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Applying WSR-88 Radar Rainfall on Short Time Scales to Hydrological Modeling of a Small Basin in Florida

by

Harry. J. Cooper [1]
Henry. E. Fuelberg [1]
T. S. Wu [2]
Douglas. Gilbert [2]
J. Mandrup-Poulsen [2]
Richard. J. Lanier [3]
Andrew. I. Watson [3]
John. L. Sullivan, Jr. [1]

Abstract

The Black Creek Basin in North Florida has been the site of flash flooding in 1992, 1996, 1997 and 1998, with flood damage to property exceeding $2 million, and a Local State of Emergency declaration in 1997. WSR-88-derived rainfall rates are applied to the Systeme Hydrologique Europeen distributed hydrological model (Mike-SHE) to discover the comparative advantages of using fully distributed versus Thiessen-derived rainfall rates over this small (1253 km^2) basin of modest topography under convective and synoptic scale weather conditions. Model discharge using hourly Thiessen Polygon and WSR-88 rainfall rates are compared to observations of discharge at two USGS gauging stations in the basin during two case studies for February and July 1998. Results show a distinct advantage of using WSR-88 rain rates. Specifically, WSR-88 provides much greater understanding of model behavior and basin response than when using the less discrete Thiessen inputs, even over such a small basin. With all model parameters and initializations the same for both types of rainfall inputs, results show significant differences in the calculated flows. On these time and space scales, the Thiessen method can introduce spurious runoff at the river gauges under convective conditions, distributing discharge evenly over two sub-basins when there are actually significant differences between them. This latter condition is relevant to tracking locally distributed pollutants that find their way into the main branches of the basin. The results are relevant to the use of WSR-88 rain-rates and Thiessen-Polygon rainfall for small basins on monthly time scales.

1.0 Introduction

Black Creek Basin in North Florida is a small basin (1253 km^2) located southwest of Jacksonville Florida. It consists of two main tributaries, the North Fork and the South Fork, which merge near Middleburg, Florida, and from there empties into the St. Johns River. In this paper, WSR-88-derived rain rates are input to MIKE-SHE, the Systeme Hydrologique Europeen distributed hydrological model (Refsgaard and Storm 1995; Refsgaard 1997) to examine the comparative operational and diagnostic advantages of using fully distributed versus Thiessen-derived rainfall rates over this small

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[1] Department of Meteorology, Florida State University, Tallahassee, Florida

[2] Florida Department of Environmental Protection, Tallahassee, Florida
[3] NOAA NWS, Tallahassee, Florida

basin of modest topography under convective and synoptic scale weather conditions. The analysis is performed during two months, February and July 1998, to obtain a better understanding of how WSR-88 data might aid distributed hydrological modeling during wintertime widespread rainfall regimes, and under summertime conditions of quasi-tropical, small-scale convective activity.

1.1 Instrumentation

Black Creek Basin contains one rain gauge, 29 HRAP WSR-88 radar grid points and three river gauging stations operated by the USGS. The St. Johns River runs from south to north on the eastern side of the basin. The southernmost river gauge is the Penney Farms gauge; the northernmost river gauge is at Middleburg; and the easternmost river gauge is at Doctor's Inlet. The river gauge at Doctor's Inlet was inoperable during 1998, which was the only year that the rain gauge near Penney Farms was operating. The Penney Farms rain gauge dominates the Thiessen Polygon estimates of rainfall over the basin. The basin includes most of Clay County, with a significant portion in Duval County to the north, including the city of Jacksonville, Florida. Black Creek consists of two main branches, the South Fork and the North Fork. Discharge from the South Fork passes through the Penney Farms gauge, while discharge from the North Fork passes through the Middleburg gauge. The combined discharge from both streams passes the gauge at Doctor's Inlet, and thence to the main basin outlet at the St. Johns River.

