Public Abstract
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Using Radar and Hydrologic Data to Improve Forecasts of Flash Floods in Missouri
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advisor's signature

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The new decision making process investigated combines the use of meteorological and hydrological data into a scoring chart. In developing this new method of decision-making, the author examined two case studies of flash floods to determine what factors play a role in flash flood development, and developed a preliminary way that radar data and hydrologic information can be used differently by forecasters. The scoring chart can be used to analyze data, and it is shown that this chart produces scores that are correlated with flood severity, thereby helping forecasters focus on particular storms, and on particular streams that may cause more severe flash flooding.

Radar data was also examined for the case studies, and a new method of assessing storm motion was investigated and used in the forecasting method. The new radar tracking method looked at the speed of the rear edge of the storm, rather than at the more commonly observed storm centroid. The rear edge was used because the total duration of time a system spends over a particular area is a better way to gauge the potential of particular storms for causing flash floods than looking at individual cell motion.

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Elizabeth Hatter

Dr. Neil Fox, Thesis Supervisor

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

USING RADAR AND HYDROLOGIC DATA TO IMPROVE FORECASTS OF FLASH FLOODS IN MISSOURI

Presented by Elizabeth Hatter

A candidate for the degree of Master of Science

And hereby certify that in their opinion it is worthy of acceptance.

USING RADAR AND HYDROLOGIC DATA TO IMPROVE FORECASTS OF FLASH FLOODS IN MISSOURI

A Thesis presented to the Faculty of the Graduate School
University of Missouri-Columbia

In Partial Fulfillment
Of the Requirements for the Degree
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by

Elizabeth Hatter

Dr. Neil Fox, Thesis Supervisor

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Chapter 1

Introduction

The most annual fatalities related to convective storms are not due to tornadoes or lightning, but are caused by flash floods. Despite this fact, forecasting the occurrence and severity of flash floods is still an imperfect science. This type of event is of great concern to forecasters as flash flooding can have dramatic impacts on the population, in terms of both economic and human losses (Doswell *et al.* 1996). The forecaster has the challenge of forecasting the occurrence of the event, as well as attempting to determine the magnitude of the flooding. Since the public often does not recognize the threat of heavy flooding rainfalls, forecasters must also be able to warn the public adequately of the threat of floods. By providing advance notice of dangerous conditions, forecasters can help minimize the damage that can occur from this type of event.

When issuing warnings, forecasters have many things to consider. They have many different sources of data available and must make choices about which source they will examine more closely, as time is very often limited in warning situations. There may be different ways to use data that may better suit the forecaster's needs. These are important factors that will be explored further in this work.

Several programs provide information that aids forecasters in narrowing their focus to particular storms, such as the severe weather potential algorithms used with the WSR-88D radar system (Kitzmiller *et al.* 1995). These automatic systems look for particular radar signatures and alert forecasters to cells that have the potential of producing severe weather in a specific time frame, and can also track cells and forecast their future positions. However, these systems have some limitations when used to forecast flash floods, including how the storm cells are tracked. These systems do not necessarily require human input to operate, but instead rely on computer algorithms to provide information to forecasters.

Other situations require more human input. Forecasting for flash flood events is one example of this type of situation. While radar can provide information on rainfall rates and storm movement, the decision to issue a flash flood warning is primarily driven by human knowledge and experience. Forecasters tend to develop a ‘feel’ for their area and develop experience as to which rivers or streams tend to flood more quickly. It is hoped that by examining the decision-making process for flash flood events, the process can be made faster and more efficient, leading to increases in warning times.

1.1 Statement of Thesis

The purpose of this research is to increase warning lead times in flash flood events. This will be accomplished by improving the decision-making process used by forecasters in identifying which particular catchment the forecaster should focus attention on, and to examine how radar tracking of cells can be adjusted to be more useful in forecasting flash floods.

It is hoped that the new process will better combine the use of meteorological and hydrological data. To develop this new method of decision-making, the author will examine two case studies of flash floods to determine what factors play a role in flash flood development, and will develop a preliminary way that radar data and hydrologic information can be used differently by forecasters.

Radar data will also be examined for the case studies, and a new method of assessing storm motion will be developed and used in the forecasting method. The new radar tracking method will examine the speed of the rear edge of the storm, rather than at the storm centroid. The rear edge will be used because the total duration of time a system is over a particular area is a better way to gauge the potential of particular storms for causing flash floods than looking at individual cell motion.

The objectives of this study are to:

- Develop a scoring chart to analyze data and test its usefulness as a flash flood forecasting tool.
- Demonstrate that assessing storm motion by examining the rear edge of the storm system using radar data can be a more useful measure of forecasting flash floods than using centroid-tracking algorithms.

Chapter 2

Literature Review

While there are many approaches to studying flash flood events, there appears to be a lack of work connecting the meteorological aspects with the hydrological aspects that lead to flash flood development. Doswell has studied severe weather events for many years, and has conducted several studies on flash floods that focus on the atmospheric conditions (Johns and Doswell 1992; Doswell *et al.* 1996). Doswell *et al.* (1996) admitted to the problem of examining both meteorology and hydrology in their paper; they stated that addressing the hydrological aspects would be outside the scope of that particular paper. In many research studies, meteorology and hydrology are viewed as separate entities, when they should be examined together to develop the best overall picture of the situation. One focus of this thesis will be the combination of these two factors. First, however, a literature review of previous research on forecasting flash floods will be undertaken and presented in this chapter.

2.1 Current Forecasting Techniques – The Human Element

Weather forecasting is still an imperfect science, yet advances are continuously being made, especially as improvements in computing power and instruments occur. In order to forecast flash flood events, forecasters must make use of many different types of data and attempt to make the most informed decision that they can. Even though great advances have been made in numerical weather prediction, humans still have an important role in forecasting.

Doswell (1986) discussed the “human element in weather forecasting”. He stated that the prediction of the weather could be explained in terms of the current state of the atmosphere plus an understanding of the time rate of change of the atmosphere. Forming a diagnosis of the current state of the atmosphere is a crucial first step. While technology can assist in providing data, it is important for the forecaster to form his or her own impression of the current state of the atmosphere. Forming this impression can be done in several ways, but usually includes analyzing maps, viewing satellite and radar data, and looking at upper level data. Forming an idea of how the atmosphere will change, or the prognosis, follows the diagnostic phase.

The prognostic portion of the forecast usually includes information from objective sources such as numerical weather models, and some from the own forecasters’ intuitive ‘feel’ of how the atmosphere is going to change. As Doswell (1986) stated, guidance products can produce fairly skilled forecasts, particularly during ordinary weather conditions. However, their skill can drop considerably during times of changing or severe weather conditions, which is when they would be most useful to the forecaster. It is during these times that forecasters must rely more on their own skill than on information provided to them from models.

Several articles (Roebber and Bosart 1996a, Roebber and Bosart 1996b, and Roebber *et al.* 1996) also discussed the value of human input in weather forecasting. Roebber and Bosart (1996a) examined the relationship between experience and education on forecasts of local temperatures and probability of precipitation. In a similar article, Roebber and Bosart (1996b) examined the relationship between forecast skill and forecast value. In their research, they evaluated the value of National Weather Service forecasts in real-world situations and found the dollar value of forecasts. In both of these articles, they found that there was a definite, although in some cases slight, advantage to having human input in weather forecasting rather than just relying on numerical-statistical guidance. Both of these articles examined temperature and probability of precipitation forecasts, and not at severe weather forecasting. In severe weather forecasting it would be likely that the value of human input would be even higher, as operational models are not as able to forecast such small-scale phenomena at this time.

Roebber *et al.* (1996) also examined how distance from the forecast site affects forecast skill. They examined results from the national collegiate weather forecast contest to determine if regional knowledge could help improve forecasts for temperature and precipitation, as regional or local knowledge of model output biases could be expected to improve forecasts. The study found that regional knowledge does provide a slight advantage to experienced forecasters when forecasting temperatures. Precipitation forecasts did not show the same level of increase in skill as temperature forecasts, although the authors felt that this could partially be explained due to the lack of local forecasts, rather than just regional and distant ones. The authors felt that forecasters can learn to use and interpret numerical model guidance based on local peculiarities after they become more familiar with their forecast area. They applied these findings to the National Weather Service by discussing how moving forecasters frequently during their careers might be detrimental to their forecast skill, as they lose their 'local knowledge' when they move. This is one concern that will hopefully be addressed by this study, and will help improve forecasters' local knowledge when forecasting a flash flood event by 'storing' that knowledge in the scoring chart.

Another, similar, method of forecasting was also discussed in articles on severe local storm forecasting by Johns and Doswell (1992), and Doswell *et al.* (1993). Doswell *et al.* (1993) developed a two part procedure for forecasting tornadoes that also can be applied to other types of severe weather: anticipation of severe potential in a storm environment and recognition of a severe storm once it has developed. Johns and Doswell (1992) focused on the first part of the process, the relationship between the storm and its environment. The forecasting process used involves parameter evaluation, pattern recognition, and climatology. Severe local storm forecasters focus their efforts on issuing watches for significant weather events and concentrations of severe weather events. They issue many types of products and rely heavily on synoptic and mesoscale data, as parameter evaluation and pattern detection both rely on synoptic and mesoscale analyses. Data used includes surface data, satellite imagery, radar, lightning data, and wind profiler information. Mesoscale model data is also used.

Johns and Doswell (1992) also included the idea of 'ingredients-based' forecasting, where particular key components are sought in anticipation of severe weather. This article focused on severe weather, but Doswell *et al.* (1996) later developed and extended this idea to flash floods. Most severe weather is associated with deep convection. There are three 'ingredients' for deep convection: a sufficiently deep moist layer in low or mid-troposphere, potential instability, and sufficient lifting mechanism. Radiosonde data play an important role in determining the current thermodynamic structure of the atmosphere. The forecasters use the surface data, model data, and radiosonde information to develop various prognoses from the initial composite chart. They then use the parameter values and patterns on the prognoses to locate areas of possible convection and severe weather. If a forecaster decides that deep convection is likely, they must then determine whether it will produce large hail, strong winds, or tornadoes. They must often make the decision quickly if they are going to provide sufficient lead-time to emergency services.

Subramaniam and Kerpedjiev (1998) discussed how emergency services use forecast information. They found that disseminating local weather information can be improved by using graphics and other means of expression in addition to the text bulletins currently used. One system they examined was the

MeteoAssert system, which uses several data sources, including radar, numerical models, and land use information, to make assertions, which are then sent in many formats to emergency service personnel. The system is simple to use and highlights the information important to the users' needs. This highlights some similar needs that forecasters require and that need to be considered in this study. In order for the proposed scoring system to be useful, it needs to be both easy to use, and supply the forecasters with the information that they need to improve their decision making.

2.2 Flash Flood Factors

Flash floods are caused primarily by heavy rainfall events, but there are other factors that influence both the occurrence and severity of flooding. These factors include both meteorological aspects of the particular storm as well as hydrological features of the particular watershed. Flash flood forecasting is a difficult process, as one must not simply forecast precipitation intensity, but must also take into consideration timing, motion, and location of the precipitation.

Maddox *et al.* (1979) conducted a study of more than 150 heavy precipitation events in the United States. They found that common characteristics of heavy precipitation include the following: convective type storms, high surface dewpoint temperatures, high moisture content through a deep layer of the troposphere, and weak to moderate vertical wind shear. These characteristics were present in all cases, although the authors went further and divided the types of storms producing heavy precipitation into four types, synoptic, frontal, mesohigh, and western. Synoptic events were related to an intense synoptic scale cyclone or frontal system, and were common in the spring and fall months. Frontal events were triggered by stationary or slow moving frontal boundaries. Mesohigh events were the most common, and were associated with a thunderstorm outflow boundary from prior convective activity (Maddox *et al.*, 1979).

Doswell *et al.* (1996) also examined the factors that lead to flash floods. The first 'ingredient' is heavy precipitation. Heavy precipitation is the result of sustained high rainfall rates. These situations are dependent upon rapid ascent of air with substantial water vapor and the precipitation efficiency. Other major factors that contribute to the occurrence of flash floods include antecedent precipitation, the size and topography of the basin, the type of land usage in the basin and other such hydrological factors. Doswell *et al.* (1996) chose to focus more on the atmospheric conditions leading to the heavy rainfall events than on the hydrological factors.

