EFFECTS OF RADAR AND RAINGAGE REPRESENTATIONS
OF PRECIPITATION ON THE FLOOD MODELING OF THE
REMNANTS OF TROPICAL STORM HENRI IN THE
RED CLAY CREEK WATERSHED

by

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partial fulfillment of the requirements for the degree of Master of Science in
Geography

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ABSTRACT

Tropical Storm Henri produced flooding in the Red Clay Creek Watershed that surpassed the 500-year flood event. For this research, the effect of different precipitation data sets on the modeling of the flood hydrographs was investigated. The modeling was performed with the United States Army Corps of Engineers HEC-HMS 3.5 modeling package using both raingage data as well as radar data. Raingage data were acquired from the National Weather Service's (NWS) First-Order gage network. The radar data from the Fort Dix (NJ) radar was converted to precipitation using the National Weather Service's Convective and Tropical Z-R relationships as well as a calibrated Z-R relationship was derived from radar-gage pairs from the convective radar scans. Point observations also were extracted from the radar data at the density of the Delaware Environmental Observing System gage network.

Differences in the simulated hydrographs range from the sparse NWS First-Order network, with peak flows underestimated by 70% of the observed flow and timing of the peak lagging the observed by over three hours to the NWS radar data using the Tropical Z-R relationship where peak flow was simulated to within 1% of the observed flow with the timing of the peak matching exactly. Differences between the simulations and the observed values for both Wooddale, DE and Kennett Square, PA were also both compared. While the simulation based off of the Tropical Z-R radar data produced an exaggerated peak value at Kennett Square, the simulation produced a near exact hydrograph for Wooddale. At both Kennett Square and Wooddale for
both data sets based off of the Tropical Z-R data, the average differences between the observed and simulated flow were the lowest. From these simulated hydrographs, the simulations using the Tropical Z-R data of which there are both radar and extracted gage values, produced results comparable to the observed data.
Chapter 1

INTRODUCTION

Flooding is one of most common natural disasters to affect the United States. Major population centers historically were located on or near a river outlet or on the ocean to facilitate transportation and commerce. This began the tradition where humans continue to live and work in flood plains.

Understanding the causes of flooding is critical to more accurately predicting when flooding will occur and understand the impact on human activity. This allows for better preparation and planning by communities affected by floods.

Over the years, modeling the environment has become more important as we possess the ability to account more accurately for important processes such as overland flow, precipitation interception by a forest canopy, and water flow through a stream channel. Flood modeling is no different and incorporates land surface types as well as detailed characteristics about stream channels. Moreover, computational capabilities and our measurement of precipitation and understanding its spatial variability has improved considerably. Yet our ability to model hydrology is still limited by our representation of the spatial and temporal characteristics of precipitation, which are generally under-represented by all measuring systems, including rain gages, weather radar, and satellite methods. Thus, the efficacy of any hydrologic model is entirely dependent on the quality of its precipitation input.
Attempts have been made to compare how different types of data (rain gage, radar) affect the results of different models (Taffe and Kucera 2005). Few, however, have examined how the quality of the data affects the modeled results.

In this research, rain gage and radar data, both of which are rainfall amount datasets, will be compared in a hydrologic model to examine the differences between these data sets for Tropical Storm Henri in Chester County, Pennsylvania and New Castle County, Delaware. This area lies on the edge of the Piedmont and Coastal Plain and is home to a growing population and land use change. Investigating the differences in model results can assist hydrologists in better understanding the role of the precipitation input on hydrologic models. Furthermore, it also can lead to helping local community officials and emergency personnel use these data sets in case of a future flooding event more effectively.
Chapter 2

RESEARCH QUESTION AND LITERATURE REVIEW

2.1 Introduction

Remnants of Tropical Storm Henri (T.S. Henri) are classified as the worst flooding event to affect the Red Clay Creek watershed (DGS 2010). On September 15, 2003, T.S. Henri caused significant amounts of rainfall in southeast Pennsylvania and northern Delaware with over 254 mm (10 in) falling in Kennett Square (PA). According to the Delaware Geologic Survey’s (DGS) records (DGS 2010), the Red Clay Creek observed record flooding levels with a maximum discharge of nearly 1019.4 m$^3$/s (36,000 ft$^3$/s) and a gage height of over 7.62 m (25.5 ft) at the USGS gauge in Stanton, DE (DGS 2010). These amounts equate to an approximate 500-year flood according to the USGS report on the storm (DGS 2010). An examination of an averaged one hour precipitation radar scan for an hour during the storm (Figure 2.1) shows a distinct center of heavy rainfall over the northern reaches of the watershed.
Figure 2.1 One hour averaged precipitation radar image from the Fort Dix (KDIX) radar showing an area of heavy precipitation for September 15, 2003 over the Red Clay Creek Basin (outlined in black). Locations of the three stream gauges – located in Kennett Square, Stanton, and Wooddale – are shown with the black dots.

This research, will examine this extreme precipitation event to determine the impact of four different spatial representations of the rainfall distribution on the simulated streamflow. Level II radar data are available from the Fort Dix NJ (KDIX) National Weather Service (NWS) radar and rain gage data also are available from NWS First-Order and Cooperative rain gage sites. These datasets will be summarized into six groups to represent rainfall estimates
made using (a) only the NWS rain gage data, (b) uncalibrated Level II radar data with the standard reflectivity-to-radar relationships used by the NWS for convective and tropical events, (c) calibrated Level II radar data where the rain gage data are used to determine the effective reflectivity-to-rainrate relationship, and (d) a dense station distribution of data created by sampling from the calibrated and tropical Level II radar data sets at rain gage locations in Chester (PA) and New Castle (DE) Counties operated by the Delaware Environmental Observing System (DEOS).

The research question addressed by this thesis is to determine to what extent the NWS weather radar data enhance the hydrologic model representation of the event by comparing sparse and dense gage networks with uncalibrated and gage-calibrated Level II radar data. Conventional wisdom indicates that radar data, with its higher spatial fidelity, should provide better hydrologic simulations of precipitation events; however, it has been argued (e.g., Quirmbach and Schultz 2002, Berne et al. 2004) that gage data are sufficient to represent small watersheds. Examining this claim in the context of the Red Clay Creek basin, a relatively small watershed, is therefore the focus of this research.

