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Advanced Methods for Improving the Lead-Time and Accuracy of a Flood Alert System in an Urban Watershed

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

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ABSTRACT

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Jude A. Benavides

The lead-time and accuracy of a flood alert system designed for a quickly responding urban watershed have been improved by incorporating a variety of new tools and methodologies. These include: the use of computer-mediated voice and data communication systems such as the Internet, high-quality hydrologic data including radar rainfall, real-time hydrologic models, assessment and use of a Quantitative Precipitation Forecast (QPF) algorithm, and the development of improved flood notification levels – providing earlier and more accurate warnings to critical institutions and emergency personnel in flood-prone areas throughout the watershed. While the research focused on one watershed in an urban setting (Brays Bayou in Houston, Texas), the results found are applicable across a broad spectrum of watershed types, provided that the need for more timely and accurate flood forecasts exists.

System lead-time improvements were accomplished through the implementation and evaluation of a QPF algorithm increasingly used for short-term weather prediction
across the United States. The Brays Bayou watershed provided an excellent test-bed for the collection and evaluation of QPF data. Algorithm accuracy and effectiveness were evaluated at various forecast times and basin sizes commonly found in urban watersheds. Generalized results of these analyses are presented.

System accuracy improvements were accomplished with improved radar-rainfall data input and the development of real-time hydrologic models. A real-time interface for the industry standard HEC-1 hydrologic model was created, allowing the hydrologic predictions developed by this model to take greater advantage of the spatial and temporal distribution of real-time radar-rainfall data. The successful implementation of this real-time hydrologic model at the scale of Brays Bayou also provided significant lead-time improvements by providing estimates to when peak flows would actually occur.

A successful validation and operational test of the entire system occurred during the November 17th, 2003 storm event. This storm event is utilized as a case study, with results illustrating wide-ranging improvements.
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Chapter 1. Introduction and Research Objectives

1.1 Problem Statement

Accurately predicting the occurrence of a natural disaster with sufficient time to allow the evacuation of those in danger and the implementation of damage control measures, allows for the minimization of the human and economic losses incurred by that event. Every region of the world is subject to some form of natural, devastating event, whether it be tornados, earthquakes, hurricanes, volcanic eruptions, or flash floods. Their effects are indiscriminate and far reaching. Consequently, the scientific and engineering communities have, over the years, devoted significant resources to the search for accurate prediction tools for these phenomena. In the case of localized weather events, such as severe thunderstorms, flash floods, or even high winds, the development of adequate prediction methods is severely hampered by the fact these events occur over very short time frames and are part of a larger, very complex driving mechanism – the atmosphere. Effective early detection and warning of these types of events is difficult. The National Weather Service has estimated that more than 70% of flash flood warnings may be issued with less than a one-hour lead-time and that more than 50% of flash flood occurrences allow no lead-time whatsoever.

With respect to loss of life and property, floods are considered the number one natural disaster in the United States (Galloway 1994; NWF 1998; Pielke Jr., Downton et al. 2002). By the late 1990’s, annual flood damages for the nation had risen to $4.0 billion. Locally, the Houston area has suffered severe flood related losses on a number of occasions, most recently due to Tropical Storm Allison in 2001. TS Allison has been
categorized by the National Oceanic and Atmospheric Association (NOAA) as the most
damaging urban flood in U.S. history. While the event brought widespread flooding to a
majority of central Harris County and caused over $5.0 billion in damages (Figure 1.1),
the storm also served as a catalyst for revamping the entire flood damage reduction plan
for the area (FEMA and HCFCD 2002).

Figure 1.1: Maximum observed rainfall over a 9-hour period
during Tropical Storm Allison

The susceptibility of the Houston region to this type of flooding is heightened by a
variety of factors including its flat terrain, poorly drained clay soils, and intense
development often associated with urban areas. In the past, flood control methods have
largely been limited to major structural measures such as the channelization of White
Oak Bayou and Brays Bayou. However, it has become clear that, while effective at
reducing the extent of flood damages, these measures have failed to fully solve the flood
problem. This is especially true in densely populated regions such as downtown Houston and the location of the Texas Medical Center.

Flood alert systems (also called flood warning systems) are becoming more prevalent as tools to reduce the flood damage susceptibility of critical areas in watersheds throughout the United States. A flood alert system is designed to collect, handle, analyze, and disseminate hydrologic information, in real-time, for the purpose of providing advanced warning of a flood condition. Their increased use is due to a variety of factors including the growth of computer-mediated voice and data communication systems including the Internet, increased availability of high-quality hydrologic data including radar, advances in hydrologic modeling, and a resurgence of the non-structural flood control method in flood risk management plans. Research aimed toward maximizing the benefits of these advances, and in turn, developing new advances in system operation, will undoubtedly benefit communities that choose to implement this flood damage reduction option.

1.2 Problem Approach

This research seeks to improve upon two of the most critical performance factors of an existing flood alert system designed for the Texas Medical Center located in Brays Bayou (Figure 1.2). These factors are system accuracy and lead-time. The accuracy of a hydrologic prediction can be determined by a variety of methods. For flood alert purposes, the most important are the accuracy of the maximum flow predicted (peak flow) and when that flow will occur (time-to-peak). These factors are in turn, dependent on both the quality of the hydrologic model used and the quality of the rainfall input to
Figure 1.2: The Brays Bayou watershed and its location with respect to the downtown Houston and the Texas Medical Center

the model. The most accurate prediction possible is useless if it is not issued in a timely manner. Lead-time is essentially the amount of time between the issuance of a flood warning and the actual occurrence of the event. Maximizing this variable is critical because it allows more time for the implementation of mitigation efforts in anticipation of the floodwaters.

Recent technological advances in hydrology, and a number of its related fields including meteorology and computer science, have made available a variety of tools capable of increasing the performance of a flood alert system – especially for quickly responding, urban watersheds. Some of these advances include: the continued research in the application of Next Generation Radar (NEXRAD) and the tremendous spatial and temporal detail it provides to hydrologic modeling, the development of more accurate
Quantitative Precipitation Forecast algorithms that can handle the vast amount of rainfall data now available in real-time, the development of powerful yet efficient distributed parameter and lumped parameter hydrologic models capable of running in real-time, and the linkage of all of these advances within the ever-improving Geographic Information Systems (GIS) field. Another technological advancement is the availability of a large amount of historical rainfall and streamflow information from data collection systems that have now been in operation for several years. This data not only allows for the improved calibration and validation of hydrologic models but makes possible a number of flood modeling techniques based on statistical analysis. Specifically, this research will apply a number of these advances with the expected results of an improved flood alert system that will produce more accurate and efficient flood forecasts for its end users.

1.3 Research Objectives

The overall objective of this research focuses on determining if the accuracy and lead-time of a flood alert system for a quickly responding, urbanized watershed can be improved by incorporating advances in hydrologic modeling, short-term quantitative precipitation forecasts, data availability and information technologies. In order to make a thorough evaluation, three primary objectives were identified and are used as a guide in performing the research.

Objective 1

Objective one is to evaluate the accuracy and effectiveness at increasing lead-time of a short-term Quantitative Precipitation Forecast (QPF) algorithm from a watershed perspective. This objective will focus on one particular QPF called the
Growth and Decay Storm Tracker (GDST) developed at the Massachusetts Institute of Technology. The original purpose of the GDST was to provide high-resolution, advanced warning to air traffic control personnel for safe traffic management during storm events. It is already known that the system is adept at forecasting the location of future storm cells up to one hour for frontal system; however, research is still in progress as to how well the system quantifies future precipitation. As part of this research, the QPF will be applied to and viewed from a flood alert perspective. Performance will be evaluated at various forecast times and basin sizes with the goal of determining if there is an optimum point of trade off between these two. Specific questions involved in this research include: Can the expected reduction in forecast skill due to increased forecast times be sufficiently compensated for by increasing the basin size over which the projected data is averaged? Is there an optimum basin size and forecast time at which the algorithm performs acceptably for input into a hydrologic model for the generation of a Quantitative Flood Forecast (QFF)?

Important tasks to be accomplished in this section:

1. Record and archive QPF data over a specific and adequate period of record;
2. Develop a QPF performance evaluation/skill methodology and metric;
3. Evaluate the QPF forecasts at various forecast times and basin sizes;
4. Determine if the results support an optimum basin size / forecast time;
5. Generalize the above results so that they may be applied to a variety of different sized watersheds in other locations.

**Objective 2**

Objective 2 is to develop and evaluate a real-time, lumped parameter hydrologic model for application within a flood alert system. A lumped parameter model, HEC-1, will be developed for Brays Bayou and modified to run in real-time,
thereby utilizing real-time input rainfall data to produce near immediate hydrologic predictions for Brays Bayou. This section will seek to highlight some of the specific challenges faced by a real-time, operational hydrologic model. The model, including the real-time interface, will be referred to as Real-Time HEC-1 (RTHEC-1).

Important tasks to be accomplished in this section:

1. Create a real-time operational (RT) structure to support HEC-1 models;
2. Calibrate the baseline HEC-1 model for Brays Bayou to storms of significance and incorporate it into the real-time structure (August 15th, 2002 storm event);
3. Validate both model output and the real-time operational interface during 2-3 additional storm events;
4. Identify specific advantages of a real-time model as well as any limitations.

**Objective 3**

Objective 3 is to **identify and address important operational issues involved with a flood alert system, such as flood protection action levels, with the goal of improving overall system effectiveness**. This objective will focus on the actual realized gains in accuracy and lead-time from the above research as well as the development of newer flood forecast metrics and alert action levels that are a direct result of these gains. The objectives above are expected to provide individual improvements; however, they will also provide significant improvements when used collectively and are operating efficiently within a flood alert system. Specific attention will be paid to the flood situation at the Texas Medical Center, including a discussion of the Harris Gully box culvert / Brays Bayou confluence and how this confluence affects the flood potential at the TMC. Some of the specific questions involved in this research include: Can a robust, real-time flood forecast metric be devised for the TMC based on Harris Gully box culvert levels and the improvements presented in previous sections? Can improved flood
protection action levels be developed as a result of the above technologies? Can and
should the RTHEC-1 hydrologic model be directly coupled with the QPF algorithm to
produce real-time Quantitative Flood Forecasts (QFFs)?

Important tasks to be accomplished in this section:

1. Gather Harris County Office of Emergency Management (HCOEM) historical rainfall
   and streamflow data over Brays Bayou for the period of record from 1993-2002;
2. Process and smooth the data from identified storms of significance for analysis;
3. Develop new Harris Gully alert levels based on a statistical analysis of rain gage data;
4. Develop a methodology for coupling the QPFs and hydrologic models developed
   above;
5. Lay down the framework for implementing this methodology in real-time;
6. Update the alert level classification system for Brays Bayou as a result of the above
   findings;
7. Validate the operational effectiveness of the improved FAS (known as FAS2) during
   an actual storm event.
Chapter 2. Background and Literature Review

Flood damage continues to increase in the United States despite extensive flood management efforts to curb this most expensive of natural disasters. Major floods and severe storms continue to take their toll not only throughout this nation, but throughout the rest of the world. Figure 2.1 illustrates the increasing trend of total flood damage across the U.S. through the period 1934-2000 as recorded by the National Weather Service (Pielke Jr., Downton et al. 2002). Flooding is only one type of natural disaster.