The heaviest precipitation occurs where the rainfall rate is the highest for the longest time (Doswell *et al.* 1996). The amount of precipitation produced can be calculated by:

$$P = R_{av}D \quad (2.1)$$

where R_{av} is the average rainfall rate and D is the duration. There were crude thresholds given for rainfall events, with moderately high rainfall rates beginning at about 25 mm or 1 inch per hour, and moderately long durations of approximately one hour.

For significant rain to develop, rising air needs a substantial water vapor content and a rapid ascent rate. The instantaneous rate (R) at a given point can be given by:

$$R = Ewq \tag{2.2}$$

where w is the ascent rate, q is the mixing ratio and E is the precipitation efficiency given by:

$$E = \frac{m_p}{m_i}. \tag{2.3}$$

where m_p is mass of water falling as precipitation, and the influx of water vapor mass is given by m_i. Instantaneous values of E will vary by location in the storm and also over time. Rainfall rates associated with convection are generally higher than those associated with other processes. Deep moist convection is associated with buoyancy and depends on lapse rates as found in parcel theory. The environmental lapse rate must be conditionally unstable, there must be sufficient moisture, and there needs to be some source of lift to initiate deep convection.

Duration is also important for determining heavy rainfall events. Duration is related to many factors, including system movement speed, the system size, and variations in rainfall intensity within the system. Most important flash flood cases are produced by quasi-stationary convective systems, where propagation of storm cells leads to new development and many cells propagating over the same area. Cell movement is often associated with the mean wind through a deep tropospheric layer. Strong winds generally lead to faster moving storms, while slow winds will mean a slower moving system (Doswell *et al.* 1996; Corfidi *et al.* 1996). Storm duration (especially over a particular catchment) is an important factor in this study, and will be examined using radar data in later sections.

Flash floods can develop from several types of storm systems. As stated previously, Maddox *et al.* (1979) identified four classifications of flash flood events: frontal, synoptic, mesohigh, and western. Most flash flood rainfall events are multicellular in nature (Doswell *et al.* 1996). Mesoscale convective systems (MCS) produce virtually all flash floods in the central United States. Supercells tend to have strong updrafts and significant low-level moisture, both necessary ingredients for flash flood rainfalls. However, many supercells have dry mid-levels and tend to move quickly, which decreases the amount of rainfall they will produce over a given area. Some supercells will evolve into MCSs, which will then produce flash floods. MCSs can also form repeatedly over days and weeks, which will lead to both flash floods and river flooding as seen in the Midwest in 1993. Some flash floods occur in non-convective environments where updrafts are forced. Orographically forced storms will fit into this category (Dowell *et al.* 1996).

Flash floods are somewhat difficult to predict operationally. Forecasters may face a lack of experience for forecasting flash floods on particular streams if they are new to a forecast area. Also, reliance on forecasting indices can be misleading as the necessary ingredients may not be in place during the morning sounding. It is important for forecasters to understand the atmospheric situations that can lead to heavy rainfall events. Synoptic-scale systems do play a role in the smaller scale processes leading to flash floods. Large-scale vertical ascent can lead to a moistening and destabilization of the atmosphere. Also, many events occur near a 500mb ridge axis. This is an area that allows for moisture to accumulate, and storms tend to occur on the margins of a ridge giving the 'ring of fire' effect (Doswell *et al.* 1996). Mesoscale processes play a large role in storms, as these processes tend to provide the lift, affect the storm movements, and also initiate new development along outflow boundaries. Winds play a large role in system propagation and in the location of new cell development. It is important to forecast the location and strength of the outflow to determine storm propagation. If forecasters become aware of how these different scales interact and what atmospheric processes lead to heavy rainfall producing storms, they will be better prepared to forecast flash flood events. Forecasting the location and the timing of a flash flood also needs to be improved (Johns and Doswell 1992; Doswell *et al.* 1996).

While many forecasters are not hydrologists, it is important to have an understanding of how catchment characteristics lead to flash floods. Fox and

Collier (2000) discussed developing a system that would predict flooding in individual river catchments. In a similar manner to Doswell *et al.* (1996) above, they forecasted flooding by estimating potential convective rainfall. They used a simple hydrological model that measures peak flow produced per mm of rain over the catchment, which is given by:

$$Q_p = \frac{22}{100T_c} RA_c \tag{2.4}$$

where Q_p is peak flow in m^3s^{-1}, R is rainfall in mm, A_c is catchment area in km^2, and T_c is time of concentration in hours given by:

$$T_c = 0.00025\left(\frac{L}{\sqrt{s}}\right)^{0.8} \tag{2.5}$$

where L is length of river channel in m, and s is the catchment slope.

This simple hydrological model (2.4) can be inverted to calculate that amount of rainfall required to produce a particular flow height. The required rainfall then can be used to forecast whether a particular set of atmospheric conditions would be able to produce sufficient rainfall to cause flooding over particular catchments. Using precipitation forecasts that can be produced reasonably far ahead of the event, potential flood cases can be monitored and advanced warning may be able to be issued if conditions look ripe for particular rainfall amounts.

2.3 Modeling Flash Floods

Many authors have undertaken modeling studies of historic flash floods, or have attempted to develop models to predict the occurrence of floods. Yoshizaki and Ogura (1988) chose to model the Big Thompson Storm that occurred on 31 July to 1 August 1976. This storm caused devastating flash flooding in the canyon and killed at least 139 people. The storm was of additional interest because of its interesting precipitation pattern; most of the rain fell on the basin area and not on the mountain peak. On the day of the storm, there was a secondary cold frontal surge on the foothills with moist unstable air behind the front. The storm was modeled using both two- and three-dimensional models to examine the orographic and convective features of the system.

Yoshizaki and Ogura (1988) first used a two-dimensional compressible moist cloud model that they had developed. They stated that they wanted to investigate the dependence of orographic/convective precipitation on the air conditions and terrain shape, and so performed many experiments with different model specifications for each one. The model storm showed many of the same characteristics of the actual storm. The lower portions of both the model and observed storms had a westward tilt while the upper part was more upright. Most of the precipitation was modeled to fall on the downstream side of the storm, which fits observations. The model also showed the same secondary convective cells as the actual observations. The model showed that storm cells formed and moved downstream towards the mountain peak, with a new cell developing where the old one had developed. This area of development was pushed further down the mountain because of the formation of a cold pool. The cells drifted towards the peak because of an induced low-pressure center at the top of the cold pool area. The models showed that the location of heavy precipitation is related to the location of the first deep convective cells, and could form areas other than the mountain peak.

In the three-dimensional model a northerly flow developed due to the Coriolis force. As a result, the rain fell over the southern part of the valley and not at the north / south symmetry line as in the 2-D model. The rainfall rate was also higher, which was expected due to more vigorous convective development. There was also a much stronger outflow beneath the storm in the 3-D model. The updraft still maintained the slanted vertical structure, but it was less than that found in the 2-D model. The negative pressure anomaly was also weaker in the 3-D model storm. The 3-D storm tended to be nearly stationary, while the 2-D storm had been much more transient. Also, the two-dimensional storm showed a more distinct multicellular development than the three-dimensional models developed. This study focused on the atmospheric properties of a flash flood, and shows both the possibilities as well as limitations of using explicit atmospheric modeling.

Baker *et al.* (2004) examined the case of 6-7 May 2000 (which is one of the case studies in this paper presented in a later chapter). They performed high-resolution simulations using two types of model initiations and also two different land surfaces. Using different land surfaces allows for modeling of land-atmosphere interactions, which are significant in cloud formation and development. One land surface used kept soil moisture constant, the other allowed for rainfall to affect soil moisture patterns. The authors felt that using the more sophisticated land surface model may help improve the model precipitation forecasts. The authors found that using the high-resolution model and the variable land surface model combined gave the most realistic precipitation forecasts, both in location and amount of precipitation. The forecast from the coarse resolution model, combined with the constant soil moisture, was off by nearly 150 km. It was also found that by allowing the soil moisture to vary in the more sophisticated land surface model, the low-level jet (LLJ) was more accurately forecast. In this case, the low-level jet interacted with outflow boundaries to produce additional convection, so the location of the LLJ was vital to an accurate precipitation forecast. Baker *et al.* (2004) feel that numerical weather prediction of flash floods could benefit greatly from increased use of high-resolution numerical models coupled with interactive land-atmosphere schemes.

There also are many hydrologic models that can be used to predict the response of a catchment. Simple models, such as unit hydrographs, use basin characteristics to predict the streamflow from a given unit of direct runoff uniformly distributed over the catchment (Benient and Huber 2002). Many hydrological computer simulations are also available, such as the Hydrologic

Engineering Center (HEC) hydrologic modeling system, Environmental Protection Agency (EPA) storm water management model, and several models from the Soil Conservation Service.

Rainfall duration and intensity are the important parameters to the rainfall-runoff process, which is translated into streamflow based on the watershed characteristics. Many hydrological models use precipitation amounts from raingauge data as input (Benient and Huber 2002). However, a few models are able to use radar data to supply precipitation amount and spatial variation over a watershed. Radar data can give a more accurate spatial picture of precipitation over the watershed, and the resulting streamflow from each segment and from the entire watershed may be more accurate if radar data is used (James *et al.* 1993). A common problem with hydrological models is that they are not able to be run operationally, or require data that is not easy to update or obtain (Benient and Huber 2002).

Collier and Fox (2003) developed a forecasting system for flash floods in the United Kingdom that is similar to the goals of this study. The paper examined the susceptibility of river catchments to flooding in extreme rainfall events. In the UK, the eight Environment Agency regions have autonomy in deciding when to issue flood warnings. Some regions use a simple time-accumulation threshold for determining when to issue warnings. There have been proposals to use probabilistic rainfall forecasts from NWP, but this has not yet been widely accepted. The authors of this paper suggested the use of a scoring system that can be easily used, and that represents the major hydrological and meteorological factors that contribute to flooding. Flash floods are caused by heavy rainfall on a rapidly responding basin, and the amount and distribution of rainfall are prime factors in determining the occurrence of a flood. Since they occur quickly after rainfall, quantitative precipitation forecasts must be used to predict the occurrence of floods. At this point, forecasting the occurrence of convection in clear air and determining the life cycle point of a storm are both in need of improvement if better precipitation forecasts are to be made. Some work has been done on forecasting clear air convection by examining boundary effects such as those from gust fronts and convergence zones, leading to increased detection of thunderstorm initiation (Roberts and Rutledge 2003).

Collier and Fox (2003), unlike others, put an equal weight on both meteorological and hydrological factors leading to floods. In assessing the likelihood of extreme floods, a number of parameters were considered. These include the likelihood that heavy rain will become stationary and long lasting, the availability of significant precipitable water in the lower atmosphere, the likelihood that heavy precipitation producing cells will move parallel to the main watercourse, the steepness of catchment, soil moisture conditions in the catchment, blocking or debris in the channel, and snowmelt. It is important for forecasters to be able to use the information quickly during critical times. The different parameters were given a scale of zero to four. The total score would indicate the likelihood of an extreme flood occurring. The score would also relate to the severity of the flood in terms of area covered and duration of event. If hydrologists could use scores routinely updated through the storm event, they could forecast the likelihood and possible severity of the flood.

The scoring system was used to examine historical flood events. For the historical floods studied the system appeared to work, giving higher scores to more damaging cases. The scoring system identified the more damaging flood events, as the highest scores did not necessarily belong to the most intense rainfall, but to the worst flood occurrence. It also shows that even without having perfect data for all parameters, the scoring system can still be of use to forecasters. This system could be implemented into a computer program to aid forecasters. The most difficult component of the scoring table to assess was found to be storm motion; this critical factor is discussed in the next section.

