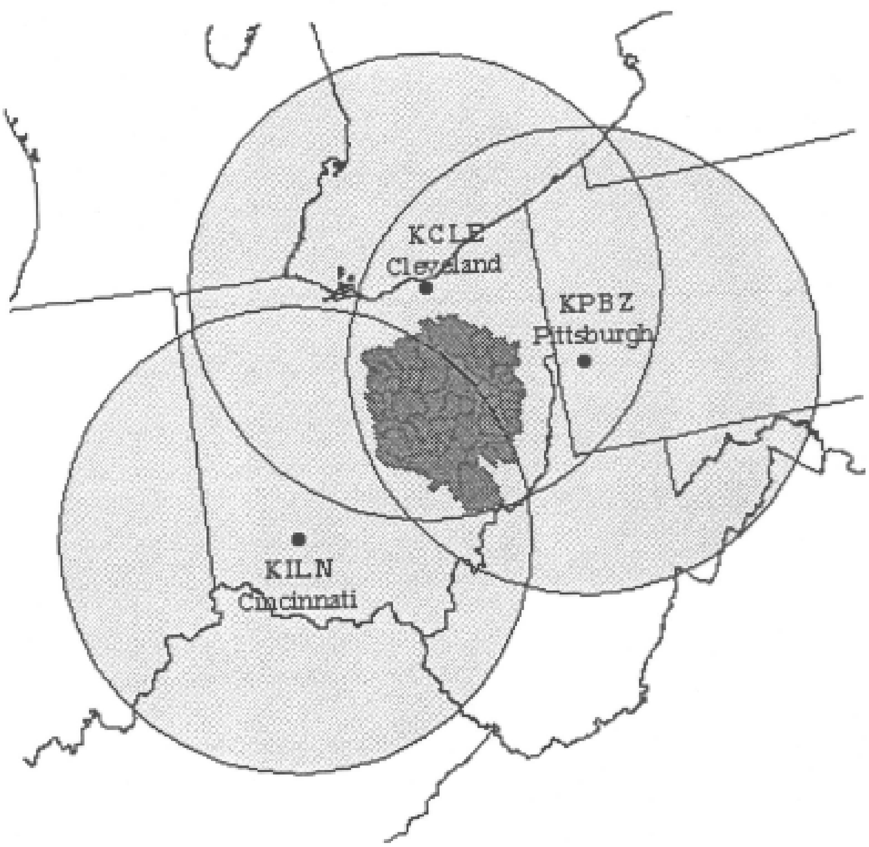
US Army Corps
of Engineers
Hydrologic Engineering Center

ModClark Model Development for the Muskingum River Basin, OH



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14. ABSTRACT
The purpose of this report was to evaluate water quality impacts associated with supplying whitewater releases on the Russell Fork of the Big Sandy River and a qualitative assessment of the water quality impact on the Ohio River at the confluence with the Big Sandy River. The tool used for this study was the Hydrologic Engineering Center's HEC-%Q computer model.

15. SUBJECT TERMS
modClark, Muskingum River Basin, model, parameters, basin characteristics file, grid-cell, verification, adjustment, management, simulation, outlet travel distance, HEC-HMS

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Chapter 1

Introduction

1.1 Summary

The ModClark computer program is a new tool that incorporates NEXRAD precipitation data into rainfall-runoff modeling (USACE 1995c). As it was intended that ModClark be relatively easy to implement, most of the tasks required for the model development are similar in scope to those associated with HEC-1 (USACE 1990). ModClark model development does require some effort above that which is required for HEC-1. In particular, processing of a digital elevation model (DEM) is required using a geographic information system (GIS). In hilly terrain, this task is readily performed through a series of user-friendly Arc/Info macros developed at HEC (USACE 1995a). For flat regions, as are considered in this study, some additional GIS manipulation may be necessary. The final product is a series of input files that are used by ModClark to transform radar-measured precipitation into subbasin outflow. The comprehensive spatial coverage provided by NEXRAD weather-radar is an improvement over the fields of point values associated with rain-gage networks. This enhanced representation of natural rain patterns yields an improvement to rainfall-runoff modeling.

The Huntington District of USACE contracted with HEC to develop a ModClark model for the Muskingum River Basin. The model will eventually be used for real-time flood forecasting, which is a general objective in HEC's development of the ModClark method. The Muskingum River drains an area of 20818 km^2 (8038 mi^2), covering a large part of eastern Ohio. Figure 1 shows the location of the basin. The outlet of the basin is at Marietta, OH, where the Muskingum River flows into the Ohio River.

Appendix A contains a list of references, and Appendix B describes the development of the input files for use with the Hydrologic Modeling System (HEC-HMS). Appendix C lists the files produced during the study; these will be provided to the District.

1.2 Model Development Approach

The methodology by which real-time forecasting models are developed follows four steps: calibration of parameters from historical events, adoption of parameters, verification of adopted parameters, and parameter adjustment in operational forecast mode. The HEC-1F flood forecasting model of the Muskingum River Basin is well established and its parameters have been verified in an operational mode (USACE 1986; 1989). Theoretically, the distributed nature of ModClark may demand some adjustment for parameters developed from a spatially lumped model. Previous studies, however, have shown this not to be the case. Two assumptions were therefore made for the unit hydrograph parameters in the original HEC-1F model: they are appropriate for the Muskingum subbasins and are adequate for the ModClark modeling effort.

Figure 1
Muskingum River Basin Location

At this time, only Stage 1 NEXRAD radar data is available for the Muskingum River Basin. This is raw data that has not been ground-truthed to rain gages within the radar sweep. Although the radar is able to pick up the timing and location of rain cells, it can be off by a factor of two or more in absolute magnitude. This, in addition to the experience gained from a previous study (USACE 1996a), resulted in a decision not to try to adjust and calibrate unit hydrograph parameters based on Stage 1 radar-measured precipitation. This task is left to the District once Stage 3 NEXRAD or an equivalent product becomes available.

1.3 Acknowledgments

This study was performed by Daniel Kull. Troy Nicolini provided study guidance and management. John Peters, David Goldman, and Arlen Feldman provided additional study guidance and management. Thomas Evans performed most of the Arc/Info GIS related tasks, while providing guidance for those performed by others. Carl Franke retrieved and managed all NEXRAD radar data. Jerry Webb and James Schray of the Huntington District provided valuable assistance in supplying information and assembling data.

Chapter 2

Development of the ModClark Model

2.1 Estimation of Clark Parameters

Figure 2 shows the Muskingum Basin with its subbasins and subbasin outlet locations. The HEC-1F model provided by the District contained the Snyder unit hydrograph parameters for 40 of the 41 subbasins. HEC-1 was used to transform the Snyder parameters to Clark parameters. When the Snyder method is used in HEC-1, the Clark method is used for internal computations. This feature was used to determine Clark parameters that are equivalent to the input Snyder parameters. Table 1 shows the subbasin areas and Clark parameters of time of concentration (T_C) and the storage attenuation coefficient (R) for the subbasins.

No Snyder's parameters were available for the contributing area local to the outlet of the Muskingum River into the Ohio River at Marietta (LMTOH6). For this subbasin, equations developed as part of a separate regional regression analysis were used. These equations are:

$$T_C = 5.22\ DA^{0.246}\ S^{-0.258} \qquad (2.1)$$

$$T_C + R = 62.58\ DA^{0.081}\ S^{-0.539} \qquad (2.2)$$

where: DA = drainage area in square miles
S = slope in feet per mile

Table 1 shows the results from the application of these equations to the LMTOH6 subbasin using DA = 616 mi^2 (1595 km^2) and S =2 ft/mi (0.38 m/km). The slope was measured between the upstream watershed boundary and outlet gage location.

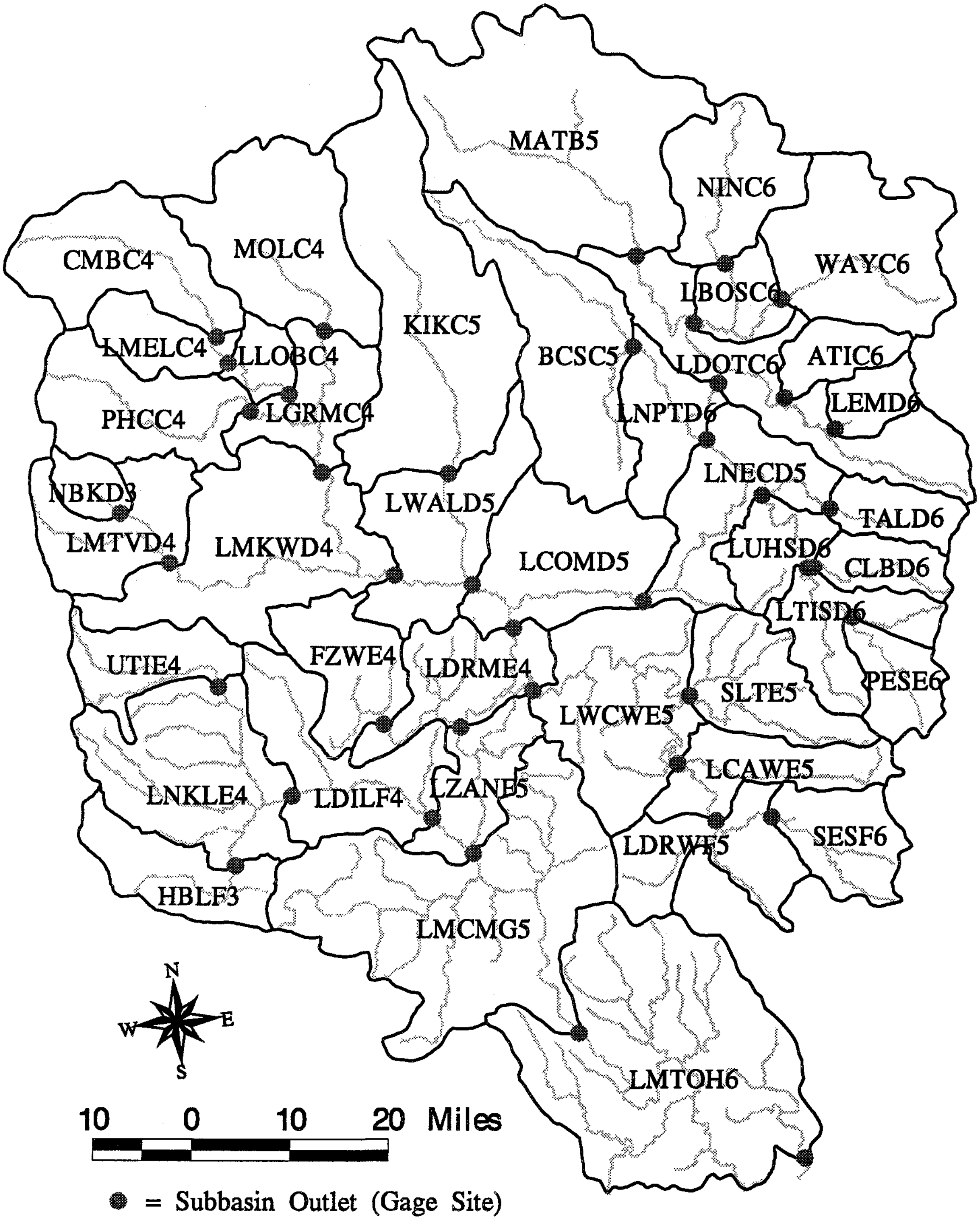

Figure 2
Muskingum River Subbasins and Outlet Locations

Table 1
Subbasin Area and Clark Unit Hydrograph Parameters

Subbasin ID	Name	Area km^2 (mi^2)	T_C (hr)	R (hr)
ATIC6	Atwood Reservoir	181 (70)	5.0	20.6
BCSC5	Beach City Reservoir	777 (300)	12.8	22.6
LBOSC6	Bolivar Reservoir	192 (74)	6.0	16.3
LCAWE5	Cambridge	339 (131)	39.8	42.8
CLBD6	Clendening Reservoir	179 (69)	8.6	16.9
CMBC4	Charles Mill Reservoir	562 (217)	21.6	47.4
LCOMD5	Coshocton	603 (233)	11.5	25.7
LDILF4	Dillon Reservoir	531 (205)	7.5	11.8
LDOTC6	Dover Reservoir	692 (267)	7.1	12.5
LDRME4	Dresden	394 (152)	15.7	15.7
LDRWF5	Derwent	407 (157)	13.3	38.0
FZWE4	Frazeysburg	363 (140)	14.5	21.1
LGRMC4	Greer	355 (137)	9.6	16.1
HBLF3	Hebron	344 (133)	6.1	13.7
KIKC5	Killbuck	124 (48)	29.9	59.7
LEMD6	Leesville Reservoir	1202 (464)	7.0	7.2
LLOBC4	Loudenville	104 (40)	5.1	5.3
MATB5	Massilon	1342 (518)	16.7	83.1
LMCMG5	McConnelsville	1497 (578)	14.4	17.8
LMELC4	Melco	220 (85)	12.8	26.7
LMKWD4	Mohawk Reservoir	919 (355)	29.9	59.7
MOLC4	Mohicanville Reservoir	702 (271)	9.5	14.6
LMTOH6	Marietta	1595 (616)	21.2	51.3