2.2 The Hydrologic Cycle

Modeling any watershed requires a physical representation of the hydrologic cycle. Water vapor in the atmosphere, evapotranspiration, evaporation, surface water, subsurface water, and precipitation are the key components of this cycle that must be simulated. While each of these is an important component, for flooding events, precipitation, surface water, and
overland runoff are the most important components. Numerous models have attempted to represent these processes with particular emphasis on flood simulation (HEC-HMS 3.5 User's Manual 2010). As with all models, the data that is input into them – precipitation in this case – will directly affect the quality of the results from these models.

Components such as surface water and overland runoff are greatly affected by precipitation before and during the storm events. When precipitation falls to the ground, it will either be absorbed by the surface or become surface runoff. This depends greatly on the landuse and land surface type upon which the precipitation falls. However, if precipitation occurs at a sufficient rate or for a long enough time, the ability of the surface to absorb the water diminishes drastically. At that point, incoming precipitation contributes to the overland surface flow (Dingman 1993).

Overland surface flow depends on the type of surface over which the water flows (Dingman 1993). Vegetated surfaces allow for the water to infiltrate, thereby slowing its conversion to streamflow. However, urbanized environments allow the water to quickly enter the stream channel through urban street flooding and storm drains. The difference between the ability of the surface to control the water flow into the stream affects the height and timing of the measured peak in the downstream hydrograph. In hydrologic models, these aspects about the surface are taken into account by what are known as ‘transform methods’ such as the SCS Unit Hydrograph Transform or the Modified Clark Method Transform (HEC-HMS 3.5 User's Manual).
Once the water reaches the stream or river, the flow is governed by certain aspects of the channel such as its width, depth, slope, and the flood plain. These routing characteristics are described in HEC-HMS by different methods, one of which is the Muskingum-Cunge method. Which allows for HEC-HMS to describe both channel and overbank flow (Muskingum-Cunge Routing 1991). These characteristics can affect how quickly the water flows downstream as a stream with a shallow depth or many obstructions can lead to more turbulent flow (Dingman 1993). With the Muskingum-Cunge method, the diffusion of the water downstream is weighted by two things, the physical characteristics of the stream are one part while the flow characteristics are another (Muskingum-Cunge Routing 1991). One approximation of flow, the Chézy equation, is based on the concept that flow velocity depends mainly on the channel's roughness, irregularity, and depth (Dingman 1993). The shape of the channel is used to account for the irregularity of the channel, as depth is computed from simplified measurements of its complex cross-section. Channel depth is also used to determine the roughness of the channel through use of the Chézy's equation or other formulae such as Manning's roughness coefficient, $n$ (Dingman 1993). Manning's roughness coefficient is dependent on the channel type and knowing information about the flood plain. These values range from as small as 0.020 for flood plains that consist of fallow farmland to 1.60 for a heavily forested flood plain when the water reaches the branches (Chow 1959). It is important to account for these stream characteristics that play a critical role in hydrograph shape and size.
2.3 Precipitation Gage Data

As previously indicated, precipitation is a primary hydrologic process that must be accurately measured to adequately simulate a watershed hydrologically. Precipitation in its various forms is most commonly measured by a conventional rain gage, which is often little more than a modified metal can. However, rain gages used in the United States usually have orifice diameters of 200 and 384 cm$^2$ (i.e., up to 8 inches in diameter – Groisman and Legates 1994). At best, this represents the precipitation at a single point; however, precipitation is known to vary considerably even over small distances (Osburn and Keppel 1966; Goodrich 1990; Goodrich et al. 1995; Faurès et al. 1995). An example of such variability was documented by Osburn and Keppel (1966) in which two gages 300 m apart were separated by a strong gradient in a thunderstorm. One gage recorded 10 mm while the other recorded 20 mm. However, precipitation over small areas (less than 0.1 km$^2$) is often assumed to be uniform (Faurès et al. 1995). Nevertheless, precipitation gage networks still provide some information about the precipitation over a larger area. Thus, the density of a precipitation gage network is crucial in determining how much error exists in the spatial representation of precipitation. For hydrologic models, and specifically for rainfall-runoff models, this can be especially troublesome depending on the size of the catchment as well as the types of major land use in these catchments.

Schilling (1991) established gage density requirements for different sizes of urbanized catchments. These values are fairly generalized and could be affected by local climate types. An experiment in the Southeast of France (Berne et al. 2004) tested six different catchments around three major
cities and compared the model-derived estimate of runoff using the corresponding local gage networks. Both Schilling (1991) and Berne et al. (2004) agreed that as the size of the catchment decreased, the density of gages must increase and the recording time step of the gages must decrease to provide commensurate accuracy in streamflow. This is because small basins have faster response times to the precipitation input and even small errors in the representation of precipitation become magnified.

In the United States, two national gage networks are operated by the National Weather Service (NWS). The NWS Cooperative Observer Program (COOP) consists of daily observations of rainfall and snowfall that are recorded by local observers. In addition, the NWS further operates a more comprehensive network called the Automated Surface Observing System (ASOS) which take hourly (or finer) measurements. This automated system derives from the First-Order weather observer network where trained meteorologists took measurements manually, most often at airport sites in the United States (ASOS User's Guide 1998). The spatial resolution of the COOP network is much higher but more disparate temporally. Legates (2000) states the distances between these stations easily range from 50 km to 100 km.

This disparity over time has lead to local networks of weather stations, commonly referred to as Mesonets, to be established. Networks have been established in research areas such as the Walnut Gulch Experimental Watershed in Arizona (Garcia et al. 2008) and Wallops Island in Virginia (Taffe and Kucera 2005) have densities of ~0.570 gages per square km and inter-station distances of at most 8 km. Statewide and regional mesonets, such
as the Oklahoma (Brock et al. 1995) and Kentucky (Grogan 2010) Mesonets and the Delaware Environmental Observing System are examples where higher raingage densities are available. While these networks provide better spatial and temporal coverage for certain areas, they may not provide adequate coverage for urban runoff modeling.

