A preliminary appraisal of Thurnham dual polarisation radar in the context of hydrological modelling structure

D. Zhu and I. D. Cluckie

ABSTRACT

The Thurnham radar is a prototype of a potential operational C-Band dual-polarisation weather radar designed specifically for the measurement of rainfall. It is also designed to increase the radar coverage over London when operating as a conventional C-Band radar as a direct consequence of the Lewes floods of October 2000. Dual-polarisation processing is expected to provide improved estimation of rainfall rates, especially at higher intensities, in terms of clutter removal, attenuation correction and rainfall estimation. In this study, three hydrological models with different mathematical structures were selected to evaluate the impact that dual-polarisation technology could have on operational hydrology and recommendations provided on the further development of the dual-polarisation algorithms in the short term. The preliminary appraisal was focused on the Upper Medway Catchment (south of London, UK) using different precipitation inputs, including raingauge measurements, radar rainfall estimates from single-polarised algorithms (cartesian format) and five different dual-polarisation algorithms (polar format). The influence of the different rainfall inputs on the various hydrological models were compared using a extreme flood event to provide an initial evaluation of the performance of the Thurnham radar. Recommendations for applying dual-polarisation radar to real-time flood forecasting are discussed in detail.

Key words | clutter removal, dual-polarisation radar, flood forecasting, hydrological modelling, rainfall estimation, signal attenuation

INTRODUCTION

When considering the accuracy of a real-time flood forecasting system, meteorological data, and especially precipitation that has a high spatial and temporal resolution, is one of the most important and critical input variables. However, raingauge measurements are often of relatively poor spatial and temporal resolution. The application of quantitative weather radar in hydrological modelling has demonstrated the prospect of improving the accuracy of real-time streamflow prediction. Many studies have focused on using high temporal and spatial resolution of single-polarisation-derived weather radar rainfall in hydrological models in order to assess the application of weather radar in hydrological simulation and flood forecasting applications (Collier & Knowles 1986; Owens 1986; Cluckie & Owens 1987; Cluckie et al. 1990; Bell & Moore 1998a, b; Borga 2001; Carpenter et al. 2001; Tachikawa et al. 2003; Hossain et al. 2004; Reichel et al. 2008).

However, the advantage of estimating precipitation using weather radar has been limited by a variety of sources of uncertainty during the rainfall estimation process. Some of the factors that affect radar measurements are hardware calibration, signal attenuation, clutter and anomalous propagation, variation of the vertical reflectivity profile (VRP), extrapolation of the measurements to the ground, variation of the drop size distribution, the selection of the proper reflectivity–rainfall (Z–R) relationship, sampling effects and beam overshooting shallow precipitation. Many of these problems were investigated during the Dee Weather Radar Project (DWRP) carried out in the UK between 1970 and 1976, as well as the research led by Harrold...

Theoretically, dual-polarisation processing is expected to mitigate those uncertainties and provide better rainfall estimation than compared to the conventional single-polarisation radars (Battan 1973; Browning 1978; Collier 1996; Bringi & Chandresakar 2001; Illingworth 2003; Cluckie & Rico-Ramirez 2004; Sugier & Dempsey 2008). This is especially true at higher intensities and when better discrimination between snow and ice is required. Additionally, high spatial and temporal resolution radar rainfall data may contribute to an improvement in the lead-time and accuracy in both flood forecasting and flood monitoring in operational systems. However, much of this promise has been identified on non-attenuating S-band research radars and not on operational frequencies such as the C-band devices currently implemented throughout the UK and much of Europe.

The Environment Agency and the Meteorological Office in the UK have jointly considered the operational deployment of dual-polarisation radars across the current national radar network within the UK. With this background, the Thurnham radar was installed in 2005 in order to increase the radar coverage over London and the southeast of England and also serve as a platform for investigation of a prototype design. It is the first operational dual-polarisation weather radar in the UK that incorporates an antenna-mounted receiver and simultaneous transmission in both horizontal and vertical polarisations. This design is likely to be less contaminated by errors due to variations in the radar power emission and the system noise generated during the signal transmission through the rotating joints and waveguides. The polarimetric radar measurements are in addition to the existing single-polarisation radar parameters and will potentially provide a better understanding of the different precipitation types, identification of non-meteorological particles and better rainfall accumulation estimates (Anagnostou et al. 2004; Sugier & Dempsey 2008). A typical two-transmitter, two-receiver dual-polarised radar system is depicted in Figure 1 (after Bringi & Chandresakar 2001).

By providing additional information such as the horizontal and vertical polarised reflectivity factors $Z_{hh}$ and $Z_{vv}$, the differential reflectivity $Z_{dr}$ (related to the shape and degree of common orientation of the precipitating hydrometeors, which can be utilised to provide better rainfall estimates); the specific differential phase $K_{dp}$ and correlation coefficient $\rho_{hv}$ (the statistical correlation between the reflected horizontal and vertically polarised return power, which indicates the shape of the hydrometeors); and linear depolarisation ratio (LDR), a range of precipitation types can be identified.

The polarimetric radar observables used in this study are related to the scattering elements of the backscattering matrix and are defined as follows (Doviak & Zrnic 1993).