Table 1 (Continued)

Subbasin ID	Name	Area km^2 (mi^2)	T_C (hr)	R (hr)
LMTVD4	Mt. Vernon	409 (158)	15.1	15.2
NBKD3	North Branch Kokosing Reservoir	117 (45)	7.2	9.6
LNECD5	Newcomerstown	502 (194)	19.4	25.3
NINC6	North Industry	453 (175)	9.4	12.5
LNKLE4	Newark	746 (288)	14.8	26.4
LNPTD6	New Philadelphia	275 (106)	8.7	18.4
PESE6	Piedmont Reservoir	223 (86)	8.6	19.2
PHCC4	Pleasant Hill Reservoir	513 (198)	5.1	16.4
SESF6	Senecaville Reservoir	306 (118)	4.1	15.1
SLTE5	Salt Fork Reservoir	412 (159)	13.2	18.1
TALD6	Tappen Reservoir	184 (71)	14.3	16.4
LTISD6	Tippecanoe	329 (127)	37.3	58.0
LUHSD6	Uhrichsville	220 (85)	27.2	74.9
UTIE4	Utica	300 (116)	6.9	13.4
LWALD5	Walhonding R.P.	554 (214)	12.7	21.1
WAYC6	Waynesburg	655 (253)	17.3	46.0
LWCWE5	Wills Creek Reservoir	717 (277)	9.3	14.2
LZANF5	Zanesville	282 (109)	8.7	9.0

2.2 Basin Characteristics File

The basin characteristics file is of the same format as the standard HEC-1 input file. It contains for each subbasin: total subbasin area, Clark's unit hydrograph parameters, loss rate parameters, and base flow parameters. Parameters were kept the same as those used in the original HEC-1F model (with the Snyder's changed to Clark's). The basin characteristics file also specifies the pathnames for storage of generated flow hydrographs. For all ModClark output, the A, B, C, D, and E pathnames used in HEC-DSS (USACE 1994) are the same as those generated by HEC-1. The F part is set to "MODCLARK".

2.3 Development of the Grid-Cell Characteristics File

To develop the grid-cell characteristics file, the GridParm-DEM2HRAP (USACE 1995a) procedure was performed using the Arc/Info GIS. Seven USGS Digital Elevation Model (DEM) quadrangles covered the Muskingum Basin: Canton-east, Canton-west, Clarksburg-west, Cleveland-west, Columbus-east, Marion-east, and Toledo-east. These were downloaded from the USGS EROS Data Center through a file transfer protocol (ftp). Figure 3 shows the Muskingum River Basin DEM and RF1 streams. Figure 4 shows a perspective view of the same, with a 2 km spatial resolution. RF1 is the USGS's 1:500,000 scale digital line graph (DLG) representation of streams in the United States. When the subbasin and stream delineations generated from the DEM with the GridParm-DEM2HRAP procedure were compared to those supplied by the District, some major discrepancies were found. Most of the differences were in the north-west corner of the basin. Regions were modeled as draining into the wrong subbasins, and in some cases known Muskingum contributing areas flowed north into the Vermillion and Sandusky Rivers. Additionally, many of the delineated streams were not aligned with those in the RF1 files. The most noticeable error was comprised of the Lake, Black, and Clear Forks of the Mohican River flowing into Killbuck Creek instead of into the Mohawk Reservoir. These large delineation errors were due to the DEM representation of the extremely flat topography of north-central Ohio. In such flat terrain, even the slightest elevation error can change flow directions considerably.

One way that this delineation problem could have been overcome was through the use of a more detailed DEM. The DEM that was used was part of the 1:250,000 scale, 1° x 2° USGS series. These have a mean cell resolution of 90 m (295 ft). The 1:24,000 scale, 7.5' USGS series has a 30 m (98 ft) cell resolution. Unfortunately, these DEM's are still under development and only about 1/3 of Ohio was available at the time of this study. None of the available 30 m DEMs covered the north-west corner of the Muskingum Basin.

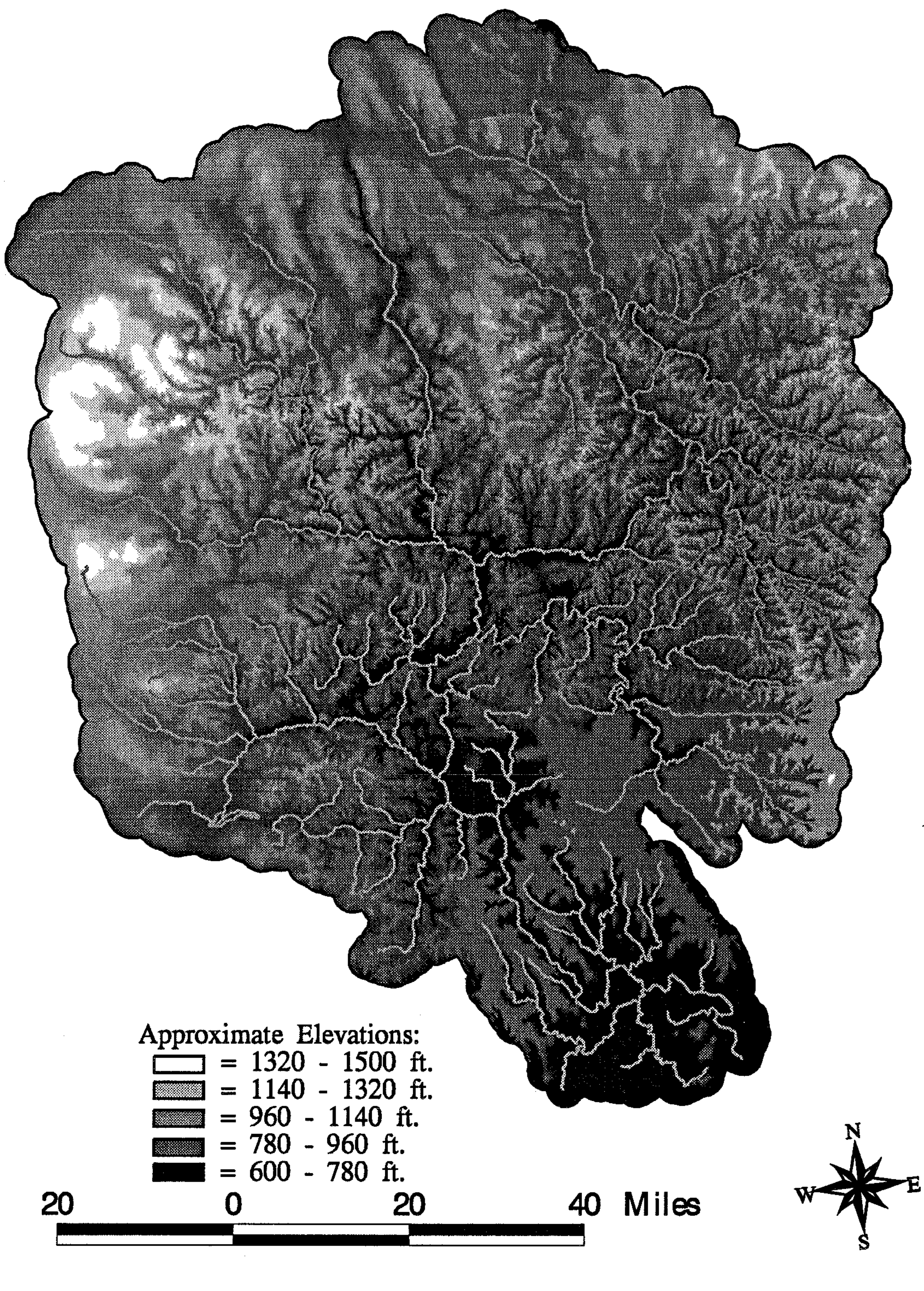

Figure 3
Muskingum River Basin DEM with RF1 Streams

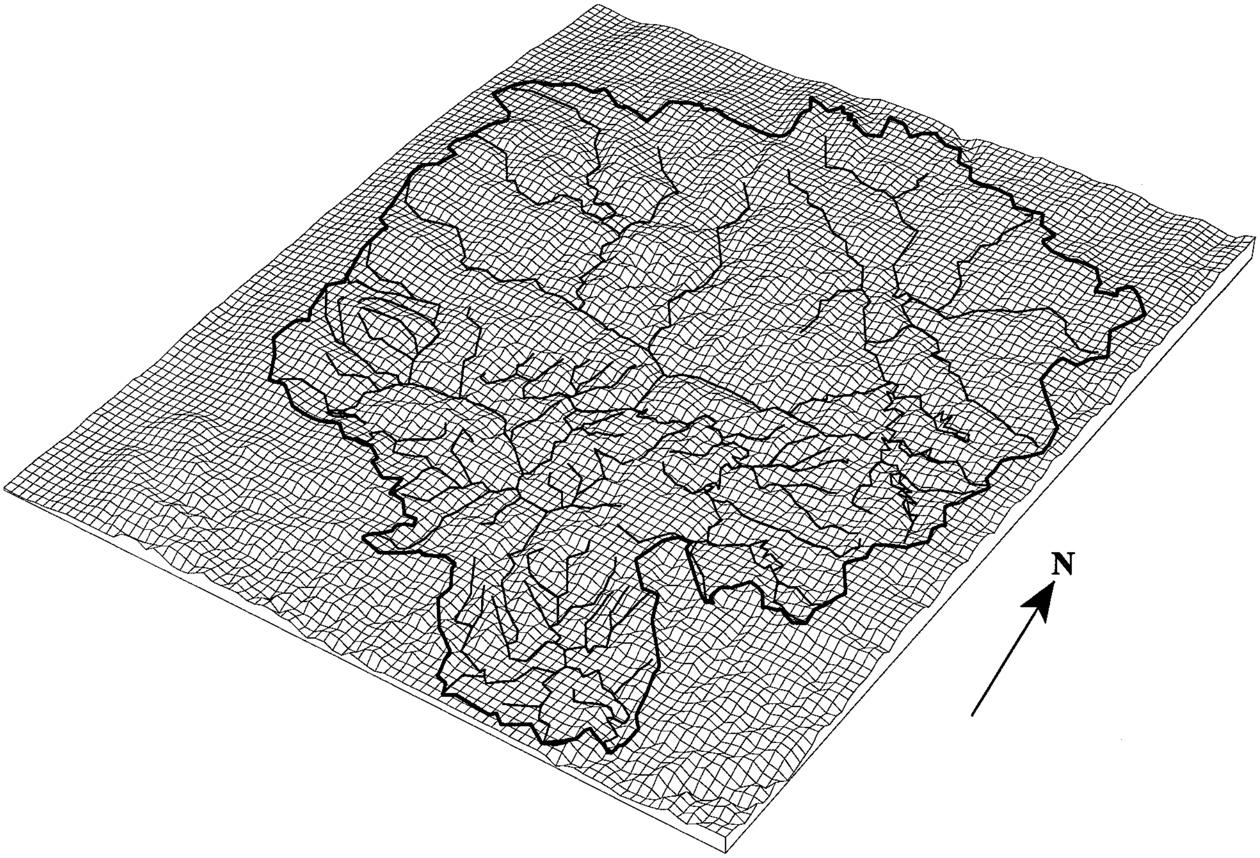

Figure 4
Perspective View of the Muskingum River Basin DEM with RF1 Streams
(2 km grid resolution)

A manual manipulation of the DEMs was tried in an effort to overcome the stream and watershed delineation problems. To ensure proper stream locations, the RF1 streams were "burned" into the DEM through Arc/Info. This involved overlaying the RF1 stream arcs on the DEM. Any DEM cell which had a stream arc passing though it was then lowered by a certain elevation. In the case of the Muskingum River Basin, the burn-in was attempted at different increments between 5 and 100 meters (16 to 328 ft). It was concluded that during such a procedure, conservative burn-in depths are not useful. The DEM is already being significantly altered, so a deep burn-in better ensures proper stream locations without increasing the damage to the DEM caused by a shallow burn-in. This was done both before and after a fill operation. Filling ensures that there are no sinks within the basin; all cell outflows will eventually reach the basin outlet. The burn-in was performed before the filling so that all stream locations were lower than the surrounding areas. After the fill, however, some of the streams may have been filled to the point of incorrect flow direction. It was thus necessary to perform the burn-in again so that the flow directions matched the known patterns. This procedure worked well and the resultant stream delineations were satisfactory.