2.4 Forecasting Storm Motion and Propagation

Forecasting where a storm will be located and how long it will be over a particular area are necessary when forecasting flash flood events and are components of the scoring system that will be developed in this study. There have been several studies that examined the relationship between storm motion and storm propagation from the development of new cells within the storm system. Corfidi *et al.* (1996) looked at the movement of mesoscale convective complexes (MCC). MCC movement is composed of two parts: the advective component that is proportional to the mean wind flow in the cloud layer, and the propagation component that is related to, but opposite in sign from, the low-level inflow of the storm. Stronger winds in the cloud layer lead to a larger advective component, and the storm will move over an area rather quickly.

The propagation component plays an important role in flash flood forecasting. Propagation of a system is defined by the rate and location of cell formation relative to the existing storm system. The center of a MCC tends to propagate antiparallel with the system inflow, typically the low-level jet. If sufficient propagation occurs on the rear flank of a storm, the system can become nearly stationary and produce heavy prolonged rainfalls over a particular area.

Chappell (1986) also discussed quasi-stationary systems. Slow moving systems are typically composed of many individual storms that can, and often do move repeatedly over the same areas. Chappell, like Corfidi *et al.* (1996), describes storm motion as the sum of two vectors: the first being the mean velocity of the individual cells that make up the system, and the second being the propagation velocity from the formation of new cells. The magnitude of propagation depends on the rate of cell formation, the distance between new cells and the existing system, and the rate at which the new cells grow and join the system.

The development of quasi-stationary systems depends on the larger scale environmental features, the nature of the synoptic-scale forcing, and on the location and rate of new cell formation and dissipation. If propagation occurs on the leading edge of the system it provides an accelerating effect. However, if it occurs more on the rear edge of the storm system then an effective deceleration of the system occurs. For a system to become stationary, new cells must form on the edge opposite the direction of cell motion, while cell dissipation must occur on the same edge as cell motion. The new cell growth at the rear flank is often the more active portion of the system that leads to the heavier rainfalls.

The current storm-cell identification and tracking algorithm (SCIT) in the WSR-88D radar systems tracks the storm centroid rather than any particular edge. In the updated version of the SCIT algorithm, seven reflectivity thresholds are used to identify storm cells, rather than just one. This means individual storm cells are easily tracked. A linear least squares method is used to determine movement using current and past mass-weighted centroid location (Johnson *et al.* 1998). While this algorithm is very useful in determining the motion of severe weather events (ie. tornadoes, large hail) associated with individual cells, it is less useful when trying to forecast flash floods. Because the cells can be moving relatively quickly in comparison to the storm propagation as a whole, the cell motion predicted by the storm tracking algorithm can be misleading in trying to determine the period of time it will rain over an area. It would be more beneficial to take into account storm motion and propagation as a whole, rather than individual storm cell motions. This study will take this under consideration and attempt to determine the motion of the rear flank of the storm as compared to individual cell motion.

Overall, forecasting flash flooding has been studied by many different people who all approach the problem in different ways. One common theme is that, as is the case in all severe weather events, humans play an important role in forecasting flash floods. They make the decisions, based on available data, on when to issue the warnings. Many of the papers covered above discuss just a few of the aspects of forecasting flash floods; very few treat both meteorology and hydrology in one paper. It is hoped that this study will encourage forecasters to utilize both in forecasting flash floods by providing new methods of presenting data, particularly hydrologic data to meteorologists, who may not be as familiar with using that type of data.

Chapter 3

Methodology

3.1 Study Focus

Previous flash flood research has often focused on either the atmospheric conditions that lead to extreme rainfall events, or on the hydrologic conditions of a catchment. Fewer papers have combined these two related parts of forecasting flash flood events. This study will attempt to combine both meteorology and hydrology and make an equal consideration of both in the attempt to forecast the occurrence and severity of flash floods and will also focus on a different way to track storm motion using radar data.

3.1.1 Area of Study

The focus area of this study is the state of Missouri. The central U.S. is prone to convective heavy rainfall events, and experiences many flash floods. In a typical year, the state of Missouri will experience approximately 200 flash flood events. The geography of Missouri is quite varied, from flat plains in the northern part of the state to the beginnings of the Ozark Mountains in the southern half of the state. There are many streams and rivers in the state prone to flooding, from small streams to major rivers such as the Missouri River. This study will focus on the small- to mid-size streams, as they are prone to flash floods on the short time-scales that are a challenge for forecasters.

3.1.2 Selection of Case Study Events

The National Climatic Data Center's (NCDC) online storm events database was used to select the two storm events that were studied. The case study events were chosen to be after 1990, and to have resulted in at least one death. These constraints were established to narrow the field of potential case studies, which helped to increase the availability of good quality data. The case study events chosen for the study were selected for various factors, including storm type and location. The locations of the events can be seen in Figure 3.1, and the storms occurred over areas that have a variety of land uses, from urbanized cities to rural farmland.

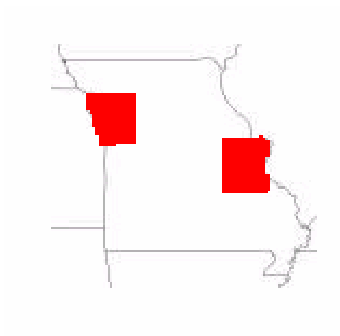

Figure 3.1 The locations of the two case study events are marked by the red areas.

As proposed by Maddox *et al.* (1979), there are four types of flash floods. The storm events chosen for the case studies were caused by different forcing mechanisms, which was done to show that the scoring chart and radar tracking could potentially work in different environmental conditions. Summaries of each event will be given later in the paper, but Table 3.1 gives basic characteristics of the case studies.

Date	Location	Total Rainfall (in)	Associated Storm Type
4-5 Oct. 1998	Central West MO	2-8	Front
7 May 2000	Central East MO	3-14	Mesohigh

Table 3.1 Characteristics of case study events

3.2 Data

In order to develop the flood prediction table, several key pieces of information were needed about each event. An overall examination of the atmospheric and hydrologic conditions leading to the event was completed. According to Doswell *et al.* (1996), key ingredients for flash floods include precipitation rate, precipitation duration, antecedent precipitation, the size and topography of the basin, and the type of land usage in the basin. Each of these pieces of information was collected for the study events, and is presented in the tables in chapter five.

Data were gathered from several sources. Atmospheric data from each storm event were gathered from climate records, including those from NCDC, which provided storm event descriptions, and the Midwestern Regional Climate office, which provided specific rainfall amounts for certain stations. Archived surface maps from Unisys provided basic maps and information on storm type and location. More detailed atmospheric data was analyzed using Gempak. Hydrologic data came primarily from Skelton and Homyk (1970), which provided catchment drainage area, slope and main channel length. Land use data were available online from United States Geological Society (USGS) watershed websites. Radar data from the National Weather Service (NWS) radar network were used to analyze the storms.

3.3 Procedure

To develop the scoring method for flash flood forecasting, several tasks were completed. Initial case study events were examined to determine measurable characteristics that contribute to flash flooding, including those factors discussed previously by Collier and Fox (2003). Each factor was examined individually, and possible values were divided into ranges. Each range was then given a numerical ranking on a scale from 0 to 4. These ranking scores were then totaled to give a score for each flood event. These scores were then compared to the depth of the flooding to determine whether the score accurately portrayed the severity of the flooding that occurred.

For the radar tracking, Nexrad level II radar data was obtained from the NWS radars located in Pleasant Hill (EAX) near Kansas City, MO, and Weldon Springs (LSX) located near St. Louis, MO. Data were analyzed to determine where the rear edge of the storm was located. The rear edge was determined to be the edge of the storm opposite the storm motion, where new development was occurring. The threshold for tracking was set at 20 dBZ. Using the raw data, the position of the rear edge could be found. This rear edge was then tracked over time, and the speed of motion was calculated by determining the distance change as compared to previous scans. This was then compared to the speed as determined by the cell-tracking algorithm.

Chapter 4

Case Studies

In the first section of this chapter, summaries of the atmospheric conditions at the time of the events are presented. In the next section, the hydrologic data are given for streams that were affected by flooding.

4.1 Atmospheric Data

4.1.1 04 – 05 October 1998

The first case occurred on 04-05 October 1998, near Kansas City and St. Joseph, Missouri. Thunderstorms produced extremely heavy rain, which led to severe flash floods over west-central Missouri during this event. The environment prior to the event was conducive to convection and heavy precipitation. Data were taken from the 0000 UTC soundings of 05 October 1998 from Springfield, MO and Topeka, KS, which are the two nearest ascent sites to the area of concern. Dewpoint depressions in the lower levels (up to 850 hPa) were quite small, as shown in Figure 4.1. The surface flow was southerly which allowed warm moist air to flow into the region from the Gulf of Mexico. The winds through the lower atmosphere showed fairly strong directional shear, which is conducive to thunderstorm development. However, the wind speed in the lower levels remained low, with strongest speeds on the order of 30 knots. This would have aided in the development of nearly stationary thunderstorms.

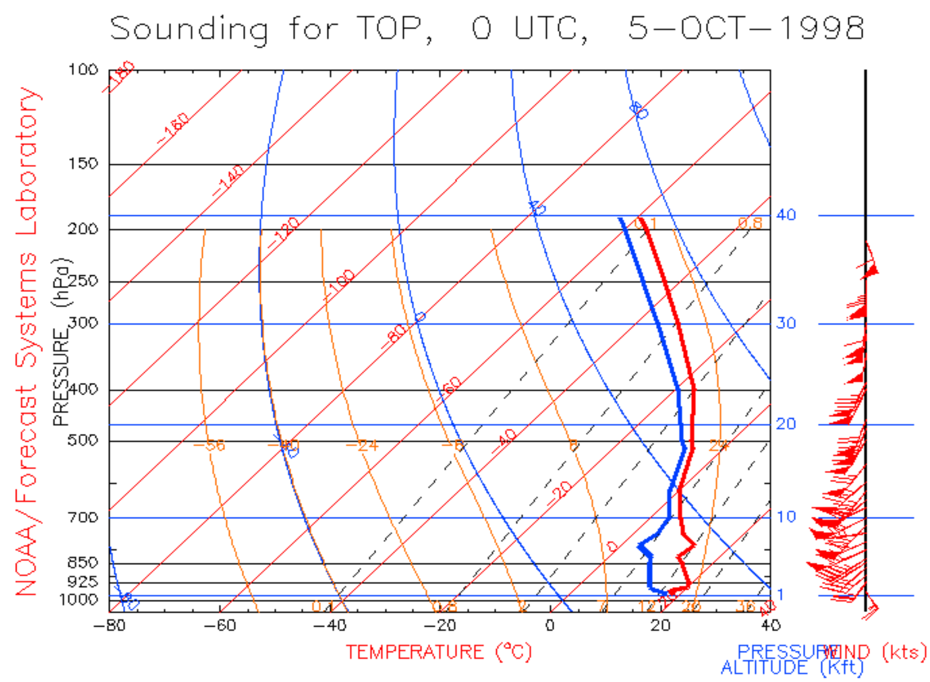

Figure 4.1 Skew-T plot of atmospheric conditions at 0000 UTC on 05 October 1998 from Topeka, Kansas.

The main focusing mechanism for the thunderstorm activity was a quasi-stationary frontal system. This is one of the common situations described by Maddox *et al.* (1979). The warm front had drifted northeastward towards west-central Missouri by 0000 UTC on 04 October. By 1200 UTC, thunderstorms producing heavy precipitation could be found both south and west of the Kansas City, MO area as seen in Figure 4.2.