Rain gage data are also inaccurate due to gage measurement biases caused by the instrumentation. Issues regarding gage accuracy and its ability to consistently describe the precipitation over an area have been extensively documented (Groisman and Legates 1994; Fulton et al. 1998). This problem is compounded by (a) numerous types and variations of gages are used throughout the world, and (b) precipitation falling in various forms causing gage biases to be different for diverse weather events. These issues have been covered by three World Meteorological Organization (WMO) reports and many other published scientific works. The first WMO intercomparison studied the different types of national gages that were used and then created catch reduction coefficient values for each (Poncelet 1959; Struzer 1971). The second was an intercomparison to see the differences between that nation’s standard gage and the reference Mk 2 pit gage and to create correction procedures (Sevruk and Hamon 1984). Goodison et al. (1989) reported on the third WMO intercomparison which specifically addressed solid precipitation, most notably, the wind-induced error for the derivation of standard bias adjustment procedures.

Depending on gage design, the type of wind shield (if any), the siting of the gage, wind speed at the precipitation gage orifice's height, and
evaporation and wetting loss are all important factors that lead to gage measurement biases. Sevruk (1972, 1979, 1982, 1984), Legates et al. (2005), Yang et al. (1998) and others have created equations that are typically used to adjust for these biases. Bias-adjusted precipitation data are extremely important to local water budgets as underestimates of precipitation can greatly alter any conclusions that are based on gage-measured data. Although these data may be biased, variability can be reduced by understanding the gage design and proper installation and siting of the gage itself. Therefore, adjustments of this type are necessary for the most accurate data but require knowledge of the type and site of the gage. This information is not readily available for most gage networks including the networks mentioned above so the data acquired will be used as is for this research.

2.4 Radar Data

While rain gage networks are a source of precipitation data, radar data are widely available for much of the United States and provide a better areal coverage than even high density gage networks can provide. While they provide better coverage, radar data, as with rain gage data, have inherent limitations associated with estimating area-averaged precipitation. The NWS operates a network of weather radars, originally called the Next Generation Weather Radar (NEXRAD), more commonly referred to as the Weather Surveillance Radar 1988 Doppler radar (WSR-88D). This radar is a 10.5 cm (S band) radar that has a spatial resolution of 1° of azimuth by 1 km range (Glickman 2000). It produces a full volume scan every six minutes when precipitation is detected.
It is important to note that radar does not measure the actual rainfall. From the returned signal, three quantities are extracted – volume reflectivity, radial velocity, and spectrum width (NEXRAD User's Handbook 2005). Volume reflectivity, derived from the amount of energy that is returned to the radar, is determined from the cross sectional area that the beam makes as it moves away from the radar. This area of the beam is related to the resolution of the radar. Resolution for the NEXRAD base data is marginally 1 degree in azimuth by 1 degree in elevation by 1 km in distance. The volume of the beam is directly proportional to the horizontal and vertical beam widths and a sample volume depth (NEXRAD User's Handbook 2005).

Radar data from the NWS WSR-88D can be acquired in two different formats. Level II data include the data measured on reflectivity, spectrum width, and radial velocity in range, azimuth, and tilt (i.e., in spherical coordinates). Level III data are the processed suite of radar products that include processed precipitation estimates at 4 km x 4 km resolution using whichever Z-R relationship the NWS selected at the time of the event (Klazura and Imy 1993). As it is based on the original resolution of the data, any Z-R relationship and/or averaging technique can be applied. Level II data will be used for this research because it allows more freedom and ease to create a custom Z-R relationship.

The WSR-88D weather radars measure reflectivity ($Z$ in mm$^6$ m$^{-3}$) in decibels of reflectivity, or dBZ. The range of dBZ values is mainly correlated with the type of weather system but ranges from less than 0 dBZ to over 60 dBZ. These values are then converted to rainfall amounts, $R$, using an equation
called the Z-R relationship. The Z-R relationship is described by an exponential relationship

\[ Z = a R^b \]

where the rainfall is measured in mm h\(^{-1}\) and the coefficients, \(a\) and \(b\), are the multiplier and the exponent, respectively. These constants are determined from drop size distributions that are used to conform to specific type of weather events or specific areas (i.e., Joss and Gori 1978; Rosenfield et al. 1993). In general, values of \(a\) range between 30 and 500 while for \(b\), they range between 1.2 and 2.0 (Legates 2000). In the radar handbook, it is noted that rainfall rates and reflectivities are not always equal, depending on the distribution of drop sizes (NEXRAD User's Handbook 2005). Thus, it is important to note that for any given \(R\) value (\(Z\) value), there are many different \(Z\) values (\(R\) values) possible (WSR-88D Operations Training Manual 1994). In practice, only a small number of Z-R expressions have been allowed by the National Weather Service for regular operational use. Some of the more notable ones are the Marshall-Palmer relationship, \(Z = 200R^{1.6}\), that was derived from stratiform rain events and mid-latitude systems. Another one is an older National Weather Service convective rain relationship \(Z = 55R^{1.6}\) while the more commonly-used current relationships by the NWS are \(Z = 300R^{1.4}\) for convective and \(Z = 250R^{1.2}\) for tropical events (Jorgensen & Willis 1982, Legates 2000). These Z-R relationships are not perfect and corrections to known errors have been suggested as well as new and different equations have been calculated. Legates (2000) provides an equation that includes a distance
correction that helps account for beam overshoot error and partial beam filling and coalescence errors as well. There is also a common adjustment that is done by creating gage-radar pairs to provide a better calibration for the radar. This adjustment comes from the assumption that the biases in the reflectivity data remain constant enough during a storm event to provide a constant bias (Fulton et al. 1998, Legates 2000, Rosenfield et al. 1993). It is this style of adjustment that will be used with the radar data in this research.