To correct the watershed delineations, a procedure opposite to the stream burn-in was used. Subbasin boundaries, obtained from maps generated during the development of the original HEC-1F model, were digitized into an Arc/Info polygon coverage. These boundaries were overlaid on the DEM. This time, any grid-cells having a watershed boundary pass through them were raised a given amount, thus creating a "wall" around the watershed. When the fill operation was performed, the land surface leading to the "wall" was raised to the point that water would flow away from the boundary and into the proper watershed. This procedure did not yield satisfactory results. If the "wall" were raised enough to become the highest point in the basin, the procedure is expected to work. It was judged, however, that such a drastic alteration of the DEM and thus abstraction of the natural land forms was not a wise course of action. Additionally, there is a very good chance that in many places the accepted watershed boundary would not align with the ridges represented by the DEM. In this case, a pool would be formed. This sink would then be filled during further GIS processing, yielding a large corruption of the natural flow patterns.

Based on a suggestion by Dr. David Maidment of the University of Texas at Austin, a stream burn-in was performed with the 1:100,000 digital line graph (DLG) stream network on a single subbasin. This series of stream arcs is much denser and more comprehensive than the RF1 series. The Killbuck subbasin (KIKC5) was one of the worst delineated by the previous mentioned DEM analyses. This burn-in was performed on only the KIKC5 subbasin because full Muskingum Basin coverage by the 1:100,000 DLGs would be inefficient and require an enormous amount of computer memory. After the burn-in, the GridParm-DEM2HRAP procedure was performed. This resulted in a satisfactory watershed delineation. The dense network represented by the DLGs was able to "force" the previously errant contributing areas to flow in the proper direction.

It was concluded that efficient manipulation of DEMs could not yield satisfactory delineations for the very flat areas of the entire Muskingum River Basin. These delineations would affect some of the cell-to-outlet travel distances generated by the GridParm-DEM2HRAP procedure. The DEMs were abandoned and a simpler approach to find the travel distances was used. This involved, through Arc/Info, the direct calculation of the distance from the grid-cells to their associated subbasin outlets. Two different methods were evaluated. The first was a simple straight line procedure, measuring from the grid-cell centroid directly to the basin outlet. The second involved measuring from the centroid of the grid-cells to the nearest point on a RF1 stream arc. The downstream distance from this point to the subbasin outlet along the RF1 streams was then added to the "overland" portion. Although these two methods fail to take into account the full surface topography, they do provide a means of conveying radar-measured rainfall to the subbasin outlets. Results from both of these methods are presented later in this report.

Within the ModClark procedure, these cell-to-outlet distances are used to prorate the subbasin time of concentration, yielding a travel time for each grid-cell. Individual cell-to-outlet distances are more important in their relativity to other cells' distance values than in absolute magnitude. Additionally, the main objective of ModClark is to incorporate NEXRAD rainfall into rainfall-runoff modeling. Although it is considered more physically accurate to incorporate

DEMs into the model development, it is not necessary for an acceptable working model. Section 3.4 presents a comparison of rainfall-runoff modeling results from the three different methods used to develop the grid-cell to outlet travel distance on the Killbuck subbasin (KIKC5): the 1:100,000 DLG stream burn-in followed by GridParm-DEM2HRAP; the straight line grid-cell to outlet; and the grid-cell to the nearest RF1 arc to the outlet following RF1 arcs.

Near the end of this study, it became apparent that there would be sufficient time and resources to perform a full burn-in of the 1:100,00 scale stream DLGs. This, followed by the GridParm-DEM2HRAP procedure, was performed on the entire Muskingum Basin. A faster method for downloading the DLGs was discovered. Additionally, the algorithms used during the retrieval and burn-in of the DLGs were refined, resulting in greater efficiency. During the testing and verification runs presented in Section 3.3, ModClark was used with the grid-cell characteristics file developed from the grid-cell to RF1 to outlet method. The grid-cell characteristic file based on the aforementioned 1:100,000 scale stream burn-in and GridParm-DEM2HRAP procedure was developed after the modeling runs had been completed.

The grid-cell characteristics file contains for each subbasin a list of the grid-cells with their x and y coordinates, area, and average travel length to the subbasin outlet. Files were produced in both the SHG and HRAP formats. SHG is the Standard Hydrologic Grid proposed by HEC as a standard for spatial representation and analysis of hydrology (USACE 1996b). HRAP is the Hydrologic Rainfall Analysis Project grid and is the format in which NEXRAD data is delivered. Figures 5 and 6 show the HRAP and SHG grid-cells comprising the Muskingum River Basin, respectively. HEC encourages the use of the SHG format. The HRAP grid-cell characteristics file was produced for the purpose of comparison with SHG and as a back-up if any trouble is encountered in converting radar data from HRAP to SHG format.

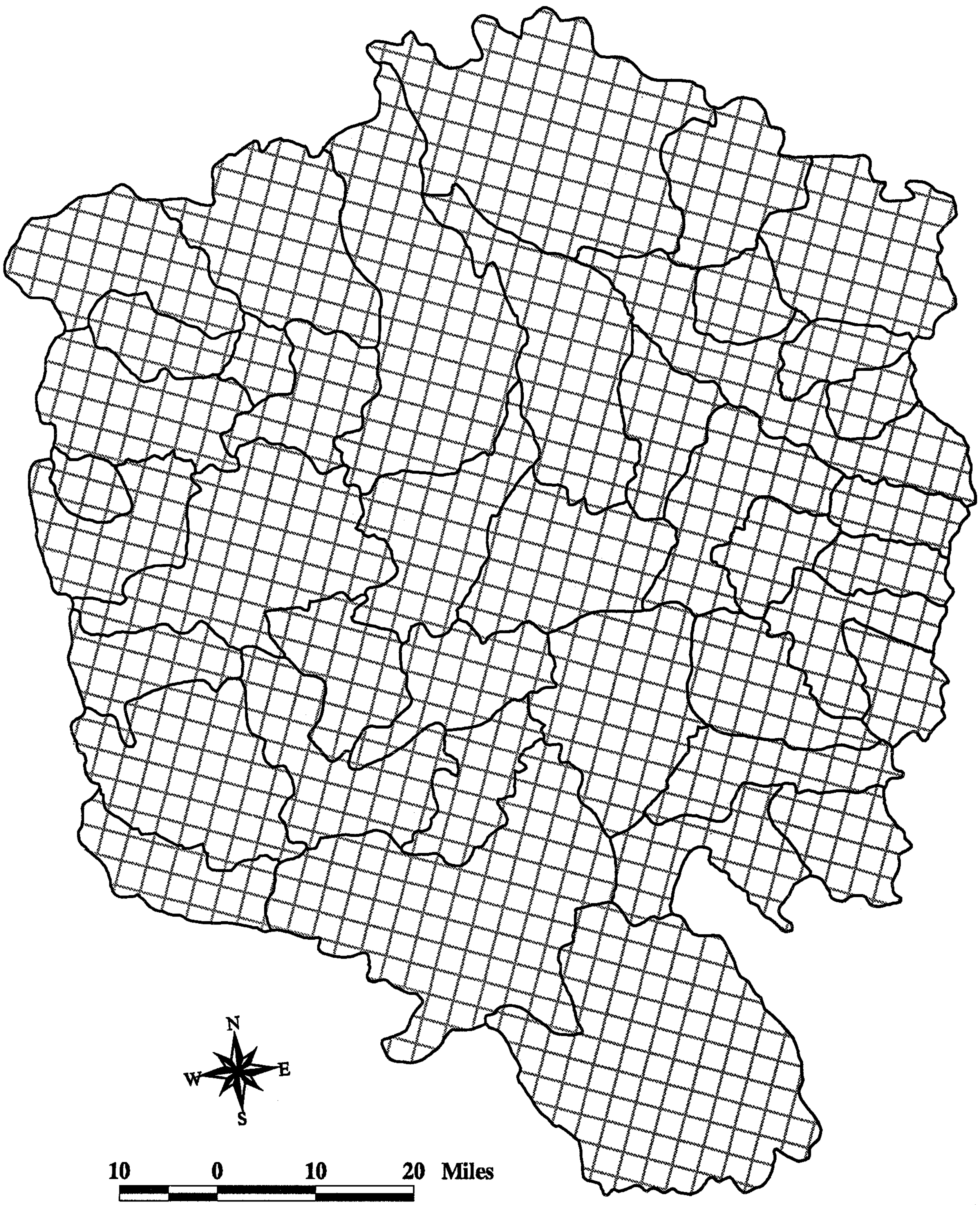

Figure 5
HRAP Cells Comprising the Muskingum River Basin

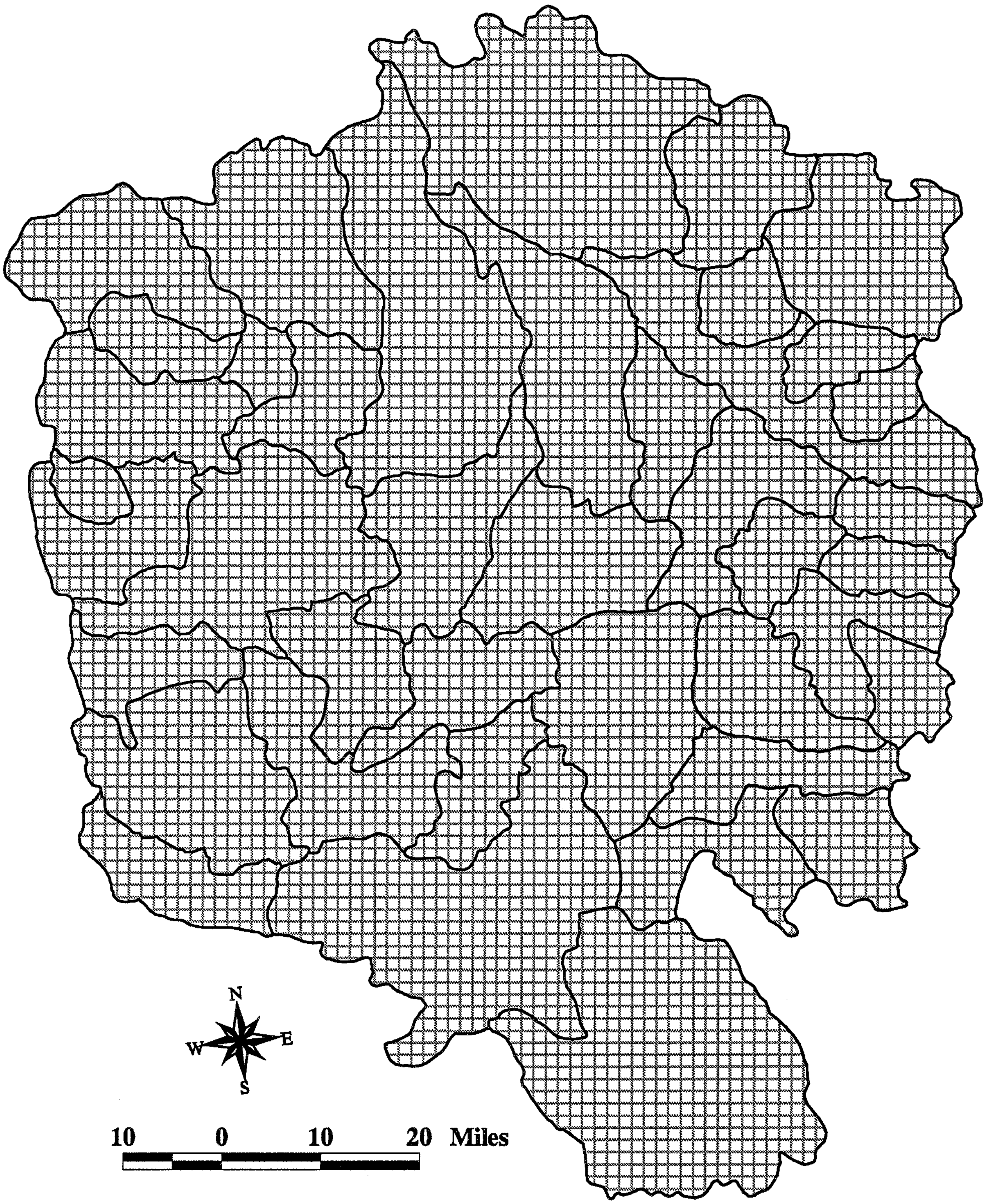

Figure 6
SHG Cells Comprising the Muskingum River Basin (2 km resolution)

Chapter 3

Verification and Testing of the Model

3.1 Approach

An HEC-1 model was developed for comparison with the ModClark model. The input file for HEC-1 was a replica of the ModClark basin characteristics file, with a few minor changes to specify the use of the traditional Clark's unit hydrograph method instead of the ModClark method. Also, the input file was modified so that results would be stored in an HEC-DSS file with a pathname which is unique from those computed using the ModClark method. As with the ModClark model, only subbasin outflows were computed; there was no routing and combining of downstream flows. Comparisons between ModClark, HEC-1, and observed flows were performed only on headwater subbasins. This approach was required by the high level of flow regulation in the Muskingum River Basin. Considering the goal of comparing different rainfall-runoff transformations with observed flows, simple subbasin runoff situations were needed. For non-headwater subbasins, modeled flows would need to include upstream regulated flows.