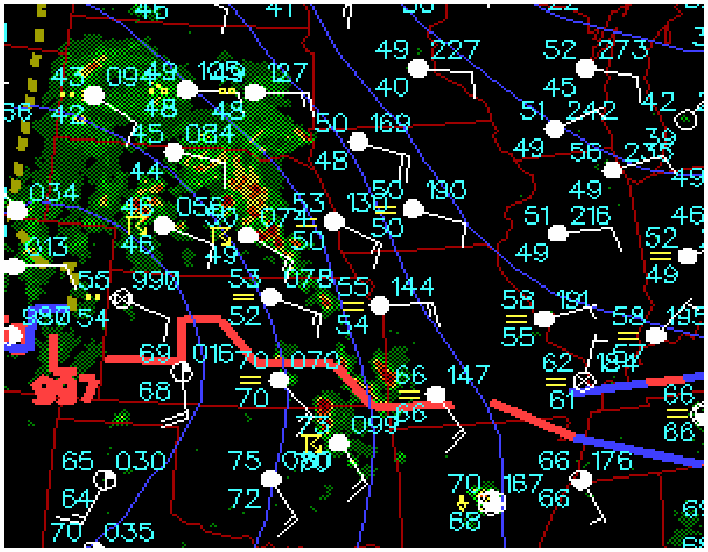

Figure 4.2 Surface analysis at 1200 UTC on 04 October 1998 (from Unysis). Green shaded areas show location of precipitation, which at this time was located northeast of the center of low pressure and along the associated warm front.

The thunderstorms were relatively slow moving and convection continued to redevelop over the same areas. These factors allowed for heavy precipitation to fall for an extended period of time. The location of the precipitation can be seen in Figures 4.3 and 4.4.

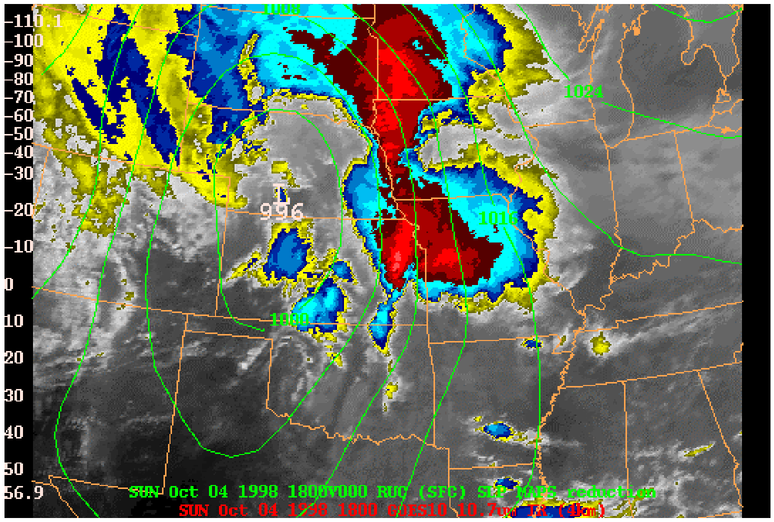

Figure 4.3 Satellite image and surface isobars at 1800 UTC on 04 October 1998 (from UCAR-COMET). The dark red portion in center indicates colder cloud top temperatures, indicating deeper convection. The isobars indicate southerly flow, which helps to feed warm, moist air into the storm system.

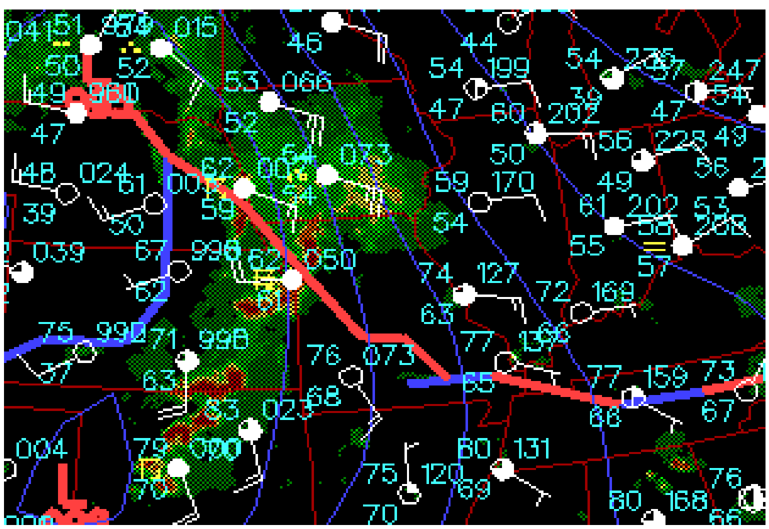

Figure 4.4 Surface analysis at 0000 UTC on 05 October 1998 (from Unisys). The green and red shaded areas show the locations of precipitation, which at this time were located near the slow moving (nearly stationary) frontal system to the west of Kansas City.

Precipitation totals varied widely over the area. Gauges at Kansas City, MO and St. Joseph, MO, recorded totals of 71.88 mm and 61.47 mm, respectively. In the storm event reports, however, much heavier amounts were recorded in the area. Some areas received as much as 76.2 mm to 127 mm in 2 hours. The highest 24-hour rainfall totals of 177.8 mm were reported in Ray and Carroll Counties.

4.1.2 07 May 2000

The second case study examined the event of 07 May 2000 over east-central Missouri. Thunderstorms produced extreme flash flooding over east central Missouri during the overnight and early morning hours of 6-7 May 2000. Glass *et al.* (2001) described the conditions before the event as seemingly “benign.” Initially the case lacked the recognizable surface features characteristic to flash floods described by Maddox *et al.* (1979). The environment prior to the storm was supportive of convection. Data taken from the 0000 UTC sounding from Springfield, MO show that the Lifted Index was only -1°C, but the K Index was 38. This was accompanied by a high precipitable water value of 36.58 mm, which is 185 percent of normal (Market *et al.* 2001). Fairly strong and persistent southerly low-level flow had allowed for substantial low-level moisture to be transported to the area from the Gulf of Mexico region.

The storm was spawned by a midlevel cyclonic vortex that can be seen over northeastern Oklahoma earlier on 6 May 2000. This system produced heavy rainfall over Oklahoma, as seen in Figure 4.5, before moving over the east central Missouri area.

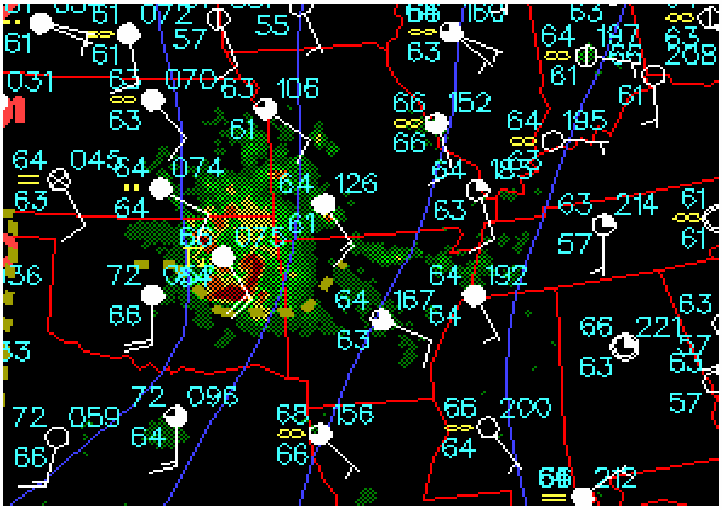

Figure 4.5 Surface analysis at 1200 UTC on 06 May 2000 (from Unisys). The green shaded area shows location of precipitation over northeastern Oklahoma, which later developed into the system causing heavy rainfall over Missouri.

By 0000 UTC on May 7 (Figure 4.6) the midlevel vortex was located over central Missouri, and began to produce thunderstorms between 0100-0200 UTC (Glass *et al.* 2001). Continual convective development on the back edge of the system led to a nearly stationary system for several hours.

Rainfall totals associated with this storm were quite dramatic. Over 305 mm of rain fell over a fairly broad span of Franklin County, MO with unofficial reports of up to 406 mm west of Union, MO (Glass *et al.* 2001). According to the event record for the storm, the rain fell at a rate of 76.2 mm per hour from about 0800 to 0900UTC.

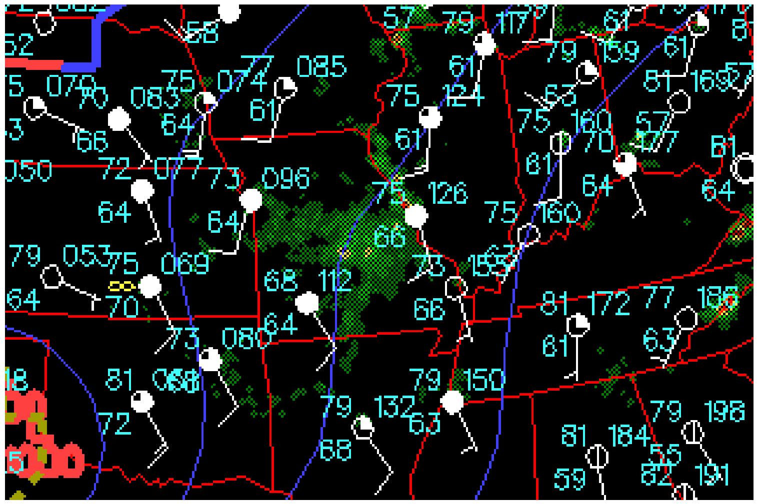

Figure 4.6 Surface analysis at 0000 UTC on 07 May 2000 (from Unisys). The green shaded area represents the location of precipitation over Missouri, which developed off the same system that previously produces heavy rainfall over Oklahoma.

In Table 4.1, a summary of the atmospheric conditions is presented for the two case studies. It is divided by river name, so as to be used in the scoring chart presented later in the study. The first four streams are associated with the 04-05 October 1998 case study, and the last four are associated with the 07 May 2000 case study.

	04-05 October 1998				07 May 2000			
River Name	**Blue River**	**Little Blue River**	**Brush Creek**	**Brush Creek**	**Bour-beuse River**	**Big River**	**Big River**	**Dar-denne Creek**
Precip Rate (in/hr)	0.80	0.60	0.60	0.80	2.00	0.60	0.90	.70
Duration of Storm (hrs)	3 hrs	3 hrs	3 hrs	3 hrs	6 hrs	6 hrs	6 hrs	6 hrs
Motion of Storm	slow	slow	slow	slow	station -ary	station –ary	station –ary	station -ary
Soil Moisture	v. wet	v. wet	v. wet	v. wet	mod	mod	mod	mod

Table 4.1 Summary of atmospheric conditions for each case study event. The first four streams are examined in the 04-05 October event, while the last four streams are examined in the 07 May 2000 event. These values will later be incorporated into the scoring chart.

4.2 Hydrological Data Overview

One important consideration for the 04-05 October case was antecedent precipitation. It had rained on 6 of 7 days prior to the event, so the soil in the area was quite saturated. Also, much of the area is urbanized, with a relatively high proportion of impervious surfaces such as concrete or asphalt. This, coupled with saturated soil, meant that almost all of the precipitation would become runoff, which would exacerbate any flash flooding. The Brush Creek watershed runs through Kansas City and it experienced quite severe flash flooding. Many of the deaths in the case were associated with flooding along this watershed. Many roads throughout the area were covered with between one to two meters of water.

The area affected by the 07 May 2000 event is more rural area than that considered in the other case study. In this case, although previous rainfall had made the ground less receptive to additional rainfall, the major reason for the flooding was the intense rainfall over an extended period of time. It rained at very high rates in some areas (upwards of 50mm/hr), so hard that the rate of absorption by the ground could not match the rate of rainfall. The worst flooding occurred in the Flat Creek watershed, which runs through Union, MO. This creek rose almost 4.5 meters from the rainfall (NCDC). Many other streams in the area also flooded causing damage to several areas.

Several different characteristics of the streams in the area were collected from Skelton and Homyk (1970) and the USGS, and are presented in the tables below. These factors, such as the slope and area of a catchment, play a role in how rainfall runs off during a storm event, and how flash floods develop in particular areas. In most cases of flash flood forecasting, these factors are not given the consideration they deserve. These will be incorporated into the scoring chart.

River Name	Blue River	Little Blue River	Brush Creek	Brush Creek	Bour-beuse River	Big River	Big River	Dar-denne Creek
Location	Kansas City	Kansas City	Kansas City	Kansas City	Union	Rich-woods	Byrnes-ville	O'Fall-on
Drain-age Area (mi^2)	188	184	15	17	808	735	917	57
Channel Slope (ft/mi)	12.4	6.3	3.5	3.7	2.8	4.6	3.4	2.6
Channel Length (mi)	22.5	35.4	3.1	8.6	135	82.2	127	12
Land Use	Urban	Sub-urban	Mostly Urban	Urban	Mostly Rural	Rural	Rural	Sub-urban
Flood Depth (ft)	29.9	12.8	13.7	21.7	24.6	11.2	22.3	3.6

Table 4.2 Hydrologic data for case study events. Flood depth is what occurred for the relevent case study event.