Figure 2.1: U.S. Total Flood Damage and Trend, 1934-2000 (Pielke Jr., Downton et al. 2002)
Figure 2.2 shows the distribution of natural disasters across the nation and associated damages according to the National Climatic Data Center (NCDC), with many of these occurring near highly urbanized cities and coastal areas. The figure shows a total of 39 disasters, each responsible for at least $1 billion worth of damage. Eight of the 39 disasters occurred in the 1990s and were either solely due to floods or directly flood related. These eight disasters, in addition to the more recent Tropical Storm Allison event, are detailed in Table 2.1. This data demonstrates the severity of the flood problem at the national level, despite years of investment in various types of flood control.

Figure 2.2: Billion Dollar Weather Disasters, 1980-1999 (NCDC, 2000)
Table 2.1: Selected Flood Related Disasters and Damages, 1980-1999

<table>
<thead>
<tr>
<th>Storm or Flood Related Disaster</th>
<th>Damages (Billions of Dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Hurricane Andrew</em></td>
<td>$27.0</td>
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<tr>
<td>Florida, August 1992</td>
<td></td>
</tr>
<tr>
<td><em>Great Midwest Floods</em></td>
<td>$21.0</td>
</tr>
<tr>
<td>Upper Mississippi / Missouri Basins, Summer 1993</td>
<td></td>
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<tr>
<td><em>Hurricane Floyd</em></td>
<td>$6.0</td>
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<tr>
<td>South Carolina, Virginia, Northeast U.S., September 1999</td>
<td></td>
</tr>
<tr>
<td><em>South Central Flooding</em></td>
<td>$6.0</td>
</tr>
<tr>
<td>Texas, Oklahoma, Louisiana, Mississippi, May 1995</td>
<td></td>
</tr>
<tr>
<td><em>Hurricane Georges</em></td>
<td>$5.9</td>
</tr>
<tr>
<td>Florida and Alabama, September 1998</td>
<td></td>
</tr>
<tr>
<td><em>Tropical Storm Allison</em></td>
<td>$5.0</td>
</tr>
<tr>
<td>Houston, Texas, June 2001</td>
<td></td>
</tr>
<tr>
<td><em>California Flooding</em></td>
<td>$3.0</td>
</tr>
<tr>
<td>January through March 1995</td>
<td></td>
</tr>
<tr>
<td><em>Texas Flooding</em></td>
<td>$1.0</td>
</tr>
<tr>
<td>October and November 1998</td>
<td></td>
</tr>
<tr>
<td><em>Southeast Texas Flooding</em></td>
<td>$1.0</td>
</tr>
<tr>
<td>October 1994</td>
<td></td>
</tr>
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</table>

This chapter commences with a brief overview of the various flood control alternatives available and which have been implemented in the past. Specific attention is paid to flood alert (also called flood warning) systems. A review of the literature with respect to these systems and the improvements associated with the research presented in this dissertation is included.
2.1 Structural and Non-structural Methods of Flood Control

Any general flood control approach can be described by one of the following categories: structural, nonstructural, or combination (Mays 1996). Methods that seek to modify flood runoff through the creation and implementation of engineered structures are classified as structural. Examples of structural methods include channel modifications (channelization), reservoirs, detention / retention ponds, diversions, and levees or dikes. Those methods that seek to modify the damage susceptibility of developed regions within a floodplain are classified as nonstructural. Nonstructural measures serve to adjust the use of flood-prone lands to the flood hazard by a variety of means including: floodplain land acquisition (also commonly referred to as voluntary relocation or property buyouts), land use restrictions (zoning), flood proofing, flood warning systems, drainage maintenance programs, and public awareness or information programs. Each of these approaches has associated advantages and disadvantages that will briefly be highlighted in the following sections. The reader is referred to the 1996 U.S. Army Corps of Engineers document entitled “Federal Perspectives for Flood-Damage-Reduction Studies” (USACE 1996), for a detailed discussion of the advantages and disadvantages of each approach.

The traditional flood control approach, from the early 1900’s through the 1960’s, relied upon major structural alternations to channels and the building of dams and reservoirs. Many of these projects were implemented as part of the development of the arid western United States (Reisner 1993). The Hoover, Grand Coulee, Shasta, and Tennessee Valley Authority dams of the 1930s and 1940s, followed by others such as the
Glen Canyon and Amistad dams in the 1950s and 1960s, are all examples of major water resources projects. While these were primarily designed for water supply, they also provided flood control and protection to downstream areas. This reliance on structural measures at the large basin scale carried over to flood control policies for smaller basins.

With the advent of the environmental movement of the 1960s, the structural approach to flood control came under criticism in the U.S for not adequately solving the flooding problem, while at the same time creating significant environmental impacts. One excellent example of this problem was the extensive use of channelization as a flood control option throughout the United States, particularly in the meandering streams of the South and Southeastern Coastal Plains (Brookes 1988). From 1820 to 1970, more than 200,000 miles of the nation’s waterways were modified to some degree (Schoof 1980). Due to concern over the widespread use of this particular flood control option, the Council on Environmental Quality commissioned the Arthur D. Little Corporation to perform a nationwide survey of both the effectiveness and environmental impact of channelization. The report concluded in 1973 that while significant benefits were being afforded by channelization (reducing flood damages by $1 billion each year), projects were often over-designed at the large basin scale and under-designed at the small basin scale. The under-designed modifications would not adequately address flood control in the future and the over-designed modifications would result in significant environmental impacts to the natural floodplain and downstream areas (A.D. Little 1973).

The Brays Bayou watershed in Houston, Texas is a premier example of how the effectiveness of a purely structural flood control scheme can be limited in the long term as a result of floodplain over-development and under-designed modifications. The main channel of the watershed was channelized and partially concrete-lined in the late 1950s,
with the goal of accommodating flows exceeding a 100-year rainfall event. Due to years of urban expansion throughout Houston in the 1970s, the channel is no longer able to even contain a 10-year rainfall event, corresponding to about 6 inches in 6 hours. Additionally, Brays Bayou now responds even faster than before, with response times (time to peak) ranging on average from 2-6 hours, depending on the spatial and temporal distribution of the rainfall. Major floods occurred in Brays Bayou in 1976, 1983, and 2001, and came close to occurring in 1994 and 1998. More than 90% of the watershed is now considered developed, with an estimated 30,000 structures inside the 100-year floodplain, including the Texas Medical Center (TMC), the largest medical complex in the U.S.

The channelization scheme has been heavily criticized for having promoted development in the floodplain by fostering a false sense of security commonly attributed to structural systems. Figure 2.3 illustrates the increase in annual peak flows for Brays Bayou at Main St. over the period from 1936 through 2001. It is estimated that a 100-
year flood event over the Bayou would now result in approximately $1.8 billion in damage (HCFCD 2000). This data, and other historical streamflow data, support the theory that the 1960 channelization, combined with continued upstream development and poor stormwater management practices, resulted in the need for a flood warning system that would provide early detection of intense rainfalls and resulting stream flows.

Criticism was not only limited to channelization, but extended to other structural methods as well, due to their combination of associated environmental impacts, poor aesthetics, and overall performance. The recurrence interval design methodology of these methods often translates to minimum effectiveness when their design specifications are exceeded. For example, a levee system designed to protect against a 100-year storm (1% annual probability of occurrence), provides little protection against the 500-year storm that will eventually occur. Additionally, these methods often foster a false sense of security amongst members of the communities they are designed to protect, resulting in the unwise encroachment into floodprone areas (NWF 1998). Fortunately, floodplain management and flood control agencies are now recognizing the significant limitations of these approaches when relied upon solely. As a result of this and other factors, including policy changes at the federal level and recent technological advancements, alternatives to structural methods have become increasingly more predominant in recent flood control management strategies.

In contrast to the primary aim of structural measures to reduce flood hazard by actually altering flood flows, non-structural methods seek to reduce the damage potential of a structure or facility within the floodplain by a variety of means. The amounts of reduction in damage potential achieved by nonstructural measures vary significantly, depending on the mechanism implemented. Some of these mechanisms include flood
proofing, flood warning and flood alert mechanisms, land-use regulatory controls such as zoning and development ordinances, flood insurance programs, flood preparedness activities, public awareness and education programs, and the acquisition of floodplain land or voluntary flood-prone property buyouts. (Galloway 1994).

Non-structural methods of flood control have only recently been given serious consideration as a primary means of reducing flood damages, despite their potential usefulness having been researched for over 50 years. Alternative options to structural methods were perhaps first articulated by White (1945). In the 1950s, the Tennessee Valley Authority, with its broad mandate for water-management experimentation, proved an effective pilot program for many nonstructural measures. Leopold and Maddock (1954) as well as Hoyt and Langbein (1955) somewhat popularized the nonstructural movement in professional circles by creating guidance for the development of floodplain regulations accepted by the American Society of Civil Engineers (ASCE).

In 1966, a Presidential Task Force on Floodplain Regulations was charged with making recommendations for improving existing federal flood control policy in order to create a unified national program to manage flood losses. One of the principal outcomes of the task force findings was the creation of the National Flood Insurance Program (NFIP) by way of the Flood Control Act of 1968. This was the first major non-structural flood control alternative implemented at the national level. The NFIP was placed under the cognizance of the newly formed Federal Emergency Management Agency (FEMA) in 1979. While the program has experienced major shortcomings in the form of policy and financial distortions, repetitive loss properties, and poor regulatory enforcement, it has nevertheless enjoyed some success. Flood insurance premiums, paid by property owners
who live within the 100-year floodplain in communities that have established a minimum standard of hazard mitigation provisions, have covered $10.4 billion in losses and program expenses between the years of 1977 and 1997 (NWF 1998). The NFIP, although certainly not the singular flood control answer, spurred an ever increasing awareness of the benefits of a sound flood mitigation strategy, highlighted the benefits of the natural floodplain, and proved that a non-structural methodology could be effective from both the flooding and financial perspectives.

The buyout of high-risk floodplain properties from willing sellers and the relocation of at-risk buildings and structures out of the floodplain are additional nonstructural alternatives that have received increased attention in recent years. The catastrophic Midwest flood of 1993 along the Mississippi and Missouri Rivers, as well as several resulting post-flood studies and recommendations, spurred national interest in this particular alternative. Interest was raised due to the significantly reduced flood damages experienced by communities throughout these major watersheds that had implemented this control measure as compared to those relying solely on levees or other upstream structural measures (NWF 1998).

Three major documents in support of non-structural flood control alternatives were written in the 1990’s. The first report, often referred to as the Galloway Report after its author General Gerald E. Galloway, USAR, is entitled “Sharing the Challenge: Floodplain Management into the 21st Century” (Galloway 1994). The report was prepared for the Administration Floodplain Management Task Force in response to harsh criticism of failed structural control systems throughout the Mississippi and Missouri River basins during the Great Flood of 1993. This report, along with the National Research Council’s document entitled “New Directions in Water Resources Planning for the U.S. Army
Corps of Engineers’ (NRC 1999), prompted new approaches toward and evaluations of existing flood control schemes. The third major report to have a significant impact on the importance of non-structural alternatives was the National Wildlife Federation’s “Higher Ground” (NWF 1998). This document highlighted the important roles the NFIP and floodplain property buyouts could play in reducing annual flood damages experienced by the nation. These reports have already had a profound impact in the development of more balanced flood management strategies across the board.

