Application of weather radar data for urban hydrology

K A Tilford*, N I Fox and C G Collier, The Telford Institute of Environmental Systems, School of Environment and Life Sciences, University of Salford, Manchester, M5 4WT, UK

*A Present Address: WS Atkins Consultants Ltd, WS Atkins House, Birchwood Boulevard, Birchwood, Warrington, WA3 7WA, UK

A weather radar and processing system has been developed in conjunction with North West Water Ltd., a water utility responsible for the supply of potable water and the treatment of wastewater in the north-west of England. The primary objective has been to develop a radar system which can produce accurate and reliable quantitative estimates of rainfall at a temporal and spatial resolution commensurate with the requirements of urban drainage system modelling. This paper describes procedures for removing ground clutter and adjusting radar estimates of rainfall (using the Probability Matching Method). An archive of stratiform rainfall event data has supported an objective assessment of the radar data quality using a dense gauge network and simulated flow hydrographs for an urban drainage system. The results indicate that the adjusted radar data are of comparable accuracy to the dense raingauge data and are therefore of sufficient accuracy to be used for the management of water resources within an urban environment. The data processing and adjustment procedures have been incorporated into a real-time data processing and display software package (ARTIST) which is briefly described in the paper.

1. Introduction

The use of radar rainfall data for hydrological modelling has been motivated by the need to define and accurately measure the spatial rainfall field and the potential provision of short-term quantitative precipitation forecasts. One of the first quantitative hydrological applications for weather radar rainfall data was as an input to rainfall-runoff models of rural river systems. Building on the work that commenced in the 1970s (see, for example, Anderl et al., 1976), radar rainfall estimates now form a key input to a number of operational river flow forecasting systems (e.g. Aucott et al., 1988; Baldini et al., 1998; Braga et al., 1998). For a review, see Collier (1996).

The modelling of urban drainage system (storm) flows using radar rainfall data as a model input has seen an upsurge in interest in recent years (Johann & Verworn, 1996; Raunch et al., 1998; Sempere-Torres et al., 1999; Yuan et al., 1999). The reason for this is that large expanses of impervious areas produce a flow response that is more rapid, 'peaked', sensitive to the spatial distribution of the rainfall (Blanchet et al., 1998) and typically has lower rainfall losses due to infiltration and storage than most natural drainage systems. These factors render the numerical modelling of flows within these highly complex drainage networks challenging yet ideally suited to radar data.

An urban drainage system in north-west England has provided the focus for an investigation of the feasibility of using radar rainfall data for the numerical modelling of flows in a complex combined sewer pipe network. Bolton is a predominantly industrial town situated to the north-west of Manchester on the western edge of the Pennine uplands. The prevailing westerly airstream from the Atlantic produces annual rainfall of 1300 mm. The Bolton urban drainage area (UDA) consists of a complex network of approximately 1200 km of pipes ranging in diameter from 150 mm to 1400 mm. These pipes feed an interceptor sewer (up to 2.35 m box section) that conveys flows to a wastewater treatment works at the catchment outlet. The UDA consists of 13 sub-drainage areas, occupies a total area of 93 000 hectares (93 km²) and serves a total population of 260 000. Most of the sewer network was built between 1890 and 1930 and the system has insufficient capacity to deal with rainfall generated surface runoff and the combined domestic, industrial and commercial effluents. As a result, Bolton has a long history of flooding with over 80 significant flooding incidents occurring in the period 1976–88 many of these being located in the town centre. Combined sewer overflows (CSO) offer a partial solution to the flood problem, acting as a relief valve if the pipe flow approaches the pipe capacity. However, although reducing the incidence of flooding, their operation leads to a reduction in the quality of the receiving surface waters. This is, in part, the reason for the principal rivers within the catchment (the Tonge, Bradshaw Brook, Croal and Irwell) being officially classified as having poor water quality (UK Class 3). Since 1990, three large offline storage tanks have been constructed in order to alleviate the stress on the
system at times of high flow. These have significantly reduced the frequency of CSO, but there is continued interest in increasing their effectiveness using real-time control (RTC) techniques involving radar rainfall information.