Chapter 5

Results

5.1 Development of Scoring Chart

For each case study, atmospheric and hydrologic data were analyzed as presented in Chapter 4, and then used to develop a scoring chart for flash flood intensity. Following previous authors' work (Doswell *et al.* 1996; Collier and Fox 2003), and from the analysis of the case study events, several factors were chosen to be included in the scoring chart. The factors are: precipitation rate, duration of storm, movement of storm, soil moisture, land use of a catchment, area of catchment, slope, length of channel, and the ratio of area to length (this ratio represents catchment shape).

The decision to use these particular factors was made for several reasons. Each factor has an impact on the likelihood of flash flooding, and meteorological factors such as precipitation rate, movement of storm and duration of storm are commonly used when making a decision to issue a flash flood warning. Slow moving storms that are producing intense precipitation are much more likely to produce a flash flood than a fast moving storm without much precipitation. Hydrological characteristics were included with the intention of increasing the use of these factors by meteorologists who are forecasting flash floods. It is hoped that by including the hydrological characteristics even forecasters who are unfamiliar with the geography of the forecast area can include those factors in their forecasts. The set of characteristics chosen influences flash flood severity, and can be measured somewhat objectively. All of the factors were chosen in part because such data are relatively easy to obtain and can be found for all areas of the country, making the chart easy to change for different forecast areas.

Each of these characteristics was divided into ranges, and each range was given a score, which can be seen in the scoring chart below (Table 5.1). The ranges were based partially on previous work by Collier and Fox (2003), and were adjusted using the case study data. The chart can then give a separate score to each stream that was affected by the event.

	Score				
Category	**0**	**1**	**2**	**3**	**4**
Precip Rate in/hr	<0.25	0.25-0.50	0.50-0.75	0.75-1.00	>1.00
Duration of storm	<30 min	30-60 min	60-120 min	120-240 min	>240 min
Motion of Storm	Rapid	Fast	Medium	Slow	Stationary
Soil Moisture	Very Dry	Dry	Moderate	Wet	Very Wet
Land Use	Rural	Mostly Rural	Suburban	Mostly Urban	Urban
Slope (ft/mi)	<1	1-3	3-7	7-10	>10
Area (mi^2)	<50	50-100	100-150	150-200	>200
Length (mi)	<25	25-50	50-75	75-100	>100
Area/ Length	3-5	5-10	2-3 >10	0.5-2	<0.5

Table 5.1 Scoring chart for forecasting flash floods.

Precipitation rate was taken to be an average precipitation rate for the storm event, in in/hr. It is generally thought that storms with higher rates of precipitation tend to lead to more flash floods than storms with a lower rate of precipitation, as the ground absorption rates cannot keep up with precipitation rates. More water entering the catchment faster may mean more flooding. This assumption is not always accurate, as many other factors play a role in flash flood occurrence. However, precipitation intensity is still an important factor in predicting flash floods, so it is considered in the chart. The ranges were chosen based on rainfall intensities common to Missouri for typical storms.

Storm duration is another factor that plays a role in flash flood forecasting. Even if a storm has very high rainfall rates, it may not cause flash flooding if the storm is moving quickly or only lasts a short period of time. Typical durations of storms in Missouri were used in the table, and can be related to the type of storm that is producing the precipitation. For example, single cell 'pop-up' thunderstorms are typically shorter in duration and less likely to cause flash floods than longer lived systems like mesoscale convective systems.

Related to storm duration is the movement of the storm. In the initial table, the movement was qualitatively described. Later in the study, radar data will be examined to determine how fast the rear edge of the storm was moving. As described by Corfidi *et al.* (1996), storm motion depends on movement of cells as well as storm development. Even if the individual cells in a storm are moving relatively quickly, if development on the rear edge continues the storm can be effectively motionless, which is more likely to lead to flooding.

Soil moisture also is an important consideration in forecasting flash floods. If previous rainfall has saturated the soil, then it will be less able to absorb further precipitation and so flash floods may be more likely. In Table 5.1, previous precipitation was used to determine how moist the soil was prior to the onset of the flood-producing rainfall. If rain had fallen in the previous 24 hours, the soil was assumed to be wet or very wet. If precipitation occurred 72 to 24 hours prior to the system it was moderate, and if it had not rained for more than 72 hours then it was considered dry or very dry.

The last group of factors is essentially the hydrological conditions of the catchment. Most of these are not likely to change for each storm event, since things such as channel length and catchment area do not typically change. However, these are still important considerations, as they affect how precipitation runs off and how quickly a flash flood may form. It is possible to calculate the baseline susceptibility to flooding, which is related to the catchment slope, area, and length of main channel.

Land use was found from Skelton and Homyk (1970) and from the USGS watershed websites. It is taken to be a measure of how much forest, grassland, and impervious material covers the area. Rural and mostly rural watersheds had little impervious material, while urban watersheds are almost completely covered by impervious materials. The slope gives an indication as to how fast the water will flow into the stream or river, as a steeper catchment is likely to have faster runoff and therefore quicker flooding. The catchment area gives an idea of the amount of rainfall that could potentially reach the stream, as a larger catchment will have more area for precipitation to fall on. The length of the main channel gives an idea of how large the river or stream is. Larger streams generally have larger catchments. The ratio of area to length gives an idea of the shape of the catchment. A long narrow catchment may flood more quickly that a more round one as the water will not have as far to flow before it reaches the stream channel. The ranges for these factors were determined largely by the previous work of Collier and Fox (2003) and were adjusted slightly for this study.

5.2 Predictions by Chart

For each stream in the case study, a score was calculated using the scoring chart. In Table 5.2, each stream is listed along with the score in each category. The lowest possible total score is 0, with the maximum score being 36. The scores were compared to the depth of the flooding to see how severe the flood was on each stream. The use of the scoring chart allows forecasters to identify which factors play a role in development of a flash flood.

	River							
Category	**Blue River**	**Little Blue River**	**Brush Creek (1)**	**Brush Creek (2)**	**Bour-beuse**	**Big River (1)**	**Big River (2)**	**Dar-denne Creek**
Precip Rate	3	2	2	3	4	2	3	2
Duration of Storm	4	4	4	4	4	4	4	4
Motion of Storm	3	3	3	3	4	4	4	4
Soil Moisture	4	4	4	4	2	2	2	2
Land Use	4	2	3	4	1	0	0	2
Slope	4	2	2	2	1	2	2	1
Area	3	3	0	0	4	4	4	1
Length	0	1	0	0	4	3	4	0
Area/ Length	1	1	0	3	1	1	1	0
Total	26	22	18	23	25	22	24	16

Table 5.2 Scores from chart for each stream that experienced flooding.

The overall scores are presented along with flood depth in Table 5.3. The score is generally higher as the flood depth increases. This is a major result, as one goal of this study was to develop a scoring chart that could objectively classify the potential severity of a flash flood. Streams that are more likely to have a severe flash flood score higher than those where the flooding would be less severe, as shown by the scores in Table 5.3. Figure 5.1 also shows the general trend of higher scores being related to streams that experienced greater flooding, as there is a somewhat linear relationship between score and potential flood depth.

Location	Score	Flood Depth (ft)
BLUE RIVER	26	29.9
BOURBEUSE	25	24.6
BIG RIVER (2)	24	22.3
BRUSH CREEK (2)	23	21.7
BRUSH CREEK (1)	18	13.7
LITTLE BLUE RIVER	22	12.8
BIG RIVER (1)	22	11.2
DARDENNE CREEK	16	3.6

Table 5.3 Scores and flood depth in feet for the two case study events.

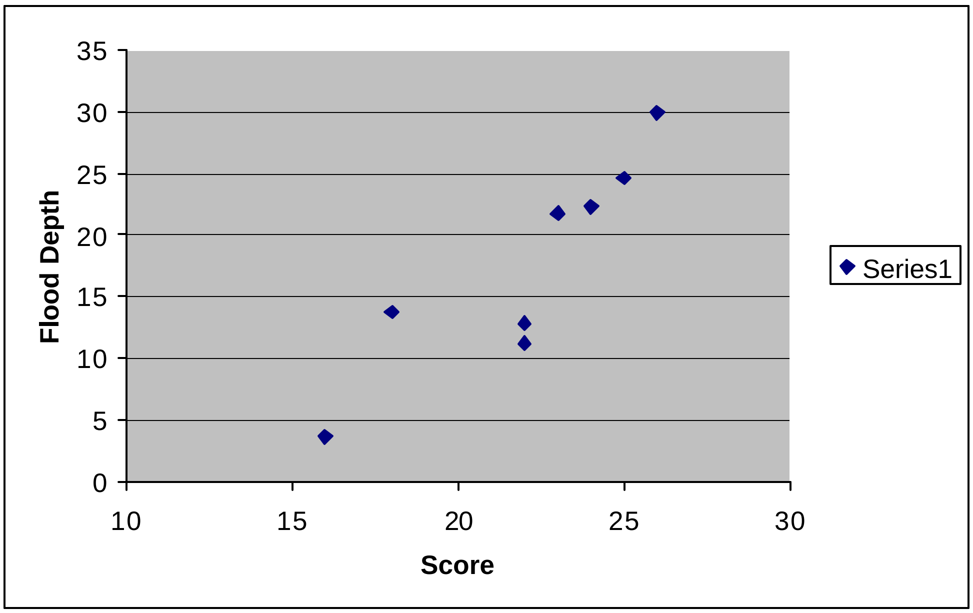

Figure 5.1 Scatter plot showing scores from chart and flood depth for each stream.

The probability of flash flooding depends on the interaction of several factors. For example, the scoring system predicts which streams that are more likely to have severe flash floods given similar atmospheric conditions. In the first case study of 04 October 1998, the storm conditions were essentially the same for each stream involved, but the catchment conditions were different. If one looks at the scores for simply the atmospheric conditions, the streams score between 13 (Little Blue River and Brush Creek (1)) to 14 points (Blue River and Brush Creek (2)). However, when examining the hydrologic characteristics, the streams show significant differences. The Blue River scores 12 points, the Little Blue River scores 9 points, Brush Creek (1) scores 5 points, and Brush Creek (2) scores 9 points. Of this group, Brush Creek (1) and Little Blue River scored the lowest on the hydrological portion of the table, and they also experienced the lowest flooding depth. The Blue River scored the highest on this portion, and experienced the deepest flooding. The use of the chart shows that it is important to include these catchment characteristics in forecasting flash floods, as it would allow for attention to be focused on streams that are more likely to flood and will have a more severe flood when one occurs.

The chart also emphasizes the role of atmospheric conditions in developing flash floods. In the second case study of 07 May 2000, some of the streams that were involved in flooding had similar hydrologic characteristics. For example, the Bourbeuse River scored an 11, Big River (1) a 10, and Big River (2) an 11 on the hydrological portion of the scoring chart. While the Bourbeuse River and Big River (2) experienced similar flood depths (24.6 feet and 22.3 feet respectively), the Big River (1) experienced significantly lower flood depths, at only 11.2 feet. The explanation for these differences can be found by examining the atmospheric conditions that led to this event. The Bourbeuse River catchment experienced the heaviest rainfall amounts, and even though the duration of storm and storm motion were the same for the event, the heavy rain over that particular catchment allowed for more intense flooding on that river.

The use of the scoring chart shows that the right combination of factors is important for serious flash floods to develop. In similar atmospheric conditions over a range of streams, using the chart will allow the forecaster to examine which streams possess the hydrological characteristics that will make a stream be more likely to experience flooding, and may help forecasters that are unfamiliar with the area gain local knowledge about the streams in their area. It will also allow the forecasters to focus attention on those streams that are experiencing the atmospheric conditions that will lead to flash flooding, such as intense rainfall over a long period of time. The chart provides an easy way to present both hydrologic and atmospheric conditions, and will allow a forecaster to make more specific warnings about which particular streams are most likely to experience the worst flooding by identifying which streams have the highest overall score.