1.2 Topography, soils and vegetation

There is a significant topographical component to flows in the Black Creek Basin. There is a 60 - 70 m MSL ridge lining the western side of the basin along which the North Fork flows from south to north. This fork curves to the east before emptying into the main branch at the junction of the North and South forks between Middleburg and the Doctor's Inlet gauge. Gentler topography drives the flow in the South Fork through Penney Farms toward the intersection with the main branch just west of Doctor's Inlet. Thus, the gauge at Middleburg records flow mostly from the western and northwestern basin, while the gauge at Penney Farms records flow from the southern part of the basin.

Based on the STATSGO soils database, the surface layer of soils in the basin is mostly fine sand, with some fine sandy loam, loamy sand and muck in the river valleys. A surficial aquifer system approximately 50 meters thick above a confining layer (the Hawthorn Formation) separates the surficial aquifer from the Floridan aquifer below (USACE, 2000). The vegetation in the basin is more than 60% coniferous forest, either natural or in silviculture; 20% of the basin is in water or wetlands; and the rest is a mixture of residential (~10%), commercial mining, crops and dairy farms (USACE, 2000).

2.0 Observations

2.1 The Thiessen Polygon data

Hourly rain gauge data from each of the state's Water Management Districts and from gauges operated by the National Weather Service were obtained for the project. These data were rigorously quality controlled to remove anomalies, and Thiessen rain rates were derived for the basin as a whole.

2.2 The WSR-88 rainfall data

The Multisensor Precipitation Estimation (MPE) software developed by the National Weather Service (NWS) was used to calculate the rain gauge plus WSR-88 rainfall product for the basin. The continental United States is continuously scanned by approximately 100 Doppler radars operated by the NWS and the Department of Defense. Each radar produces an hourly estimate of rainfall on a 4 x 4 km grid. Since most grid points within the U.S. are viewed by more than one radar, a precipitation climatology is prepared for each radar to determine which radar provides the best coverage for each individual 4x4km grid point. This climatology is then used by MPE for all subsequent calculations. The result is that numerous radars are used to calculate precipitation over the total area, with the radar providing the best coverage of each individual 4x4 km grid point being used at that location.

Radars used to compile the parent data set for Black Creek include those at Tampa (KTBW), Jacksonville (KJAX), Melbourne (KMLB), Moody AFB Georgia (KVAX), Eglin AFB Florida (KEVX), Peachtree City Georgia (KATL), and Tallahassee (KTLH).

Hourly radar-derived precipitation amounts within each radar's area of optimal coverage were used in succeeding computations. Although radars provide excellent spatial resolution of rainfall, there are various limitations, many of which are described in Baeck and Smith (1998) and similar publications. These limitations include improper beam filling and the overshooting of low cloud tops at farther ranges, hail contamination, radar mis-calibration, and not knowing the proper relation between radar reflectivity and rainfall (Z-R relations) for a given storm. Because of these limitations, the MPE procedure also incorporates rain gauge data into its algorithm.

Using pairs of rain gauges and raw radar precipitation estimates, the MPE software calculates bias correction factors each hour for each radar to improve the remotely sensed precipitation values. When the hourly radar-derived precipitation values are multiplied by this correction, radar wide biases such as due to radar mis-calibration are removed. Then as a second step, the bias corrected radar-derived precipitation data are merged with the hourly rain gauge observations using optimal interpolation. There are a number of adaptable parameters within the MPE software that allow users to optimize the procedure for specific areas for which calculations are made. The determination of these parameters requires considerable experimentation, but this effort has produced the best possible result from the available radar and precipitation data. Since the gauge network over Florida, Georgia and Alabama is much coarser than over the peninsula, values of the adaptable parameters are different in these two areas. The MPE software is considered by many to be a major advance compared to earlier procedures.

2.3 MPE observations over Black Creek, 1996-2001

The temporal distribution of hourly MPE-derived basin averaged rain rates over Black Creek for the years 1996 through 2001 shows that, in general, smaller hourly rain rates are observed during April through June, and larger rates from July through September. In terms of the magnitudes of the rain rates, February and July 1998 are typical of climatology.