3.2 Data Acquisition and Management

Precipitation and flow data for 1995 and 1996 were obtained from the Huntington District through ftp (file transfer protocol). Figure 7 shows a map of the rain gage locations. To estimate basin-averaged precipitation data for input to the HEC-1 model, the PRECIP program was used (USACE 1989). The PRECIP input file was supplied by the District. All subbasins except for the contributing area local to the outlet of the Muskingum River at Marietta (LMTOH6) were in this original PRECIP input file. The centroid of the LMTOH6 subbasin was estimated and incorporated into the file. The PRECIP program was run for the modeled events and stored with an HEC-DSS F-path of AVE.

NEXRAD Radar data comes in UTC - Coordinated Universal Time. Existing software could not conveniently change the radar data from UTC to local time. The gaged data from the District is in Eastern Time. Using DSSMATH (USACE 1994), the gaged precipitation and streamflow data were shifted 5 hours forward in time to account for the difference and make data and model comparisons easier. This shifted data includes the term "UTC" in its HEC-DSS record F part (i.e. F=UTC-OBS, F=UTC-COMP, F=UTC-AVE, etc.)

To fully cover the Muskingum basin, NEXRAD data was needed from three sites: Pittsburgh (KPBZ), Cincinnati (KILN), and Cleveland (KCLE). Figure 8 shows the coverage of the radars. Each site has a sweep radius of approximately 230 km (143 mi). Archived data for

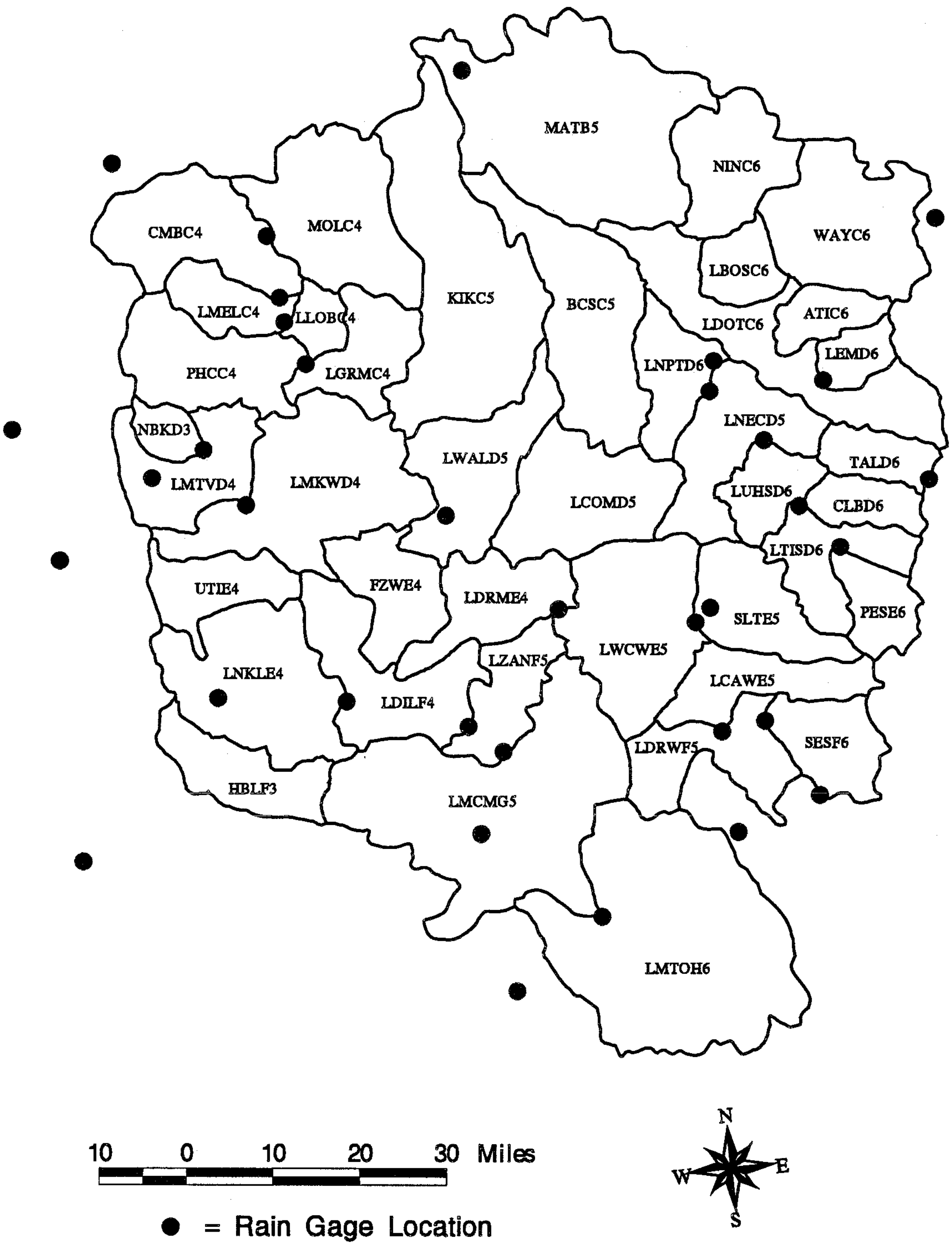

Figure 7
Muskingum River Basin Rain Gage Locations

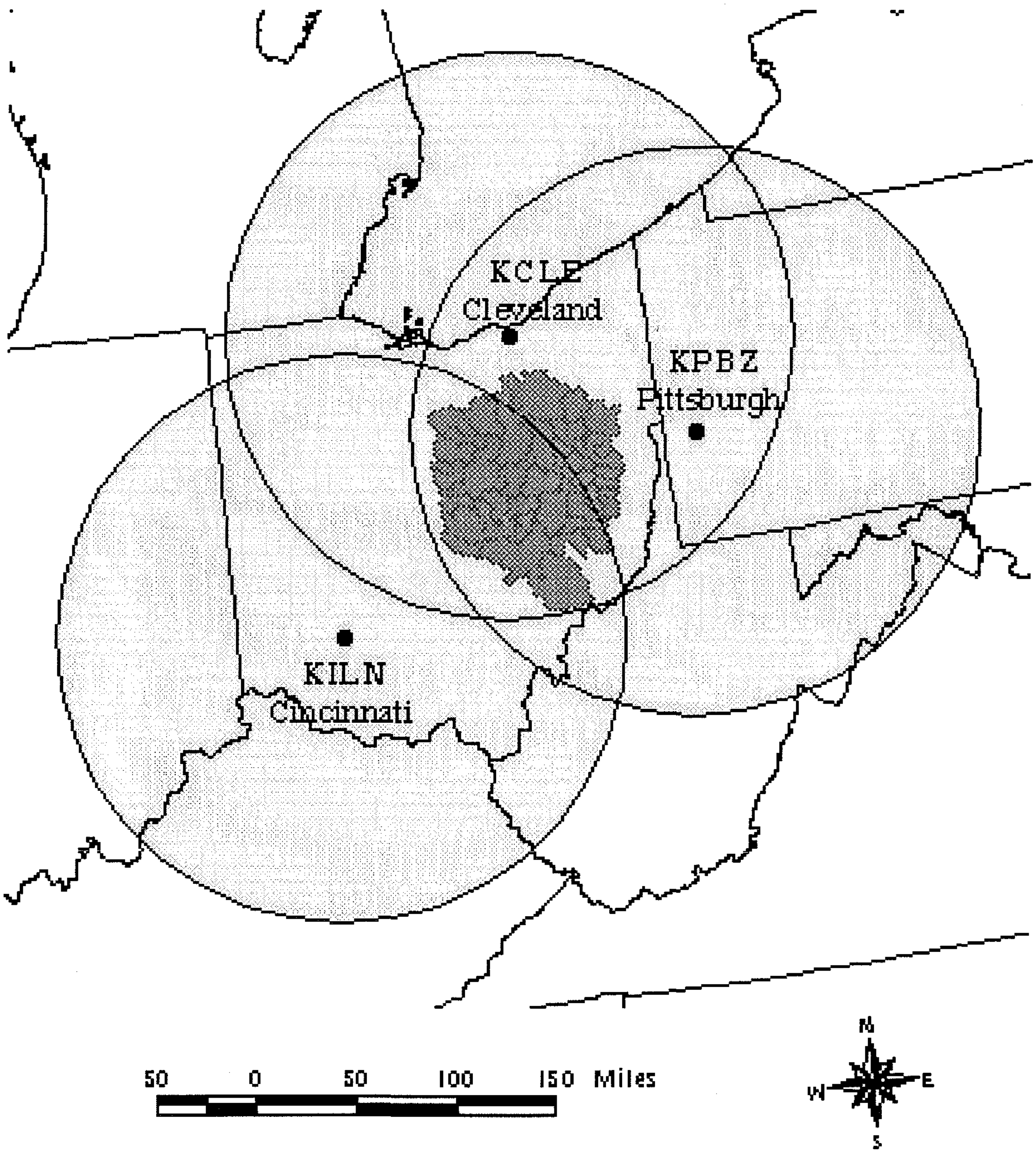

Figure 8
NEXRAD Radar Sites and Coverages for the Muskingum River Basin

the Pittsburgh and Cincinnati sites were downloaded from the Ohio River Division using ftp. The Cleveland radar site is the responsibility of the Detroit District. Unfortunately, the PUPIE (Principle User Processing Interactive Emulator), which is the computer used to retrieve data from the radars, had not been operational. Data was thus not available for the Cleveland radar. In preparation for the implementation of the ModClark method on the Muskingum River Basin, arrangements were made for the reactivation of the Detroit District's PUPIE.

Radar precipitation data is delivered in the DPA (Digital Precipitation Array) product format. The gridLoadStage1 program was used to load the data into HEC-DSS format. gridLoadStage1 is part of the gridUtl (USACE 1995b) suite of software, which is a series of utility programs used for the loading and manipulation of NEXRAD data. The gridMosaic program, also part of the gridUtl group, was used to mosaic the data from the different radars for HRAP grid-cells common to both sites. There are three different values that can be used for this mosaicking: the maximum cell precipitation, the minimum, or an average of the different values. For the test simulations, the maximum value was used.

All ModClark simulations were performed in the HRAP format, although it is recommended that SHG be used whenever possible. HRAP was used because the 1:100,000 DLG burn-in followed by the GridParm-DEM2HRAP analysis of the Killbuck Creek subbasin (refer to sections 2.3 and 3.4) was performed only in this format. Had SHG-format simulations been performed, it would have been necessary to convert the NEXRAD data to SHG format. This would be done with the SHG option in the gridLoadStage1 program. Using a conversion table that is generated by HEC and stored in an HEC-DSS file, gridLoadStage1 can automatically convert between the two formats. Mosaicking would then again be performed by the gridMosaic program.