1. The horizontal and vertical polarised reflectivity factors: $Z_{hh}$, $Z_{vv}$:

$$\rho_{hv} = \frac{\langle S_{hv}^2 \rangle}{\sqrt{\langle |S_{hh}|^2 \rangle \langle |S_{vv}|^2 \rangle}}$$

2. Differential reflectivity: $Z_{dr}$

$$Z_{dr} = 10 \log \left( \frac{Z_{hh}}{Z_{vv}} \right)$$

3. Specific differential phase: $K_{dp}$ (km$^{-1}$)

$$K_{dp} = \frac{1}{2} \frac{d\Phi}{dr}$$

4. Correlation coefficient: $\rho_{hv}$

$$\rho_{hv} = \frac{\langle S_{hv}^2 \rangle}{\sqrt{\langle |S_{hh}|^2 \rangle \langle |S_{vv}|^2 \rangle}}$$

![Figure 1](https://iwaponline.com/hr/article-pdf/43/5/736/370071/736.pdf)
5. Linear depolarisation ratio: LDR

\[
\text{LDR} = 10 \log \left( \frac{\langle |S_{vh}|^2 \rangle}{\langle |S_{hh}|^2 \rangle} \right)
\]

In parallel with the UK, Meteo-France has also considered upgrading the French radar network to dual-polarisation capability and initiated a project to evaluate the benefits to hydrology within the operational radar context in 2004; this project is entitled ‘The Programme Aramis Nouvelles Technologie en Hydrometeorologie Extension et Renouvellement (PANTHERE)’. Germany also launched a similar dual-polarimetric C-band Doppler radar (POLDIRAD) project, located in the Alpine region in southern Germany in 2006. It is necessary to evaluate the benefits of dual-polarisation technology when compared to existing (single-polarisation) radar data processing systems for weather and flood forecasting using the Thurnham dual-polarisation radar as an operational prototype. The primary reason for this evaluation is that the majority of research and development has so far focused on the non-attenuating S-band frequency; the UK network however comprises C-band radars that are subject to some attenuation losses and introduce errors to the sensitive calculations carried out within the real-time radar processing system. It is not yet clear if the advantages seen at S-band frequencies with research radars, such as the UK Chilbolton S-band radar system, will be replicated for operational purposes at C-band.

The current investigation is focused on the performance of dual-polarisation algorithms that attempt to maximise the potential benefits of radar rainfall estimation, such as those developed by Bringi & Chandreskar (2001), Rico-Ramirez & Cluckie (2006, 2008) and Sugier & Dempsey (2008). This paper is a preliminary appraisal of Thurnham dual-polarisation radar in the context of various hydrological mathematical modelling structures, and attempts to analyse the impact that dual-polarisation could have on operational hydrology. Several recommendations are provided for the future development of the algorithms in the short term and evidence is provided to enable decisions to be made regarding the introduction of dual-polarisation radar technology across the UK network in the near future.

**METHODOLOGY**

Three hydrological models with different mathematical structures and hydrological mechanisms were selected. These consisted of (1) the physically based, fully distributed MIKE SHE/MIKE 11 fully coupled system (Abbott et al. 1986a, b; DHI 2007); (2) the semi-distributed Probability Distributed Soil Moisture (PDM) model (Moore 1985, 1986, 1999; Moore & Bell 2002); and (3) the lumped Physical Realisalbe Transfer Function (PRTF) model (Han 1991).

The purpose of this choice was not to compare a specific set of models but rather to consider the impact of rainfall estimation processes on a set of different mathematical model structures. All the models chosen have been widely used across the globe and are representative of a set of mathematical structures that span from complex to simple, reflecting a decreasing ability to specifically represent the distributed (spatial) nature of the rainfall–runoff process.

Five algorithms with different combinations of clutter removal, attenuation correction and rainfall estimators were used to evaluate the performance of the Thurnham radar in terms of the precipitation estimation.

**Algorithm 1**

Clutter classification was carried out using a clutter map and the standard error of the reflectivity (single-polarisation). Rain rates were estimated using the standard Marshall–Palmar (MP) relationship \(Z = 200 R^{1.6}\). Clutter is a set of apparent echoes in a circle around the radar that is largely consistent over time, due to ground reflections from buildings, trees or terrain due to obstruction of the radar beam. These non-meteorological echoes can be misinterpreted as heavy precipitation. An accurate clutter map or real-time algorithmic classification of echoes is therefore crucial for clutter removal.

**Algorithm 2**

Clutter classification was carried out using a clutter map and all the polarimetric variables. Rain rates were estimated using the standard MP relationship.
Algorithm 3

Clutter classification was carried out using all the polarimetric variables, followed by application of an attenuation correction method. Rain rates were estimated using the MP relationship.

Algorithm 4

As for Algorithm 3, but rain rates were estimated using (Bringi & Chandresakar 2001):

\[ R = 0.01583 \times Z_h^{0.8349} \times 10^{-0.3732Z_{dp}} \]

Algorithm 5

As for Algorithm 3, but rain rates were estimated using (Rico-Ramirez & Cluckie 2006):

\[ R = 5.8 \times 10^{-3} \times Z_h^{0.91} \times 10^{-0.209Z_{dp}} \]

The estimated precipitation from these different dual-polarisation algorithms was compared with raingauge measurements and the Nimrod radar product (Golding 1998). An extreme flood event in 2007 was selected to evaluate the performance of the Thurnham radar by using all rainfall products as inputs to the three hydrological models, followed by a comparison of the performance of the dual-polarised and single-polarised algorithms and the raingauge records.