2.2 History of the Flooding Problem and Flood Policy in Houston, Texas

The City of Houston was founded in 1836 on the banks of Buffalo Bayou, which provided a water route for both commerce and flood flows to the Gulf of Mexico. Destructive flooding had been reported as early as 1843, but was not considered a large problem because of the low population density of Houston and Harris County before the 1950’s. The Houston Ship channel was built in 1915 by the U.S. Army Corps of Engineers, and Houston soon after became a major outlet for agricultural and petroleum products.

The Brays Bayou watershed, which drains approximately 128 sq. mi., is located in southwest Harris County and runs through the cities of Houston, Missouri City, Stafford, Bellaire, West University, and Southside Place. Brays Bayou flows in an eastward direction for 31 miles from its headwaters in Fort Bend County to its confluence with the Houston Ship Channel. Except for the western regions, undeveloped areas of significant size are rare.
Included in the Brays Bayou watershed are critical developments such as the Texas Medical Center, the Houston Zoo, Houston Baptist University, Rice University, and the intensely developed commercial corridor along the Loop 610 and U.S. 59 interchange.

The watershed contains forty-six sub-basins. The portion of the watershed upstream of Main Street, located in the Medical Center, has an area of about 95 square miles and contains thirty-nine of the sub-basins. The Harris County Office of Emergency Management (HCOEM) currently has over 14 raingages and 11 stream gages (plus 3 USGS stream gages) operating along the bayou recording rainfall amounts and resulting stream flows during storm events (see Figure 2.4). Harris Gully is a smaller tributary that flows underneath the Medical Center and is important due to its close proximity to the Medical Center.

Figure 2.4: Brays Bayou and the Rain Gage Network Operated by the Harris County Office of Emergency Management

Recharge areas of the Texas Coast are structured such that rainwater is introduced slowly into the aquifer systems. Unless the rain falls directly upon the recharge area of an aquifer, the storage capacity of the soil eventually becomes exhausted, and the water
added by the storm can no longer be absorbed by the ground surface. The runoff is then diverted to the bayou system or a reservoir (natural or improved).

A major factor that influences the size of Houston streams and bayous is the size of the area they drain. Another factor is the ability of the land surface to absorb the precipitation that it receives. The initiation of large-scale urbanization within a watershed caused an unintended alteration of the natural hydrologic system. When urbanization renders soil impervious, the net result severely limits the storage capacity of the soil. Additionally, the volume of water stored in the drainage channels is more quickly concentrated – the same volume of water must drain out of the system, but in the urbanized system it will happen in a matter of hours instead of days or weeks. The quick response makes the watershed susceptible to flooding from relatively short intense rainfall events.

Despite several large flooding events that caused severe damage in the early 20th century, no flood control action was taken until 1937, when the Harris County Flood Control District (HCFCD) was created. The HCFCD did not become effectual until 1939 when a flood control master plan was developed. The 13,100-acre Barker Reservoir was completed in 1945, and the 11,600-acre Addicks Reservoir was completed later that decade to serve the Buffalo Bayou watershed. During this time, the eleven independent drainage districts in the Harris County area were merged under the HCFCD so that drainage issues would be handled in the best interest of the Houston area as a whole.

As mentioned earlier, Brays Bayou was channelized and concrete lined from 1955 to 1960 after a destructive flood proved that Buffalo Bayou was not the only area of concern. In 1969, the Houston Post reported that during the previous month, Brays Bayou carried three times as much water as caused in the 1949 flood without resulting in serious
damage, leading to the conclusion that this work was highly successful. After these channel improvements were made on Brays, White Oak Bayou was also lined, and was the last bayou in Harris County to be completely concrete-lined.

Flood control activities in Harris County in the 1960’s became more complex and had further reaching effects than ever before. Houston and Harris County experienced unprecedented growth during the 1950’s as the city doubled the area within its boundaries each decade. Substantial amounts of development occurred outside the city limits during the 1960’s, and the trend accelerated during the 1970’s. Measures were taken in 1973 to restrict development in the floodplain, which had previously gone unchecked.

In June 1976, approximately 10 inches of rain fell in a six-hour period in southern Harris County, in the Brays and Sims Bayou watersheds. Flooding and damage was extensive, but the most heavily damaged area was the Texas Medical Center, where damages exceeded $20 million dollars. Rice University, the University of Houston, and the Museum of Fine Arts suffered over one million dollars in damage. Flood waters backed up through sewer pipes and flowed overland through homes and institutions in the lower Brays Bayou watershed. Brays Bayou never overflowed its banks, and thus the cause of the flooding has been contributed to the lack of capacity in the storm sewer system to contain the resulting flow.

This storm identified a previously unrecognized problem regarding urbanization and channelization of streams. When the $26 million Brays Bayou channelization project was undertaken, certain assumptions were made with regard to urbanization in the watershed, and the stream was channeled to accommodate the flow predicted from a 100-year storm event falling on this urbanized watershed. However, the urbanization that
occurred exceeded the design estimates, and Brays Bayou could only hold a 33-year return frequency storm as of 1979. Today, Brays Bayou will flood between a five and ten year rainfall event.

In 1980, the Harris County Flood Control District initiated a formal "no downstream impact" policy for new developments. This resulted in widespread use of onsite detention facilities, which was further developed in the HCFCD design criteria manual, adopted by Commissioners Court in 1984.

In 1985, the Harris County Flood Control District commissioned a study to evaluate alternatives for controlling flood peak discharges on Brays Bayou that focused on the goal of eliminating over-bank flooding for storms up to and including the 100-year event. Pate Engineers, Inc. developed a final report which recommended the construction of four regional detention facilities (2 each on the upper Brays and Sims Bayou), along with the construction of flow diversion channels to route a portion of the Keegans Bayou storm water flow to Sims Bayou. For economic and political reasons, these measures were not implemented.

While Brays Bayou has not had an out-of-bank flood since 1983, there were near misses in March 1992, October 1994, March 1997, September 1998, June 2001, and November 2003. Recently, large scale flood protection plans along Brays Bayou have been initiated by the HCFCD and the United States Army Corps of Engineers (USACE) which include increased channelization, upstream detention and raising over 30 bridges. This flood protection effort is known as the Brays Bayou Flood Damage Reduction Plan.

The upstream study was completed in 1988. This part of the project involves the excavation of 3 major storm water detention basins upstream of the Sam Houston Tollway, which will provide approximately 8,100 acre-feet of storage on 520 acres of
land. It also includes 3.7 miles of channel enlargements between Old Westheimer Road and State Highway 6.

Construction on the upstream project began in 1994, and is scheduled to be complete in 2008. The projected cost is estimated to reach $195 million, one half of which will be reimbursed by the US Army Corps of Engineers. It will provide 100-year flood protection along Brays Bayou between the Sam Houston Tollway and Highway 6. As of July 2001, about 98% of the land had been acquired and the excavation was in progress.

The downstream study has only recently been completed. It sought a more effective alternative to the diversion element that was proposed in 1985. After much discussion, the public and HCFCD finally agreed upon an approach. The downstream plan involves enlarging the channel for a 17 mile length, from the mouth of Brays Bayou at the ship channel to Fondren Road. All channel widenings necessitate the modification of roadway, railroad, pipeline, and utility crossings. 14 bridges spanning Brays Bayou will be replaced, including State Highway 288. An additional 17 bridges will be extended. It also includes a large detention basin along Willow Waterhole, a tributary of Brays Bayou, whose simulated peak flow coincides with the peak of Brays Bayou. The detention basin will hold 1,865 acre-feet.

As of July 2001, 4 of 55 tracts were purchased for the detention area, and channel design was in the preliminary stages. Construction is scheduled to begin in 2006. It will cost about $242 million, providing 50-year flood protection between the Ship Channel and the West Sam Houston Tollway.

Community input played a large part in the planning stages of the project. As a result, the project will incorporate extensive aesthetic, environmental, and recreational improvements. The upstream element includes attractive detention layouts, including
playing fields, trails, landscaping, and the planting of 20,000 trees and shrubs. Some detention areas will include wet bottom marshes to improve water quality and create wetland habitats. The detention area just upstream of West Sam Houston Tollway will be a Harris County Precinct Three Park. During the planning of the downstream element, several public meetings and coordination with the Brays Bayou Citizens Advisory Committee provided a substantial voice to community concerns. In the downstream reach, the Willow Waterhole Detention Basin will also incorporate wetlands and park and recreation features, though the exact design is not yet complete.

The entire Brays Bayou Federal Project is planned be completed around 2012. It should significantly reduce flood elevations along Brays Bayou, bringing the number of homes in the 100-year floodplain down from 30,000 to 1,700. The total cost is projected to be $437 million, reducing flood damages by about $98 million per year. This amounts to a net benefit of $62 million per year. In the interim, however, the only alternative is to be forewarned of an impending flood on the scale of the many discussed above.

2.3 Flood Alert Systems as a Flood Damage Reduction Tool

Flood Alert Systems (also called flood warning systems) are becoming more prevalent as tools to reduce the damage susceptibility of critical areas in watersheds. This is due to a variety of factors including the growth of computer-mediated voice and data communication systems, increased availability of high-quality meteorological and hydrologic data, advances in hydrologic modeling, as well as the previously discussed resurgence of non-structural flood control methods in flood risk management plans.

The World Meteorological Organization has defined flood forecasting as "the prediction of stage, discharge, time of occurrence, and duration of a flood – especially of
peak discharge at a specified point on a stream – resulting from precipitation and/or snowmelt" (Singh 1989). The purpose of flood forecasting is to minimize the losses incurred due to a flood event by providing an advance warning of the occurrence of the flood such that protective actions may be taken. When compared to structural methods of flood control, flood alert systems are generally cost effective, and in many circumstances, their warnings are the only available means of avoiding flood damage (Johnson 1988). Singh (1989) identified three criteria by which the usefulness of a flood forecast system may be measured: accuracy, reliability, and timeliness.

The accuracy of a forecast system may be defined by the relative number of warnings issued in comparison with the number of flood events observed over a specific period of time. The Critical Success Index (CSI) is a statistical measure often used in the atmospheric sciences to quantitatively describe the accuracy of a forecasting system (Wilks 1995):

\[
\text{CSI} = \frac{H}{H + M + FA}
\]

While a more specific application of the CSI with respect to radar images and Quantitative Precipitation Forecasts (QPFs) will be discussed later in this work, the equation can be used to discuss the accuracy of flood forecasts in general. Hits (H) represents the number of successful forecasts of an event over a specified period of time, misses (M) represents the number of times an event occurred but was not forecast, while false alarms (FA) represents the number of time an event was forecast but did not actually occur. A high CSI score indicates a high degree of accuracy for a forecast system so it is clearly desirable to reduce, as much as possible, the number of misses and
false alarms for the time period of interest. While it is clearly desirable to avoid circumstances in which a warning is warranted but fails to be issued, it is equally desirable to avoid a large number of false forecasts. The “cry wolf syndrome” is a well-recognized phrase in natural hazards research and warning response (Mileti 1999), describing the undesirable situation where individuals become conditioned to ignore flood warnings after too many false alarms. In addition, there is always a cost involved with the implementation of any mitigation effort, and this requires that careful consideration be given to avoid the development of an overly conservative flood warning system.