To create these gage-radar pairs, the radar data must be paired with the bin (range and azimuth) in which the raingage lies. The sizes of these bins vary depending on their distance from the radar, ranging from 2km x 4km at maximum range (230km) to 2km x 0.3km at close ranges (20km). The watershed in this research is roughly 100 km from the radar which, according to Fulton et al. (1998), has a radar bin size of about 2km x 2km. Gage observations and the radar reflectivity were then compared (see Klazura and Kelly 1995 and Glitto and Choy 1997) to create a bias for the radar. Mathematically,

\[\text{Mean Radar Bias} = \frac{\sum_{i=1}^{N} G_i}{\sum_{i=1}^{N} R_i}\]

where \( R \) is the radar rainfall estimate and \( G \) is the raingage amount. Glitto and Choy (1997) state that for this equation, a value higher (lower) than 1 indicates underestimation (overestimation) by the radar (1997). Legates (2000) points out that there are errors with pairs such as these, specifically with the precipitation gradients present in storms. These along with horizontal advection can create pairs of high gage values and low reflectivity. To alleviate
that and other issues a modified version of the calibration equation stated in Legates (2000) will be used:

\[ Z' = a R^b \]

where \( R \) is the rainfall rate measured by the gage, \( a \) and \( b \) are the empirical coefficients in the standard \( Z-R \) equation used by the radar, and \( Z' \) which is reflectivity value to compare to the actual value for the radar bin. This should be done for as many gage-radar pairs as are available to account for the spatial variability and drop size variability that is present in storms. By creating a bias value, it allows for a corrected rainfall estimate to be made from a standard \( Z-R \) equation. This bias does not need to be equated for every radar sweep due to the fact that the overall bias will not change much during the storm (Fulton et al. 1998, Legates 2000, Rosenfield et al. 1993).

One problem is that the radar bin increases in size as the distance from the radar increases. Even at small ranges, however, the radar estimates rainfall over an area of approximately 0.6 km\(^2\) while the raingage covers only an area of 200 to 384 cm\(^2\) – a difference of more than nine orders of magnitude. While this depends on the density of the gage network, this bias and any associated errors between rain gage and radar sub-pixel variability should be calculated using multiple rain gages in a bin (Zhang et al. 2007). This is a separate issue and is in addition to the idea of creating a bias for the entire scan using multiple rain gages in multiple bins which will help alleviate radar specific errors in the reflectivity data.
2.5 Summary

Precipitation data are not without their own issues and problems; however, steps can be taken to adjust or account for the vast majority of these errors. Rain gage and radar data are spatially and temporally different with respect to how they record precipitation. Gage data represent points on a surface and the quality of the measurement is dependent on the gage type, weather conditions, and precipitation type. Radar data, however, represent precipitation over a much larger area but do not measure precipitation directly. The quality of data is dependent on the radar hardware, as well as the equations used to transform the reflectivity data to rainfall. These Z-R equations are based specifically on precipitation drop sizes which vary in time and space within a storm, among storm types, and even seasonally and geographically. One way to adjust for this is to use gage data to compare radar derived rainfall rates to gage values. This relies on quality gage data. These differences and interconnections will be explored in greater detail for an extreme rain event comparing the quality of each data type in adequately describing runoff in a hydrologic model.
Chapter 3

STUDY AREA AND METHODS

3.1 Study Area

The majority of the precipitation during Tropical Storm Henri fell in the upper reaches of the Red Clay Creek Watershed. This watershed is made of five sub-basins (Table 3.1) which covers part of the Southeastern Pennsylvania, Chester County and the northern most county in Delaware of New Castle County. It is part of the larger Christina River Basin which includes the White Clay Creek, the Red Clay Creek, the Brandywine River, and the Christina River. The Red Clay Creek meets the White Clay Creek near Stanton, DE which then flows East-Southeast to meet the Christina River Southwest of Newport, DE. Within the Red Clay watershed are two branches both of which begin north of Kennett Square, PA and flow through its borough. They then join right before the Pennsylvania-Delaware line northwest of Yorklyn, DE (see Figure 3.2).
Four radars cover the Red Clay Creek watershed at their full range of 250 km – State College, PA (KCCX), Sterling, VA (KLWX), Fort Dix, NJ (KDIX), and Dover Air Force Base/Ellendale, DE (KDOX). Their relative distances from the watershed are 233.4 km, 181.2 km, 109.2 km, and 111.2 km, respectively, from Yorklyn, DE which lies near the center of the watershed. Due to the availability of Level II data and the distance from each radar, only data from Fort Dix (KDIX) are used (Level II data from KLWX and KDOX are not available).

### 3.1.1 Climatology and Hydrology

Climatologically, Southeastern Pennsylvania and Northern Delaware receive, on average, between 1000 mm and 1250 mm of precipitation per year with a relatively even distribution by month (Figure 3.1). Tropical events can result in considerable precipitation as Tropical Storm Henri, for example, produced 254 mm of rain in Kennett Square – nearly one quarter of the annual total and double the second highest gage record within the Red Clay Creek watershed. While there is not a large range in precipitation on average throughout the year in the region, the largest amounts of
precipitation occurs during the summer months from May to September (Figure 3.1).

Figure 3.1  Average Monthly Precipitation Amounts (mm) for National Weather Service gages in or near the Red Clay Creek Watershed.

Three USGS stream gauges (Figure 3.2) are located on the Red Clay Creek near Kennett Square (PA), Stanton (DE), and Wooddale (DE). All three gauges measure stream discharge as well as gage height. Of the three, Wooddale has the longest station history dating back to April 1943 while Kennett Square and Stanton date back to only January and October 1988, respectively (USGS Water Watch). All three measured record values for Tropical Storm Henri (September 2003), with the highest being a discharge of 1019.4 m$^3$s$^{-1}$ and a gauge height of over 7.62 m at Wooddale (DGS 2010). Historically, the monthly average discharge at Wooddale for its 67 year record is 2.3 m$^3$s$^{-1}$, while the averages for Stanton and Kennett Square gauges are 78.04 m$^3$s$^{-1}$ and 42.8 m$^3$s$^{-1}$, respectively. However, these values are considerably lower than those observed with Tropical Storm Henri where the
monthly averages for Kennett Square to Stanton were 211.7 m$^3$·s$^{-1}$, 326.6 m$^3$·s$^{-1}$, and 353.5 m$^3$·s$^{-1}$s, respectively.

During the event, gauge data at Stanton (DE) were compromised leaving only the peak flow. Timing of the peak and the full hydrograph were not recoverable. Thus, only the peak flow will be evaluated for the Stanton (DE) stream gauge.

