisbane, Sydney, Melbourne and Wimmera.

The following data was used in the analysis:

- BoM AWS METAR and SYNOP rain gauges, providing hourly rainfall data.
- Australian Water Availability Project (AWAP) dataset which provides gridded daily precipitation data from 1900 to 2014 covering Australia [17].
- BoM raw radar data coming from high resolution Doppler radars which provides 6 minute precipitation intensities for each 1x1 km grid cell (BoM product code IDBRAACC).
- BoM Rainfields calibrated radar product, which provides 6 minute precipitation intensities for each 1x1 km grid cell, calibrated against BoM AWS METAR Rain Gauges.

The AWAP data was used for quantifying the level of improvement of radar rainfall data when compared to interpolated rain gauge data. It is not considered as a potential operational precipitation source. Rain gauges were used in the validation as the independent truth.

The correlation between the rain gauge and the radar rainfall was estimated by linear least squares regression in which the regression line originates at the zero point. Two performance indicators of quantitative precipitation estimation were obtained. The first was the regression coefficient of fitting model (a) with corresponding standard deviation, in a model according to Equation 2. The second was the coefficient of determination (R2), given in equation 3.

$$Rp = a\ Rg \qquad (2)$$

$$R2 = 1 - SS\ res\ /\ SS\ tot \qquad (3)$$

Where Rp is the precipitation estimation in an event of the analysed product, Rg is the precipitation estimation in an event of the rain gauge, $SSres$ is the sum of squares of residuals and $SStot$ is the total sum of squares.

The regression coefficient estimates how much the analysed precipitation product underestimates (<1) or overestimates (>1) compared to gauge data and the coefficient of determination indicates how well the analysed precipitation product is estimated by the linear regression line. It varies from 0 (bad fit) to 1 (good fit).

The study found that:

- Calibrated radar performs better than both nearest station data and AWAP data over events that are limited in their extremeness, for both stratiform and convective events. Calibrated radar is thus a precipitation estimator of high quality up to a certain threshold of extremeness.

- The calibrated radar product shows better results for estimation of the amount of extreme precipitation in an event when compared to AWAP data, but slightly underestimated the extreme rainfall as compared to the nearest rain gauge for extreme convective events. This also contributes to the theory of areal reduction in precipitation estimation in grid-cells because convective precipitation happens at smaller spatial and temporal scale compared to stratiform precipitation.
- The regression coefficient for calibrated rainfall data for all events was 0.83, 0.82 for convective events and 0.9 for stratiform events. Moreover, the R-squared values indicate good representation of precipitation observations by the fit-model. R-squared values were 0.90 for all events, 0.89 for the convective events and 0.96 for the stratiform events.
- The calibrated radar product has an improved (i.e. reduced) variance in residuals for stratiform events than that estimated by the nearest station.
- The data gaps in the calibrated radar data product were 1.7 % in Melbourne, 4.0 % in Sydney and 8.9% in Brisbane [10], which goes some way to explaining the underestimation of the radar product for extreme convective events.
- The raw radar rainfall product provided the largest underestimation, and contained data gaps of 5.7% in Brisbane, 13.3 % in Sydney and 34.6 % in Melbourne. It is not recommended for use.

3 CONCLUSIONS

Calibrated radar rainfall data is a burgeoning data source in Australia that can provide much improved rainfall data to both rural and urban water managers for many water management activities at a significantly reduced cost when compared to the alternative of expanding existing rain gauge networks.

The need for easy, timely access to this data is also becoming ever more important due to the ever-increasing frequency of occurrence of excessive rainfall events. Thanks to the modern advances in ICT, online platforms such as those used by the authors of the studies discussed in sections 2.3.1 to 2.3.3 are a burgeoning method of accessing this vital forecasted, observed and historical rainfall data.

3.1 RADAR RAINFALL DATA AND WSUD

Monitoring and evaluation of Water Sensitive Urban Design (WSUD) assets is essential to assess the performance of a system long term. WSUD assets generally treat small upstream catchments that are responsive to short, isolated storm events that are often missed by the installed rain gauge networks available to municipalities. The availability of calibrated radar rainfall data gives the spatial and temporal resolution necessary to assess the small urban catchments.

The calibrated radar rainfall data enables WSUD designers and asset managers alike to not only use this accurate, high spatial and temporal resolution data in their planning and design, but also to easily set improved rainfall thresholds to better target performance measurement and maintenance programs to ensure the long term success of WSUD projects.

REFERENCES

[1] Anagnostou, E. N., Krajewski, W. F., & Smith, J. (1999). Uncertainty quantification of mean-areal radar-precipitation estimates. Journal of Atmospheric and Oceanic Technology, 16(2), 206-215.

[2] Ashton, H.T. A review of hydrometeorological studies and planned Bureau activities in hydrometeorology, Proceedings of the Hydrometeorology Discussion Group, Melbourne, Bureau of Meteorology, 1967

[3] Bell, A., Seed, A., & Bunn, R. (2013) 15B. 1 Radar Precipitation Estimates and Nowcasts: The Challenging Road from Research to Warnings.