The spatial variability of rain rates over Black Creek, based on the standard deviation each hour of the rain rates from a basin average is such that the magnitudes of the spatial standard deviations within the basin follow the general pattern of the rain rates, with the greatest standard deviations during the summer convective regime and smaller standard deviations in winter. The spatial variability during February and July 1998, as represented by the standard deviations, is not extraordinary.

2.4 River gauge data

Observed daily discharge data were available from USGS river gauges at Penney Farms (1939-2003) and Middleburg (1931-2003). and distributions of observed daily discharge by month were calculated for the two gauges. The range of discharges during February is relatively large at both gauges, and during July it is relatively small at both gauges. In general, the discharge at the Middleburg gauge is greater than at Penney Farms. Thus, the two cases (February and July) are taken from the high and low ends of the river discharge spectrum.

3.0 Case studies

Two months, February 1998 and July 1998, were arbitrarily selected for case studies involving observations and modeling. The year 1998 was chosen because it is the only year when the Penney Farms rain gauge was in operation. Although the Doctor's inlet river gauge was not operating during these two months, those at Penney Farms and Middleburg were in operation during both months. July was chosen as representative of a summer convective regime, and February as representative of a winter, more synoptic regime. Section 3.1 describes analyses relating basin rainfall, as estimated by radar and Thiessen polygons, to discharge as measured at the river gauges. Section 3.2 details the effects of the two different kinds of rainfall inputs on the discharge calculated by a distributed hydrological model.

3.1 Observation case studies

3.1.1 February 1998

MPE basin averaged rainfall, Thiessen polygon (gauge)-derived basin rainfall, and the observed daily discharges at both river gauges were plotted for February 1998. There are obvious differences between the two rainfall rates over the basin. However, the MPE rainfall, the Thiessen rainfall, and the peaks in river discharge generally are in phase as the discharge responds to runoff. In this case, the Thiessen rainfall, dominated by observations at the Penney Farms rain gauge, represents the basin-wide rainfall reasonably well, in that the discharges at both river gauges respond with a similar delay and appropriate magnitudes to both the MPE and Thiessen rain rates. However, the analysis does not explain why the discharge at Middleburg is greater than at Penney Farms. The accumulated monthly rainfall from the MPE product during February 1998 shows that the rainfall during that month was heavy throughout the basin. No grid point accumulated less than 6 inches of rain, and there are local maxima between 10 to 12 inches over the Penney Farms rain and river gauges. However, most of the greatest accumulation, between 12 - 14 inches, are found along the western ridge, and in the northern sub-basin that feeds into the North Fork of Black Creek, which passes the gauge at Middleburg.

On 17 February, MPE rainfall rates greater than four inches per hour were observed by the radars in the North Fork sub-basin, while in the South Fork sub-basin smaller accumulations of 1.5 inches were observed. A daily gauge total of 2.66 inches of rain fell at Penney Farms and 3.13 inches at Normandy Village. Thus, the gauge rainfall observations give some indication that heavier rain occurred in the northern part of the basin. During this time the MPE data shows that the Penney Farms rain gauge was on the edge of the heavy rain over the North Fork. The Thiessen rainfall reflects the Penney Farms and Normandy Village rain gauge observations for that period, overestimating the rainfall into the South Fork, and underestimating the rainfall into the North Fork. This occurs because the Penny Farms polygon carries much more weight than the Normandy Village polygon Consequently, the MPE gridded rainfall data explain why the runoff at Middleburg was greater than at Penney Farms. The MPE high resolution data therefore is an effective tool for evaluating rainfall-runoff models, even over such a small basin and over such short periods of time.

3.1.2 July 1998

The observed rainfall and discharges at Penny Farms and Middleburg for July 1998 show that the discharge at both gauges is small compared to February 1998 and other summer observations. During the summer much of the rainfall is a result of localized convection that is generated by sea breeze convergence zones across the Florida Peninsula on a daily basis. Therefore, the rainfall reaching the ground is associated with quasi-tropical convection that can be intense and highly localized. The MPE rain rates over Black Creek and the discharge observed at the Penny Farms and Middleburg river gauges show that both rainfall estimates show a pattern of almost daily convection over the basin.