Figure 3.2 The Red Clay Creek Watershed showing the stream gage locations, the break line between the Piedmont and Coastal Plain region, and the elevation of the watershed above mean sea level.
3.1.2 Land surface Properties

The Red Clay Creek watershed covers two distinct physiographic areas (Figure 3.2) with the northern portion lying in the Piedmont region and the southern portion lying in the Coastal Plain region (Paulachok et al. 1995). The Piedmont region is made up of crystalline bedrock and is nearly impervious (Doheny 1998). Dillows (1996) and Doheny (1998) both describe the area as a rolling hill and ridge system with elevations below 122 m M.S.L. (400ft) but comprised of streams that drain with fairly steep gradients. Thus, flash floods are common to this region. By contrast, as Simmons (1986) and Doheny (1998) explain, the Coastal Plain is composed of layers that alternate between sand and gravel, silt, and clay. This area is fairly low with the highest elevation being roughly 30 m M.S.L. (100 ft) and dropping down to sea level. As a result, flash flooding that is typical in the Piedmont is not found in the Coastal Plain; however, coastal flooding and larger-scale stream flooding (from runoff of the Piedmont Region) has been increasing (Dillows 1996; Doheny 1998).

3.1.3 Landuse

The entire Red Clay Creek Watershed drains an area of 140.11 km². Land use data was acquired from the United States Geological Survey (USGS) for the Red Clay Creek watershed from their latest assessment in 2001 (Figure 4.3). Major land use in the Red Clay Creek Watershed includes agriculture (48.1%), followed by developed land (24.8%) and forest (24.3%) with the creek and its watershed comprising 2.8% (USGS 2001). Most of the developed land is concentrated in New Castle County; however, the developed
land in Chester County and specifically the area around Kennett Square is easily identifiable. The Chester County Planning Commission (CCPC) expects significant growth of suburbanization and urbanization across the entire county, including the Red Clay Creek watershed (CCPC 2009). Graff (1977) states that urbanization at the headwaters of the watershed has a more serious effect on the change of the watershed's hydrology and, more importantly, the change in the amount of time and the size of the discharge peak than changes downstream have. Thus, the effects of land use in Chester County, and specifically Kennett Square, are likely to have a greater hydrologic impact on the watershed than land use in New Castle County.
3.2 Hydrologic Model of the Red Clay Creek Watershed

The HEC-HMS model (Hydrologic Engineering Center’s Hydrologic Modeling System) is a GIS-based rainfall-runoff model of a watershed that incorporates a variety of hydrologic modeling techniques to provide useful results for planners and researchers. This model takes the precipitation input and converts it through physical processes to streamflow (HEC-HMS 3.5 User’s Manual 2010). Specifically,
where $t$ is time, $S(t)$ is the time-series of streamflow, $A$ is the area of the watershed, $R(A,t)$ is the spatial and temporal distribution of rainfall, and $I(A,t)$ are the initial abstractions (e.g., soil moisture recharge, pond retention). Thus, streamflow is the spatial integration of the effective precipitation (rainfall minus initial abstractions).

While any model is limited by our ability to convert the physics and land surface into mathematical representations, the HEC-HMS model generally works well for runoff modeling (Anderson et al. 2002, Chu and Steinman 2009). When the data are adjusted for known biases and errors are minimized, the model will more accurately represent the watershed and its response to extreme rain events.

Basin and subbasin characteristics are generated from a DEM and landuse file that has been integrated through ArcHydro in ArcGIS (HEC-GeoHMS 4.2 User's Manual 2009). The information that is generated for each subbasin represents the infiltration, surface runoff, and subsurface processes interacting together (HEC-HMS 3.5 User's Manual 2010). Specifically, values for the SCS curve number, initial loss and abstraction, time of concentration, basin lag and others are derived from the DEM by the model which takes zonal statistics based on the grid cells that are intersected over basin (HEC-GeoHMS 4.2 User's Manual 2009) – the grid cell pattern that is used for the radar data. The stream is represented by the reach element which describes how the stream routes through each subbasin as well as taking in account any loss or gain that is attributed to the subsurface processes of the subbasin. Information
used for routing methods, such as Muskingum-Cunge which was used in this study, can be retrieved from the DEM files if they are not too coarse. However, measurements or previously published survey data and photos are recommended to help assist the user specify more accurate channel characteristics (HEC-GeoHMS 4.2 User's Manual 2009).

In addition, the Manning's n roughness coefficient is needed and is generally estimated from streams that are similar in appearance or that have a known roughness coefficient (HEC-HMS 3.5 User's Manual 2010). The shape of the reach is assumed to be that of a trapezoid with similar slopes on each side but this assumption can be changed to another cross-section representation. This option is known as the eight-point method, and shares similarities to the trapezoid shape but allows for additional information from the cross-section data to be included about the stream and flood plain. Beighley and Moglen (2003) suggest using the eight point method because it allows for both the stream and flood plain to be modeled which in the case of Henri happened to a large extent throughout the Red Clay Creek. Figure (3.4) shows a comparison between the two types.
In both cases, the same side slope and channel bottom width are used. The addition of the floodplain at the edges of stream extending out to an arbitrary distance in the eight-point method allows the model to simulate the flow after it has left the main stream channel. This allows for a greater level of detail that was needed to accurately model Tropical Storm Henri.

The HEC-HMS model requires three different meteorological variables to be specified – precipitation, evapotranspiration, and snowmelt (HEC-HMS 3.5 User's Manual 2010). For the simulation of Tropical Storm Henri, both evapotranspiration and snowmelt can be ignored. Evapotranspiration is small over the time scales considered (especially for streamflow generated by very small watersheds such as the Red Clay Creek) and snow was not an issue with Tropical Storm Henri.

Precipitation can be input to the HEC-HMS model through a number of methods (HEC-HMS 3.5 User's Manual 2010). Here, two methods – gage weights and gridded data – will be used. As the radar data are available...
in spherical coordinates \(i.e.,\) range, azimuth, and elevation) and will be converted to rainfall estimates over a regular grid, the gridded data method will be used for radar data. By contrast, the gage data are measured at irregularly distributed locations and spatial estimates will be obtained through the use of raingage weights.

In addition to precipitation, the HEC-HMS model requires a basin model to provide information about the physical characteristics of the watershed. This includes flow direction and accumulation, streamflow routing, and basin/sub-basin delineation. This information is then used to create a representation of the watershed which can be supplemented with information about the surface, canopy loss, and base flow for each grid point within the basin. The model also requires the time period and temporal resolution of the simulation be specified.