[4] Bureau of Meteorology. About Radar-Derived Rainfall Accumulations, Available at http://www.bom.gov.au/australia/radar/about/using_rainfall_accumulations.shtml.17 June 2016.

[5] Chumchean, S., Sharma, A. and Seed, A., 2006. An integrated approach to error correction for real-time radar-rainfall estimation. Journal of Atmospheric and Oceanic Technology, 23(1), pp.67-79.

[6] Daly, A et al. *Radar Rainfall Calibration of Flood Models* – the future of Catchment

Hydrology? Paper presented at the Stormwater Queensland Conference, 2016.

[7] Delany, C. Recognising radar rainfall as a conventional method of estimating rainfall patterns with hydraulic models. Report submitted in partial fulfilment of the degree of Civil Engineering. Griffith University. 2016.

[8] Goudenhoofdt, E. and Delobbe, L., 2009. Evaluation of radar-gauge merging methods for quantitative precipitation estimates. Hydrology and Earth System Sciences, 13(2), pp.195-203.

[9] Holleman, I. (2007). Bias adjustment and long-term verification of radar-based precipitation estimates. Meteorological Applications, 14(2), 195-203.

[10] Hydrologic Systems BV. Validation of operational Radar-based and Satellite-based Precipitation Estimators in extreme Events in Australia. Unpublished. 2015.

[11] Jones, D.A., Wang, W. and Fawcett, R., 2009. High-quality spatial climate data-sets for Australia. Australian Meteorological and Oceanographic Journal, 58(4), p.233.

[12] Kellog, Brown & Root Pty Ltd. Performance Review of the Flood Warning Gauge Network in Queensland. Department of Natural Resources and mines, Queensland. ABN 91 007 660 317. 2016.

[13] King, A.D., Alexander, L.V. and Donat, M.G., 2013. The efficacy of using gridded data to examine extreme rainfall characteristics: a case study for Australia. International Journal of Climatology, 33(10), pp.2376-2387.

[14] Lobbrecht A. H., Clemens F. H. L. R., & Einfalt T. Neerslaginformatie op basis van Nederlandse en buitenlandse radars nu beschikbaar. 2012.

[15] Lobbrecht, A, Einfalt, T., Reichard, L. Decision support for urban drainage using radar data of HydroNET-SCOUT. Weather Radar and Hydrology. (Proceedings of a symposium held in Exeter, UK, April 2011) (IAHS Publ. 3XX, 2011).

[16] Pardo-Igúzquiza E. 1998. Optimal selection of number and location of rainfall gauges for areal rainfall estimation using geostatistics and simulated annealing. Journal of Hydrology 210: 206–220. DOI: 10.1016/S0022-1694(98)00188-7.

[17] Raupach, M.R., Briggs, P.R., Haverd, V., King, E.A., Paget, M. and Trudinger, C.M., 2009. Australian water availability project (AWAP): CSIRO marine and atmospheric research component: final report for phase 3. Centre for Australian weather and climate research (bureau of meteorology and CSIRO). Melbourne, Australia, 67.

[18] Reichard H.L, Clemens F.H.L.R, Lobbrecht A.H, Hertemink J.W., Mantje W., Poortinga I.M., Korving J.L. Neerslaginformatie voor het bebouwde gebied, Stand van zaken en ontwikkelingen. ISBN 97 890 73645 29 5, 2011.

[19] Ruiz-Leo, A. M., Hernández, E., Queralt, S., & Maqueda, G. (2013). Convective and stratiform precipitation trends in the Spanish Mediterranean coast. Atmospheric Research, 119, 46-55

[20] Smith, J. A., Seo, D. J., Baeck, M. L., & Hudlow, M. D. (1996). An intercomparison study of NEXRAD precipitation estimates. Water Resources Research, 32(7), 2035-2045.

[21] Sun, X., Mein, R.G., Keenan, T.D. and Elliott, J.F., 2000. Flood estimation using radar and raingauge data. Journal of Hydrology, 239(1), pp.4-18.

[22] U.S. Army Corps of Engineers, 1996. Hydrologic Aspects of Flood Warning – Preparedness Programs. Technical Letter 1110-2-540, Washington, DC

[23] Vallabhaneni, S., B. Vieux and T. Meeneghan. 2004. "Radar-Rainfall Technology Integration into Hydrologic and Hydraulic Modeling Projects." Journal of Water Management Modeling R220-02. doi: 10.14796/JWMM.R220-02.

[24] Vieux, B. and J. Vieux. 2005. "Rainfall Accuracy Considerations Using Radar and Rain Gauge Networks for Rainfall-Runoff Monitoring." Journal of Water Management Modeling R223-17. doi: 10.14796/JWMM.R223-17. © CHI 2005 www.chijournal.org ISSN: 2292-6062 (Formerly in Effective Modeling of Urban Water Systems. ISBN: 0-9736716-0-2).

[25] Yilmaz, K. K., Hogue, T. S., Hsu, K. L., Sorooshian, S., Gupta, H. V., & Wagener, T. (2005). Intercomparison of rain gauge, radar, and satellite-based precipitation estimates with emphasis on hydrologic forecasting. Journal of Hydrometeorology, 6(4), 497-517.