STUDY CATCHMENT AND HYDROLOGICAL MODEL DESCRIPTION

The Upper Medway Catchment covers an area of around 220 km². The catchment is located south of London, 50 km from the Thurnham radar. Predicting and managing fluvial flooding has historically been a considerable challenge in the Medway catchment due to the confluence of subcatchments (with highly different responses to rainfall) and the tidal influences from the Thames Estuary. High flows in the River Medway are today controlled by sluice gates at Leigh, operated during heavy rainfall on the Upper Medway Catchment. Figure 2 shows the location of the Thurnham radar, the Leigh barrier and the Medway subcatchments.

A spatially weighted precipitation map, based on data acquired from the nine real-time tipping bucket raingauges (TBRs) operated by EA, could then be processed to any time interval (see Figure 3). The rainfall data were obtained automatically from the TBR for hydrological model calibration and validation, and calibrated using the measurement from rainfall storage gauges which are located next to the TBRs; there was around 8% discrepancy in the calibration.

The density of the raingauge network, the distance to the radar and the flood risk management issues make the Upper Medway Catchment ideal for a ground-based study of the possible use of quantitative radar rainfall data from the C-band dual-polarisation weather radar commissioned at Thurnham.

The catchment topography varies between 30 and 220 m above mean sea level. The majority of topographic slopes (around 70%) in the Upper Medway Catchment vary over the range 2–8°, which suggests that the Upper Medway Catchment is predominantly small hills surrounded by relatively flat low-lying areas without much variation in elevation (see Figure 3).

Figure 4 shows that the vegetation cover can be simplified to almost all permanent grassland as it was dominant over the catchment (over 95%). The major soil types in the Upper Medway Catchment can be categorised as silty loam and clayey silt, according to the National Soil Resources Institute (NSRI) data.

The soil types of the Upper Medway Catchment are shown in Figure 5 and were derived from the national soil map (NATMAP) made available by NSRI. Additionally, the soil map used in MIKE SHE was categorised using the Hydrology of Soil Types (HOST) number as defined by the Institute of Hydrology (see Table 1).

The geology of the catchment is a mixture of permeable (chalk) and impermeable (clay) and the dominant aquifers consist of the Ashdown Formation and the Tunbridge Wells Formation of the Hastings Group.
The MIKE SHE model

MIKE SHE is a hydrological modelling system based on the Systeme Hydrologique Europeen (SHE) concept introduced in 1976. MIKE SHE has been extensively developed by the Danish Hydraulics Institute (DHI) and is a complex deterministic model, covering the entire hydrological system at a catchment scale (see Figure 6).

For the Upper Medway Catchment, the overland flow module in MIKE SHE employs a two-dimensional Saint-Venant equation to describe the water movement on the surface, and the finite difference method is used to solve this equation. If the cartesian \((x, y)\) coordinates are applied in the horizontal plane, the flow depth on the ground surface is denoted by \(h(x, y)\) and the flow velocity in the \(x\) and \(y\) directions is \(u(x, y)\) and \(v(x, y)\), respectively. According to the conservation of mass, the net rainfall \(i(x, y)\) added to the overland flow is defined:

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (uh) + \frac{\partial}{\partial y} (vh) = i
\]

and the momentum equations are:

\[
S_t(x,y) = S_o(x,y) - \frac{\partial h}{\partial (x,y)} (Z_g + h) = \frac{\partial z}{\partial (x,y)}
\]

where \(S_t\) and \(S_o\) represent the friction and ground surface slopes, respectively, in the \(x\) and \(y\) directions and \(Z_g\) is ground surface level.
The Strickler–Manning coefficient $K$ is employed for each friction slope and the diffusive wave approximation equations can be written:

$$
\begin{align*}
uh &= K_x \left( -\frac{\partial h}{\partial x} \right)^{1/2} \frac{h^{5/3}}{C_{18}/C_{19}} \\
vh &= K_y \left( -\frac{\partial h}{\partial y} \right)^{1/2} \frac{h^{5/3}}{C_{18}/C_{19}}
\end{align*}
$$

where $uh$ and $vh$ represent discharge per unit length along the cell boundary.

The water movement through the soil profile along with the evapotranspiration is modelled by a simplified two-layer evapotranspiration/unsaturated zone (ET/UZ) model, which is suitable for application to catchments that have a shallow groundwater table. It can also be used in the unsaturated zone to calculate the actual evapotranspiration and the amount of water that recharges the saturated zone. The infiltrated water in the unsaturated zone will increase the soil moisture and may alter the groundwater table. The soil moisture content in the unsaturated zone is assumed to vary from a maximum soil moisture amount $\theta_{\max}(Z_d)$ to a minimum soil moisture capacity $\theta_{\min}(Z_d)$, where $Z_d$ is the water table depth below the ground surface. Both $\theta_{\max}(Z_d)$ and $\theta_{\min}(Z_d)$ represent the average soil water capacity over a moisture profile and can be expressed:

$$
\theta_{\min}(Z_d) = \frac{1}{Z_d} \int_{z=0}^{z=Z_d} \theta(z) \, dz
$$

where $\theta(z)$ ranges from $\theta(w)$ at $z = 0$ to $\theta(sat)$ at $z = Z_d$ and $\theta(w)$ and $\theta(sat)$ are the soil moisture content at the wilting point and the saturated condition, respectively, and

$$
\theta_{\max}(Z_d) = \frac{1}{Z_d} \int_{z=0}^{z=Z_d} \theta(z) \, dz
$$

Figure 3 | Raingauges and elevations on Upper Medway Catchment.
Figure 4 | Vegetation cover on Upper Medway Catchment.