### 3.2.1 Gage Weights Method

Gage data are an integral part of the comparison of this study and require careful implementation. While the density and type of gage used varies with the two different networks that are used, the process uses the same method.

The Gage Weights method refers to its ability to allow the model to provide weights to each raingage; specifically,

\[
R(t) = \int \int R(A, t) dA \approx \sum_{i}^{N} R_i(t) w_i
\]

where \(R(t)\) is the area-averaged precipitation, \(N\) is the number of raingages, \(R_i(t)\) is the gage observation from raingage \(i\), and \(w_i\) is the weight assigned to each
raingage for each sub-basin. Weights are usually assigned to the area that each gage represents and the weights must sum to unity (HEC-HMS 3.5 User's Manual 2010).

Within the HEC-HMS model, gage data can be assigned as either a time-series or a cumulative storm-total. Both types can be used within the same model run; however, time-series data must conform to the same time-step (HEC-HMS 3.5 User's Manual 2010). Since the NOAA first-order weather station network provides hourly observations, the existing gage network product will be input at an hourly time-step. By contrast, DEOS station data are available at a five-minute resolution and thus the simulated DEOS data product will be applied at a higher temporal resolution than the existing gage network.

3.2.2 Gridded Precipitation Method

The Gridded Precipitation method allows for the use of pre-calculated gridded data, such as with radar data (HEC-HMS 3.5 User's Manual 2010). As previously discussed, Level II radar data from the Fort Dix (KDIX) radar will be used in this study. This will allow for use of the traditional NWS Tropical Z-R relationship and radar-gage pairs to be used for calculation of a calibrated Z-R relationship. Calibration was described briefly in Chapter 2 and will be explained in more detail in the following section. Since Level II radar data are given in spherical coordinates, the data must be transformed into a regular grid for use by the HEC-HMS model. This is accomplished by spatial sampling from the radar data (described in Chapter 4).
3.3 Radar Data

Level II radar data from KDIX was acquired for September 13-15 2003 – the time period over which the remnants of Tropical Storm Henri influenced the Red Clay Creek. This data was downloaded from the National Climate Data Center (NCDC) in Asheville, NC. Specific Level II product and elevation angle were extracted from the archive (NOAA Toolkit Tutorial 2011). For this analysis, reflectivity data for the lowest elevation angle was selected and it was output to the ArcGRID format so that they could be converted to rainfall amounts within ArcGIS. Then the gridded precipitation values were converted to a 2km x 2km grid using the USGS Albers Equal Area projection, which is one of two preferred projections for gridded data in the HEC-HMS model (HEC-HMS 3.5 User's Manual 2010). These data then were converted to precipitation totals, first using the NWS convective and tropical Z-R relationship and then using a Z-R relationship calibrated from gage observations and the convective Z-R using the method of Legates (2000). This data was then added to the HEC-HMS model using the gridded precipitation option.
Chapter 4

RESULTS

4.1 Precipitation Gage Networks

Two precipitation gage networks were considered for input to the hydrologic model. The NWS First-Order Station network is spatially limited in that the station distribution is rather sparse. To simulate the potential impact of a denser network, the precipitation gage network represented by the Delaware Environmental Observing System (DEOS) also will be used. Unfortunately, the DEOS network was not installed for Tropical Storm Henri so to simulate its potential effect, sampling was made from both the calibrated and tropical radar scans at the locations of existing DEOS stations.

For gage-derived basin precipitation estimates, Thiessen Polygons (Thiessen 1911) were used to determine the relative importance of each station on the gage-weighted basin precipitation. Thiessen polygons were computed for each station and only those stations for which its polygon intersected with the basin were included. For the NWS First Order Station network, the Thiessen polygon of only one station, located at the New Castle County (DE) Airport, covered the entire watershed. Thus, the data from this single station represents the precipitation for the NWS network. As the DEOS network is more dense, several stations contribute to its gage-weighted basin precipitation (Figure 4.1).
From Figure 4.1 and Table 4.1, the Kennett Square-Bucktoe gage represents the largest portion of the watershed, while the raingage at the New
Castle-DMV site represents the smallest. Since the gage weight method was used in the model, the gages that represent the most area have a greater influence on the models output. Below is a table with the three day totals and the area they contribute to the watershed for all of the stations that were used. The two different precipitation data sets are evaluated separately.

Table 4.1  Three day totals of precipitation for each rain gage and the area that they contribute to the model.

<table>
<thead>
<tr>
<th>Location</th>
<th>Area (km²)</th>
<th>Convective (mm)</th>
<th>Tropical (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marshallton</td>
<td>2.8</td>
<td>237.9</td>
<td>364.5</td>
</tr>
<tr>
<td>Kennett Square - Longwood</td>
<td>39.1</td>
<td>187.9</td>
<td>216.8</td>
</tr>
<tr>
<td>Kennett Square - Bucktoe</td>
<td>38.8</td>
<td>273.5</td>
<td>418.0</td>
</tr>
<tr>
<td>Greenville</td>
<td>7.99</td>
<td>122.2</td>
<td>127.3</td>
</tr>
<tr>
<td>Hockessin - Mt. Cuba</td>
<td>27.6</td>
<td>132.6</td>
<td>115.4</td>
</tr>
<tr>
<td>Hockessin - VFC</td>
<td>10.37</td>
<td>167.0</td>
<td>174.9</td>
</tr>
<tr>
<td>Wilmington - Prices Corner</td>
<td>13.31</td>
<td>108.5</td>
<td>78.6</td>
</tr>
<tr>
<td>New Castle - DMV</td>
<td>0.14</td>
<td>89.6</td>
<td>67.1</td>
</tr>
</tbody>
</table>

For five of the eight gages, the convective radar Z-R equation provides rainfall estimates that exceed the tropical radar equation. From those five, three of them showed increases of over 20 mm for their storm totals. In comparison of the three that showed decreases from the convective to tropical, their differences were between 17 and 30 mm. Two of the three gages are located in the lower portion of the watershed where changes in precipitation would have less influence.