3.3 Event Simulation

NEXRAD data availability forced the simulation events to be constrained to the time period of October, 1995 to the present. Events were chosen based on their large magnitude, lack of snowmelt contribution, and relative isolation from other events. Three events were chosen: April 22-28, April 29-May 7, and May 8-25, 1996. Unfortunately, these events immediately follow each other, therefore not being as "isolated" as desired. The limited available time window required the selection of these particular events. January of 1996 experienced a high-magnitude and well-isolated event, which was unfortunately largely due to snowmelt.

During the ModClark and HEC-1 modeling runs, loss rate parameters were kept the same as those found in the HEC-1F model input files. 7.62 mm (0.3 in) of initial loss and 0.76 mm (0.03 in) of constant hourly loss were used for all subbasins. Using the same loss rates for all subbasins and modeling runs allowed for easier comparisons between the ModClark, HEC-1, and observed hydrographs. In many cases, loss rate adjustments could have yielded more accurate model results. It was decided, however, that for the purposes of this study and considering the available data, using unadjusted global loss rates was preferred.

Initial baseflow was adjusted globally for each event, with the same values being used in both the ModClark and HEC-1 models. These were: 0.009 cms/km^2 (0.8 cfs/mi^2) for the April 22-28 event, 0.016 cms/km^2 (1.5 cfs/mi$^{2)}$ for the April 28 - May 7 event, and 0.027 cms/km^2 (2.5 cfs/mi^2) for the May 8- 25 event.

Figures 9 and 10 show the gage and radar measured rainfall for 1100-1200 UTC, April 23 (all spatial rainfall plots presented in this section are in millimeters, whereas the rainfall shown and used with the associated simulation models is in inches). Spatial rainfield plots were developed with the WCDS-SVT (Water Control Data System - Spatial Visualization Tool) program, which is currently under development (USACE 1995d). For the gage-measured rainfall plots, the interpolation method used to develop isohyets needed to extrapolate data for the entire area within the plot boundaries. As a result, areas outside the vicinity of the gages often have irregularities in the plot. In the radar plots, the yellow area in the upper left corner represents the region not covered by the Pittsburgh and Cincinnati radars, as can be seen in Figure 10.

Figure 11 shows the simulations for the April 22-28 event for the North Branch Kokosing Reservoir Subbasin (NBKD3). It can be seen that for the NBKD3 simulations, there was not enough radar-measured rainfall to produce the runoff volume needed to model the observed flow. These results are representative of what occurred for many of the subbasins. Reducing the loss rates to zero would have improved the simulation results, but would also be unrealistic. These model shortcomings show some of the magnitude errors that Stage 1 NEXRAD data can contain. Figure 12 shows the simulations for the Frazeysburg Subbasin (FZWE4) for the same time period. For this subbasin, both ModClark and HEC-1 modeled flows were well below the observed data. A loss rate adjustment would also have improved the results of the simulation, perhaps even with realistic non-zero parameters.

It is of interest to view the different rain patterns shown at the top of Figure 12. What is labeled "Radar Rainfall" is an average of NEXRAD data for the subbasin. This is produced for comparative purposes; it is not used in the simulations. Although both rain measurements yielded similar total volumes (proven by the similar resultant flows), the patterns by which the rain was applied to the basin are very different. This is also seen in Figures 9 and 10. A major drive behind the implementation of ModClark is the improved representation of the spatial and temporal rainfall distributions by NEXRAD. Precipitation input from NEXRAD radar should be more closely aligned with reality than basin-averaged gaged data.

Figures 13 and 14 show the gage and radar measured rainfall for 0000-0100 UTC, April 30. Figure 15 shows the simulations for the Atwood Reservoir subbasin (ATIC6) for the associated April 28 to May 7 simulation window. It can be seen that the peak timing of the ModClark produced flow is in better alignment with the observed data than the HEC-1 produced flow. This is due to the spike of rainfall recorded by the radar during 0000-0100 (UTC), on April 30, as can be seen in Figure 14 and at the top of Figure 15. The gages did not record this rainfall activity (Figure 13), thus influencing the HEC-1 modeled flow. Figure 16 shows the simulations for the Piedmont Reservoir subbasin (PESE6). This plot again shows the absolute magnitude errors that can occur in Stage 1 data, this time demonstrating both over and under estimations. For the first flow peak, the NEXRAD data did not yield enough volume to model the observed flow. For the second peak, however, there was too much volume reported by the radar. Adjusting loss rates to improve the modeling of both peaks is impossible.

Figures 17 and 18 show the gage and radar measured rainfall for 0100-0200 UTC, May 9 while Figures 19 and 20 show the same for 2100-2200 UTC, May 16. Figure 21 shows the simulations for the Frazeysburg subbasin (FZWE4) for the May 8-25 simulation window. Here, again, the radar did not record enough rainfall volume for ModClark to adequately model the first two peaks. The third peak, occurring on May 17 and 18, is modeled well by ModClark. This event, however, is almost completely missed by the rain gages. The resultant HEC-1 calculated flow is far below the observed data. Locally intense rain cells, as are associated with convective storms, are often missed by a rain-gage network.

If the network is sparse, a storm cell can travel between the gages and never be recorded. Such an event occurred over the FZWE4 subbasin, as displayed in Figure 19. The radar, due to its comprehensive coverage, was able to record the localized rain cell (Figure 20). The simulations for the Leesville Reservoir subbasin (LEMD6), as shown in Figure 22, demonstrate a similar problem associated with basin-averaged gaged rainfall. HEC-1 produces a large flow peak during May 9-10, which is not in the observed data. The rainfall causing this can be seen at the top of Figure 22. This false spike was produced by the basin-averaging of the gaged data. During the event, the rain gages at Cadiz (CADD6) and Piedmont Reservoir (PESE6), both located to the southeast of the LEMD6 subbasin, reported intense rainfall activity during 0000 - 0300 (UTC) on May 9 (Figure 17 shows the middle hour of this period). The resultant basin-averaged rainfall for LEMD6 includes this spike. The raincell that produced the intense rainfall at the two rain gages (CADD6 and PESE6), however, did not extend to the LEMD6 subbasin. A false spike was thus incorporated into the HEC-1 model. The radar did not report this intense rainfall over the LEMD6 subbasin (Figure 18), so the resultant ModClark simulation did not have an erroneous flow peak. Again, the full spatial coverage provided by NEXRAD is the major impetus for the incorporation of radar data into rainfall/runoff modeling.

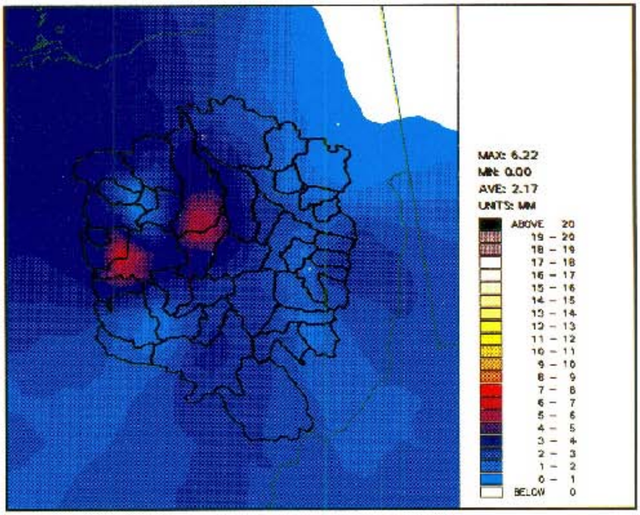

Figure 9
Gage Measured Rainfall for 1100-1200 UTC, April 23, 1996

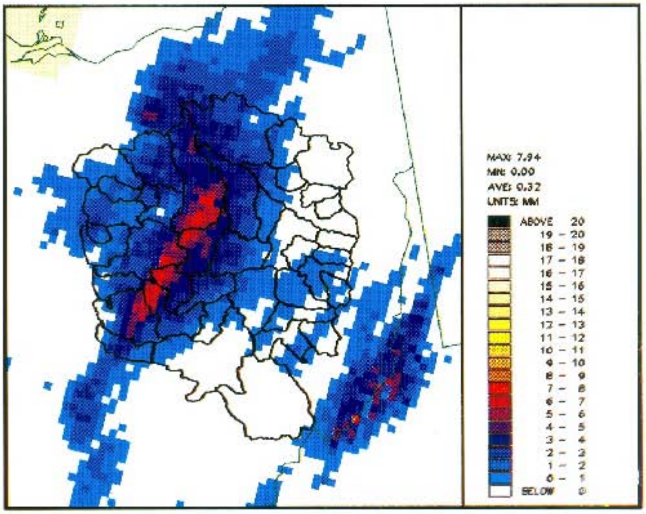

Figure 10
Radar Measured Rainfall for 1100-1200 UTC, April 23, 1996

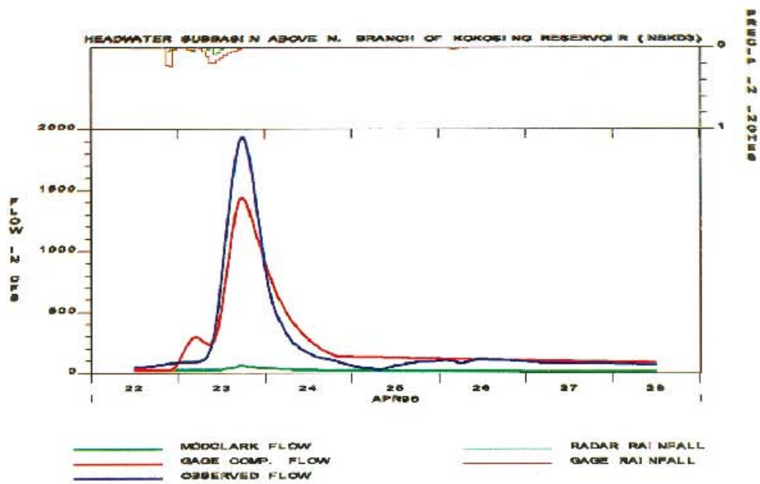

Figure 11
Simulations for North Branch Kokosing Reservoir subbasin for April 22-28, 1996