Figure 5 | Soil types of the Upper Medway Catchment.
\[ \theta(z) \text{ ranges from } \theta(fc) \text{ at } z = 0 \text{ to } \theta(sat) \text{ at } z = Z_d \text{ and } \theta(fc) \text{ is the field capacity soil water content.} \]

Here, \( \theta_{\text{max}}(Z_d) \) corresponds to an equilibrium stage of the recharge process related to the water table depth which can be reached by the infiltration from rainfall without changing the water table depth significantly. If the infiltration continues after the average soil water content is reached, the water table will be altered and the soil water content will be greater than \( \theta_{\text{max}}(Z_d) \). When the rainfall stops the soil water content starts to decrease until \( \theta_{\text{max}}(Z_d) \) is reached, at which time the water table stops rising.

The model was established using a grid size of 100 m x 100 m, calibrated using 15 min raingauge measurements and compared with 15 min observations of discharge at the catchment outlet at Chafford. This process was performed for a 6 month period (from September 2003 to February 2004); the first 2 months were used as a warm-up period (so the initial soil moisture level of the model could reach a level similar to the catchment) and the remaining 4 months were used to evaluate model outputs.

Trial-and-error minimisation was employed to calibrate the model. First, the baseflow was the main target and the relative baseflow controlling parameter was set in a range and the parameters adjusted by validating the model iteratively. The peak flow was then taken into account and several sensitive parameters are selected for the calibration due to the contribution of the variability of parameters in relation to the peaks. The final calibrated model parameters are listed in Table 2. The MIKE SHE model performance (Nash–Sutcliffe efficiency) in calibration and for the validation period (from September 2006 to February 2007) were 0.93 and 0.91, respectively, which indicate a relatively good calibration and that a representative model of the catchment had been identified.

**PDM model**

The Probability Distributed Model (PDM) is a fairly general lumped rainfall–runoff model that transforms rainfall and evaporation data to flow based on probability distributed moisture stores. It propagates the runoff via routing stores to the catchment outlet by considering that different points in a catchment have differing storage capacities and that the spatial variation of capacity can be described by a probability distribution (Moore 1985, 1986, 1999; Moore & Bell 2002).

The PDM model assumes that the store depth is distributed across the catchment within the range minimum depth \( C_{\text{min}} \) to maximum depth \( C_{\text{max}} \) and that one of the most common forms of the distribution is a truncated Pareto distribution. The shape of this distribution varies with a parameter \( b \). The rain not only fills up the stores and produces the overland flow, but also infiltrates and forms the groundwater recharge and some of the water is then evaporated. The standard PDM model employs two linear stores to describe the surface flow with time constants \( k_1 \) and \( k_2 \), while the moisture stores drain to form the groundwater recharge as a non-linear function of the effective store contents with a time constant \( k_g \). This recharge forms the input to the subsurface storage which is usually taken to be a cubic store with time constant \( k_b \). The subsurface flow is finally added to the surface runoff to form the total flow at the catchment outlet (see Figure 7).

The truncated Pareto distribution of store capacities employed in the standard form of PDM model contains the probability density function \( f(c) \) and distribution

**Table 1 | Soil type of Upper Medway Catchment**

<table>
<thead>
<tr>
<th>HOST Number</th>
<th>Substrate hydrogeology</th>
<th>Flow mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Soft sandstone, weakly consolidated sand</td>
<td>Weakly consolidated, macroporous, by-pass flow uncommon</td>
</tr>
<tr>
<td>9</td>
<td>Coverloam</td>
<td>Unconsolidated, macroporous, by-pass flow common</td>
</tr>
<tr>
<td>16</td>
<td>Soft shales with subordinate mudstones and siltstones</td>
<td>Slowly permeable</td>
</tr>
<tr>
<td>18</td>
<td>Very soft bedded loam, clays and sands</td>
<td>Slowly permeable</td>
</tr>
<tr>
<td>24</td>
<td>Till, compact rocks</td>
<td>Slowly permeable</td>
</tr>
<tr>
<td>25</td>
<td>Very soft massive clays</td>
<td>Impermeable (soft)</td>
</tr>
</tbody>
</table>
function $F(c)$ given by:

$$f(c) = \frac{dF(c)}{dc} = \frac{b}{C_{\max}} \left( 1 - \frac{C}{C_{\max}} \right)^{b-1}$$  \hspace{1cm} (11)$$

and

$$F(c) = 1 - \left( 1 - \frac{C}{C_{\max}} \right)^b$$  \hspace{1cm} (12)$$

where $C_{\min} \leq C \leq C_{\max}$ and the shape parameter $b$ controls the degree of spatial variability of the storage capacity over the catchment. The volume of the catchment direct runoff per unit area generated from this distribution of store over the time interval $(t, t+\Delta t)$ with net rainfall is given by:

$$V(t+\Delta t) = \int_{C_{\min}}^{C_{\max}(t+\Delta t)} F(c) \, dc$$  \hspace{1cm} (13)$$

and the depth over the catchment $S(t)$ is used to express the total water in store across the catchment, which is given by:

$$S(t) = C_{\min} + (C - C_{\min}) \left\{ 1 - \left( \frac{C_{\max} - C(t)}{C_{\max} - C_{\min}} \right)^{b+1} \right\}$$  \hspace{1cm} (14)$$
and

\[ C^*(t) = C_{\text{min}} + (C_{\text{max}} - C_{\text{min}}) \left\{ 1 - \left( \frac{S_{\text{max}} - S(t)}{C - C_{\text{min}}} \right)^{\frac{1}{b+1}} \right\} \]  

(15)

where \( C^* \) is the mean storage capacity over the catchment and \( C^*(t) \) is related to the total water in store across the catchment. The value of the exponent \( b \) is used to sustain the evaporation in high soil moisture deficit conditions, where it is usually assigned typical values of 1 or 2.