4.2  Radar Calibration

Radar data provide a more spatially dense representation of precipitation than can be afforded by raingage networks. To evaluate its
efficacy, three different radar products will be considered. First, the standard NWS Z-R equation \((Z = 300 R^{1.4})\) was employed as it is the most widely used equation by the NWS and was used in real time by forecasters at the NWS in Mt. Holly, NJ to monitor Tropical Storm Henri. A second choice was the tropical Z-R relationship \((Z = 250 R^{1.2})\) that is often applied to tropical events.

The third approach is to use gage data to calibrate the radar and derive an appropriate Z-R relationship from the station data (Legates 2000). Using all stations from the NWS First Order Weather Station network under the Mt. Holly (NJ) radar (not just the single station that represented the watershed), a calibrated Z-R relationship was computed (Figure 4.2). Pairs of data for which the raingage value was below 1 mm were removed from the analysis since the accuracy of the raingage is only 1 mm. From this graph, a line was fit to the data using weighted regression (with the rainfall amount as the weight) and the calibrated Z-R relationship was created \((Z = 34.93 R^{1.9944})\).
Figure 4.2  Gage Precipitation versus Radar Precipitation for calibrated radar equation.

From hourly data for the entire three and a half days of the event, seventy-three valid gage-radar pairs were found of which only twenty-eight met the above criteria. This fit was based on only the convective Z-R radar scans from Fort Dix, as that was the Z-R relationship in use at the time of the storm.

4.3 Adjustments to observed hydrographs

Tropical Storm Henri produced an observed flow in the Red Clay Creek that corresponded to a 250-year flood at the Stanton, DE stream gauge and a 500-year flood at the Kennett Square, PA and Wooddale, DE stream gauges in the basin (DGS 2010). The largest peak flow, 917.5 m$^3$/s, was observed at the Wooddale station. This value was adjusted from original gage
measurements (Figure 4.3) following site observations by the USGS (USGS 2011). Note that data for the Stanton stream gauge were limited to only the peak flow; the full hydrograph is unavailable (note the odd shape to the hydrograph in Figure 4.3).
Figure 4.3  Observed hydrographs for Tropical Storm Henri at the three USGS stream gage locations in the Red Clay Creek Watershed. Note that only peak flow information was available from the Stanton (DE) gauge.
4.4 Adjustments to Model Specifications

To compare the modeled hydrographs with the observed, steps were taken to account for Tropical Storm Henri’s unique characteristics. Base flows in the upper basins were added to the modeled hydrographs to generate a peak flow at levels that were observed. These flows were based on the average flows documented by the DGS (DGS 2010). In addition, other basin characteristics were also adjusted for this storm from previously-used values. This included routing information that was adjusted for the sub-basin above Stanton to more accurately model the overbank flooding that occurred. In addition, the shape of the stream was changed from the standard Trapezoid shape to the Eight Point shape. The characteristics about that part of the stream such as bottom width and side slope were kept the same, but the Eight Point shape allows for water above flood stage to be properly taken into account.

While the change in the shape of the stream helped to account for some of the difference between the observed and simulated hydrographs, water loss through percolation on the flood plain and through the stream sides was added to account for the water leaving the flood plain through the ground.

4.5 Hydrograph Results

After these precipitation data sets were prepared, the hydrologic model was applied using the adjustments outlined earlier. Comparison of the results between the six data sets and the observed flow at each of the three stream gage locations are shown (Figure 4.4). As can be seen for each location,
only the two precipitation inputs that use the tropical Z-R relationship – the
tropical radar data and the DEOS tropical data – did not require additional base
flow adjustments. The base flow additions are most apparent in the two gage
locations that are in the upper sections of the basin, namely Kennett Square
and Wooddale. In all three locations, the results favor the two tropical data sets
and the two radar data sets. These two data sets both compared favorably to the
observed hydrograph from the beginning of the model run to its end. The
values for the flow as well as the timing of the peak matched nearly perfectly
for all three locations. Kennett Square was the only location that the tropical
radar data produced a flow peak that was far from the observed values.
Figure 4.4 Observed and Modeled hydrographs for Stanton, DE (a), Wooddale, DE (b), and Kennett Square, PA (c). Observed data and the six data sets are as follows: the National Weather Service gage, the Delaware Environmental Observing System gage locations for both calibrated and tropical data, the convective radar, the calibrated radar, and the tropical radar.
Table 4.2 shows the peak flow values that the hydrologic model produced for each of the data set in comparison to the observed flow. The convective radar and the calibrated radar input produce the best results, with the exception of the tropical radar input at Kennett Square. In each of these cases, an underestimation still exists which is most likely due to both the spatial variability of rainfall as well as the complexities of the various model characteristics. Note that the streamflow simulation which least resembles the observations uses the single National Weather Service Gage. This is to be expected, however, as the single station is not centrally located in the watershed and does not represent the spatial distribution of the precipitation. Timing of peak flow and the shape of the hydrograph is also an important consideration. Table 4.3 shows the time at which peak flow occurred at each station for each simulation run as well as the observations.
At each of these locations, all precipitation inputs led to peak flows that were lagged by fifteen to thirty minutes behind the observed peak. While this is not the case for the NWS gage distribution, the hydrograph is the least well represented. The consistency of the timing of the peaks from the three radar simulations is to be expected due to the fact that they are based on the same set of reflectivities. Any part of the small lag or lack-thereof may be due to the differences between the Z-R equations and the way the model handles the two different precipitation methods. The difference between the Z-R equations can be seen even between similar precipitation methods because the different equations can change when peak precipitation occurs.