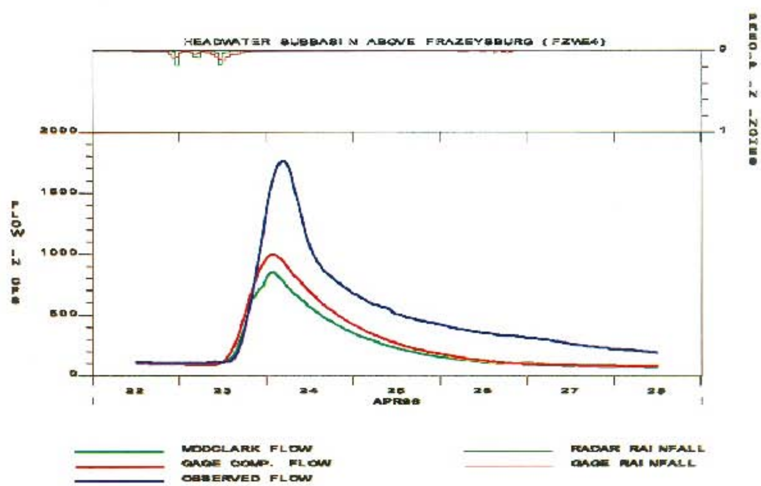

Figure 12
Simulations for Frazeysburg Subbasin for April 22-28, 1996

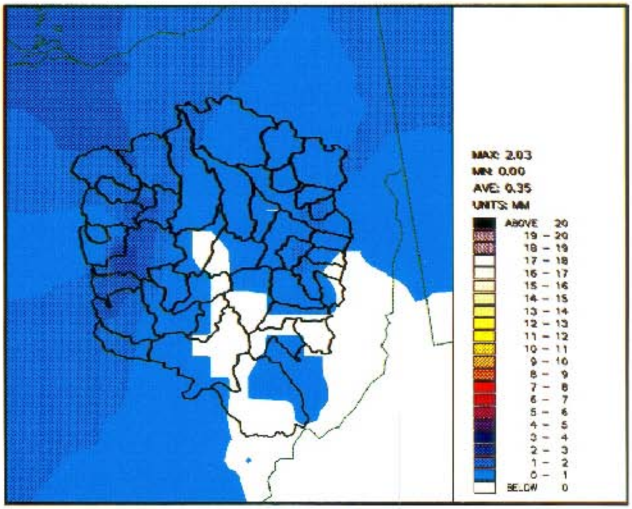

Figure 13
Gage Measured Rainfall for 0000-0100 UTC, April 30, 1996

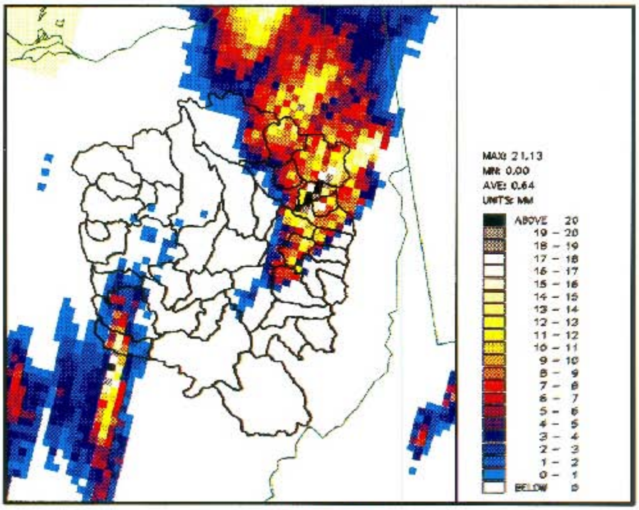

Figure 14
Radar Measured Rainfall for 0000-0100 UTC, April 30, 1996

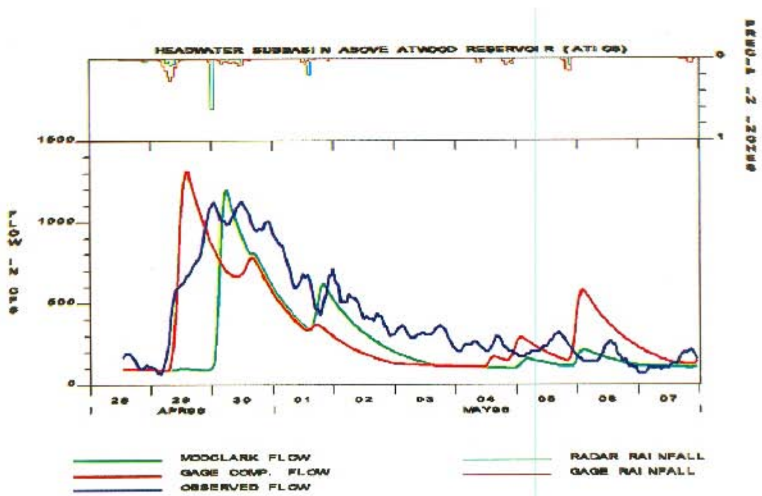

Figure 15
Simulations for Atwood Reservoir Subbasin for April 28 - May 7, 1996

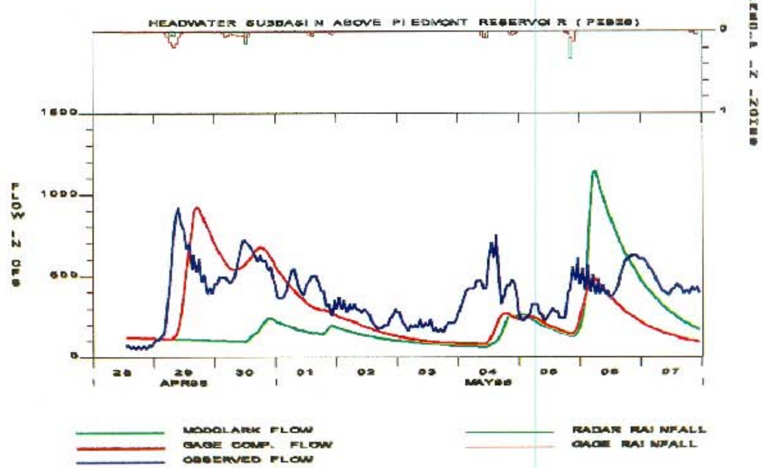

Figure 16
Simulations for Piedmont Reservoir Subbasin for April 28 - May 7, 1996

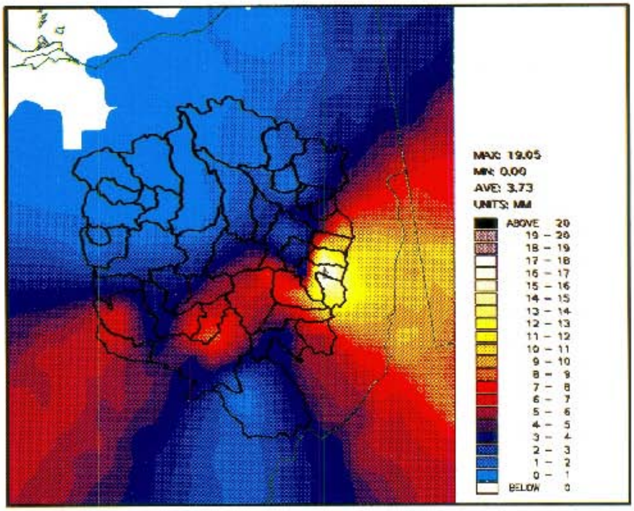

Figure 17
Gage Measured Rainfall for 0100-0200 UTC, May 9, 1996

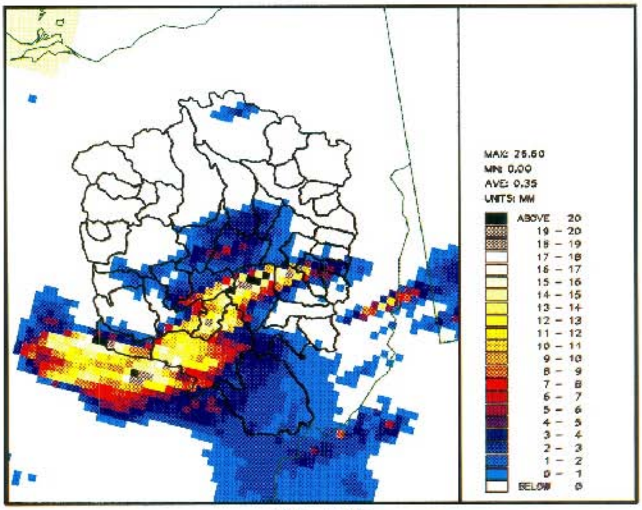

Figure 18
Radar Measured Rainfall for 0100-0200 UTC, May 9, 1996

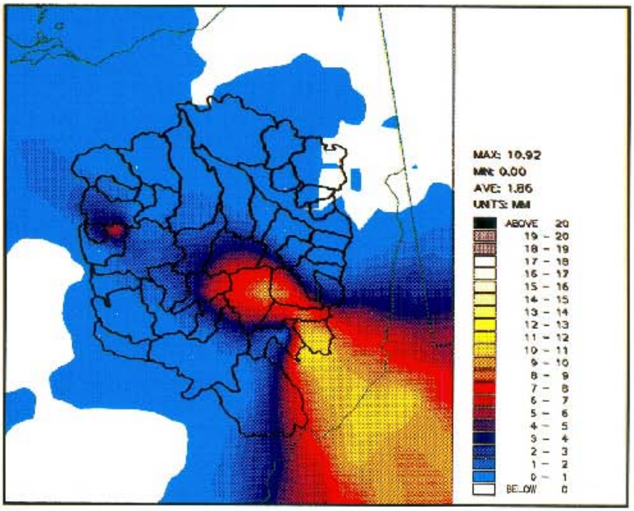

Figure 19
Gage Measured Rainfall for 2100-2200 UTC, May 16, 1996

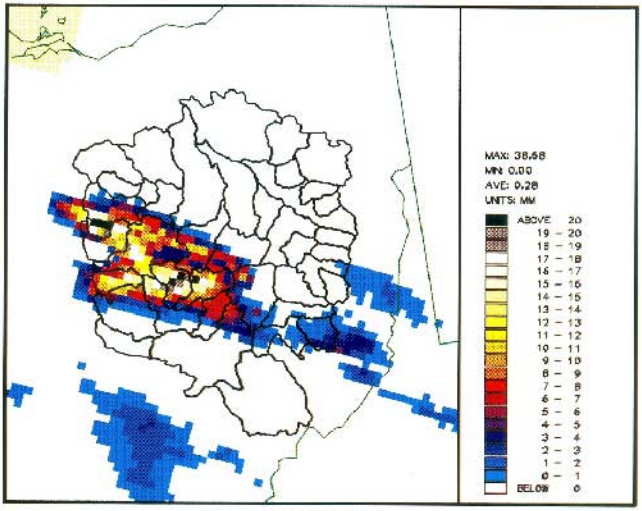

Figure 20
Radar Measured Rainfall for 2100-2200 UTC, May 16, 1996

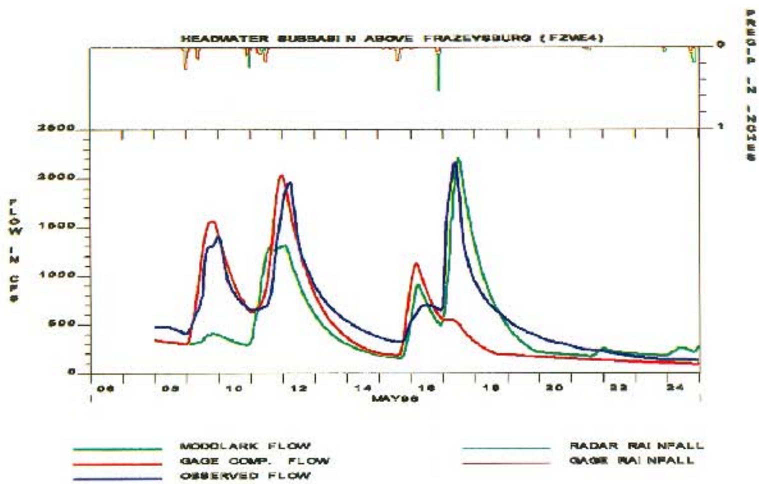

Figure 21
Simulations for Frazeysburg Subbasin for May 8-25, 1996

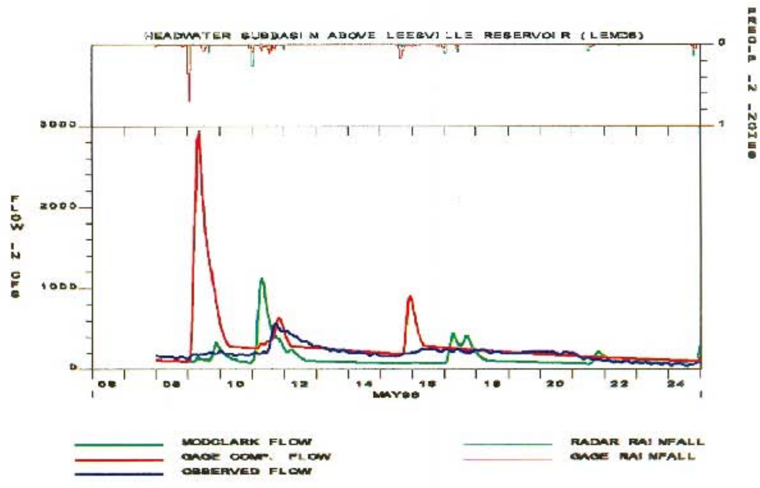

Figure 22
Simulations for Leesville Reservoir Subbasin for May 8-25, 1996

3.4 Analysis of Different Grid-Cell-to-Outlet Travel Distance Techniques

The three different methods used to develop the cell-to-outlet travel distances for the Killbuck subbasin (KIKC5), as reviewed in Section 2.3, were tested for their effects on modeled subbasin hydrographs. These methods were: the 1:100,000 DLG stream burn-in followed by GridParm-DEM2HRAP; the grid-cell to the nearest RF1 arc to the outlet following RF1 arcs; and the straight line grid-cell to outlet (these will be refered to as the GridParm, RF1, and straight line methods, respectively). This comparison was made to examine the sensitivity of the rainfall-runoff model to different levels of spatial accuracy. Figure 23 shows the HRAP cells composing the KIKC5 subbasin and the 1:100,000 stream DLGs within the subbasin.