The recharge of the groundwater storage from the probability-distributed soil moisture content is introduced by assuming that the rate of drainage over the interval \( d_i \) is in proportion to the water in store when it exceeds the water storage threshold \( S_t \) and is given by

\[ d_i = k_g^{-1} (S(t) - S_t)^{b_g} \]  

(16)

where \( k_g \) is a drainage time constant, \( b_g \) is an exponent and usually set to 1 and \( S_t \) is the threshold storage below which there is no drainage (water being held under soil tension).
In order to achieve the best fit between observed and modelled flow, the model parameters were calibrated in simulation mode using a mixture of manual and automatic parameter adjustment (a simplex direct search procedure; Nelder & Mead 1965) according to their functionalities in the model. Similar to the MIKE SHE model, the PDM model was applied to completely dry conditions before the calibration and a period of at least two months was needed before the soil was fully saturated.

Table 3 summarises the PDM calibrated parameters for the Upper Medway Catchment in this study. The PDM model performance (Nash–Sutcliffe efficiency) in the calibration and validation periods were 0.90 and 0.87, respectively.

### PRTF model

The rainfall–runoff transfer function (TF) model used in this study is an advanced form of transfer function model known as the physically realisable transfer function (PRTF). PRTF (Todini 1988; Han 1991; Box et al. 1994) attempts to replicate the non-linear and time-variant nature of the rainfall–runoff process by matching the model response as closely as possible to the catchment response by three real-time adjustment factors (shape, volume and timing). Crucially, the PRTF model structure is unconditionally stable which means the adjustment of any of the model parameters cannot result in model instability or fluctuations in model output. Mathematically, it represents the simplest structure chosen to assess the advanced dual-polarisation radar processing algorithms and is a distant cousin of the Unit Hydrograph.

The typical rainfall–runoff transfer function model can be described by:

\[
y_t = a_1 y_{t-1} + a_2 y_{t-2} + \cdots + a_p y_{t-p} + b_0 u_t + b_1 u_{t-1} + b_2 u_{t-2} + \cdots + b_q u_{t-q}
\]

and

\[
SSG = \frac{b_0 + b_1 + b_2 + \cdots + b_q}{1 - a_0 - a_1 - a_2 - \cdots - a_p}
\]

where \(a_i, b_i\) are the model parameters, \(y_t\) and \(u_t\) are river flow and rainfall rate at time \(t\) respectively, and SSG is the percentage runoff of the process.

The PRTF model shares similar features with general TF models, but the poles of the PRTF model are constrained in order to avoid instability, fluctuation and negative impulse responses so that it is easy to identify, is always in a physical realisable form and is suitable to be applied in rainfall–runoff simulation and forecasting. In order to calibrate the model, the related parameters for effective rainfall calculation are listed in Table 4.

Finally, the auto-calibration function was employed and the identified PRTF model for the Upper Medway Catchment using effective rainfall can be written in the form:

\[
y_t = 2.866626 y_{t-1} - 2.739182 y_{t-2} + 0.872468 y_{t-3} + 0.0083970 u_t
\]

with time lag=15 min and time to peak=10.799 hour, where \(y_t\) and \(u_t\) are recorded river flow and precipitation rate at time \(t\), respectively.
The impulse response and pole location of model calibration are illustrated in Figure 8. The PRTF model performance (Nash–Sutcliffe efficiency) in calibration and validation were 0.85 and 0.80, respectively.

**RADAR RAINFALL ESTIMATION PERFORMANCE IN HYDROLOGICAL MODELS**

A extreme flood event from 2007 was selected to evaluate the performance of the polar rainfall estimates. The precipitation produced by the different polarimetric algorithms were compared with the raingauge measurements and Nimrod rainfall data in terms of rainfall accumulation over the Upper Medway Catchment. Four major assessment criteria were utilised in this study: mean absolute error (MAE); root-mean-square error (RMSE); correlation coefficient; and Nash–Sutcliffe efficiency. In addition, two more statistics were introduced to assess the simulation performance of the highest peak flow in particular, which were percent absolute peak error (Ap) and peak time error (Pt).

In terms of the flood magnitude of this event, there was around 80 mm of precipitation recorded by the raingauges during 10 days which caused over 40 m$^3$ s$^{-1}$ discharge at the catchment outlet. However, there were no other peaks before the highest flow and there was around 50 mm cumulative rainfall over the catchment in 1.5 hours, which implied that this was a flash flood (sudden high peak flow and short period). The accumulative precipitation clearly showed that there was a significant increase (over 40 mm difference) on 20 July for the cumulative catchment mean precipitation calculated from all rainfall measurements and rainfall estimation algorithms, especially during the period 20/07/2007 08:00–11:00 when over 30 mm precipitation fell on the catchment in 3 hours, as detected by the raingauge network (see Figure 9).