There are peaks in runoff at both river gauges on 14 July at Penney Farms and on 16 July at Middleburg. The peak at Penney Farms on 14 July is preceded on 13 July by a spike in the Thiessen rainfall. The peak that occurs at Middleburg on 16 July is preceded by a peak in the MPE rainfall on 15 July. A local maximum of 12 to 14 inches is located near the center of the basin and downstream from the Penney Farms rain and river gauges. Only 5 grids received less than 3 inches of rain during the month, and they were on the periphery of the basin. There is another local monthly maximum of 10 - 12 inches over the ridge to the west. The east to west maximum across the basin is in between Penney Farms and Normandy Village, indicating that most of the monthly rainfall fell in between those two rain gauges.

The spike in the Thiessen rainfall on 13 July deserves further examination. On 13 July, the Penney Farms rain gauge recorded 1.92 inches, while the gauge at Normandy Village recorded 2.66 inches. On the same day, the Gold Head State Park gauge recorded 0.23 inches. The distance between Penney Farms and Gold Head is about 20 km, and between Penny Farms and Normandy Village approximately 40 kilometers. The variability in daily rainfall between these three stations on 13 July indicates the spatial variability of rainfall delivered to the surface during the Florida summertime convective regime.

The MPE estimate of daily total rainfall on 13 July shows a local maximum of 1.5 to 2.0 inches is seen over a tributary of the South Fork. This maximum suggests that the greater runoff at Penney Farms on 14 July is reasonable in spite of the relatively small basin average rainfall on 13 July that is seen in the MPE basin averages. The spike in the Thiessen rainfall on 13 July is explained by MPE estimates on 13 July for the six grid points surrounding the Penney Farms rain gauge, the rain recorded at the gauge itself, and the associated Thiessen estimates of rainfall over the entire basin. The rain gauge at Penney Farms records 1.46 inches per hour at 0600 LST, which was the maximum rainfall for that gauge on that day. The gauges at Normandy Village, Gold Head, Trout Creek and Bostwick all recorded zero rainfall. Since in this case the Thiessen rainfall is determined solely by the rain rate at the Penney Farms gauge, which was located beneath the rain shaft of a convective cell or cells, it probably overestimates the amount of rain falling into a 4 x 4 km^2 grid. This demonstrates again the local nature of convection in this region during warm season, and the likelihood of obtaining misleading estimates of basin rainfall when applying Thiessen polygons during these conditions.

The peak in MPE basin averaged rainfall on 15 July and the peak in runoff at Middleburg on 16 July is occurs on both days which show bands of maximum daily rainfall between the rain gauges at Penney Farms and Normandy Village. On 15 July, the total daily gauge rainfall at Penney Farms, Normandy Village and Gold Head State Park were 0.30, 0.02 and 0.33 inches, respectively. Local maxima in the MPE estimates lie between these gauges, ranging from greater than 4.0 inches near the Doctor's inlet river gauge and the northern perimeter of the basin, to 2 to 3 inches over the western ridge. On 16 July, the three rain gauges recorded a total of 0.39, 0.27 and 0.13 inches respectively, while MPE shows accumulations of 2 to 4 inches over tributaries to the North Fork. These rainfall maxima in the MPE estimates generate the peak in runoff at the Middleburg river gauge on 16 July that is missed by the Thiessen rainfall estimates.

3.2 Hydrological modeling case studies

3.2.1 Model Configuration

The MIKE-SHE model was set up to calculate flow within the Black Creek Basin using MPE and Thiessen rainfall values for July and February 1998. Both rainfall data sets provided distributed hourly rain rates at 4x4 km^2 resolution during both months.

MIKE-SHE was applied in its simplest two-layer soil mode, an unsaturated soil layer overlying a saturated layer. The depth of the unsaturated layer was determined from the rooting depth of the vegetation and the soil matrix saturated potential in the saturated zone that is the surficial aquifer. Soils were considered saturated below the bottom of the unsaturated layer. Boundary conditions for inflow to the basin were set in steady state to the minimum discharge observed at each river gauge over the last 30 years, and tide gauge observations at Red Bay Point across from the mouth of Black Creek were used to assign the oscillating stage conditions at the main outlet to the St. Johns River.