The reliability of a forecast system may best be related to matters of its physical operation. Data collection and transmission are some of the biggest variables in system reliability. Both collection and transmission systems may fail during system operation and the system should be robust enough to handle these eventualities. Redundant systems, such as multiple data feeds and communication systems, are often employed to improve the mechanical reliability of a system; however, reliability is not only limited to mechanical systems. Any warning system depends heavily on forecast personnel. Flood warning systems in particular, can cut across a variety of legal boundaries including Federal agencies, regional weather services, local jurisdictions, and the private sector, in which case the division of responsibility / actions among these various groups is not always clear. Schultz (1986) makes reference to the “human factor” that is a part of all flood alert systems. He claimed that the optimal operation of any flood forecasting system could never be realized if it was subject to the risk-aversion mentality of a human decision maker; however, he also pointed out that the development of a fully automated forecast system should be approached with caution.
Even the most accurate flood forecast is ineffective if it is not delivered sufficiently in advance to allow personnel to take specific actions to mitigate flood damage. In hazard warning research, this time is referred to as lead-time. In an operational flood warning system, the forecast lead-time is the maximum possible time in advance by which a meaningful forecast can be made. Actual warning lead-times will always be less than the theoretical available lead-time due to delays associated with the operational components of a flood warning system, including data collection, processing, formulation of the forecast, and transmission of the warning to the end user. Figure 2.5, adapted from Johnson (1988) and Singh (1989), illustrates the various sub-processes of a flood alert system. The time scale is dimensionless but is dependent on watershed size and response time. Larger basins have larger times of concentration and longer times

![Figure 2.5: Elements in the Preparation of a Flood Warning Forecast (Singh, 1989)]
to peak \( t_p \). Correspondingly, the time between a rain event and the observation of a flood event for a large basin (basins on the order of several thousand square miles) could be days or weeks. The challenge is amplified for smaller basins with response times on the order of a few hours.

Flood forecast systems generally exhibit a trade-off between the accuracy of a prediction and the lead-time of the warning. This trade-off should be intuitive, as the maximum effective available lead-time (illustrated in Figure 2.5) is realized when receipt of the system warning occurs as soon as possible. This, in turn, requires faster data collection, assessment and model forecasting at the obvious expense of accuracy. This trade-off is even more apparent when flood warning systems attempt to increase lead-time by using Quantitative Precipitation Forecasts (QPFs), which are discussed in detail later in this chapter.

2.3.1 History of Flood Warning Systems

Flood warning systems have improved drastically over the second half of the 20\textsuperscript{th} century. The National Weather Service first provided flood warning capability shortly after World War II. Initially, flood warnings were based on simplified tables that related rainfall totals to water levels. While the basic hydrologic science existed to convert rainfall amounts to runoff, more advanced methods for flood warning were simply not possible due to the lack of efficient real-time data collection, transmission and analysis methods. Data collection methods would improve as gage network density increased, providing increased spatial detail with respect to rainfall amounts. Electronic transmitters and telemetry systems would later enable the rapid transmission of data from the increasing number of rain gages to base stations for computational analysis and real-time
forecasts at the larger basin scale. The advent of new technologies such as weather radars and satellites, geographic information systems (GIS), high-speed computer workstations, and the Internet would provide new opportunities for improved hydrologic forecasting in the 1980's and 1990's. These advances should improve the real-time performance of flood warning systems so that they could possibly be operationally effective at the relatively small basin scale (Mimikou and Baltas 1996).

The first automated local flood warning system was installed in northern California in the early 1970s. Growth of local flood warning systems was slow until the later 1970s, when the California-Nevada River Forecast Center developed the first ALERT (Automated Local Evaluation in Real-Time) system. This system integrated data from rain and stream gages via telemetry, into a central location where flood warnings could be made. IFOWS (Integrated Flood Observing and Warning System), a system very similar to the ALERT system, was installed by the National Weather Service in Appalachia. As of 1997, there were over 400 local flood warning systems in the United States, primarily in California, Arizona, Texas and Appalachia using telemetered rain and stream gage data to make flood warnings.

At the larger basin scale, the National Weather Service River Forecast System (NWSFRS) supports 12 nationwide River Forecast Centers (RFC) that monitor the nation's major river systems. The RFCs provide flood warnings to local community authorities through the NWS Weather Forecast Offices (WFOs) based on the comparison of flash flood guidance (FFG) values with rainfall amounts. FFG refers generally to the volume of rain of a given duration necessary to cause minor flooding on small streams. Carpenter et al. (1999), states that several shortcomings with existing FFG procedures have been identified by the NWS and that smaller river systems throughout the nation
still remain largely unmonitored and those that are monitored do not adequately address
the routing of flood waves at the small scale. Additionally, training of personnel on this
system has become a major concern among NWS personnel – with few personnel
actually being able to fully utilize the system effectively (Personal Communication, Bill
Reed, June 2004).

2.4 Modeling the Rainfall-Runoff Process

Hydrology is a multidisciplinary field that studies the dynamic relationship
between the climate and the land-surface. Scientists and engineers have attempted to
quantify this relationship for decades using hydrologic computer models. The central
challenge to the flood forecast hydrologist is to develop a model that will predict the flow
response of a watershed to a given rainfall as illustrated in Figure 2.6. A hydrological
catchment model typically transforms a time series of precipitation amounts (spatially
averaged or spatially distributed) into a time series of river stages, river discharges, or
runoff volumes (Collier and Krzysztofowicz 2000).

Figure 2.6 Basic Concept of a Hydrologic Model (Bedient and Huber 2002)
The field of hydrology has its roots in the early civil engineering days of the nineteenth century (Singh and Woolhiser 2002). Many of the concepts and theories in today's models were largely developed before the middle of the 1960s. The work of many people produced descriptions of the individual hydrological components such as infiltration, evaporation, overland flow, channel flow, storage, and flow routing. It was not until after the 1960s, that computing power made possible the integration of each of these hydrologic processes into a single model simulating an entire watershed (Singh and Woolhiser 2002).

Today, hydrologists have available a wide variety of forecast models from which to select. These models may be broadly categorized into two basic types: deterministic and probabilistic (Bertoni, Tucci et al. 1992; Krzysztofowicz 2001). Deterministic models and their associated forecasts specify a point estimate of the variate being forecasted, often either a flow rate or water level at a given point. A probabilistic, or stochastic, forecast specifies a probability distribution function of the predictand.

The prevailing format of operational hydrological forecasts has been deterministic. Additionally, most research in operational hydrology has been devoted to finding the 'best' estimates rather than quantifying the predictive uncertainty associated with a forecast. Krzysztofowicz (2001) presents a compendium of reasons for the probabilistic forecasting of hydrological variates and claims that they are scientifically more honest, enable risk-based warnings of floods, enable rational decision making, and offer additional economic benefits over their deterministic counterparts. Unfortunately, widely applicable operational probabilistic forecasting models are still an unrealized goal for hydrologic science with the major limitation to their application stemming from
insufficient historical data. The following sections on distributed and lumped
deterministic models are, in part, adapted from Stewart (2003).

2.4.1 Physics-Based and Conceptual Models

Given the diverse nature of hydrologic models, they can be broken down into two
general groups, physics-based and conceptual. A physics-based or theoretical model
contains a set of theoretical principles or laws. If the model describes all of the physical
laws governing the behavior of the watershed and if these laws can be solved with
mathematical equations, then the model is physics-based (Grayson, Moore et al. 1992).
Depending on the model, these equations are solved analytically or with numerical
methods. When the physical system is simplified by using parameters that are
empirically derived, then the model becomes conceptual. Conceptual models ignore the
physical laws and merely represent the data after a significant calibration effort (Vieux
2001). Since the parameters that control the runoff computations are not directly
measurable, the modeler must determine the parameters by fitting computed hydrographs
to observed hydrographs.

A further distinction must be made regarding the classification of models. A
model can either be lumped or distributed depending on how it handles spatial variability
(Bedient and Huber 2002). The most general mathematical description of a hydrologic
component would be described by partial differential equations in three space dimensions
and time (Singh and Woolhiser 2002). Lumped parameter models, however, do not
consider the spatial variability of the model inputs or outputs and ignore the spatial
derivatives. The modeled watershed is divided into sub-basins, each described by
averaged values of the hydrologic parameters (Molnar and Julien 2000). The simplicity
of these models may be advantageous, but their applicability is somewhat limited by their failure to account for internal variations of the hydrologic processes (Muzik 1996). If the spatial variability of the sub-basin and parameters influence the outcome of the rainfall event, then their use may not be justified without further subbasin division.

Lumped parameter models often describe a watershed's response to rainfall with conceptual relationships. This broad class of model is often referred to as conceptual rainfall-runoff (CRR) models. These types of models attempt to simulate the physical hydrological processes associated with a rain event using mathematical relationships that describe a conceptualized idea of the rainfall-runoff process. The mathematical relationships are formed to represent as nearly as possible the underlying physical phenomena. Models of this type that are widely used in the United States include the Hydrologic Engineering Center's HEC-1 (Center 1968; Center 1998), HEC-HMS (Center 2001), Technical Report-20 (TR-20) Model (Service 1965), EPA-SWMM (Huber and Dickinson 1988), and others. These models require a thorough calibration procedure, requiring historically measured event data. The goal of the calibration is to determine the representative value of the spatially variable parameter. This process, however, may introduce error related to data acquisition or the method used to incorporate the measured data (Colosimo and Mendicino 1996). Furthermore, lumped models can experience unsystematic parameter interactions where changing one parameter affects another unpredictably. Fundamentally, there is a lack of constraint on each parameter and the optimal value is difficult to determine when curve fitting (Vieux 2001), although with sufficient hydrologic experience and practice this is not a very common problem. Nevertheless, when a single objective function like stream flow is used to calibrate a model, multiple sets and/or changes of parameters may produce identical results (Freer,
Beven et al. 1996). This result ensues because each parameter describes a specific internal process of the model, but only the product of the interactions between these values is investigated (Dunn and Lilly 2001). The model therefore, may become over-parameterized because different combinations produce the same product. However, the same argument can be used when discussing distributed, physics-based models that introduce a significantly larger number of variables that, despite being calculated with physical equations, may also over-parameterize the model and introduce errors that may not be able to be accounted for adequately by the physical equations.

In contrast to lumped models, distributed models attempt to preserve spatial variability and typically use conservation of mass, momentum, and energy equations to represent the hydrologic process (Vieux 2001). The model domain is not lumped, but rather is subdivided into smaller interconnected cells where the parameters are assumed to be homogeneous (Colosimo and Mendicino 1996). This continuous domain differs from the discrete space of the lumped subwatershed models as illustrated in Figure 2.7.
Figure 2.7 Lumped and Distributed Modeling Approaches (Maidment 1993)

Many distributed models attempt to be fully deterministic where each parameter is purely physics-based and free from random variables (Abbott, Bathurst et al. 1986a; Abbott, Bathurst et al. 1986b). Mathematically, a physics-based distributed model uses equations that are solved analytically. The equations are continuous but they are solved discretely with finite difference or finite element methods. However, the non-linear equations are difficult to solve analytically and the boundary conditions may not be known (Woolhiser 1996). As a result, stochastic parameters having random variables with distributions in probability are often introduced. These simplifications are often justified because the level of detail, solution scheme, and subdivided domain result in large computational loads and simulation times. Consequently, there is trade-off between the level of detail in the model and computational load.