In the distributed model MIKE SHE, the modelled peak flows triggered by the raingauge measurements were overestimated compared to the observations; the Nimrod rainfall data underestimated the rainfall, however. The 1 and 5 km resolution data generated 25 and 10 m$^3$ s$^{-1}$ streamflow, respectively, which was much less than the recorded data of 40 m$^3$ s$^{-1}$. Considering the differences between the raingauge measurements and Nimrod rainfall data, the precipitation estimated by the radar was probably heavily attenuated. The cartesian conversion process introduced smoothing, which could explain why the 5 km resolution data underestimated more than the 1 km resolution data (see Figure 10a). In effect, the conversion from polar to cartesian format acts like a low-pass filter and smooths the data by averaging.

In this extreme case study, compared to the largely overestimated flows from the raingauges and underestimated simulations from the Nimrod rainfall data, the flows triggered by the five dual-polarisation rainfall estimation algorithms were smaller than the flows using the raingauge measurements but bigger than the flows produced by the Nimrod rainfall data. Additionally, the five algorithms performed differently; MIKE SHE applied to Algorithm 3 performed the best in terms of the corresponding simulation of the peak flows, yielding flows relatively close to the

**Table 4** | Effective rainfall calibration parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment drying constant ($\tau$)</td>
<td>6</td>
</tr>
<tr>
<td>Catchment area</td>
<td>225 km$^2$</td>
</tr>
<tr>
<td>Target difference</td>
<td>1</td>
</tr>
<tr>
<td>Volume forcing coefficient ($C$)</td>
<td>0.5631</td>
</tr>
<tr>
<td>Baseflow coefficient</td>
<td>0</td>
</tr>
<tr>
<td>Initial SMI value</td>
<td>0</td>
</tr>
<tr>
<td>Maximum SMI value</td>
<td>0.8</td>
</tr>
<tr>
<td>Temperature modulations factor ($f$)</td>
<td>1</td>
</tr>
</tbody>
</table>

The impulse response and pole location of model calibration are illustrated in Figure 8. The PRTF model performance (Nash–Sutcliffe efficiency) in calibration and validation were 0.85 and 0.80, respectively.
measured flows (although slightly underestimated). Similarly, according to the simulated peak flows on 20 July, the performance of the other algorithms on the peak flow simulation in the distributed model can be rated in order (best first): Algorithm 5, Algorithm 2, Algorithm 1 and Algorithm 4 (see Table 5).

Because the model rainfall input is the catchment average precipitation in the lumped model, the rainfall distribution and heterogeneities are not simulated and so modelled flow was not comparable with observations in this extreme rainfall flood event (see Figure 10(b)). In this case, Algorithm 3 was still the best rainfall estimation algorithm according to the peak flow performance in the PDM model. However, there was little difference between Algorithm 3 and 1 km Nimrod rainfall data; when compared to the MIKE SHE model, the PDM model gave a very poor performance in the simulation of the peak flow.

In the PRTF model, the model had a similar performance to MIKE SHE (see Figure 10(c)) and Algorithm 3 was the best rainfall estimator according to the simulation results. The model performance statistics suggested that the performance of the modelled flow by the five polarimetric algorithms in PRTF was very close to the performance of MIKE SHE; furthermore, the 1 km resolution Nimrod rainfall (which demonstrated a poor performance in the MIKE SHE and PDM models) performed relatively well in the PRTF model. The model performance statistics also indicated that MIKE SHE and the PRTF model outperformed the PDM model in terms of the overall model performance according to MAE, RMSE, correlation and Nash–Sutcliffe efficiency (see Table 6). The comprehensive statistics of the model performance are listed below.

Attenuation was the main error source for radar rainfall estimation in this event, due to the presence of the extreme rainfall rates. The poor rainfall measurement from the rain-gauge and Nimrod product generated a low Nash–Sutcliffe value in the MIKE SHE model simulation, in particular. In this case, adoption of an attenuation correction could contribute significantly to the rainfall estimation algorithms, indicated by the performance of the peak flow simulation using Algorithms 3 and 5 in the distributed model. Algorithm 4 provided the worst simulation of the five algorithms, although the attenuation correction method had been applied. The only difference between Algorithms 3, 5 and 4 is the rainfall estimator; in this case, the MP relationship outperformed the other more sophisticated rainfall estimators.

However, the other two algorithms (with no attenuation correction) outperformed Algorithm 4 in this event. Both of them used the MP relationship as the rainfall estimator but Algorithm 2 employed the dual polarimetric variables for clutter removal. This gave Algorithm 2 a better performance than Algorithm 1, which only used a single-polarisation map for clutter removal.
CONCLUDING COMMENTS

In general, the simulated flows produced by the five algorithms had more heterogeneities in the distributed model MIKE SHE than in the lumped model PDM and the PRTF model, because the distributed model could better reflect the spatial distribution of the precipitation as represented in terms of the original polar data.