2. Radar urban hydrology

The response of urbanised catchments to rainfall imposes stringent data requirements on any rainfall observation instrumentation to be used for the numerical modelling of pipe flows. The radar described in this paper was initially developed by a team led by Professor G. Austin at McGill University, Canada. It was designed using aspects of existing radar technology tailored to meet the rainfall data requirements of urban hydrology. The range is limited to 48 km. This helps restrict the height of the beam above the ground minimising the impact of errors associated with inhomogeneities in the vertical reflectivity profile (in particular, errors associated with enhanced reflectivity arising from the beam intersecting the melting layer–bright band) and errors due to wind drift (Collier, 1999). A two-minute scan cycle is used to provide high frequency temporal observations. Finally, the data are processed to a Cartesian grid with a spacing of 250 m providing the potential to model drainage systems in great detail, even for highly localised rainfall.

The radar transmitter operates at 5.4 GHz (C-band) with a mean power of 35 kW. It has an antenna diameter of 1.8 m, a beam width of 2.5º and scans radially at four beam elevations (0.8º, 1.2º, 2.2º, 5.3º). Analogue received signals are converted to a seven-bit digital representation. These polar data are then converted to a (250 m) Cartesian representation, resulting in a regular 384 × 384 grid for each beam elevation. This information is stored locally prior to additional processing using the clutter cancellation and raingauge adjustment procedures described in this paper. This procedure leads to a certain degree of oversampling of the radar data, as the beam is significantly wider than the Cartesian grid spacing at most ranges. However, in order to investigate the impact of these technologies on urban drainage system (UDS) management it is important to simulate high resolution data (Collier, 1999).

The radar is sited at Lingley Mere, several kilometres to the north of Warrington, roughly midway between Liverpool and Manchester (see Figure 1). In addition to providing coverage of both these conurbations, the radar range also encompasses nine other large towns, including Preston, Bolton, Blackburn, Chester and Wrexham. These towns have urban drainage systems which are similar in many respects to the Bolton system described in this system: namely, insufficient pipe capacity causing flooding and pollution, sewer dereliction and siltation. All of these could therefore benefit from improved design and operation.

3. Clutter cancellation

If not removed, ground clutter echoes can be so detrimental to the estimation of rainfall that the radar data cannot be used for UDS modelling. Hence, removal of ground clutter is the first phase in converting the raw digitised radar data to rainfall intensity data. Figure 2 shows the extent of the permanent ground clutter for the lowest and highest beam. The clutter to the east and north-east of the radar is due to the Pennine hills. Ground clutter close to the radar is due to side lobes of the radar beam impinging on the ground.

Raw polar data are mapped to a cartesian representation in real-time and at present are neither recorded nor recoverable. A clutter removal procedure has therefore been developed which utilises the cartesian data information (from all four beams). The procedure is based on a detailed statistical analysis of the temporal variability (i.e. ‘permanency’) of the permanent ground clutter. The analysis (shown in Figure 2) revealed little variation between images, indicating that the permanent clutter does not have high temporal variability.

Table 1 shows the occurrence frequency $f_c$ with which pixels at each beam elevation are (a) never cluttered and (b) always cluttered, for a range of different probabilities. As previously, the statistics have been calculated for all clear air images in January 1999 (4720 images). For beam 1, 66% of pixels are never cluttered, and 21% of pixels are always cluttered. The remaining 13% of pixels are occasionally cluttered with a frequency somewhere between. For beam 4, the corresponding figures are 89% never cluttered and 4% always cluttered.
Figure 3 demonstrates this information and also incorporates the frequency with which pixels are ‘occasionally’ cluttered – i.e. for which the frequency of pixel clutter is between 0 (never cluttered) and 1 (always cluttered). Note that the percentage occurrence is plotted on a log scale. The figure demonstrates that the clutter percentage occurrence between the frequency of pixel clutter range 0.1 to 0.85 is remarkably consistent, with little temporal variation in the permanent clutter.

Table 1. Pixel ground clutter occurrence frequency for different beams.

<table>
<thead>
<tr>
<th>Occurrence frequency, $f_c$</th>
<th>Beam 1</th>
<th>Beam 2</th>
<th>Beam 3</th>
<th>Beam 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Never cluttered)</td>
<td>66.4</td>
<td>70.9</td>
<td>85.6</td>
<td>88.9</td>
</tr>
<tr>
<td>1 (Always cluttered)</td>
<td>21.2</td>
<td>17.7</td>
<td>5.5</td>
<td>4.2</td>
</tr>
</tbody>
</table>