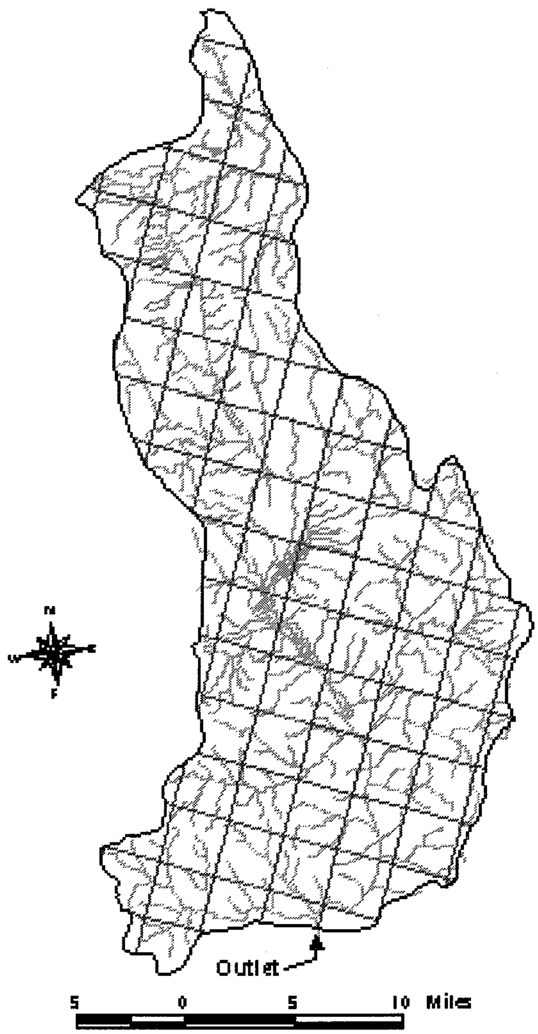

Figure 23
Killbuck Creek Subbasin (KIKC5) with HRAP Cells and 1:100,000 Scale Stream DLGs

Figure 24 shows an example of each of the three methods for the same grid-cell. The straight line method will always yield shorter distances than either of the other two methods. The RF1 method can yield distances both shorter and longer than the GridParm method. Most often, the former will occur.

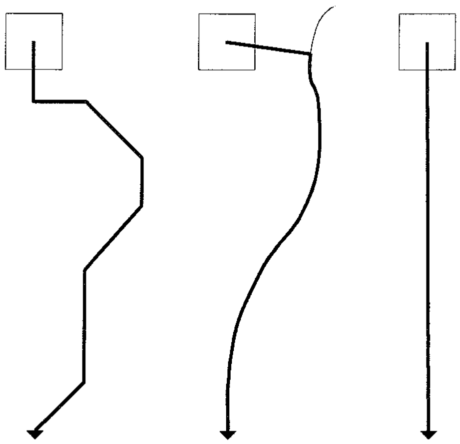

Figure 24
Example of the Three Cell-to-Outlet Distance Methods

Figure 25 shows the ModClark produced hydrographs using the three different grid-cell characteristics files for the three simulations events. For all events there is little difference between the results of the various simulation techniques. An analysis was made on the cell-to-outlet distances found by the three methods. Compared to the GridParm method, the RF1 method yielded an average of 12% less per cell travel distance, while the straight line method yielded an average of 33% less per cell travel distance.

It is important to note that this analysis of the different cell-to-outlet distance methods is only demonstrating the relative differences between the methods. Earlier in this report, comparisons are made between computed results using the RF1 method and observed hydrographs. Therefore, the conclusions drawn from the present analysis is that the other methods would have produced results, when compared to observed hydrographs, which would have been similar to those using the RF1 method. The ability of all three of these methods to perform reasonably well is due the fact that they all are based on proportions of an existing, verified TC value. Travel distance computation will eventually be performed directly using DEMs and GIS tools. As this technology evolves, the issue of selecting a criteria for computing a cell-to-outlet distance will need to be reexamined.

It may be that with certain shaped watersheds the different cell-to-outlet techniques will produce varied enough values such that consequential ModClark simulations will have noticeable differences. Complex drainage patterns that are not well represented by the RF1 coverages could cause appreciable variations between the GridParm and RF1 measurements. The subbasin analyzed in this study (KIKC5) was relatively straightforward in both its shape and drainage pattern. Another consideration is that an overland delay factor could be applied to the length between the grid-cell and the RF1 stream in the RF1 method. This factor could address the difference between the RF1 and GridParm methods, as well as enable a distinction between slower overland flow and faster channel flow. Further research is clearly needed before such factors could be proposed.

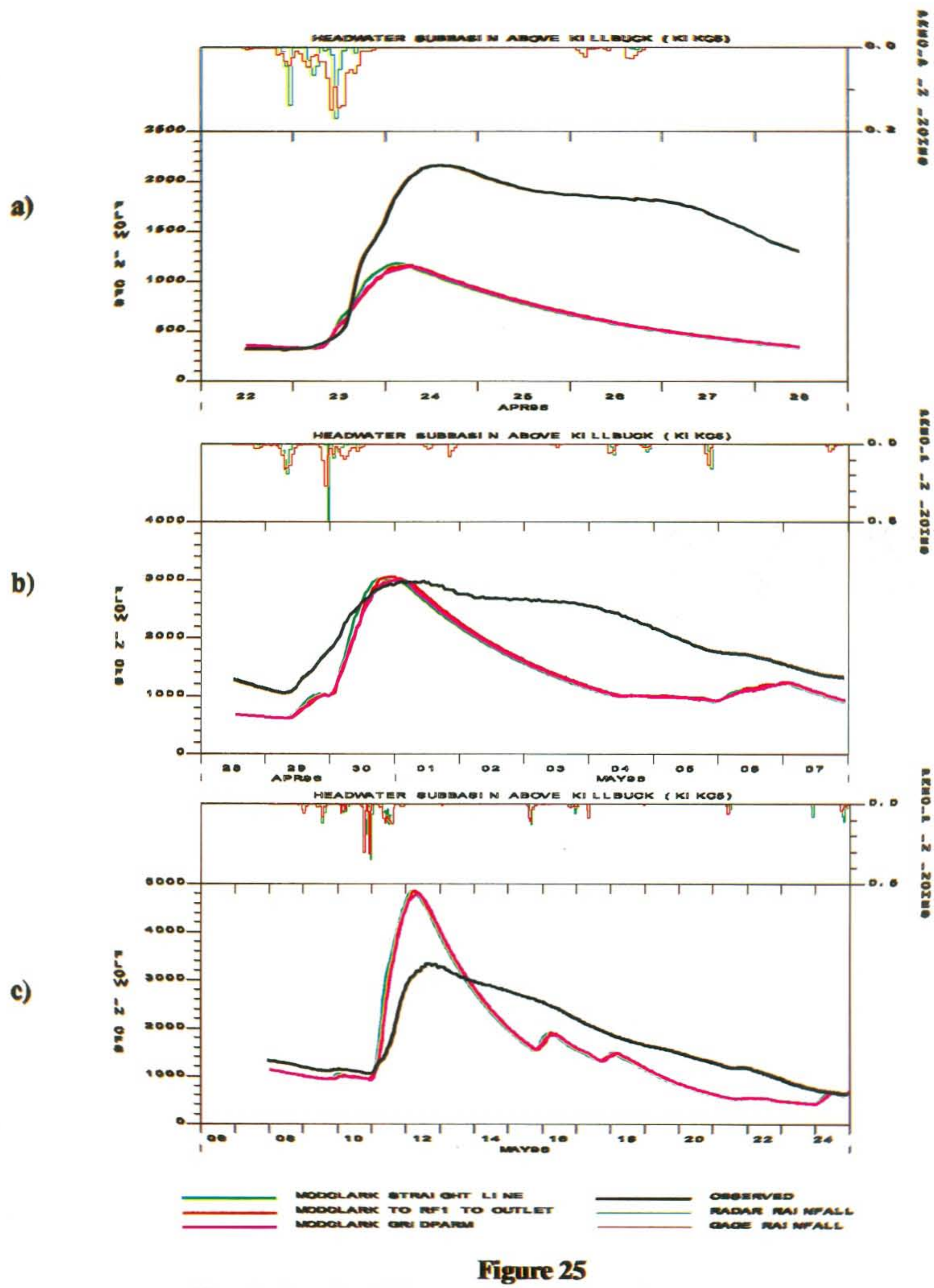

Figure 25
Simulations for Killbuck Creek Subbasin for a) April 22-28, b) April 28 - May 7, c) May 8-25, 1996

Chapter 4

Observations and Conclusions

The Muskingum Basin is the third basin to which the ModClark method has been applied, the first two being the Tenkiller (Peters and Easton 1996) and the Salt River (USACE 1996a). Although this is a small number of applications, some commonalities have surfaced that are worth mentioning while describing observations unique to the Muskingum Basin.

One conclusion evident from both the Salt River and the Muskingum River is that Stage 1 radar rainfall is of limited value for flood forecasting. As shown in several plots in this report, runoff hydrographs generated using Stage 1 rainfall can be grossly in error compared to observed hydrographs, and even compared to hydrographs generated using gaged rainfall. In other cases, however, radar rainfall generated hydrographs were significantly better that those generated using gaged rainfall. Other plots in this report demonstrate this as well. The trend is that Stage 1 radar rainfall can be very inaccurate in absolute magnitude (both over and under estimating).

When storms are of a broader, more homogeneous nature, this inaccuracy can be amplified to produce discouraging results. When the storms are locally intense, two things differ. First, the actual Stage 1 inaccuracies - in the absolute sense - are in some cases smaller (this appears to be a characteristic of radar measurement), and second, any inaccuracies are somewhat masked by the superior spatial and temporal resolution compared to gaged rainfall. Because of this unpredictable performance of Stage 1 radar rainfall, it is recommended that forecasting for water control decisions should not be based solely on Stage 1 radar rainfall. Instead, superior radar rainfall products should be used, such as Stage 3 or equivalent commercial products, which includes ground truthing and other quality enhancements. Fortunately, as improved radar rainfall products become available, they can be used in the current ModClark capability without modifications.

Another conclusion is that there are scenarios for which ModClark simulation of runoff using radar rainfall is superior to simulations based on gaged rainfall data. This was evident during verification modeling for the Muskingum and Salt Rivers even with the Stage 1 data problems described above. The scenarios for which this was observed are characterized by locally intense rainfall occurring over portions of the watershed with few rain gages. The event occurring on May 17-18, 1996, was such an event. For these scenarios, the rain gages can misinterpret or completely miss the event. This is because locally intense storms produce rain cells that can travel between rain gage locations. Additionally, when subbasin-averaged precipitation is developed, localized rain-cells that track directly over a gage can result in the overestimation of basin-wide rainfall.

The above discussion leads naturally to the conclusion that the ModClark method has significant potential for improving forecasting capability when used with adequately accurate radar rainfall. A corollary to this is that at this point in the development of the ModClark capability, it is important to separate evaluation of the method from that of the radar rainfall product used.

The application of ModClark to the Muskingum River Basin revealed some limitations of various model components that did not surface during the first two applications to the Tenkiller and Salt Rivers. The GridParm-DEM2HRAP procedure, when performed as originally designed, can yield erroneous results under certain conditions. In the case of the Muskingum Basin, these conditions appear to be the flatness of portions of the basin relative to the scale of the DEM used. In other words, the magnitude of the errors in the DEM, which follows from the scale of the DEM, was greater than the magnitude of the relief. The first two study basins were topographically "well-defined." This resulted in the GridParm-DEM2HRAP procedure working as designed. However, the flat portions of the Muskingum Basin necessitated the development of alternative approaches. These included alteration of the DEM using 1:500,000 and 1:100,000 scale river networks before application of GridParm-DEM2HRAP, and two simplified techniques for computing cell-to-outlet distances.

The findings from these activities were: 1) DEM alteration using the 1:500,000 River network produced poor results; 2) DEM alteration using the 1:100,000 river network produced good results but was time consuming; and 3) the more sophisticated of the two simplified cell-to-outlet techniques produced comparable results to those from using GridParm-DEM2HRAP on the DEM altered using the 1:100,000 scale river network. While the standard GridParm-DEM2HRAP procedure requires little Arc/Info experience, application of these alternative approaches requires a working knowledge of Arc/Info. As further experience warrants, these approaches may be incorporated into the GridParm-DEM2HRAP procedure.