For the medium and high rainfall rate events, the algorithms that employed attenuation correction demonstrated advantages in the hydrological model simulations of peak flow performance. The difference in the simulations not using the attenuation correction depended on the magnitude of the peak flow. For example, for the extremely high rainfall rates, Algorithm 3 employed the dual-polarisation variables for clutter removal, attenuation correction and the MP relationship for precipitation estimation, and the advantage was significant in this case. It was the best algorithm for estimating the high rainfall rate cases and at this early stage reinforces the use of dual-polarisation in the case of extreme flood-producing storms.

The MP relationship was fairly reliable to use in precipitation estimation for both low and high rainfall rate events. For low rainfall rates, the MP relationship should be used in conjunction with the clutter classification from the single-polarisation radar. For high rainfall rates, the attenuation correction should be applied using the dual-polarisation measurements. Regarding the evaluation of other rainfall estimators that utilised the dual-polarisation variables, more events and reliable data are needed for future analysis.

Although the prospect identified on the basis of the initial research on the large S-band system at Chilbolton indicated much promise, it is clear in this preliminary analysis of the early Thurnham C-band data that this has not yet been realised. However, the hydrological simulations show that in a fairly low rainfall rate event, the radar was likely to perform better using the single-polarisation variables due to the absence of the attenuation effect, especially in terms of the distributed models. When the rainfall rate became higher, the algorithms with attenuation correction outperformed the algorithms without; the difference was amplified during the flash flood event due to the extremely high rainfall rates. Regarding the rainfall estimator, the results suggested that the traditional rainfall estimator (MP relationship) outperformed the other rainfall estimators that used the dual-polarimetric variables most of the time.

Finally, it is still difficult to draw up precise and robust conclusions from the preliminary data. Thurnham has continued to improve throughout the period of the study but...
the data collected have not been consistent at any stage. The following conclusions can be drawn from the study.

1. Fully distributed hydrological model structures do manage to capture the spatial information contained in the quantitative weather radar rainfall, but are better at high rainfall rates in more extreme storms. These model structures are of course needed for future land-use management applications where the spatial distribution of properties, such as soil, vegetation, slope, etc., is important.

2. For operational hydrology, the much simpler structures based upon semi-distributed or lumped forms are generally sufficient. Unfortunately, this means that the spatial information contained in the radar rainfall data is often spatially averaged, diminishing the impact of the measurement resolution.

3. The increased ability to recognise rainfall hydrometeor types via dual-polarisation radar does not at present reflect upon the model output. This has been shown via the variations in the rainfall estimation algorithms that convert raw reflectivity into rainfall rates.

4. The dual polarisation parameters provided a considerable input to the correction of the attenuation of the reflectivity signal in intense rainfall events; this was particularly the case at the C-band frequency. Operational radars in the UK national network are all C-band radars, and the virtue of the real-time attenuation correction capability of the dual-polarisation radars was found to be of assistance in the case of a severe storm.

5. The increased capability of the clutter rejection algorithm was only partially seen in the model output results. However, improvements over conventional single-polarisation procedures were evident in the model structure intercomparison.

The current difficulty with drawing a clear conclusion regarding the benefit of the dual-polarisation versus single-polarisation radar debate is that the case is far from

### Table 5 | Peak flow performance for different rainfall input

<table>
<thead>
<tr>
<th></th>
<th>SHE</th>
<th>PDM</th>
<th>TF</th>
<th>SHE</th>
<th>PDM</th>
<th>TF</th>
<th>SHE</th>
<th>PDM</th>
<th>TF</th>
<th>SHE</th>
<th>PDM</th>
<th>TF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge</td>
<td>22.51</td>
<td>22.51</td>
<td>22.51</td>
<td>75.05</td>
<td>75.05</td>
<td>75.05</td>
<td>35.32</td>
<td>35.32</td>
<td>35.32</td>
<td>21.22</td>
<td>21.22</td>
<td>21.22</td>
</tr>
<tr>
<td></td>
<td>8.75</td>
<td>8.75</td>
<td>8.75</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>6.75</td>
<td>6.75</td>
<td>6.75</td>
</tr>
<tr>
<td>PDM</td>
<td>47.54</td>
<td>47.54</td>
<td>47.54</td>
<td>75.37</td>
<td>75.37</td>
<td>75.37</td>
<td>63.80</td>
<td>63.80</td>
<td>63.80</td>
<td>67.83</td>
<td>67.83</td>
<td>67.83</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>4.25</td>
<td>4.25</td>
<td>4.25</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
</tbody>
</table>

### Table 6 | Statistics of performance for different rainfall input

<table>
<thead>
<tr>
<th></th>
<th>MAE (m³ s⁻¹)</th>
<th>RMSE (m³ s⁻¹)</th>
<th>Correlation</th>
<th>Nash-Sutcliffe</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHE</td>
<td>PDM</td>
<td>TF</td>
<td>SHE</td>
<td>PDM</td>
</tr>
<tr>
<td>2.85</td>
<td>2.34</td>
<td>2.58</td>
<td>6.68</td>
<td>5.12</td>
</tr>
<tr>
<td>3.50</td>
<td>3.33</td>
<td>2.48</td>
<td>7.80</td>
<td>7.46</td>
</tr>
<tr>
<td>2.75</td>
<td>2.91</td>
<td>2.37</td>
<td>6.74</td>
<td>6.51</td>
</tr>
<tr>
<td>2.59</td>
<td>3.43</td>
<td>3.25</td>
<td>4.68</td>
<td>7.04</td>
</tr>
<tr>
<td>2.64</td>
<td>3.42</td>
<td>3.23</td>
<td>4.63</td>
<td>7.01</td>
</tr>
<tr>
<td>2.84</td>
<td>3.33</td>
<td>3.35</td>
<td>4.76</td>
<td>6.67</td>
</tr>
<tr>
<td>2.59</td>
<td>3.53</td>
<td>3.15</td>
<td>4.80</td>
<td>7.24</td>
</tr>
<tr>
<td>2.73</td>
<td>3.46</td>
<td>3.19</td>
<td>4.79</td>
<td>7.00</td>
</tr>
</tbody>
</table>
overpowering at the present time. It is too soon to make the
final judgement and much of the work described must be
continued as the Thurnham dataset expands and the techni-
cal/software problems associated with the application of an
emerging technology are resolved.