The boundary between lumped and distributed models can be blurred if the modeler tries to account for the spatial variability of the watershed by using lumped
models (Olivera and Maidment 1999). One major example is the HEC-1 hydrologic model, one of the more popular modeling packages used in the United States. One can partition the watershed into smaller sub-basins to try to account for the spatial variability of watershed attributes. The graphical user interface version (GUI) of this model, called HEC-HMS, provides Modified Clark grid-cell unit hydrograph routing as well as gridded precipitation data. Therefore this model combines both lumped and distributed modeling approaches. In essence, one could easily argue that all models remain “lumped” to some extent – depending on the scale of investigation and the end use of the model. Therefore, care must be taken in the use of these two terms when discussing the style of model and they are best used as relatively.

A summary of some of the more commonly used lumped and distributed parameter models is included in Table 2.2.

2.5 Scale and Data Issues in Hydrology and Flood Warning

The issue of scale has always been of great importance to the field of hydrology and hydrologic modeling; however, issues related to scale are receiving increased attention as hydrologic models become more refined and data becomes available in increasing detail. Scale is normally defined as the sampling interval size at which hydrologic observations are made or as the grid size used for numerical computations. Thus, the size of a scale will correspond to the length in the spatial domain and to the duration in the time domain. Scale variations have long been known to constrain the detail with which information can be observed, collected,
represented, analyzed, and even communicated (Hudson 1992). Changing the spatial scale of data without first understanding the effects of such action can result in the representation of processes or patterns that are different from those intended. Likewise, temporal scaling, a separate but related issue, is even less understood and more difficult to formalize (Singh and Woolhiser 2002). In the information era, a massive amount of hydrologic data are now collected from various sources at different scales, often presenting problems that must be addressed before the data can be integrated for problem solving.

2.5.1 Importance of Scale to the Modeling Approach in a Flood Warning System

Parameters and hydrologic processes controlling the watershed response operate at many different space and time scales. Thus, the relationship between model scale and the scale of the hydrologic processes has a significant impact on how well the model will perform. With regards to modeling approaches, the fundamental question seems to be: what is the minimum level of physical spatial scale to be used in modeling a watershed, which would adequately represent the spatial heterogeneity of that watershed?

The adequacy of a model is a function of its intended application and should not be confused with the ultimate accuracy the model is capable of obtaining. This question is of paramount importance to the debate between lumped and distributed modeling approaches discussed earlier in this chapter as well as the debate between conceptual and physics-based models, because of the additional time and expense often associated with obtaining the high-resolution data necessary to run the latter.
# Table 2.2: Important Lumped and Distributed Hydrologic Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Author</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Report-20 (TR-20) Model</td>
<td>Soil Conservation Service (1965)</td>
<td>A lumped parameter, event based, runoff simulation model. A conceptually simple model whose main use is to compute design hydrographs over heterogeneous watersheds.</td>
</tr>
<tr>
<td>Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) (Earlier DOS version called HEC-1)</td>
<td>HEC (1968,2000); Feldman (1981)</td>
<td>Physically-based, lumped parameter, event-based runoff model. Can be considered semidistributed with respect to its use of the Modified Clark unit hydrograph transformation routine. Considered the most widely used rainfall-runoff model in the U.S.</td>
</tr>
<tr>
<td>Storm Water Management System (SWMM)</td>
<td>Metcalf and Eddy et al. (1971); Huber and Dickinson (1988); Huber (1995)</td>
<td>Process-oriented, semidistributed, continuous stormwater flow model. Often used for highly detailed urban stormwater design due to its ability to handle both street and pipe flow.</td>
</tr>
<tr>
<td>Physically Based Runoff Production Model (TOPMODEL)</td>
<td>Beven and Kirkby (1979)</td>
<td>Physically-based, distributed, continuous hydrologic simulation model. Primarily a soil-moisture accounting model that uses a topographic index to group areas that have similar hydrologic behavior.</td>
</tr>
<tr>
<td>Cascade Two Dimensional Model (CASC2D)</td>
<td>Julien and Saghafian (1991)</td>
<td>Physically-based, distributed, event-based runoff simulation model. Primary features include two-dimensional diffusive wave overland routing solved with explicit finite difference method.</td>
</tr>
<tr>
<td>Vflo</td>
<td>Vieux (1994, 2001, and 2002)</td>
<td>Originally developed as r.water.fea for the U.S. Army Corps of Engineers. Current form is implemented in JAVA. Primary feature is solving the kinematic wave equation for overland and channel flow using finite elements. Grid cells are described by slope, hydraulic roughness, infiltration, precipitation, and flow direction.</td>
</tr>
</tbody>
</table>

With respect to flood warning systems, one of the most important issues of scale is closely linked to watershed size and its corresponding response time, because this is directly proportional to the maximum available lead-time an alert system can provide.
One type of deterministic model often used in large-scale flood warning systems is the flood routing model. Models of this type, in contrast to the CRR models discussed earlier, rely on flow data recorded at a gage upstream of the location for which a forecast is desired. Forecasts of downstream discharges are made by routing the observed flow through the stream channel. Routing may be accomplished by a number of techniques ranging from the solution of the Saint Venant equations for unsteady flow using numerical methods (referred to as hydraulic routing) to more simplified hydrologic methods including the single linear reservoir, the cascade of reservoirs, or the Muskingum model. Dooge (1986) provides an overview of forecasting techniques using flood routing. These types of forecast models are generally suited to large river basins with long travel times where there is sufficient lag time between the end of rainfall and the occurrence of the flood.

### 2.5.2 Data Availability in Real-Time

A limitation shared by any forecast model, regardless of type, is that of data availability. A flood warning model must be operated based only on the data available at the time of forecast. Rain gage based systems must have a dependable and redundant telemetry system that will accurately and efficiently transmit data to a central location for processing. Radar-based systems have simplified the data gathering process bystreamlining the data availability in real-time over one large area.

While the timeliness of real-time rainfall data is of paramount importance, the quality of the data is of equal importance. Extensive quality control of real-time data is difficult due to the time constraints associated with maximizing lead-time. This is perhaps one of the most difficult obstacles to the real-time calibration of radar data with
rain gage data, as it is difficult to determine a priori which rain gages used in the
calibration are operating correctly. Anagnostou and Krajewski (1999), Anagnostou et
al. (1998) and Boga (2002) all discuss various proposed solutions to this challenging
problem.

2.5.3 Selecting a Forecast Model

Singh (1989) outlined many factors that influence the type of flood forecast model
that is most appropriate for a given application. These factors include watershed
characteristics, degree of flood threat, availability of historical data, data collection
systems, and cost. Reed (1984) gave general, but insightful, guidelines for selecting a
forecast methods based on watershed response times as outlined in Table 2.3.

2.6 WSR-88D: Weather Surveillance Doppler Radar (NEXRAD)

Radar has become a rapidly growing source of spatially and temporarily
distributed rainfall data ideal for hydrologic modeling. A vast network of next generation
WSR-88D (NEXRAD) doppler radars, deployed by the National Weather Service, results
in nationwide radar coverage providing the capability of obtaining accurate estimations
of rainfall intensity over nearly any area within the continental U.S. Although radar

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Table 2.3: Guidelines for Selecting a Forecast Method Based on Basin Response Times

<table>
<thead>
<tr>
<th>Time to Peak of 1-hr Unit Hydrograph (hr)</th>
<th>Method of Forecasting</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_p &lt; 3 )</td>
<td>Rainfall-runoff modeling plus quantitative rainfall forecasts</td>
</tr>
<tr>
<td>( 3 &lt; t_p &lt; 9 )</td>
<td>Rainfall-runoff modeling</td>
</tr>
<tr>
<td>( t_p &gt; 9 )</td>
<td>Flood routing</td>
</tr>
</tbody>
</table>
technology itself is not new, the application of this technology toward hydrological purposes such as accurate hydrologic modeling and real-time flood alert systems is relatively recent (Bedient, Hoblit et al. 2000).

A key factor for accurate flood estimates and forecasts is accurate rainfall for input to the hydrological model. Rainfall data are traditionally obtained from an often sparse network of rain gauges that may not record the rainfall event with adequate spatial and temporal scales, especially for heavy convective storms when significant rainfall occurs over a limited areal extent (Sun, Mein et al. 2000). These errors arise from the fact that rain gauges are only capable of sampling rain at distinct points. Depending on the density of the network, rainfall patterns may pass between gages, resulting in an underestimation of the actual total rainfall. This is especially true in regions, such as Houston, that experience highly variable convective storm events. Recent interest in using radar estimates of rainfall in hydrologic modeling has risen from the desire to reduce this error by utilizing the radar’s capability of providing complete coverage within the area of interest (Vieux and Bedient 1998). Weather radar has enormous potential in this field, as it can measure rainfall in real-time with high spatial resolution and temporal continuity (Sun, Cornish et al. 2002).

2.6.1 History of the NEXRAD (WSR-88D) Radar

The WSR-88D (Weather Surveillance Radar 1988, Doppler) radar, commonly referred to as NEXRAD, was developed to replace pre-Doppler technology radars for the purpose of providing an advanced early warning system for tornadoes. The new Doppler technology allows meteorologists to detect specific circulation patterns within a storm that generally precede the touchdown of tornadoes. The first prototype system was
installed in Norman, Oklahoma, in 1988. The first full-scale WSR-88D radar was deployed in 1992 (Fulton, Briendenbach et al. 1998). The main objective of the National Weather Service’s NEXRAD program from a hydrologist’s perspective, is to provide, in real-time, accurate quantitative precipitation estimates (QPEs) from its network of radars (Anagnostou and Krajewski 1999).

The geographic location of radars within the network were optimized in order to provide full nationwide coverage as well as to provide effective coverage for a variety of meteorological events at different areas (NRC 1995; Maddox, Zhang et al. 2002). Figure 2.8 illustrates the coverage of the NEXRAD network over the contiguous United States at
a specified height above each individual radar. Maddox et al. (2002) have shown that this coverage is optimistic based on analyzing the beam coverage at heights lower than 10,000 feet. While this may present a problem for other regions of the United States, especially the West, coverage for the Houston area is excellent at all investigated elevations. The NEXRAD radar covering the Houston area, KHGX, was located south of the metropolitan area in order to “ideally spot frontal storms from the north to the southwest, severe thunderstorms from the west; as well as tropical storms and hurricanes from the southeast to east” (Hoblit 1999). Unfortunately, the fourth largest city in the U.S. is sufficiently covered by only this one radar, with the area lying on the outskirts of radar stations in Austin, Corpus Christi, and Lake Charles, LA.
The NEXRAD radar network currently has a number of wide ranging applications within the water resources field. Some of these include: flood forecasting and early warning systems, improved precipitation estimations, long-term water balance studies at the basin scale, as well as more localized, short-term flood prediction (Hoblit, Vieux et al. 1999).

2.6.2 System Characteristics

The NEXRAD doppler radar is a 10 cm wavelength or S-band transmitter that records reflectivity, radial velocity, and the spectrum width of reflected signals. Successive radar tilt angles are employed to cover the entire volume of the atmosphere out to 460 km for reflectivity, 230 km for precipitation, velocity and spectrum width.

Radar reflectivity is collected at 1-km range intervals and each 1-degree of radial resolution, producing a radial coordinate system of reflectivities for each tilt angle (Crum and Alberty 1993). Using basic relationships between reflectivity (referred to as Z) in units of dBZ and rainfall rate (referred to as R) in mm/hr, the rainfall rate in that 1-km by 1-degree area can be estimated, with a greater reflectivity indicating a heavier rainfall amount. During the various stages of signal processing in the data stream, anomalous reflectivities such as ground clutter are removed. The reflectivity signal is then converted to a rainfall rate using a Z-R relationship.