4. Radar adjustment procedure

Many attempts have been made to remove observed biases in radar measurements of rainfall using additional measurements provided by raingauges. The motivation for much of the early work was provided by the demands of hydrologists for reliable, accurate rainfall estimates for use as an input to river flow models as part of regional flood forecasting systems. As a consequence, operational schemes for adjusting radar data in real-time using telemetered raingauge information were developed (e.g. Collier et al., 1983; Collier, 1986a; 1986b; Fulton et al., 1998). Generally, raingauge adjustment can be effective in stratiform rainfall situations, particularly where very low level orographic rainfall is dominant (Kitchen et al., 1994). This is because stratiform rainfall has a relatively low degree of spatial variability and point raingauge measurements (and hence gauge derived adjustment factors) provide a representative indication of rainfall over a wider area. This is not the case in convective rainfall or in areas of stratiform rainfall where the beam intersects the melting layer. In such instances, the high spatial variability of the rainfall, or in the case of bright-band, the radar reflectivity, means raingauge measurements may be unrepresentative of a wider area introducing a ‘hit-and-miss’ element to the adjustment procedure. In such cases, gauge adjustment can decrease the accuracy of the radar measurements.

An alternative approach is to estimate the vertical reflectivity profile using multiple beam elevation data and apply corrections based upon this and a model of beam propagation (e.g. Kitchen et al., 1994; Andrieu et al., 1995; Joss & Lee, 1995). A number of procedures using this approach are applied operationally: in the case of the Met Office radar network, for example, the approach is successful in producing radar estimates of rainfall that are accurate to within a factor of two almost all the time (Kitchen et al., 1994).

4.1. Probability matching method

In parallel with the development of reflectivity profile techniques, Rosenfeld et al. (1993) proposed the combination of radar reflectivity and raingauge data using an approach called the Probability Matching Method (PMM). A relatively simple, yet potentially powerful technique, the approach was subsequently extended to
incorporate an objective rainfall type classifier (Rosenfeld et al., 1995).

Using the PMM, an adjustment function is derived from an analysis of historic radar data and raingauge rainfall data. Once derived, independent radar data can be adjusted using the adjustment function on a look-up basis without any further need for raingauge data. A further advantage noted by Rosenfeld et al. (1995) is that a stable relationship between raingauge measured rainfall, \( R_G \), and radar reflectivity \( Z \) can be derived from relatively small radar/raingauge samples.

A simplified form of the PMM has been developed and tested using data from the Lingley Mere radar. An adjustment function has been derived using a data period of one month (January 1999) for the radar and a network of seven raingauges in the Bolton urban drainage area (locations shown in Figure 4). The adjustment function is derived from a comparison of the probability density functions (PDF) of \( Z \) and \( Z_G \) (the rainfall intensity measured by raingauge converted to a reflectivity equivalent) for an extended period of historic rainfall data. Once the PDF for \( Z \) and \( Z_G \) have been constructed, an observed \( Z \) is assigned to a \( Z_G \) (and hence \( R \)) having the same occurrence probability according to:

\[
\int_{P_{Z_G}}^{P_{u}} p_{Z_G}(R_c) dR = \int_{P_{Z_G}}^{P_{u}} p_{Z}(R_c) dR
\]

where \( P \) is the probability for the occurrence of \( Z \) or \( R \) at the \( dR \) intensity interval, and the subscript \( u \) denotes that this is the unconditional probability as opposed to \( P_c \), the conditional probability where \( P_c = P(R) / R > 0 \). The cumulative frequency graph for hourly radar and raingauge rainfall rates converted into equivalent dBZ values for January 1999 are shown in Figure 5.

Adjustment is performed using a function to map the radar cumulative frequency onto the raingauge curve.

\[
Z_i = \begin{cases} 
Z + 2 & Z > 29 \\
\frac{10}{21}(Z + 32) & Z <= 29 
\end{cases}
\]

In these equations all values of \( Z \) are measured in dBZ.

To test this procedure, the adjustment function derived using the January 1999 data set has been applied to an independent four-day case study event (28 February 1999–3 March 1999). Figure 6 shows a comparison of the four-day storm accumulated rainfall total from seven of the raingauges and the radar rainfall estimates for the overlying pixels. In each case the lowest total is from the unadjusted radar rainfall data. The adjusted radar rainfall totals for each gauge site are, for the most part, within 10% of the gauge totals. The single exception to this is the gauge located at Smithills Primary School: a location which uses radar data infilled from a higher beam elevation due to the lowest beam(s) being subject to permanent ground clutter.