Another way to compare the hydrographs is to compare their shape and how the simulated hydrograph changes through the storm. In Figure 4.5, the difference between the modeled results and the observed are shown for Kennett Square and Wooddale. Differences in the flow at Kennett Square and at Wooddale for most of the simulations are very large. Average differences in

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**Table 4.2**  Observed Peak Flow vs. the Modeled Peak Flows for Tropical Storm Henri

<table>
<thead>
<tr>
<th>Location</th>
<th>Observed Flow</th>
<th>NWS* Flow %</th>
<th>DEOS* Flow %</th>
<th>DEOS Tropical Flow %</th>
<th>Radar Convective* Flow %</th>
<th>Radar Calibrated* Flow %</th>
<th>Radar Tropical Flow %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kennett Square, PA</td>
<td>557.8</td>
<td>-70.1</td>
<td>418.2</td>
<td>257.5</td>
<td>569.0</td>
<td>-2.0</td>
<td>556.9</td>
</tr>
<tr>
<td>Wooddale, DE</td>
<td>917.5</td>
<td>-46.0</td>
<td>867.7</td>
<td>824.4</td>
<td>898.0</td>
<td>-2.1</td>
<td>904.6</td>
</tr>
<tr>
<td>Stanton, DE</td>
<td>492.7</td>
<td>-64.6</td>
<td>529.6</td>
<td>540.6</td>
<td>487.4</td>
<td>-1.1</td>
<td>495.0</td>
</tr>
</tbody>
</table>

---

**Table 4.3**  Time of Observed Peak Flow vs. the Time of the Modeled Peak Flows for Tropical Storm Henri

<table>
<thead>
<tr>
<th>Location</th>
<th>All Times 9/15/2003</th>
<th>Observed</th>
<th>NWS</th>
<th>DEOS</th>
<th>DEOS Tropical</th>
<th>Radar Convective</th>
<th>Radar Calibrated</th>
<th>Radar Tropical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kennett Square, PA</td>
<td>9:30 AM</td>
<td>6:30 AM</td>
<td>9:45 AM</td>
<td>9:45 AM</td>
<td>9:45 AM</td>
<td>10:00 AM</td>
<td>10:00 AM</td>
<td></td>
</tr>
<tr>
<td>Wooddale, DE</td>
<td>10:45 AM</td>
<td>7:30 AM</td>
<td>10:45 AM</td>
<td>10:30 AM</td>
<td>10:30 AM</td>
<td>11:00 AM</td>
<td>10:45 AM</td>
<td></td>
</tr>
<tr>
<td>Stanton, DE</td>
<td>Unknown</td>
<td>7:30 AM</td>
<td>11:00 AM</td>
<td>11:00 AM</td>
<td>11:00 AM</td>
<td>11:00 AM</td>
<td>11:00 AM</td>
<td></td>
</tr>
</tbody>
</table>
flow for most are greater at Wooddale, with the exception of the result from
the tropical radar data. At both locations though the two data sets derived from
the tropical Z-R represent the observed flow the best of the six data sets.
Figure 4.5 Difference between observed flow and modeled flows for the entire event for (a) Kennett Square, and (b) Wooddale.
After comparing all of the results, the two tropical Z-R based data sets fared the best out of the six. While the tropical radar simulation drastically overestimates the peak flow values at Kennett Square, it best represents the hydrograph at Wooldale. The results from the simulation using the DEOS gage distribution with the tropical Z-R estimates produces results close to that of the observed flow values. However, the timing of the peak at each gage is incorrect. Each of the two tropical Z-R based data sets have their own strengths and weaknesses. As the simulation using the DEOS gages proves a model using quality gage data can provide results that are just as good as the results from radar based products. However, gage networks like DEOS are not equally dispersed throughout the country so in some instances the best data that is available will be the radar. The results will depend on the quality of data from either source so as was shown the best data in either form should be used to provide the best results. In this study, the simulation that uses the tropical Z-R relationship is superior. However, the radar-based inputs generally produce a more realistic hydrograph for the Red Clay Creek.
Chapter 5

CONCLUSIONS

5.1 Summary

The analysis of varied precipitation inputs into a hydrologic model for the Red Clay Creek for Tropical Storm Henri provides an understanding of the importance of quality data in making accurate hydrologic simulations. This study focused on both radar and station data for an extreme rainfall event produced by the remnants of Tropical Storm Henri over the White Clay Creek basin. This allows a unique focus on an extreme storm with considerable spatial variability over a relatively short distance. Three significantly different data sets were considered with two raingage distributions and NWS radar estimates. This provided an evaluation of the effect of different precipitation inputs on a hydrologic model.

The major research question of the study was to compare how well these different data sets can accurately reproduce the storm’s hydrograph at three different locations in the Red Clay Creek basin. This type of comparison of data sets provides information that is critical in understanding all storm events and flood modeling for forecasts.

5.2 Results

The remnants of Tropical Storm Henri produced flooding that ranks above the 250-year interval for flow and gage height values for all of the
three stations within the Red Clay Creek basin. The stream gauges at Wooddale and Kennett Square both had values that correspond to a reoccurrence at half of a millennia. The storm was modeled using six different sets of precipitation input data using the HEC-HMS model that had been previously created to compare and model storms of varying synoptic types in this basin. After all the calibrations on the data were complete, the model was run for each of the six types of data with varying results for each. The expectation that the data with a better resolution would provide a better estimate of the actual event was for the most part correct. However, all data sets that used the convective radar data or NWS gage data required base flow values well above the values that were actually recorded prior to the storm. This led to the conclusion that the tropical Z-R relationship provided the best results for the model. This conclusion was made after comparing all the simulations qualitatively (visually), comparing the peak values and the timing of the peak, and comparing the differences between the observed and simulated flows. By doing so we see that the timing and value of the peak flows in the simulations using the tropical Z-R data produce the best results. This was then backed up by comparing the average differences between the observed and simulated flow values which showed that these same data sets provided the most accurate representation of the entire event. It is also important to note, however, that the difference between the two simulations using the tropical Z-R relationship is smaller than between the other four data sets. Thus, if the rain gage network is sufficiently dense and reasonably
accurate, a high density raingage network can provide a representation of the storm that is commensurate with that obtained by the use of weather radar.

5.3 Future Research Questions

The results from this research provides some answers about flooding and the impact of data especially for this region as well as confirming some ideas that have been stated previously in research regarding the need for quality precipitation data and the effect of data resolution on model and forecast results. Much of the newest research will use a combination of current hydrological models with more statistically-based methods for converting rainfall hyetographs to runoff hydrographs. In addition, the modernization of the NEXRAD network to dual-polarization radars, some of the guess work and errors that are brought in by using an incorrect Z-R relationship can be removed. The radars ability to more accurately detect and view precipitation in both a horizontal and vertical axis should lead to better Z-R relationships and better estimates of rainfall amounts. But it still remains clear that any hydrologic model will only be as good as the precipitation input.
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