5.3 Tracking Storm Motion Using Radar

When examining potential flash flood cases, the storm system motion is an important factor. In the scoring chart, storm motion was described as rapid, fast, medium, slow, or stationary. Storm tracking algorithms will give speeds for individual cells that are identified. This cell identification can be extremely useful in situations that require knowledge of individual cell motion, such as tornado forecasting. For flash flood forecasting it would be useful to forecasters to know how fast not only the individual cells of the storm were moving, but the overall motion of the storm as well.

In this study, a new way of looking at storm motion using radar data was examined. This is because even though individual cells may be moving quickly within a system, if there is substantial re-development on the rear edge of the storm then the effective storm motion may be significantly slower than that of the individual cells. Since the focus of this study is forecasting flash floods, it was more useful to consider where the rear edge of the storm was located and how fast it was moving compared to the individual cell speeds.

For this study, radar data were examined from the two case study events to determine the location of the rear edge of the storm. The rear edge was taken to be the one opposite the direction the storm was primarily moving in, and where there was substantial new convective development (Figure 5.2).

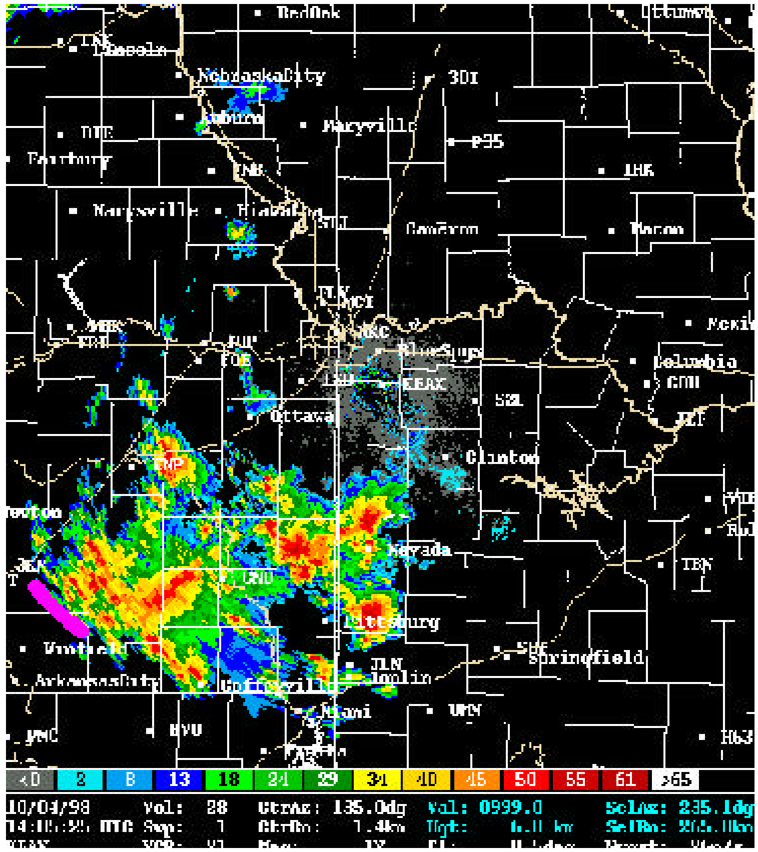

Figure 5.2 Example of finding rear edge from Kansas City case study. The magenta line indicates where development was occurring on the side of the system opposite the direction of motion, and was determined to be the location of the rear edge of the system.

The location of the rear edge was found for each scan time. Knowing the position, and the time between scans, a speed of motion was then calculated. An example of the calculations for the Kansas City case is shown in Table 5.4 and for the St. Louis case in Table 5.5, with the full tables available in Appendix 1.

Scan	Time (UTC)	Azimuth (deg)	Range (km)	Latitude (°N)	Longitude (°W)	Distance (km)	Speed (kt)
62	17:16	255.5	215.9	39.3	96.6	17.2	9.6
65	17:31	261.1	200.4	39.1	96.5	23.9	13.3
68	17:46	266.1	189.4	38.9	96.4	23.9	13.3
71	18:01	270.8	213.0	38.8	96.7	28.3	15.7
74	18:16	275.8	206.1	38.6	96.6	23.9	13.3
77	18:31	273.8	225.5	38.7	96.8	20.6	11.4
80	18:46	276.3	217.3	38.6	96.7	14.1	7.8
83	19:01	277.7	231.1	38.5	96.9	20.7	11.5
86	19:16	275.5	250.2	38.6	97.1	20.7	11.5
89	19:31	274.8	248.9	38.6	97.1	0.0	0.0
92	19:46	276.0	248.4	38.6	97.1	0.0	0.0

Table 5.4 Storm system speeds calculated for Kansas City case study. Here range and azimuth are from the radar, and were used to calculate the latitude and longitude of the rear edge. Distance is the distance the rear edge had traveled in approximately 15 minutes.

Scan	Time (UTC)	Azimuth (deg)	Range (km)	Latitude (°N)	Longitude (°W)	Distance (km)	Speed (kt)
44	3:00	244.8	129.3	39.2	92.0	8.6	4.0
47	3:18	241.6	123.9	39.2	91.9	8.6	4.0
49	3:29	239.0	114.4	39.2	91.8	8.6	6.5
52	3:47	242.6	126.1	39.2	92.0	17.2	8.0
54	4:00	243.6	119.4	39.2	91.9	8.6	5.5
57	4:18	244.6	109.6	39.1	91.8	14.1	6.5
59	4:30	242.7	102.4	39.1	91.7	8.6	6.0
62	4:47	242.5	108.2	39.1	91.8	8.6	4.2
64	4:59	241.0	94.9	39.1	91.6	17.3	12.0
67	5:17	248.3	78.5	39.0	91.5	14.1	6.5
69	5:29	250.9	79.4	38.9	91.5	11.1	7.7

Table 5.5 Storm system speeds calculated for St. Louis case study. Again, range and azimuth are from the radar, and were used to calculate the latitude and longitude of the rear edge. Distance is the distance the rear edge had traveled in approximately 15 minutes.

In these tables, the scan number was given for each scan that was examined. The time of the scan is also given, and the time between scans was used to calculate the speed of the rear edge of the storm. Most of the scan times were approximately six minutes apart, but sometimes it was necessary to skip particular scans due to missing data. This author attempted to find scans at roughly 15-minute intervals. This allows enough storm motion for a reasonably accurate distance to be found.

The azimuth and range of the back edge of the storm from the radar location were found using the raw data set. After determining where the development was occurring away from the overall motion of the storm cells, the rear edge was determined using 20 dBZ as the cut-off reflectivity amount. Using simple geometry, and assuming the earth was flat over the distances involved, the latitude and longitude of the rear edge of the storm were calculated based on the location of the radar, and the rear edge location in terms of the azimuth and range from that particular radar. Knowing the new latitude and longitude of subsequent radar scans, it was possible to calculate the distance in kilometers that the rear edge of the storm had moved. This was then used to calculate the speed, which was calculated in knots (kt) so that it would have the same units as the speed found in the cell tables from the cell-tracking algorithm. Figures 5.3 and 5.4 show the rear edge for a selected scan of both case studies.

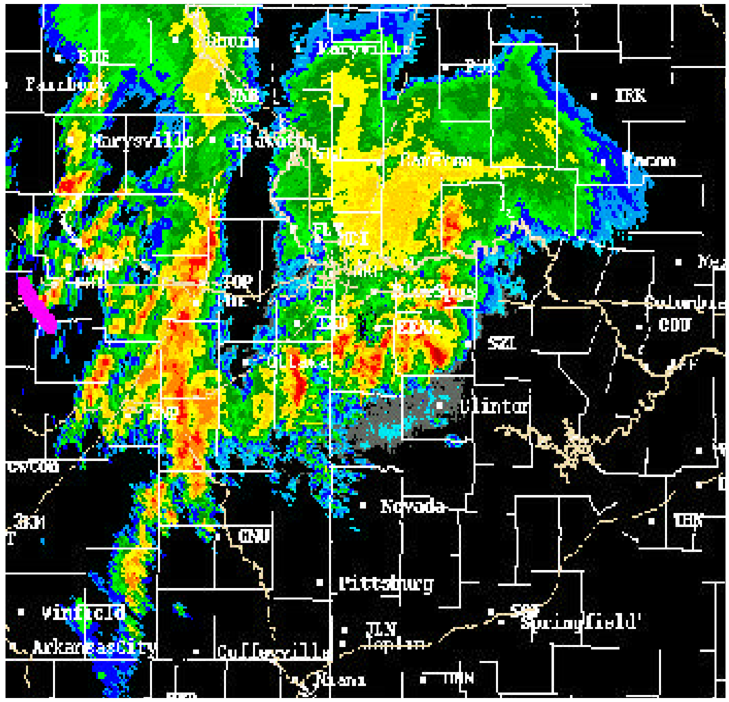

Figure 5.3 Rear edge is marked by the magenta line for Kansas City case study. The rear edge is determined by where the storm is redeveloping, and has moved northwest from the location found in Figure 5.2.

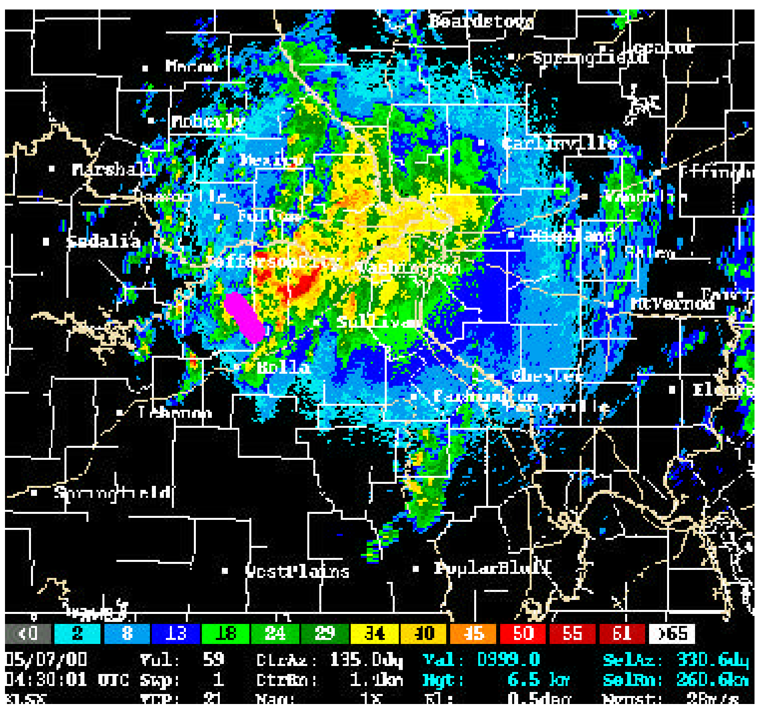

Figure 5.4 Rear edge is marked by a magenta line for St. Louis case study. The area of redevelopment that is opposite the direction of storm motion is found to be the rear edge of the storm which was nearly stationary in this case.

As shown from some examples in Table 5.6, it can be seen that the speeds calculated using the rear-flank tracking method are generally much slower than the speeds found in the cell tables calculated by the algorithms. In this table, the scan number and time are given in the first two columns. The calculated speed of the rear edge of the storm that was found as discussed above is given in the third column. From the cell-tracking algorithm, several cells were identified and information was presented in the cell table. More cells were identified by the tracking algorithm than in this study because of how the algorithm divides the thresholds for different cells. It may identify many cells in what appears to be an area of widespread rainfall. The slowest cell speed and the highest cell speed were taken from that table for each scan. This is the range that is presented in Table 5.6, which shows the slowest and fastest cells speeds found.