The initial depth to saturation for soils was set to one meter. The soil types, vegetation types, soil hydraulic conductivities, Manning numbers, Leaf Area Index (LAI) and rooting depths were held constant over the entire model domain (see Table 1), and were selected based on nominal published values for sandy and clay soils and evergreen forests (Bonan 1996; Clapp and Hornberger 1978;, Hornberger et al. 1998; Pielke 2002). A basin mean Manning's M of 5.0 was selected from the range of values reported in USACE (2000). Thus, topography was the only permanent property of the basin that was distributed in space. No attempt was made to calibrate the model, or to assess the antecedent saturation of soils for initialization, so as not to bias the results in favor of either the Thiessen or MPE inputs. Under these conditions, one cannot expect the model to calculate accurately the discharge at the USGS river gauges. However, our purpose is to understand differences in model output that may result from using Thiessen-based or distributed MPE rainfall data as input. As expected, the model responds differently to the different rain inputs. The model was run for two months at hourly time steps for February 1998, which represents a high-flow period, and for July 1998, which represents a low-flow period.

3.2.2 February 1998

The observed discharge and uncalibrated model calculations of river discharges at the Penney Farms and Middleburg river gauges were compared for February 1998. Even with all model parameters and initializations the same for both types of rainfall inputs, there are significant differences in the calculated discharges. Two major peaks appear in the observed discharges at both river gauges, at Penney Farms on 17 and 23 July and at Middleburg on 18 and 23 July. The observed discharges at Middleburg are greater than at Penney Farms in both cases. The modeled discharges at Penny Farms are in phase with the observations, but both model-calculated discharges underestimate the first maximum. The second maximum at Penney Farms is duplicated accurately by both calculations. At Middleburg, both calculated discharges are a day earlier than the first observed peak on 18 July, but they are in phase with the second peak on 23 July. Because of the relatively spatially homogeneous nature of the Thiessen rainfall, it generates maxima on both occasions of approximately the same magnitude at both Penney Farms and Middleburg. Conversely, the MPE calculations differentiate between the magnitude of the peaks at Middleburg and Penney Farms, generating more runoff on 17 July than on 23 July, in association with the greater MPE estimates in the North Fork sub-basin, as discussed in section 3.1.1. Neither rainfall input differentiates between the magnitudes of the two maxima at Penney Farms.

3.2.3 July 1998

The observed discharge and uncalibrated modeled discharges were calculated at the Penney Farms and Middleburg river gauges for July 1998. Again, with all model parameters and initializations the same for both types of rainfall inputs, there are significant differences between the calculated discharges. At Penney Farms, both the Thiessen and MPE rain inputs generate an early peak in discharge on 13 July, whereas the observed peak occurs a day later, on 14 July. Both estimates of rainfall also overestimate the maximum magnitude of the flow, with the Thiessen rainfall much more so than the MPE rainfall.

At Middleburg, the WSR-88-generated peak in discharge is in phase with the observed discharge, although the magnitude of the peak is greater than is observed. The Thiessen rain input generates an entirely spurious major peak on the 13 July, three days before the observed maximum on 16 July. This occurs because the model is responding to erroneous Thiessen rainfall over the North Fork during the early morning hours of 13 July, as discussed in section 3.1.2. The magnitude of a secondary and smaller Thiessen maximum, generated on 16 July in response to Thiessen rain rates on 15 July, is in phase with and agrees with the observed maximum at the Middleburg gauge.