Chapter 5

Implementation of ModClark as a Forecasting Tool

The ModClark methodology is included in the NexGen HEC-HMS for general use. This radar rainfall-runoff forecasting methodology was developed in conjunction with the Corps' Real-Time Water Control (now the Water Control Data System) Research program. HEC-HMS, or a version thereof, will be further enhanced to include special features for real-time forecasting. Appendix B reviews the HEC-HMS files produced during this study. It is envisioned that the basic model architecture of real-time forecasting with ModClark will be the same as the structure used in HEC-1F. The only difference will lie in the rainfall-runoff transformation. Rainfall data will be in a gridded format and be transformed to subbasin runoff through ModClark. Issues remaining before this capability is fully integrated are discussed in Section 5.1, while an approach for immediate implementation with existing software is discussed in Section 5.2.

5.1 Current Obstacles

Although a major step towards the development of ModClark as a real-time flood forecasting tool has been completed for the Muskingum River Basin, there are still obstacles barring full implementation. At this point, only the actual rainfall-runoff model has been developed. The additional components and program enhancements that are needed for full forecasting realization all involve various software development issues.

The need for Stage 3 or equivalent NEXRAD data is evident in the testing and verification runs presented in this report. When the River Forecast Center (RFC) for the Muskingum Basin area reaches full NEXRAD development, as is being implemented by the National Weather Service, Stage 3 data will become available. Commercial sources may also soon offer Stage 3 equivalent data.

An obstacle that exists in using ModClark for forecasting in either HEC-1F or HEC-HMS revolves around loss rate accounting. When HEC-1F is used with basin-averaged precipitation, each subbasin's loss rate state is saved between model executions. This is not available for the gridded precipitation and losses used by ModClark. Currently, ModClark requires all grid-cells within a subbasin to have the same loss -rates at the beginning of each simulation. ModClark tracks individual cell losses; grid-cell losses are unique because of the application of cell-specific radar rainfall data. During a forecasting run, these individual cell losses would need to be saved and used as initial state variables for the next forecast. The algorithms for this are currently under development.

The use of predicted future rainfall for forecasting is also an issue with ModClark. For full ModClark forecasting, predicted rainfall would need to be a grid-cell based data set. A question arises whether this level of detail for predicted rainfall is necessary or even realistic. One simple solution would be to use subbasin-averaged QPF (Quantitative Precipitation Forecast of the National Weather Service) values and distribute them evenly over the grid-cells within the subbasin.

Presently, HEC-HMS is not ready for use as a forecasting tool. Many of the algorithms required during forecasting runs, such as those involving optimizing, updating, and blending, have not been developed. Additionally, HEC-HMS cannot yet run in a batch mode. During forecasting operations, time is of the essence. It is necessary that the program be run efficiently through automation. Point-and-click operations can slow down the entire forecasting process and must be kept to a minimum. The capability to use files to control the entire process and command HEC-HMS to perform various tasks, similar to the MODCON file for HEC-1F (USACE 1989), needs to be developed.

Current HEC-HMS development plans include the implementation of full forecasting capabilities. The program will have not only the means to perform the various tasks needed for forecasting, but will also provide full model control. Other future development plans for HEC-HMS that will impact its forecasting capabilities include: the use of a gridded SCS curve numbers; the ability to report basin state for a specific time including infiltration rates, direct runoff still traveling through the basin, baseflow, reservoir storages and elevations, and river reach routings (these will all be editable); more sophisticated soil moisture accounting methods such as the USGS' PRMS; and new snowmelt algorithms.

5.2 Implementation with Currently Available Tools

Utilization of the current HEC-HMS ModClark capability within existing water control software is possible with a minimum of modifications. An approach which can be achieved without significant effort is desirable since it will only be used in the interim while HEC-HMS forecasting capability is developed. The modifications anticipated are described below in the context of a suggested procedure for performing forecasts using available capabilities (ignoring details and issues not related to the rainfall-runoff portion of forecasting).

Step 1 Estimate initial loss rates. This step will need to be performed without the aid of automatic calibration (for most cases, this is not a serious limitation). Instead, a model execution will be performed whereby radar rainfall is used to compute flow hyrdographs for gaged headwater subbasins. The resultant hydrographs would then be compared to the available portions of observed hydrographs, and adjustments to initial loss rates decided on. Additional runs can be performed to verify the adequacy of loss rates. The model will also have subbasin runoff computations for subbasins which are not gaged headwaters.

Modifications needed: The JBAS file used in MODCON would need to be modified to run ModClark using the basin characteristics file developed as part of this study instead of running HEC-1F.

Step 2 Make forecast which utilizes available radar rainfall and estimates of future precipitation. This can be achieved by using existing HEC-1F computation capabilities. The goal is to add runoff hydrographs computed using radar rainfall to those computed using estimated future precipitation, and then to blend the result with available observed flows.

Modifications needed: The existing HEC-1F forecast input file would need to be modified significantly. The connectivity would be maintained, but a different sequence of KK blocks would be needed for each hydrologic element. This sequence will include KK blocks to: retrieve from DSS flow hydrographs computed using radar rainfall, compute runoff using estimated future precipitation, add these two hydrographs, and perform blending with observed flow.

Appendix A

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Appendix B

Development of HEC-HMS Files

The Hydrologic Modeling System (HEC-HMS) is the GUI-based (Graphical User Interface) next generation program being developed by HEC to replace HEC-1. Included in the program is the option to use the ModClark methodology to transform gridded rainfall into runoff. Additionally, HEC-HMS will eventually include forecasting capabilities similar to those of HEC-1F. Two separate HEC-HMS basin files were developed. The first is similar to the ModClark basin characteristics file used during this study, consisting only of subbasins. It was originally intended that all ModClark verification and testing runs would be performed through HEC-HMS. Due to the present level of HEC-HMS development and the need for user-defined display macros, however, the original UNIX based ModClark was used. The ModClark subbasin-only HEC-HMS model was thus developed, but not used.

A "full" basin model was also generated in HEC-HMS. This includes all of the hydrologic elements of the Muskingum River Basin: subbasins, reservoirs, river reaches, and junctions. The model schematic, as displayed by HEC-HMS, is shown in Figure 26. In HEC-HMS, every hydrologic element must have a unique name. Headwater subbasins which drain directly into a reservoir were thus given ID's with an "SB" ending for "subbasin" (e.g. - the subbasin draining into SESF6 is labeled SESSB). Routing reaches were labeled with the first two letters from each of the upstream and downstream elements separated by a dash (e.g. - the reach from UTIE4 to NKLE4 is UT-NK).

Currently, the rainfall-runoff transformation is set to use the ModClark methodology. River routing is performed by the Muskingum method, using the parameters found in the HEC-1F model supplied by the District. Routings through the Beach City (BCSC5), Bolivar (BOSC6), Charles Mill (CMBC4), Dover (DOTC6), Mohicanville (MOLC4), Mohawk (MKWD4), North Branch Kokosing (NBKD3), Salt Fork (SLTE5), and Wills Creek (WCWE5) reservoirs use the storage-outflow data found in the HEC-1F model. In the case where both a winter and summer storage-outflow relationship is present in the HEC-1F model, just the summer relationship was entered in HEC-HMS. The storage-outflow relationships used for routing through the Atwood (ATIC6), Clendening (CLBD6), Dillon (DILF4), Leesville (LEMD6), Piedmont (PESE6), Pleasant Hill (PHCC4), Senecaville (SESF6), and Tappen (TALD6) reservoirs come from a previous HEC study (USACE 1986). The full basin HEC-HMS model is strictly a predictive model; observed reservoir outflows are not used and their is no blending with gaged flows. The District may modify this model to fit their needs. Once HEC-HMS evolves to a fully functional forecasting tool, adjustments to the current files will be necessary.

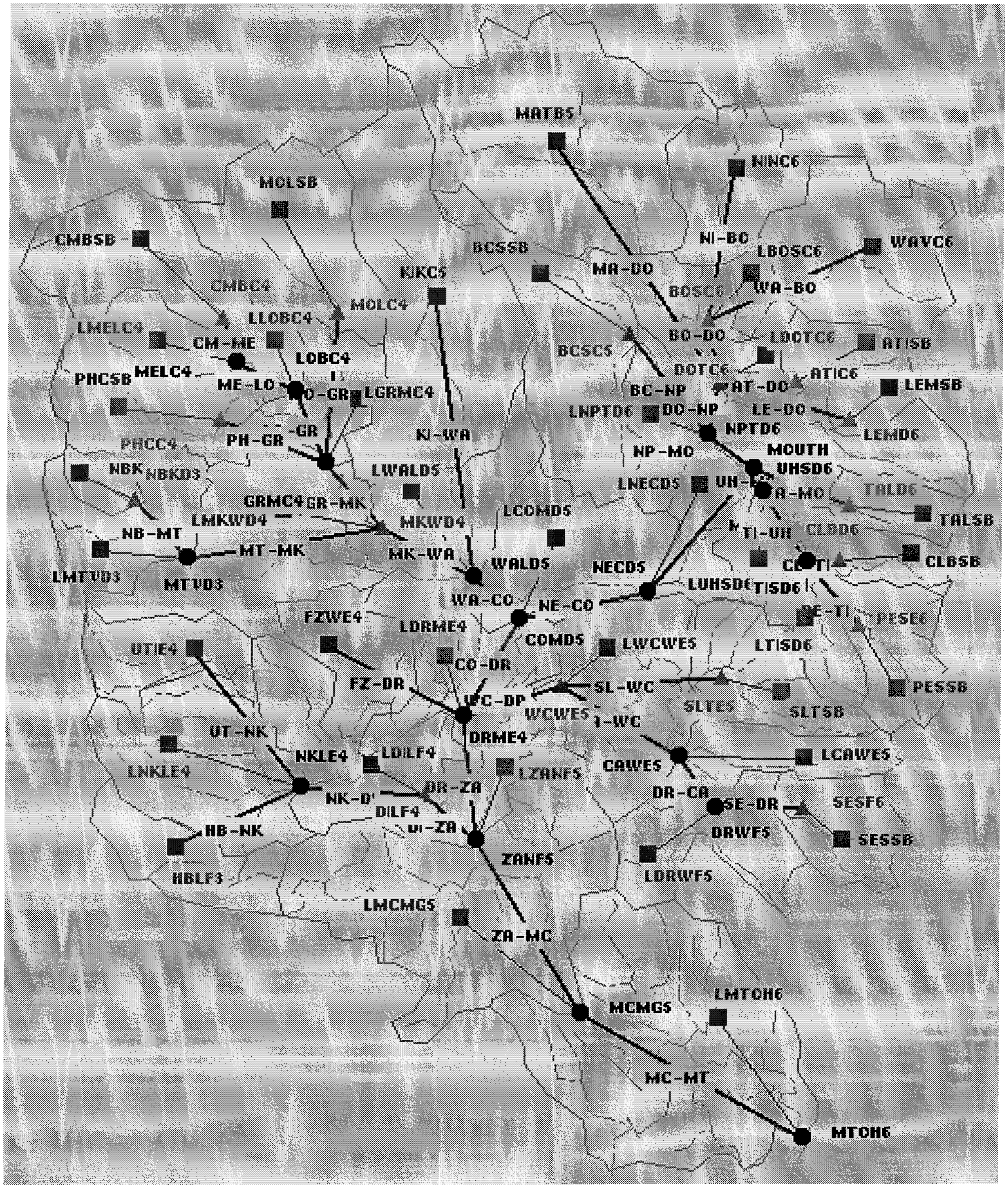

Figure 26
Schematic of the HEC-HMS Model of the Muskingum River Basin

Appendix C

Files Associated with ModClark Application

ModClark:

dspmac - macros for DSPLAY to view ModClark, HEC-1, and observed hydrographs for headwater subbasins (used to generate plots for this report)

mathmac - macros for DSSMATH to shift gage observed data to UTC time

mc - UNIX script file to run ModClark

muscells.hrap - grid-cell characteristics file in HRAP format generated by the GridParm-DEM2HRAP procedure

muscells.shg - grid-cell characteristics file in SHG format generated by the GridParm-DEM2HRAP procedure

musdirect.hrap - grid-cell characteristic file in HRAP format generated by the "direct" method

musdirect.shg - grid-cell characteristic file in SHG format generated by the "direct" method

muskmod.dat - basin characteristics file

mus2str.hrap - grid-cell characteristics file in HRAP format generated by the "RF1" method

mus2str.shg - grid-cell characteristics file in SHG format generated by the "RF1" method

HEC-HMS:

Full.basin - basin model data file for all hydrologic elements

ModClark.basin -basin model data file for just subbasins

Muskingum.hms -project file

musk.map - background map file

WCDS-SVT:

muskingum.cfg -configuration file

muskingum.bgd - background map file