Kansas city			
Scan	Time (UTC)	Calculated Speed (kt)	Cell Table Speed (kt)
71	18:01	15.7	16-62
74	18:16	13.3	17-62
77	18:31	11.4	27-76
80	18:46	7.8	16-66
83	19:01	11.5	27-89
St. Louis			
54	4:00	5.5	8-35
57	4:18	6.5	12-76
59	4:30	6.0	14-41
62	4:47	4.2	8-33
64	4:59	12.0	12-31

Table 5.6 Comparison of Calculated Storm Speeds (in knots) and Storm Speeds Found in the Cell Tables from the Cell Tracking Algorithm (in knots)

In each example, the speeds found by the calculations in this study are slower than the cell table speeds. For example, for scan number 77 in the Kansas City case, the storm speed was calculated to be around 11.4 kt. The cell table identified speeds of 27 to 72 kt. This shows that even the slowest cell, at 27 kt, was moving considerably faster than the storm edge, which was moving at approximately 11 kt.

In this study, the overall motion of the entire storm is what is important, and the wide ranges given here show that simply using the cell table speed to obtain an estimate of the entire storm motion may be misleading. This shows that the new method has important considerations in forecasting flash floods. If the individual cells are moving relatively quickly, then the speed of the system as a whole will be overestimated if a forecaster simply uses the cell table speed to estimate storm speed. This could lead the forecaster to underestimate the storm duration over a particular area. Because the precipitation duration and subsequent amount may be underestimated, a smaller flood would be forecasted than may actually occur.

Some errors may arise from this method of storm speed calculation. The largest error would be in simply determining where the rear edge of the storm is situated. Since new development plays a large role in finding this edge, and storms rarely develop in a ‘neat’ manner, determining where the rear edge is may change drastically from scan to scan. Errors in locating the rear edge will also occur when the rear edge is outside the range of the radar, and development may be occurring past the area that can be seen. Small errors may also arise from the assumption in the calculation that the earth was flat. Since the distances the storm edge moved were not extremely large, this error should remain relatively small.

By using the new tracking method, a more accurate speed of the system as it pertains to forecasting flash floods can be obtained. The forecaster should use the cell table speeds when examining severe weather like hail or tornadoes, but for flash floods they would want to consider where the rear edge of the storm is located, and how much development is occurring on the edge away from the direction of storm motion. This would give the forecaster a more accurate speed of the entire storm, which will increase accuracy in determining storm speed and duration over a river catchment. Ideally this would be programmed into a new 'storm-tracking' table, like the cell table, so that the forecaster could quickly see how fast the storm, as a whole, is moving.

5.4 Calculation of Storm Duration Factor

In the final part of the radar study, the difference in speed of the center of the storm system was compared to the speed of the rear edge. This comparison ratio could serve as a storm duration factor that could be used to forecast precipitation accumulation over an area for some distance ahead of the storm system. The storm duration factor was defined as:

$$D_s = (S_c - S_r) / (S_c S_r) \qquad (5.1)$$

For each scan, a cell that was close to the center of the entire storm system was chosen to represent the speed of the center of the storm, S_c. The manually calculated speed found in section 5.3 was used for the rear edge speed, S_r.

In Table 5.7, the results found for the storm duration factors are given for selected scans for both case studies. Values for all scans may be found in Appendix 2.

Kansas City				
Scan	Time	S_r	S_c	D_s
71	18:01	15.7	16	0.001
74	18:16	13.3	17	0.016
77	18:31	11.4	37	0.060
80	18:46	7.8	37	0.101
83	19:01	11.5	49	0.067
St. Louis				
54	4:00	5.5	17	0.123
57	4:18	6.5	21	0.106
59	4:30	6.0	23	0.124
62	4:47	4.2	19	0.185
64	4:59	12.0	21	0.036

Table 5.7 Duration factor calculated for selected scans from case studies.

In this table, the calculated speeds of the rear edge and the speeds for the center of the storm system are given, as well as the calculated duration factor for each scan. If the speed of the center of the storm is larger than the speed of the rear edge, such as in St. Louis scan number 62, then the duration factor will be relatively large. This would indicate that flooding would be more likely, as the center is moving relatively quickly, which means rain will reach a particular location faster, but the rear edge is moving relatively slowly and so the rainfall will persist over that same location. If the speeds of the center and rear edge are similar, as in Kansas City scan number 71, then the duration factor will be relatively small. This would indicate a smaller flood risk, as the storm will not last as long over a particular area since the rear edge of the storm is moving relatively quickly.

The duration factor could be used to forecast duration of a storm over a particular area, such as a particular stream catchment. If a forecaster assumes a steady state rainfall rate, this duration factor could then be correlated with precipitation accumulation, and used to forecast flooding.

There are potential errors that arise from the calculation of the storm duration factor. Errors can result from the calculation of the rear edge speed, as discussed in the previous section. Another error arises from using a cell near the center of the storm to calculate the storm duration factor. If a storm is relatively small, then selecting a cell in the middle of the storm to estimate when precipitation would begin would not result in a large error, but if the storm is large or there is development on the leading edge, then a cell near the front of the edge may give a more accurate result than one near the center.

Both parts of the radar study can be used in the scoring chart. The calculated speed of the rear edge of the storm can be used to give a quantified measure of storm speed, and the divisions of rapid, fast, medium, slow, and stationary could be adjusted for typical values found for storms over a particular area. The duration factor could be used to forecast the duration of a storm over a particular area, and when combined with precipitation rate total accumulation could be forecasted, and the likelihood of flooding for particular streams could be forecasted, as discussed in section 5.1.

Chapter 6

Conclusions

6.1 Summary

In the attempt to improve the forecasting of flash floods, two objectives were addressed. The first objective was to develop a scoring chart that would analyze data and could serve as a forecast to for the probability and intensity of a flash flood. This chart included several factors that play a role in flash flood forecasting, including precipitation rate, duration of storm, movement of storm, soil moisture, land use of a catchment, area of catchment, slope, length of channel, and the ratio of area to length. Each of these factors was divided into a range that reflects features of storm systems that produce flash floods over Missouri. These ranges were used to develop a score from 0 to 36 for each stream in the case studies.

The scores for each stream were found, and compared to the depth of flooding that the streams experienced. It was found that the general trend was that the scores were higher for streams that experienced deeper flooding. This shows that the scoring chart can predict which streams will be more likely to flood, as a higher score means the right mix of characteristics is in place to produce a flood on a particular stream.

The use of the scoring chart also allows forecasters to see which factors play a role in development of a flash flood. In a case where a storm is producing similar atmospheric conditions over a large area, the chart can focus attention on a particular stream. Streams that score higher on the hydrological characteristics are more likely to flood and will have a more severe flood when one occurs. The use of the chart shows that it is important to include these catchment characteristics in forecasting flash floods, as it would allow for attention to be focused on those streams. The chart could help forecasters new to an area gain local knowledge about streams that they might not have otherwise.

The chart also emphasizes the role of atmospheric conditions in developing flash floods. Often rainfall rates can vary within a storm, and areas that are experiencing more intense rainfall may experience more severe flooding. Since hydrological characteristics will not change much on a day–to–day basis, it will be relatively easy for a meteorologist to determine the atmospheric conditions for the particular storm, and then use the chart to help issue more specific flooding forecasts. The chart can be used as a forecasting tool by using quantitative precipitation forecasts as a proxy for the first two rows of the scoring chart.

For the radar study, several steps were completed in order to develop a new way of tracking storm systems to improve flash flood forecasting. For each scan, the range and azimuth from the radar was used to calculate the rear edge's position in terms of latitude and longitude. Then, by using this position from successive scans the distance that the storm traveled was calculated. Using the time between scans, the speed was then calculated and compared to the speeds found by the cell-tracking algorithm. It was found that the manually calculated speed for the rear edge of the storm was generally lower than those found for the individual cells. The development of new cells at the rear of the storm will make the system overall appear to move more slowly than the individual cells. This is an important finding in forecasting flash floods, as the motion of the storm will play a large role in storm duration, and therefore have an effect on the total precipitation that will fall.

In the final part of the radar study, a storm duration factor was found by comparing the calculated rear edge speed and the speed of the storm center. This duration factor can be used as a measure of storm motion, and when combined with rain rate can allow for a forecasted precipitation accumulation for some distance ahead of the storm. This could eventually be automated in some way, and provide further information to forecasters about possible rainfall accumulations.

6.2 Future Work

There are several things that could be done to further extend this work. In regards to the scoring chart, additional factors may need to be considered for the chart to be useful in other areas. Factors that were not used here, such as snowmelt, may play a large role in spring flash flooding in more mountainous areas.

It would also be valuable to automate the scoring chart into an algorithm or model. Many hydrologic models are too complicated to run in real-time situations, but it may be possible for this one to be automated. The computer could import quantitative precipitation forecasts, and use radar data for storm speed. The other information could be considered constants, such as catchment area, or can also be found from some source, as in the case of soil moisture.

As for the radar tracking method, it would be of interest to develop a new algorithm that would track the rear flank of the storm, as was done manually here. This would obviously not be much help in some situations such as tornado or hail forecasting, but could prove very useful in flood forecasting.

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Appendix 1

In these tables, the radar studies are summarized. The back edge of the storm was found in terms of azimuth and range from the radar. This was used to find the change in latitude and longitude from the radar position, and so the latitude and longitude of the back edge was calculated. The distance moved is how far the rear edge traveled in 15 minutes, which was used to find the speed of the rear edge of the storm.

Kansas City 04 October 1998									
Radar location 38°49' N, 94°16'W									
		(Back edge of storm)				(Back edge of storm)			
Scan	Time (UTC)	Azimuth (deg)	Range (km)	Δ lat (°N)	Δ long (°W)	Latitude (°N)	Longitude (°W)	Dist (km)	Speed (kt)
20	13:05	235.7	251.8	1.3	2.4	40.1	96.6		
21	13:11	237.6	261.3	1.3	2.5	40.1	96.8	17.0	23.6
22	13:17	232.8	274.8	1.5	2.5	40.3	96.8	22.3	31.0
23	13:36	234.9	278.5	1.4	2.6	40.2	96.9	14.0	6.1
24	13:42	236.1	272.4	1.4	2.6	40.2	96.8	8.5	11.8
25	13:47	235.2	268.0	1.4	2.5	40.2	96.8	0.0	0.0
27	13:59	235.2	268.0	1.4	2.5	40.2	96.8	0.0	0.0
28	14:05	236.1	265.1	1.3	2.5	40.1	96.8	11.1	15.4
29	14:11	236.7	258.5	1.3	2.5	40.1	96.7	8.5	11.8
30	14:17	239.9	259.0	1.2	2.6	40.0	96.8	14.0	19.4
31	14:22	238.8	257.1	1.2	2.5	40.0	96.8	0.0	0.0
32	14:28	240.0	248.2	1.1	2.5	39.9	96.7	14.0	19.4
35	14:46	240.9	242.6	1.1	2.4	39.9	96.7	0.0	0.0
38	15:03	240.7	232.8	1.0	2.3	39.8	96.6	14.0	6.9
40	15:15	243.2	233.0	0.9	2.4	39.7	96.6	11.1	7.7
41	15:21	251.5	236.2	0.7	2.6	39.5	96.8	28.1	39.0
42	15:24	250.9	262.5	0.8	2.8	39.6	97.1	28.0	77.8