Event storm totals are summarised in Table 2 and event cumulative hyetographs for the event are shown in Figure 7. Using the raingauge network as an indication of true rainfall at the ground, it is demonstrated that adjusting the radar data using the PMM improves the accuracy of the unadjusted radar storm total estimates by an average of 27% at the raingauge sites. Catchment average rainfall totals as estimated by the adjusted radar data are 59.9 mm compared to a mean raingauge total of 58.4 mm – a difference of 2.6%.

5. Radar display and processing software

All the data processing algorithms and adjustment procedures have been incorporated into a radar data pro-
cessing, analysis and display software program. The software, known as ARTIST (Applying Radar To Integrated System Technologies) has been developed on an Intel Pentium II personal computer running the Microsoft Windows NT 4.0 operating system. ARTIST features a Windows interface and is driven using a mouse-controlled pointer and pull-down/pop-up menus. It has been designed to be intuitive and easy to learn and use. In addition to processing and displaying data from the Lingley Mere data, ARTIST also incorporates a fully functional display capability for Nimrod data from the Met Office network radars.

In summary, ARTIST incorporates the following displays:

- Raw Lingley Mere radar data with beam elevation selection option (rainfall intensity units)
- Adjusted Lingley Mere radar data (rainfall intensity units) with ground clutter removal and rain-gauge (PMM) adjustment algorithms applied
- Accumulated Lingley Mere radar field (rainfall depth units)
• Met Office Nimrod radar data (rainfall intensity units)

A replay capability exists for all of the functions. The replay can be operated in a manual single-step mode – forwards or backwards, or in an automatic replay mode (with user-defined time delay between frames) – forwards or backwards. Images are displayed in ten intensity (or depth) levels using the same colour scheme as the Met Office use to display Nimrod data.

The cumulated Lingley Mere radar depth field display includes an optional function to plot cumulative rainfall hyetographs for pre-defined areas (such as the Bolton catchment) as well as for individual pixels (e.g. those pixels overlying raingages). Output files of rainfall depths can be generated as required. Example screen displays from the ARTIST system are shown in Figure 8.

6. Combined sewer flow simulation

The town centre of Bolton forms one of the largest sub-catchments of the Bolton drainage area with a total contributing area of 2058 hectares (approx. 21 km²) and a served population of 62 000. Simulations of the drainage network have been routinely conducted in the past to support design studies and to investigate system performance. Simulations such as these typically use design storms, i.e. rainfall events with a specified depth, duration and profile, long-term synthetic storm sequences, or historic event data. Invariably, spatially lumped rainfall inputs are used, with historic event data being derived from raingages located within and/or close to the drainage area. The aim of the work described is to demonstrate the use of radar rainfall data as an input to a full hydraulic model of the Bolton town centre and to compare the simulated pipe flows at a location at the drainage area outlet with simulations obtained from raingage data.

Pipe flow simulations have been generated with a pre-calibrated model of the Bolton town centre system using Hydroworks, a commercially available software package widely used for the simulation of pipe flows, water quality and sediment transport in urban drainage systems. The model defines the drainage system in terms of the location, size, geometry, surface roughness, depth-flow relationships, etc. of the sewerage components: conduits (pipes, open channels, culverts), nodes (manholes, basins and outlets), and other ancillaries (overflow weirs, pumps, non-return valves, flow restrictors, and other controllable structures). The model incorporates a total of 1171 conduits, 45 weirs, flumes and orifices, 32 overflows and 1124 additional computational nodes.

A schematic representation of the Bolton Town Centre model, showing all the model nodes and also the locations of the two raingages within the drainage area is shown in Figure 9. A longitudinal cross-section of the Bolton Town Centre UDS from the top of the drainage network through to the network outlet along the main system trunk sewer is shown in Figure 10. The cross-section indicates the steep gradients present, the sewer pipes falling 60 m in the vertical over a horizontal distance of 8500 m. Indeed, the steep pipe gradients in the drainage area are a major factor in the local flooding problem – a risk exacerbated by the fast surface runoff generation and minimal system retention times associated with the impervious surfaces.