3.2.4 Spatial variability of rain rates over Black Creek

In general, the accumulated monthly MPE-generated runoff is greater than the accumulated monthly Thiessen-generated runoff at both stations. The exception is during July 1998 at Penney Farms, when the accumulated monthly Thiessen runoff is greater than generated by the MPE rainfall. Therefore, one rainfall input does not give consistently greater or smaller monthly runoff than the other, and the relative magnitudes of the model's runoff response to either input can be expected to vary from case to case. However, because of the nature of summer convective rainfall and the way that the Thiessen approach handles the rainfall, as described in section 3.1, it is expected that most of the relative variability in model response will depend upon the size, location and intensity of convective rainfall events, occurring mostly during the summer. During the winter, with larger scale more widespread synoptic scale activity, it is expected that the magnitudes of the runoff produced by the MPE and Thiessen inputs will remain relatively constant relative to one another as they do in the accumulated monthly runoff calculated by the model in the February 1998 case study of section 3.1.1.

Difficulties with the spatial representativeness of Thiessen-derived rainfall estimates are expected to increase as the spatial standard deviation of the rainfall rates increases. This can be inferred from the diurnal distribution of the spatial standard deviation of the MPE rain rates over the Black Creek Basin. The larger standard deviations occurring during the afternoon hours, indicate the convective nature of the afternoon rainfall. The standard deviation of 0.151 is the value observed over the basin at 0600 local time on 13 July 1998. There are many occasions during the six-year period when this value is equaled or is exceeded. Therefore, one expects that many Thiessen rainfalls under these conditions will be as unrepresentative of the spatial rainfall distribution as they were during July 1998.

Finally, many of the inaccurate results from the uncalibrated model would be solved if the model were properly calibrated for the basin. This would involve knowledge about the variability in soil hydraulic conductivity among other basin physical parameters. Calibrating a complex distributed model with this knowledge is made more tractable by using distributed rainfall inputs during the process, because the spatial and temporal variability of rainfall inputs help identify where problems are arising in the basin calibration. This is especially true if the purpose of the model analysis is to identify non-point surface water pollution by constituents washed into the reaches from different parts of the basin.

The Thiesssen approach cannot identify local sources of water entering the soils. Thus, the problem in designating the origin of surface water pollutants from non-point sources involves the residence time of groundwater pollutants as they pass from their origin into the streams. If that time period is shorter than one month, the Thiessen approach may be inadequate to determine the locations and strength of non-point source pollutants even in basins as small as Black Creek. If the residence time is much longer, then the Thiessen approach may average out the short-term inadequacies. However, such a solution would have to be considered serendipitous, and is unnecessary, given the existence of fully distributed radar rainfall data sets that are now readily available for application to any hydrological model.

4.0 Summary and Conclusions

A distributed rainfall data set, such as used here, when coupled to a fully distributed hydrological model allows one to investigate the relative speed at which different parts of the basin transmit water to the streams. This would not be possible if only Thiessen rainfall were being used.

Application of Thiessen rain rates to distributed hydrological models can lead to considerably different runoff by a distributed hydrological model. The Thiessen rainfall can cause a distributed hydrological model to generate spurious runoff at locations away from the dominant rain gauge under convective conditions.

If one is using a distributed model, even one in which the only distributed feature of the basin is topography, then the use of distributed rainfall data represents a distinct advantage over using Thiessen polygon-derived rain rates.

The radar distributed rainfall data provide a better understanding of the observed response of a basin to rainfall inputs than does the Thiessen approach. As such, these data can be a valuable tool for calibrating a distributed hydrological model.

Therefore, on space scales of $40x40km^2$, and times scales on the order of one month, the use of MPE data improves understanding and modeling capabilities, identification of the local non-point source pollutants to surface waters, captures the scale of spatial variation in intense convective rain rates, even during the winter when the spatial variation is lower. This occurs because the spatial scale of most relatively intense rain cores is smaller than the Black Creek Basin. This renders the use of Thiessen polygons suspect over monthly time scales and space scales on the order of $40x40\ km^2$. There is considerable spatial variability in rainfall even during the winter months. If the time for inserted pollutants to reach surface water bodies in a basin is less than one month, then the application of MPE rainfall inputs to models is preferable to the Thiessen approach, even over small basins like Black Creek with modest topography.

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