The particular Z-R relationship used to convert reflectivity to rainfall can have a significant impact on the accuracy of the rainfall estimation. The "standard" Z-R relationship used with the initial installation of all WSR-88D radars was \( Z = 300R^{1.4} \). The National Weather Service has adopted in some cases the "tropical" Z-R relationship \( Z = 250R^{1.2} \), which is more representative of warm tropical rainfall drop distributions.
Recent research in the Houston area has revealed significantly improved results using the tropical Z-R relationship (Vieux and Bedient 1998). Nevertheless, the Z-R relationship is often in error, because this empirical relationship depends on the drop-size distribution, which varies throughout a particular storm event.

To overcome the estimation errors inherent in the Z-R relationship, calibration with rain gauges can be performed. This procedure usually consists of comparing accumulations between radar and gauge at a particular gauge location. The ratio of the radar estimation to gauge measurement is termed a bias. A mean field bias consists of comparing many radar/gauge pairs of accumulations and then averaging them to get a mean over some geographic region. For example, if the radar is underestimating by 20%, the rainfall fields are increased by 20% to compensate for the bias. Calibration of the radar to rain gauge accumulations is the most commonly used technique for correcting radar rainfall estimates. The calculation involved with this correction is simply a ratio calculation where bias is defined as

\[
Bias = \frac{\sum_n Rain_{\text{gauge}}}{\sum_n Rain_{\text{radar}}}
\]

Using this method, a gage-radar bias of one means that on average the radar matched the rain gage rainfall. A bias greater than one indicates underprediction of the rainfall by the radar and a bias less than one indicates an overprediction.

The real-time calibration of radar data with rain gage data has proven to be a difficult task. The primary difficulty lies in determining which rain gages are functioning properly as data is being recorded. Another major difficulty is the reporting and processing time associated with the rain gage data collection system, which often results
in delays on the order of one to two hours before it is available for radar adjustment. There is present in the literature, a large body of work related to improving upon the current Precipitation Processing System (PPS) component of the NEXRAD system. The PPS is the component originally designed to, among other things, perform real-time gage-to-radar corrections. Anagnostou and Krajewski (1999), Anagnostou et al. (1998), and Fulton (1999) analyze the requirement for calibration of radar data using rain gages and present detailed algorithms to perform this in real-time.

Errors in radar rainfall estimation are not limited solely to uncertainties in the Z-R relationship. Some of the other major factors affecting radar rainfall estimation include: non-uniform vertical profile of reflectivity (Cluckie, Tilford et al. 2000), orographic enhancement of precipitation and range effects (Kitchen, Brown et al. 1994), anomalous propagation (AP) of the radar beam, and radar calibration stability effects (Illingworth, Blackman et al. 2000).

2.6.3 Hydrologic Modeling Using Radar Estimates

There have been numerous efforts at hydrologic modeling utilizing radar estimated rainfall rates. There are a number of reasons behind the application of radar in this field. Two of the most important include the previously discussed problems associated with rain gage estimation of radar and the overall success of radar at estimating rainfall amounts.

Schell et al. (1992) modeled the rainfall over a small (8.13 km²) watershed in Canada. Rainfall data was entered into a simple lumped parameter model both as gage-adjusted radar estimates and as rain gage measured data. Peak flow measurements from the radar performed better than the estimated peak flow using rain gage data in three of
the four storms. Overall runoff calculations were also improved by the radar data in three of the four model runs. Schell concluded that calibrated radar rainfall estimates could provide rainfall inputs to a rainfall-runoff model superior to those obtained from a single rain gage.

Gladwell (1998), Vieux and Bedient (1998), Bedient et al. (2000), and Bedient et al. (2003) all examined the hydrologic response of various watersheds in the Houston area to radar estimated rainfall for one or both of two major storms in the area. Vieux and Bedient showed an accurate hydrologic response in a HEC-1 model program utilizing unadjusted NEXRAD radar over the Clear Creek watershed for the October 17-18, 1994 storm event. Gladwell studied both the same October 1994 event and a January 1998 event over the Brays Bayou watershed utilizing similar methods to Vieux and Bedient. The October 1994 storm was modeled successfully using unadjusted radar data with the tropical Z-R relationship, resulting in an excellent match between the observed and computed outflow hydrographs. Bedient et al. examined three storms over Brays Bayou in Houston, again using the tropical Z-R relationship and unadjusted radar data. Nevertheless, another excellent match was obtained between the observed and computed hydrographs using both radar estimated and gage measured rainfall as separate rainfall inputs. The April 1997 and January 1998 events revealed major underestimation of the rainfall according to the rain gage data. The radar estimated rainfall model was found to perform significantly better for all three storms.

Borga (2002) analyzed the impact of radar rainfall estimates on rainfall-runoff modeling. The results of this work are significant with respect to the research conducted in this dissertation. Borga claims that his results show that radar errors may preclude the use of unadjusted radar estimates for runoff modeling; however, the results were very
dependent on the elevation angle of the radar beam, with the only marked improvement noticeable in the higher radar elevation angles. The lowest tile angle (0.5 degrees) exhibited only a 5% improvement in simulation efficiency between the use of adjusted and unadjusted radar.

Several researchers have focused on applying radar-based hydrologic models in the context of flood warning systems. Carpenter et al. (1999), in an effort to modernize the NWS flash flood watch/warning program, used Geographic Information Systems (GIS) and digital terrain elevation databases to develop a national system for determining threshold runoff. Comparisons of the threshold runoff estimates produced by the GIS procedure were compared to those based on manually computed unit hydrographs for selected catchments. Differences of up to about 0.6 inches for hourly rainfall durations were obtained for basins larger than 20 square miles. Ogden (2000) utilized both traditional NEXRAD radar and dual-polarization radar (CSU-CHILL) and the CASC2D hydrologic model to analyze a major storm event over Fort Collins, Colorado. Results showed that the most significant errors observed in runoff predictions over an urbanized watershed were due to rainfall estimation errors. Uncertainty in watershed characteristics had a considerably smaller effect on runoff predictions than uncertainty in the space/time distribution of rainfall. Koussis et al. (2003) described a system for forecasting flood risk over a large urban basin with steep terrain using an integrated hydro-meteorological system.

A chain of nested numerical weather prediction models, initialized with results of a global circulation model, yielded rainfall forecasts on a 6 km grid. The hydrologic model, driven with the forecasted rainfall, was tested for two medium-size storm events with limited results. The study did, however, show that while integrated hydro-
meteorological models are not yet mature tools, the methodology holds significant promise for longer range precipitation forecasts / hydrologic model coupling.

Other important papers that address previous attempts at utilizing radar rainfall estimates in a hydrologic model are shown in Table 2.4.

Table 2.4: Other Papers on Hydrologic Modeling Using Radar Rainfall

<table>
<thead>
<tr>
<th>Reference</th>
<th>Summary of Findings (TO BE EXPANDED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(James, Robinson et al. 1993)</td>
<td>Modeled the hydrologic response on a 785 m²² watershed in Mississippi for a November 1986 storm using the Texas A&amp;M Watershed Model. The study concluded that the rising limb and peak discharge of all streamflow hydrographs computed from gage-adjusted weather radar data were more accurate than the corresponding hydrographs computed from gage precipitation data alone.</td>
</tr>
<tr>
<td>(Mimikou and Baltas 1996)</td>
<td>Discuss the accuracy of radar compared to point rainfall values from gauges for flood forecasting. Utilized the HEC-1 modeling program to study a 2,763 km²² watershed in central Greece. The output hydrographs computed from gage-adjusted radar was more accurate than the output hydrographs computed from gage precipitation data alone for six different storms.</td>
</tr>
<tr>
<td>(Peters and Easton 1996)</td>
<td>Used the Modified Clark program, a distributed hydrologic method available in the HEC-HMS modeling program, to model three storm events over a 4,163 km²² watershed in northwestern Oklahoma and northwestern Arkansas. NEXRAD rainfall data was used as the rainfall input. Runoff hydrographs the four sub-basins and the outflow hydrograph for the entire watershed were computed for the three storms. Each computed hydrograph matched observed flows with a good fit.</td>
</tr>
</tbody>
</table>

2.7 Quantitative Precipitation Forecasting (QPFs)

2.7.1 QPFs: Types and Limitations

There exist a wide variety of QPFs with performance and skill limitations that are dependent on forecast lead-time. The four primary types of forecasting algorithms are: persistence, extrapolation, mesoscale atmospheric models, and climatology. Figure 2.9,
adapted from Zipser (1990), shows the hypothetical performance skill of these several different forecasting methods as a function of forecast lead-time.

![Graph showing the relative forecast skill as a function of lead-time for different methods.]

**Figure 2.9 Relative Forecast Skill as a Function of Lead-Time for Different Hydrometeorological Forecasting Methods (Zipser, 1990)**

At shorter lead-times, those most crucial in many flash flooding situations, it can be seen that the persistence and nowcasting (extrapolation) methods show significantly higher relative skill; however, systems relying on these types of methods should blend the forecast with longer range methods such as numerical weather prediction models to take advantage of their higher long-term forecast skill.
2.7.2 Nowcasting

The demand for rainfall forecasts with a high spatial and temporal resolution has increased in recent years. As only radar rainfall estimates are capable of providing this high resolution, most of the research in short-term QPFs has focused on extrapolating future rainfall from radar images. Early algorithms were based on pattern recognition of rainfall echoes from which cross-correlation coefficients can be calculated and used to predict the motion of the storm feature (Einfalt, Denoeux et al. 1990). Improvements on this method have followed, including feature recognition, thermodynamic atmospheric models, and many extensions on the concepts of persistence and extrapolation. A general set of methods that is currently being implemented in the generation of QPFs is called nowcasting (Browning and Collier 1989).

Nowcasting can be defined as the production of short-range (0-3 hour lead-times) precipitation forecasts based mainly on the extrapolation of future data from current radar data images (Smith and Austin 2000). Improvements in the quality of available radar data, coupled with improved computational power of computers has led to vast improvements in this particular forecasting method. Nowcasting benefits many different fields in addition to flood forecasting, including more general public weather warnings, water management, storm sewer operation, irrigation, wet deposition of pollutants, construction site management, and transportation systems (Browning and Collier 1989).

There remain many complications in the methodology and operational use of nowcasting QPFs. The simplicity of many of the algorithms used is one such drawback, as many of the models do not include methods for predicting the growth and decay of storm cells (Smith and Austin 2000). Yet another limitation is the dependency of the
forecast skill on the quality of the radar rainfall estimations. Ground clutter, bright-band contamination, system miscalibration, and other inherent errors associated with radar rainfall estimates mentioned previously in this chapter also affect the quality of the forecasts (Smith and Austin 2000).

2.7.3 Previous Research on Short-Term Forecasting

Short-term forecasting of radar-based precipitation fields is not a new concept. The early work of Ligda (1953) and the follow on work by Hilst and Russo (1960), Kessler (1961), Russo and Bowne (1961), and Boucher (1963) showed that useful forecasts could be made based on the simple persistence and movement of radar echoes. Simple extrapolation techniques were devised to propagate existing radar rainfall images according to a specified motion vector; however, more complex propagation schemes were not feasible due to the lack of affordable computing power (Kessler 1961). Boucher (1963) divided precipitation echoes into classes with different forecast qualities. Kessler and Russo (1963) and Wilson (1966) were the first to show the usefulness of the cross-correlation pattern matching technique as a method for accurately estimating the trajectories of radar echoes, albeit at small space and time scales due to computational limitations.