Pipe flows in the system have been simulated using rainfall data for the four-day case study event presented in section 4. Spatially lumped rainfall intensities have been derived from three rainfall input time-series: raingage, unadjusted radar data and adjusted radar (i.e. radar data adjusted using the PMM method). The raingage data input has been derived by averaging rainfall amounts observed by gauges located in and around the drainage area, while radar values have been computed by averaging the pixels falling within the catchment. (The radar pixels on the south-western edges of the

Figure 8. Example of ARTIST displays. Highest beam for a stratiform rainfall event clearly depicting the bright band (left) and cumulated radar rainfall field and cumulative hyetograph for the Bolton drainage area (right).
drainage area affected by permanent ground clutter at all beam elevations were excluded from this process.) The raingauge data had a temporal resolution of 30 minutes, while the radar data were available at 2-minute intervals.

The Hydroworks model was configured to simulate pipe flows and depths for all nodes at 2-minute intervals. Simulated flows at the drainage area outlet (node location indicated on Figure 9) are shown in Figure 11(a). The absolute difference between the raingauge-derived hydrograph and those derived from the two radar rainfall time-series are shown in Figure 11(b). An analysis of these results is presented in Table 3. The results indicate that if the raingauge-derived hydrographs are used as a quality standard, the differences between the mean flows, peak flows and total flow volumes generated using adjusted radar data are all significantly smaller than those generated from the unadjusted data. The overall difference, computed by the root mean square error statistic (RMSE), falls from 0.372 m$^3$s$^{-1}$ to 0.201 m$^3$s$^{-1}$ – a reduction of 54%. This pattern is repeated for nodes throughout the system.

The case study has demonstrated that radar rainfall data can be used to simulate pipe flows for a complex UDS with comparable accuracy to results obtained using a dense network of raingauges.

At this stage, no attempt has been made to compare the simulated flow hydrographs with observed data. Raingauge data are still used exclusively by the civil engineering profession for the design and assessment of drainage system performance. As such, the demonstration of the utility of radar data for UDS modelling and a comparison of the results with those obtained using raingauge data is regarded as a significant step. Also, this study has not investigated the influence of the spatial variability on UDS pipe flow simulations. This is an important area of work which is currently being investigated and which will be reported in the future.

7. Discussion

A simplified implementation of the PMM method first proposed by Rosenfeld et al. (1993) has been imple-
mented and tested for the Bolton drainage area. An adjustment function was applied to a completely independent data set. The verification demonstrated that the PMM adjustment significantly reduced the difference between individual raingauges and overlying radar pixels at each of the gauge sites and for area averaged storm totals. Furthermore, the adjusted radar data closely follow the temporal pattern of rainfall as observed by the raingauges. At present this conclusion is only valid if the adjustment function is applied for the same area for which it has been derived, although there is no reason why the adjustment cannot be extended to other areas, particularly with comparable topography and at similar ranges from the radar site. The wider application of adjustment functions is currently under investigation.

By definition, the PMM is conservative in that the maximum rain rate predicted by the model cannot exceed that observed by the raingauge data and the occurrence of rainfall intensities above those observed in the calibration data set will result in sub-optimal adjustment. This was observed for the case study event, which, although predominantly stratiform, did include embedded convective cells that produced higher rainfall intensities than observed in the calibration data set. Although not attempted, extrapolation of the PMM beyond the range covered by the calibration data set is feasible, although this might introduce significant error. This highlights the importance of using an

Table 3. Comparison of pipe-flow simulations using raingauge and radar rainfall inputs. Differences are expressed relative to raingauge values.

<table>
<thead>
<tr>
<th></th>
<th>Gauge</th>
<th>Unadjusted</th>
<th>Difference</th>
<th>Adjusted</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(mm)</td>
<td>(%)</td>
<td>(mm)</td>
<td>(%)</td>
</tr>
<tr>
<td>Mean flow (m³ s⁻¹)</td>
<td>0.342</td>
<td>0.227</td>
<td>33.7</td>
<td>0.360</td>
<td>-5.0</td>
</tr>
<tr>
<td>Peak flow (m³ s⁻¹)</td>
<td>2.077</td>
<td>1.509</td>
<td>27.3</td>
<td>2.057</td>
<td>1.0</td>
</tr>
<tr>
<td>Total flow volume</td>
<td></td>
<td></td>
<td></td>
<td>0.118</td>
<td>0.079</td>
</tr>
<tr>
<td>RMSE (m³ s⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td>0.372</td>
<td>0.201</td>
</tr>
</tbody>
</table>

Figure 11. (a) Simulated hydrographs at the drainage area outlet generated from raingauge data (thick solid line), unadjusted radar data (grey line) and PMM adjusted radar data (thin solid line). The flows have been simulated using 84 hours of contiguous rainfall data from 1200 UTC on 28 February to 1200 UTC on 3 March 1999. (b) Corresponding difference between flow hydrographs simulated using raingauge input data and unadjusted (grey line) and adjusted radar data (solid line).
extensive data set for the derivation of the adjustment function. The authors believe that different adjustment functions might be appropriate for different rainfall types, necessitating the need for adjustment to be conducted in conjunction with a rainfall type discriminator (e.g. Steiner et al., 1995). A further consideration regarding rainfall type is that the calibration and verification events exhibit limited spatial variability in the rainfall fields and more events need to be studied to quantify the impact on spatial variability, especially for convective rainfall.