43	15:28	254.3	258.7	0.6	2.8	39.4	97.1	22.3	46.5
44	15:34	254.0	258.0	0.6	2.8	39.4	97.1	0.0	0.0
45	15:39	252.1	259.6	0.7	2.8	39.5	97.1	11.1	18.5
46	15:45	253.5	257.6	0.7	2.8	39.5	97.1	0.0	0.0
47	15:51	252.4	261.2	0.7	2.8	39.5	97.1	0.0	0.0
48	15:57	254.0	258.0	0.6	2.8	39.4	97.1	11.1	15.4
49	16:03	252.1	260.6	0.7	2.8	39.5	97.1	11.1	15.4
51	16:15	256.8	253.7	0.5	2.8	39.3	97.1	22.3	15.5
53	16:27	252.1	257.4	0.7	2.8	39.5	97.1	22.3	15.5
56	16:45	250.5	254.6	0.8	2.7	39.6	97.0	14.1	6.5
59	17:01	255.6	233.3	0.5	2.6	39.3	96.8	37.5	19.5
62	17:16	255.5	215.9	0.5	2.4	39.3	96.6	17.2	9.6
65	17:31	261.1	200.4	0.3	2.3	39.1	96.5	23.9	13.3
68	17:46	266.1	189.4	0.1	2.2	38.9	96.4	23.9	13.3
71	18:01	270.8	213.0	0.0	2.4	38.8	96.7	28.3	15.7
74	18:16	275.8	206.1	-0.2	2.3	38.6	96.6	23.9	13.3
77	18:31	273.8	225.5	-0.1	2.6	38.7	96.8	20.6	11.4
80	18:46	276.3	217.3	-0.2	2.5	38.6	96.7	14.1	7.8
83	19:01	277.7	231.1	-0.3	2.6	38.5	96.9	20.7	11.5
86	19:16	275.5	250.2	-0.2	2.8	38.6	97.1	20.7	11.5
89	19:31	274.8	248.9	-0.2	2.8	38.6	97.1	0.0	0.0
92	19:46	276.0	248.4	-0.2	2.8	38.6	97.1	0.0	0.0
94	19:56	274.8	248.9	-0.2	2.8	38.6	97.1	0.0	0.0
96	20:06	276.9	248.8	-0.3	2.8	38.5	97.1	11.1	9.3
98	20:16	273.6	238.5	-0.1	2.7	38.7	97.0	23.9	19.9
101	20:31	273.5	247.5	-0.1	2.8	38.7	97.1	8.7	4.8
104	20:46	270.7	248.0	0.0	2.8	38.8	97.1	11.1	6.2
107	21:01	273.0	249.3	-0.1	2.8	38.7	97.1	11.1	6.2
110	21:16	267.9	249.2	0.1	2.8	38.9	97.1	22.3	12.4
113	21:31	264.3	250.3	0.2	2.8	39.0	97.1	11.1	6.2
116	21:46	259.5	251.2	0.4	2.8	39.2	97.1	22.3	12.4
118	21:56	253.4	258.8	0.7	2.8	39.5	97.1	33.4	27.8
120	22:06	256.5	257.1	0.5	2.9	39.3	97.1	22.3	18.6
122	22:16	255.1	256.6	0.6	2.8	39.4	97.1	11.1	9.3
125	22:31	253.4	259.8	0.7	2.8	39.5	97.1	11.1	6.2
128	22:46	251.4	260.6	0.7	2.8	39.5	97.1	0.0	0.0
132	23:06	253.3	247.4	0.6	2.7	39.4	97.0	14.1	5.9
134	23:16	252.7	232.5	0.6	2.5	39.4	96.8	17.2	14.3
137	23:31	254.9	214.4	0.5	2.4	39.3	96.6	20.5	11.4
140	23:46	258.8	190.6	0.3	2.1	39.1	96.4	28.2	15.7
142	23:56	262.2	176.6	0.2	2.0	39.0	96.3	14.1	11.8

St. Louis 07 May 2000									
Radar Location 38°42’N 90°41’W									
		(Back edge of storm)				(Back edge of storm)			
Scan	Time (UTC)	Azimuth (Deg)	Range (km)	Δlat (°N)	Δlong (°W)	Latitude (°N)	Longitude (°W)	Dist (km)	Speed (kt)
28	0:03	247.3	171.2	0.6	1.8	39.3	92.5		
30	0:15	248.5	177.3	0.6	1.9	39.3	92.6	8.6	6.0
33	0:32	250.0	178.7	0.5	1.9	39.2	92.6	11.1	5.4
34	0:44	245.3	167.3	0.6	1.7	39.3	92.4	20.5	14.2
38	1:02	248.5	161.2	0.5	1.7	39.2	92.4	11.1	5.1
39	1:08	251.6	158.1	0.4	1.7	39.1	92.4	11.1	15.4
40	1:14	249.7	155.7	0.5	1.7	39.2	92.4	11.1	15.4
41	2:42	247.7	137.2	0.5	1.4	39.2	92.1		
44	3:00	244.8	129.3	0.5	1.3	39.2	92.0	8.6	4.0
47	3:18	241.6	123.9	0.5	1.2	39.2	91.9	8.6	4.0
49	3:29	239.0	114.4	0.5	1.1	39.2	91.8	8.6	6.5
52	3:47	242.6	126.1	0.5	1.3	39.2	92.0	17.2	8.0
54	4:00	243.6	119.4	0.5	1.2	39.2	91.9	8.6	5.5
57	4:18	244.6	109.6	0.4	1.1	39.1	91.8	14.1	6.5
59	4:30	242.7	102.4	0.4	1.0	39.1	91.7	8.6	6.0
62	4:47	242.5	108.2	0.4	1.1	39.1	91.8	8.6	4.2
64	4:59	241.0	94.9	0.4	0.9	39.1	91.6	17.3	12.0
67	5:17	248.3	78.5	0.3	0.8	39.0	91.5	14.1	6.5
69	5:29	250.9	79.4	0.2	0.9	38.9	91.5	11.1	7.7
70	5:35	251.6	79.1	0.2	0.9	38.9	91.5	0.0	0.0
71	6:35	245.7	80.1	0.3	0.8	39.0	91.5		
72	6:41	240.8	77.9	0.3	0.8	39.0	91.5	0.0	0.0
73	6:47	242.7	80.1	0.3	0.8	39.0	91.5	0.0	0.0
75	6:59	242.2	81.4	0.3	0.8	39.0	91.5	0.0	0.0
78	7:16	245.7	77.9	0.3	0.8	39.0	91.5	0.0	0.0
81	7:31	242.7	74.2	0.3	0.8	39.0	91.4	8.6	4.8
84	8:41	242.6	58.6	0.2	0.6	38.9	91.3		
87	8:57	248.8	66.5	0.2	0.7	38.9	91.4	8.7	4.5
90	9:12	248.7	63.3	0.2	0.7	38.9	91.4	0.0	0.0
92	9:22	247.3	59.6	0.2	0.6	38.9	91.3	8.7	7.3
93	10:08	240.3	56.4	0.3	0.6	39.0	91.2		
94	10:13	240.9	51.5	0.2	0.5	38.9	91.2	11.1	18.5
95	10:19	236.0	51.9	0.3	0.5	39.0	91.2	11.1	15.4

96	10:24	235.3	47.4	0.2	0.4	38.9	91.1	14.1	23.5
97	10:29	239.4	56.9	0.3	0.6	39.0	91.2	14.1	23.5
98	10:34	238.9	56.1	0.3	0.5	39.0	91.2	0.0	0.0
99	10:39	238.7	59.7	0.3	0.6	39.0	91.3	8.6	14.3
100	10:44	241.2	58.2	0.3	0.6	39.0	91.3	0.0	0.0
101	10:49	239.9	57.8	0.3	0.6	39.0	91.3	0.0	0.0
102	10:54	239.6	53.3	0.2	0.5	38.9	91.2	14.1	23.5
103	10:59	237.6	48.5	0.2	0.5	38.9	91.2	0.0	0.0
104	11:05	236.0	48.3	0.2	0.5	38.9	91.1	8.7	12.1
105	11:10	235.6	46.0	0.2	0.4	38.9	91.1	0.0	0.0
106	11:15	237.7	44.9	0.2	0.4	38.9	91.1	0.0	0.0
107	11:20	235.6	42.4	0.2	0.4	38.9	91.1	0.0	0.0
108	11:25	232.3	39.2	0.2	0.4	38.9	91.0	8.7	14.5
109	11:30	228.8	42.5	0.3	0.4	39.0	91.1	14.1	23.5
110	11:35	225.9	43.1	0.3	0.4	39.0	91.0	8.6	14.3

Appendix 2

In these tables, the rear edge and storm center speeds are given, and these were used to calculate the storm duration factor as discussed in section 5.4. The speed of the rear edge comes from the calculations done in section 5.3, and the speed of the center of the storm was found from the cell identification tables from the radar data.

Kansas City 04 October 1998				
Scan	Time (UTC)	Speed of rear edge (kt)	Speed of center (kt)	Duration factor
20	13:05		35	
21	13:11	23.6	35	0.014
22	13:17	31.0	35	0.004
23	13:36	6.1		
24	13:42	11.8	45	0.062
25	13:47	0.0	31	
27	13:59	0.0		
28	14:05	15.4	43	0.042
29	14:11	11.8	43	0.061
30	14:17	19.4	41	0.027
31	14:22	0.0	41	
32	14:28	19.4	41	0.027

35	14:46	0.0	37	
38	15:03	6.9	39	0.120
40	15:15	7.7	29	0.095
41	15:21	39.0	27	-0.011
42	15:24	77.8	27	-0.024
43	15:28	46.5	29	-0.013
44	15:34	0.0	31	
45	15:39	18.5	41	0.030
46	15:45	0.0	41	
47	15:51	0.0	43	
48	15:57	15.4	45	0.043
49	16:03	15.4	47	0.044
51	16:15	15.5		
53	16:27	15.5	43	0.041
56	16:45	6.5	27	0.116
59	17:01	19.5		
62	17:16	9.6	33	0.074
65	17:31	13.3	23	0.032
68	17:46	13.3	17	0.016
71	18:01	15.7	16	0.001
74	18:16	13.3	17	0.016
77	18:31	11.4	37	0.060
80	18:46	7.8	37	0.101
83	19:01	11.5	49	0.067
86	19:16	11.5	52	0.068
89	19:31	0.0	56	
92	19:46	0.0	50	
94	19:56	0.0	54	
96	20:06	9.3	52	0.089
98	20:16	19.9	47	0.029
101	20:31	4.8	37	0.180
104	20:46	6.2	39	0.137
107	21:01	6.2	33	0.132
110	21:16	12.4	29	0.046
113	21:31	6.2	49	0.142
116	21:46	12.4	43	0.057
118	21:56	27.8	41	0.012
120	22:06	18.6	50	0.034
122	22:16	9.3	49	0.088
125	22:31	6.2	50	0.142
128	22:46	0.0	56	
132	23:06	5.9		

134	23:16	14.3		
137	23:31	11.4	17	0.029
140	23:46	15.7	49	0.043
142	23:56	11.8	72	0.071

St. Louis 07 May 2000				
Scan	Time (UTC)	Speed of rear edge (kts)	Speed of center(kts)	Duration factor
28	0:03			
30	0:15	6.0	33	0.137
33	0:32	5.4	27	0.147
34	0:44	14.2	29	0.036
38	1:02	5.1	50	0.175
39	1:08	15.4	25	0.025
40	1:14	15.4	50	0.045
41	2:42			
44	3:00	4.0	16	0.189
47	3:18	4.0	16	0.189
49	3:29	6.5	23	0.110
52	3:47	8.0	21	0.078
54	4:00	5.5	17	0.123
57	4:18	6.5	21	0.106
59	4:30	6.0	23	0.124
62	4:47	4.2	19	0.185
64	4:59	12.0	21	0.036
67	5:17	6.5	17	0.094
69	5:29	7.7	19	0.077
70	5:35	0.0	19	
71	6:35			
72	6:41	0.0	19	
73	6:47	0.0	16	
75	6:59	0.0	16	
78	7:16	0.0	12	
81	7:31	4.8	19	0.157
84	8:41			
87	8:57	4.5	14	0.149
90	9:12	0.0	12	
92	9:22	7.3	23	0.094
93	10:08			
94	10:13	18.5	16	-0.008
95	10:19	15.4	12	-0.018

96	10:24	23.5	12	-0.041
97	10:29	23.5	10	-0.057
98	10:34	0.0	17	
99	10:39	14.3	17	0.011
100	10:44	0.0	16	
101	10:49	0.0	19	
102	10:54	23.5	19	-0.010
103	10:59	0.0	31	
104	11:05	12.1	29	0.048
105	11:10	0.0	16	
106	11:15	0.0	16	
107	11:20	0.0	14	
108	11:25	14.5	14	-0.002
109	11:30	23.5	12	-0.041
110	11:35	14.3	41	0.045