Verifications of echo displacement and actual forecasts were performed by Wilk and Gray (1970), Barclay and Wilk (1970), and Zittel (1976), by modifying the method of extrapolation with a linear least-squares fit through successive positions of echo centroids. This technique proved successful with weather situations with single, isolated radar echoes. It is important to note that the method encountered considerable difficulties when echoes in the radar pattern merged or split. More sophisticated software was
implemented by Duda and Blackmer (1972) and Blackmer et al. (1973) to develop clustering techniques to deal with some of these problems. Wolf et al. (1977) used this same clustering technique to track clouds via satellite images; however, while satellite data may have greater uniformity in space as compared to radar, it is generally considered inferior to radar data for the purpose of estimating surface rainfall (Smith and Austin 2000).

The global cross-correlation technique was investigated by Zawadzki (1973), where cross-correlation coefficients were obtained from successive images and the trajectory of the storm envelope was based on the maximum value of the coefficients (gamma). The method was improved upon and first implemented in a real-time study by Austin and Bellon (1974). Several years of the technique's operational use was reported in Bellon and Austin (1978). The improvements included an intelligent "first guess" to calculate the cross-correlation coefficient. The guess was based on the displacement of the center of gravity of individual radar echo clusters, greatly saving computation time and therefore costs.

Another development in the short-term recognition of rainfall includes pattern recognition theory. Chen and Kavvas (1992) used polygons to define patterns of contours of rainfall rates within a radar rainfall field. Polygons were used to describe each contour as they require reduced computing power as related to other shapes. Bremaud and Pointin (1993) took pattern recognition a step further by incorporating a threshold to determine which areas or subsets of radar pixels would be defined as a single element in the motion of the storm envelope. Their model, PARAPLUIE, combined this threshold extraction method with the cross-correlation advection technique to begin to develop accurate short-term forecasts. A more recent model that uses thresholds for
pattern recognition and tracking is called TRACE3D, described by Handwerker (2002). This model uses an initial reflectivity threshold to divide radar images into separate regions of intense precipitation (ROIPs) and then uses an additional threshold value within each ROIP to identify convective cells.

Both NEXRAD and Quantitative Precipitation Forecasts algorithms designed around radar data provide vast amounts of rainfall data both in space and time. Hydrologic model processing of this type of data would not be possible without the speed and efficiency provided by new information technologies in the field of hydrology – the Internet and Geographic Information Systems. The following sections briefly discuss the impact these two technologies have had on the field.

2.8 Geographic Information Systems and Hydrology

A Geographic Information System (GIS) is a general-purpose computer-based technology that allows for the efficient collection, construction, integration and dissemination of vast amounts of spatially referenced digital data. A common feature to all general purpose GIS software packages is the ability to link tabular information to a location in space. As technological advancements in computer science have increased the power and capability of personal computers, there has been steadily increasing interest in discovering new applications of GIS (Maidment and Djokic 2000). Recently, the most successful applications have included data collection and processing, computer modeling, and policy formulation (Singh and Fiorentio 1996). In particular, a close relationship has developed between GIS and the hydrologic sciences due to the ability of any GIS software to relate various, spatially diverse data sets common to this field. These types of data sets include land use and soil classifications, river reaches,
topography, aerial photography, floodplain mapping, and others. GIS can also assist in the design, calibration, modification and comparison of hydrologic and hydraulic models. The integration of GIS with the hydrologic field is spreading and substantial opportunities exist for continued developments.

GIS allows one to store, retrieve, analyze, and display spatial data from a large digital database (Clarke 1997). These databases consist of two major structures: vector and raster data. Vector data uses points, lines, and polygons to describe features in two dimensions. Points can represent rain gages, stream gages, or any object located at a fixed point in space. Lines can represent streams, roads, watershed boundaries or other linear items. Polygons could be used to characterize watersheds, soil groups, or other areal entities. Each vector object includes attributes that describe its connectivity and adjacency. Raster data, on the other hand, is a structure that represents space with rows and columns of grid cells representing continuous surfaces and categories of data. Each grid cell is referenced by a row and column number and contains a value representing its attribute. Examples of raster datasets are digital elevation models (DEM's), land use coverages, and radar-rainfall data. Most applications use a combination of both vector and raster data (Garbrecht, Ogden et al. 2001; Vieux and Rifai 2002).

The principal strength of GIS technology is its combination of relational and spatial databases. All relational databases in a GIS can contain spatial relationships of both the vector and raster data variety. The spatial relationship is maintained by a unique set of geographic coordinates which is linked to descriptive data in the relational database. Figure 2.10 illustrates how entity data attributes (both spatial and descriptive) are stored in a tabular format that can be readily queried, analyzed and correspondingly
displayed in a georeferenced map format. As a result of this relationship, data entities can be linked based on geographic locations as well as physical attribute data (Dodson 1993).

GIS technologies, although in existence since the 1960s, were not extensively applied to the hydrologic and hydraulic modeling fields until the early 1990s (Singh and Fiorentio 1996; Maidment and Djokic 2000; Bedient and Huber 2002). The extensive and detailed hydrologic datasets required for a GIS-based hydrologic analysis, even when available, were rarely available in digital format. Thus, hydrologic studies at the larger basin scales were limited by expensive digitizing efforts and at the smaller basin scale by insufficient data resolution.

![Water Right Locations](image)

**Spatial Attributes**

**Descriptive Attributes**

![Sample Relational Database in a GIS](image)

**Figure 2.10 Sample Relational Database in a GIS**
As digital databases became more available due to field collection efforts, remote sensing technologies, increased computing power, and accessibility over the Internet, a stronger linkage between the fields of spatial hydrology and GIS emerged. This linkage has revamped the field of hydrology – enhancing the ability to incorporate spatial details beyond the existing capability of watershed hydrology models. Hydrologic models are being increasingly based on Digital Elevation Models (DEM s) or Digital Terrain Models (DTMs), with many existing models adapting to the new type of data (Singh and Woolhiser 2002). Integration of hydrologic models with remotely sensed, GIS and DEM-based data has started to occur, resulting in newly developed models designed specifically to make full use of the advantages of this type of data. Examples of newly developed or adapted models are those by Fortin et al. (2001), Wigmosta et al. (1994), Julien et al. (1995), and Olivera and Maidment (1999), and the Vflo™ model developed by Vieux and Associates, Inc., among many others.

An array of digital databases is now available covering the wide range of data needed for watershed hydrology including: hydrometeorologic, geomorphologic, agricultural, pedologic, geologic and hydrologic. Hydrometeorologic data include rainfall, snowfall, temperature, wind velocity, and pan evaporation. Agricultural and pedologic data include land use, land cover, soil type, classification, porosity, and antecedent moisture content. Geologic data includes a wide range of data mostly used in groundwater hydrology but is important to continuous-based surface hydrology models, such as stratigraphy, lithology, and hydraulic conductivity. Geomorphologic data include topographic maps, elevation contours, river networks, drainage areas, slopes and slope lengths, and watershed areas. Hydrologic data include flow depth, streamflow discharge, base flow interflow, stream-aquifer interaction, and water table levels (Singh and
Woolhiser 2002). Specifically, national hydrologic and elevation datasets have been established by the United States Geological Survey (USGS) and other state and local agencies (Maidment and Djokic 2000). GIS technology has also provided the interface to easily merge these datasets and has also, in some cases, automated the update process to ensure data used in current studies are up-to-date (Singh and Fiorentio 1996; Gurnell and Montgomery 2000). (Bellon and Austin 1978; Chen and Kavvas 1992)

The increase in available high-resolution data, combined with the increased computational power of the personal computer has once again raised the lumped versus distributed hydrologic model debate. In the past, lumped parameter models were more common because it was difficult to estimate parameters at a small enough scale for a distributed model (Drayton, Wilde et al. 1993). However, grid based resolutions as low as 30m are now common for many of the above listed data types – especially topographic databases. Therefore GIS data and technology are well-suited to generate parameters for several hydrologic models that are raster based on a point scheme. The digital data stored in a grid-cell structure provide a natural link to the solution methods of distributed models solved using finite elements or finite differences. (Bremaud and Pointin 1993; Handwerker 2002) (Fortin, Turcotte et al. 2001) As a counterpoint, this same data has also allowed for easier subdivisions of previously larger subwatersheds in existing lumped model, thus greatly assisting the accurate development of these types of models as well.

Some of the major associations of GIS and hydrologic models are hydrologic assessment and hydrologic parameter estimation (Maidment 1993). Hydrologic assessment is performed when a GIS is used to map hydrologic data. Hydrologic parameter estimation involves evaluating the topography and land use/land cover in the
GIS to derive parameters for hydrologic models. The GIS serves as the preprocessor for
the model and the derived parameters are exported to the model. Since the physical data
can be measured directly or calculated indirectly via interpolation or conversion, the role
of a GIS in hydrologic modeling varies (Bedient and Huber 2002).

Most parameters of interests to hydrologists can be derived from digital data that
can be collected and analyzed in a GIS. This parameter estimation process has been
suggested to be the most prevalent area in the GIS field associated with hydrology
(Ogden, Garbrecht et al. 2001). Through interpolation or direct measurement of data
within a GIS, rainfall, infiltration, evapotranspiration, hydraulic roughness, slope, and
flow direction are some of the many hydrologic parameters that can be estimated. Many
publications report how digital vector and raster data are used for this purpose (Beven
and Moore 1993; Singh 1996; Hellweger and Maidment 1999; Olivera and Maidment
1999; Gurnell and Montgomery 2000; Vieux 2001). For example, infiltration can be
derived from soil type by reclassifying the soil classification unit. Hydraulic roughness
can be derived from land use/land cover data measured by direct observation or remotely
sensed digital data. Slopes, watershed boundaries, and flow direction can be computed
from raster DEMs using automated scripts (Hellweger and Maidment 1999). Lastly,
spatially variable rainfall captured by radar-rainfall measurements can also be reprojected
and processed in a GIS (Vieux and Rifai 2002).
Chapter 3

Overall Methodology

3.1 Introduction

Traditional, gage-based flood alert systems have fulfilled the role of providing flood notification to many people and have undoubtedly saved millions in both lives and property; however, they fail to take advantage of new technologies in several fields that may improve lead times and system accuracy. This chapter provides a general overview of the methodology applied in this research to answer the hypothesis that these new technologies can positively influence the performance of flood alert / warning systems – providing earlier and more accurate warnings to critical institutions and emergency personnel in flood-prone areas. While the research focuses on one watershed in an urban setting, the results found are applicable across a broad spectrum of watershed types, provided that the need for more timely and accurate flood forecasts exists – a condition which is almost always the case. Additionally, as advances in hydrologic science and modeling, radar rainfall sensing, and information technologies continue, advanced alert systems should play an increasing role in flood damage reduction plans across the nation.

The chapter will begin by introducing the current Rice University / Texas Medical Center Flood Alert System (FAS), a system which already utilizes radar-based estimates for rainfall input, but does not implement any type of real-time hydrologic modeling or any type of Quantitative Precipitation Forecast (QPF) tools. This discussion establishes the baseline for comparing performance improvements for the newer FAS2 system. The
next section will provide a broad overview of the new system and highlight changes in system operation and modifications to specific tools utilized for flood forecasting. The chapter concludes by listing specific areas of research that were essential in the development and successful implementation of the newer system. These research areas are expanded upon in the following chapters of this dissertation.