ACKNOWLEDGEMENTS

The authors would like to thank the Environment Agency,
Meteorology Office, British Atmospheric Data Centre
(BADC) and OS/EDINA for providing hydrological and
radar data. We also thank the Danish Hydraulic Institute
(DHI) and CEH Wallingford for their support. The
financial support of EPSRC Flood Risk Management
Research Consortium (FRMRC) is gratefully acknowledged,
as was the continuing collaboration with a former
colleague Dr Rico-Ramirez of the University of Bristol.

REFERENCES

Rasmussen, J. 1986a An introduction to the European
hydrological system – Systeme Hydrologique Européen
(SHE), 1: History and philosophy of a physically-based,
distributed modelling system. Journal of Hydrology 87 (1–2),
45–59.
Rasmussen, J. 1986b An introduction to the European
hydrological system – Systeme Hydrologique Européen
(SHE), 2: Structure of a physically-based, distributed
Anagnostou, E. N., Anagnostou, M. N., Krajewski, W. F., Kruger,
A. & Miriovsky, B. J. 2004 High-resolution rainfall estimation
from X-band polarimetric radar measurements. Journal of
Hydrometeorology 5 (1), 110–128.
The University of Chicago Press, Chicago.
Bell, V. A. & Moore, R. J. 1998a A grid-based distributed flood
forecasting model for use with weather radar data: Part 1.
Formulation. Hydrology and Earth System Sciences 2 (2/3),
265–281.
Bell, V. A. & Moore, R. J. 1998b A grid-based distributed flood
forecasting model for use with weather radar data: Part 2.
Case studies. Hydrology and Earth System Sciences 2 (2/3),
283–298.
Borga, M. 2001 Use of radar rainfall estimates in rainfall-runoff
modeling: an assessment of predictive uncertainty.
Proceeding of Fifth International Symposium on
Hydrological Applications of Weather Radar-Radar
Box, G., Jenkins, G. M. & Reinsel, G. 1994 Time Series Analysis:
Forecasting and Control. Prentice Hall, Englewood Cliffs, NJ.
Bringi, V. N. & Chandrasekar, V. 2001 Polarimetric Doppler
Weather Radar, Principles and Applications. Cambridge
Browning, K. A. 1978 Meteorological applications of radar. Reports
Carpenter, T. M., Georgakakos, K. P. & Sperfslage, J. A. 2001 On
the parametric and nextrad-radar sensitivities of a distributed
hydrologic model suitable for operational use. Journal of
CEH, Wallingford. 2005 A Guide to the PDM Rainfall-Runoff
Model, 2.2 edn. Centre for Ecology & Hydrology,
Wallingford.
Cluckie, I. D. & Owens, M. D. 1987 Real-time rainfall-runoff
models and use of weather radar information. In: Weather
Radar and Flood Forecasting (V. K. Collinge & C. Kirby,
eads.). John Wiley & Sons, Chichester.
Cluckie, I. D., Yu, K. A. & Tilford, K. A. 1990 Real-time
forecasting: Model structure and data resolution. In: Seminar
on Weather Radar Networking (C. G. Collier & M. Chapuis,
Cluckie, I. D. & Rico-Ramirez, M. 2004 Weather radar technology
and future developments. In Proceedings of ICGRHW held
at the Three Gorges Dam, China, September 2003, on GIS and
Remote Sensing in Hydrology, Water Resources and
Collier, C. 1996 Applications of weather radar systems. In: A
Guide to uses of Radar Data in Meteorology and Hydrology,
Chichester.
Collier, C. G. & Knowles, J. M. 1986 Accuracy of rainfall estimates
by radar, part iii: Application for short-term flood forecasting.
Hydraulic Institute, Hørsholm, Denmark.
Doviak, R. J. & Zrnic, D. S. 1993 Doppler Radar and Weather
Duncan, M. R., Austin, B., Fabry, F. & Austin, G. L. 1993 The effect
of gauge sampling density on the accuracy of streamflow
prediction for rural catchments. Journal of Hydrology
142 (1–4), 445–476.
Fabry, F., Austin, G. L. & Tees, D. 1992 The accuracy of rainfall
estimates by radar as a function of range. Quarterly Journal of
the Royal Meteorological Society 118, 435–453.
Fabry, F., Bellon, A., Duncan, M. R. & Austin, G. L. 1994 High
resolution rainfall measurements by radar for very small
basins: the sampling problem reexamined. Journal of
Golding, B. W. 1998 Nimrod: a system for generating automated
very short range forecasts. Meteorological Applications 5,
1–16.


First received 21 January 2011; accepted in revised form 10 October 2011. Available online 3 May 2012.