A preliminary attempt to generate simulated hydrographs of pipe flow in a complex urban drainage system has been presented to demonstrate the potential utility of weather radar rainfall estimates in this field. While a number of researchers have attempted similar analyses, its application in urban radar hydrology is still in its infancy. Urban drainage systems have been designed on the explicit assumption that rainfall is uniform in space since Victorian times. While the hydrodynamic models of such systems and the ability to run simulations using small computational time steps have been revolutionised in recent years by the power of desktop computers, rainfall is likely to remain 'spatially uniform' for some years to come. Spatially varied rainfall demands a model capable of accepting a distributed rainfall input and a measurement of spatial rainfall. Although dense networks of raingauges provide an element of spatiality, such networks can be prohibitively expensive to install and maintain. Furthermore, raingauges are subject to a wide range of site and instrumentation related errors (e.g. Sevruk, 1982). Radar, with its ability to provide numerical estimates of rainfall, over a wide area at a high spatial resolution, offers an alternative. However, before the engineering community will accept the use of radar rainfall information, the reliability and accuracy of these measurements need to be unequivocally demonstrated. The results presented in this paper demonstrate that radar rainfall data can produce simulated hydrographs in close agreement with hydrographs generated using input data generated from a dense network of raingauges. In addition to the spatial information provided by weather radars and the potential for improving simulation accuracy, an equally important factor in the future utility of radar rainfall data for operational use in urban hydrology is likely to be the cost savings that may arise from the use of radars.

In the long term, further opportunities in urban hydrology also exist. In the 1980s a strategic plan for a solution to the local flooding and pollution problem in the town centre of Bolton was completed. The principal idea was to construct several on-line and off-line tanks to store excess sewer flows temporarily until sufficient capacity existed within the sewer pipes. This would reduce the frequency of pipe/tank overflow operation and the frequency and severity of surface flooding and pollution incidence. Initially these tanks would operate passively, filling by excess pipe flow spilling over a static side weir located upstream of a pass-forward flow control device. The eventual aim, however, was to move to predictive control of the system in real-time using remote control of motorised penstocks, gate valves and storage tank entrance weirs in conjunction with in-sewer sensors to control the passage of wastewater through the system. This 'active control' of urban drainage systems remains, at least in an operational sense in the UK, some years distant, if only because of the consenting issues such a mode of operation poses. However, fully predictive active control will require short-term quantitative rainfall estimates (Anderson & Anderson, 1998) in addition to spatial rainfall information, and weather radar data has a key role to play in this. (For further information on active control of urban drainage systems, refer to the numerous papers in Sieker and Verworn 1996; see also Cluckie et al., 1997.)

The high temporal and spatial resolution of weather radar data coupled with the potential ability to forecast rainfall quantitatively affords potential benefits for the management, operation and control of complex urban drainage systems. However, the radar rainfall data must routinely meet stringent quality requirements and be free from permanent and spurious clutter and not be subject to errors such as bright-band, low level growth/evaporation, etc. (Work is currently in progress to develop an objective technique of identifying and correcting for BB errors.) Failure to ensure that the data conform to these requirements will lead to poor network simulation and, in the case of a system controlled actively in real-time, to erroneous decision-making and possibly inadvertent pollution or even flooding. Success in achieving this will open up exciting new opportunities for radar hydrology, as well as providing improved UDS flow simulations, better and more cost effective designs, and improved system performance resulting in reduced flooding frequency and improved environmental quality.

Acknowledgements

The authors would like to thank North West Water Ltd. for funding this study, particularly Paul Melbourne and David Hetherington of the Technology Development Team. Thanks also to Dr Maurice Baker for his development of the ARTIST system software and technical support of the radar system, Mr David Stevens for invaluable technical support, and APT Systems for their support of the radar system.

References