3.2 The Current Rice University / Texas Medical Center Flood Alert System

The Rice University / Texas Medical Center Flood Alert System (FAS) is an integrated system that gathers NEXRAD data from the National Weather Service (NWS) and extracts rainfall totals over the Brays Bayou watershed in southwest Houston, Texas (Bedient et al. 2000; Vieux and Bedient 1998). It uses this information to provide flood forecasts for a single location in the bayou near the Texas Medical Center – the Main St. Bridge crossing. This area is prone to flooding due to its location in the downstream portion of a nearly completely urbanized watershed. The TMC has been impacted by two major floods and several minor floods over the past 25 years.

The FAS was developed in 1997-1998 for the TMC at Rice University and is available on the web at http://www.floodalert.org. Figure 3.1 shows a general schematic of the system that includes radar rainfall, conversion to watershed rainfall, an active nomograph for flood peak prediction based on earlier HEC-1 hydrologic model runs, and various flood alert action levels for the TMC based on identified “action level” or “target” flood flows in the bayou. The system is used by the TMC to disseminate flood warning information to member institutions, to develop plans for emergency response to
severe weather events, and to implement these flood responses for its 22 member institutions and hospitals. The FAS has proven successful in several small storm events from 1998 to 2003 and two major storm events (Tropical Storm Frances in 1998 and Tropical Storm Allison in 2001).

![Flowchart](image)

**Figure 3.1**: Flowchart of the original Rice University / Texas Medical Center Flood Alert System designed for Brays Bayou in 1997-1998.

Most urban alert systems operated by local emergency management agencies still rely solely on an often limited number of rain gages and stream gages to provide notifications. For example, the Harris County Office of Emergency Management ALERT system still maintains a strict reliance on rain gage / stream gage for dissemination of warnings. While their network is perhaps one of the most dense in the
world, with approximately 1 rain gage per 10 square miles, the system remains a classic reactive vice proactive alert system – waiting until at least 2 inches of rainfall is detected by a raingage and a corresponding stream flow gage nearby has verified increasing flow in the appropriate watershed prior to issuing an alert. This type of reactive approach, while almost never issuing a false alarm, is capable of providing only about 30 minutes or less of lead time (Fisher, 1993).

The current FAS was one of the first flood warning systems to utilize radar rainfall for alert notifications. The system utilized the National Weather Service’s NEXRAD Digital Precipitation Array (DPA) product. This provided 4 km x 4 km gridded precipitation data, with each grid representing the accumulation of the last 60 minutes of rainfall over that area. This data was then averaged over the Brays Bayou subbasins, allowing users to determine the amount of precipitation over specific regions of the bayou.

The radar estimates are still not calibrated against rain gages in real-time. At first, this was due to the lack of a sufficiently robust algorithm to accurately discern properly functioning rain gages from improperly functioning ones. Once algorithms were developed for this, and accepted for widespread use by vendors, the difficulty in the Houston area remains due to the lack of access to the HCOEM gage data in real-time. This has prevented the next-generation FAS2 system from utilizing real-time radar-gage calibration at the time of the writing of this dissertation. It is hoped that this barrier will soon be overcome.

Despite a significant number of references in the literature to the contrary as discussed in Chapter 2, the FAS has managed to perform well even without gage
calibration using the Tropical Z-R relationship – especially for larger storm events.

Figure 3.2 illustrates the performance of uncalibrated DPA radar against a large number of different HCOEM rain gages across Brays Bayou. This event, TS Allison, was excellent for comparison purposes because of the wide range of rainfall accumulation experienced over the Bayou. DPA performance was excellent (less than 10% error) for three of the six radar-gage pairings. The comparison between DPA and gages 480 and 490 as well as the that between DPA and Gage 410 resulted in a relatively large error of approximately 30-40%. The comparison with Gage 400 was tracking within 20% until the gage malfunctioned at 0200 in the morning – a not uncommon occurrence during extreme rainfall events.

Figure 3.2: Performance of the Digital Precipitation Array (DPA) radar product versus rain gages throughout Brays Bayou during Tropical Storm Allison in 2001.
The original FAS calculates rainfall intensities using the NEXRAD DPA rainfall estimates as they occur every 5 to 6 minutes. These intensities are plotted on the nomograph after every radar volume scan. Current intensities are calculated for the last 1 to 10 hours and plotted directly on the nomograph. The maximum rainfall intensities are calculated by searching through the last 20 hours of data and selecting the time period with the highest rainfall intensity for that specific duration. The resulting intensity-duration pairs are then plotted on the real-time nomograph, yielding a peak predicted flow rate read from the plotted isoflow lines that were generated by the previous HEC-1 runs. A sample nomograph prediction is illustrated in Figure 3.3 below.

Color-coded flood alert action levels were created for various flow levels.

**Figure 3.3**: The original FAS flow nomograph illustrating sample data during the November 17th, 2003 storm event. A storm event studied in great detail throughout this dissertation.
predicted by the FAS for Brays Bayou at Main Street. The alert status was based on
nomograph-predicted flows as shown in Figure 3.3. A flood caution (yellow) would be
issued for predicted flows between 20,000 ft$^3$/s and 24,000 ft$^3$/s. A heightened alert
status (orange) would be issued for predicted flows between 24,000 ft$^3$/s and 28,000 ft$^3$/s,
when flooding would be considered possible given additional rainfall over the watershed.
A final alert status (red) would be issued for predicted flows greater than 28,000 ft$^3$/s,
signifying that severe flooding at the TMC would be probable given the combination of
existing flow in the bayou and current rainfall estimates. The various intensity-duration
combinations that generate these alert levels are shown in Figure 3.3.

As a result of the above discussion, it should be clear that despite the detailed
spatial data provided by the DPA radar, the heart of the FAS system, the flow
nomograph, can only be run with uniform rainfall over the contributing portion of the
watershed. This significant limitation resulted in poor performance in predictions
involving highly localized rainfall accumulations. Additionally, the fact that the
nomograph provided peak flow estimates only, without a prediction of when the peak
flow was to occur, greatly diminished the utility to end-users with time specific required
actions.

In addition to the flow nomograph, the FAS provides several supplemental data
products and images to help decision-makers at the TMC determine the likelihood of
flooding and what actions should be taken to minimize potential damage. The first of
these data products are the three NEXRAD radar rainfall estimate images provided at
different scales. The first of these images, at the regional scale, displays the entire radar
sweep area. The second, mid-scale image covers Harris County and its surrounding
counties. The third image covers only Harris County, providing a close-up look at estimated rainfall totals within the Brays Bayou watershed. Each of these images can be animated over a specified time period in order to view historical storm movement as well as growth and decay trends for storm cells and frontal systems. These images and animations can help users make a qualitative determination of additional rainfall over the watershed.

The FAS divides Brays into three sections for the purpose of capturing some of the spatial variability of rainfall in the hydrologic model. These sections, Upper, Middle, and Lower, correspond to the drainage areas above gage 460, between gages 460 and 420, and downstream of gage 420, respectively. The NEXRAD rainfall estimates are automatically averaged within FAS for each of these sections as well as for the watershed as a whole. The nomograph and its flood warnings are based on the data for the watershed area upstream of Gage 420 at Main St (which includes the Upper and Middle drainage areas – see Figure 3.4). Gage 419, the stream gage associated with rain gage 420, is of particular importance to the FAS for calibration purposes because of its proximity to the TMC. The FAS also creates a table of rainfall values over each of these sections, providing data for each of the past 1, 3, 6, 12, and 24-hour time periods. Lastly, a graph of the cumulative rainfall for each of these areas is included.

FAS users rely heavily on the system’s two cameras, called BayouCams (Figure 3.5), which monitor the confluence of Brays Bayou and Harris Gully. Harris Gully is a major tributary that flows under Rice University and the TMC in dual 4.5 x 4.5 m box culverts. These cameras provide valuable, visual confirmation of flood levels as they occur during a storm event. Prior to their installation, TMC security personnel were
Figure 3.4: The existing HCOEM network of rain and streamflow gages throughout Brays Bayou as of 2003.

dispatched to physically observe these levels. The images from the BayouCams are archived during significant storm events, providing valuable data for post-event analysis and system performance evaluation.

3.3 The Next Generation Rice University / Texas Medical Center Flood Alert System (FAS2)

The next generation of the Rice / Texas Medical Center Flood Alert System, known as FAS2, has been developed with the aim of addressing many of the shortfalls of the original system. This process is on-going, but to date, has focused on utilizing many advances in the fields of radar sensing, real-time hydrologic modeling, and improved information transfer via digital systems such as the Internet, PDAs, cell phones and others.
Figure 3.5: Archived image of a live feed picture from the FAS BayouCam.

Four general areas were identified where the existing system could be improved: lead-time, accuracy, effectiveness, and reliability. The extent to which these individual areas provided opportunities for research varied. As is strongly hinted at in the title of this dissertation, the two main areas providing research opportunities were those of lead-time and accuracy; however, system effectiveness also plays an important role by ensuring the proper and efficient dissemination of vital information to end-users.

Improving the lead-time of the system is investigated by implementing and evaluating a QPF algorithm used in increasing areas of the United States. The Brays Bayou watershed and the existing FAS infrastructure provided an excellent test-bed for the collection and evaluation of QPF data – with the end goal of determining the effectiveness and accuracy of the algorithm at various forecast times and basin sizes. This research is presented in Chapter 4 of this dissertation.
Improving the accuracy of the system is to be accomplished by a variety of means including: improved radar data input and resolution, real-time calibration of the radar with rain gages if available, and the development of real-time hydrologic models – both distributed and lumped-parameter. This work focuses on the development and implementation of a real-time interface for the industry standard HEC-1 hydrologic model, allowing the hydrologic predictions developed by these models to take greater advantage of the spatial and temporal distribution of real-time radar data. This work focuses its research on the lumped-parameter approach as much of the distributed model work using Vflo was completed by Eric Stewart in his master’s thesis entitled: “Development of a Distributed Hydrologic Model with Application to a Flood Alert System.” It should be stated that the successful implementation of a real-time hydrologic model at the scale of Brays Bayou would also provide significant lead-time improvements by providing estimates to when peak flows would actually occur. The results of this research are presented in Chapter 5 of this dissertation.

The effectiveness of the system as a whole depends on nearly innumerable variables; however, some of the major ones include improved information dissemination, well-defined and researched alert action levels, and improved user friendliness for the end-user. The latter is especially important when discussing training of personnel for the use of the system, especially when critical decisions must be made in relatively short time periods – as is often the case during heavy rainfall events. The addition of many “new” technologies to the existing flood alert system must not overwhelm end-users with either too much or conflicting information. Additional information dissemination tools to the Internet should be utilized including automated notification via cellular phones, pagers,
and email. New alert action levels must be developed to incorporate the increased lead-time and accuracy expected from the new system, with the goal of lowering the number of false alarms to the TMC. Lastly, the system must be tested from start to finish over a number of events and must be flexible to adapt to changing end-user needs and input. The research in this area is presented in Chapter 6 of this dissertation. The chapter provides a validation test of the entire system during the November 17th, 2003 event, during which many of the changes discussed above had already been implemented.

System reliability provides little in the way of presentable research; however, this area is being addressed by establishing multiple server sites at various locations including Rice University, the TMC, and eventually Norman, Oklahoma. Other reliability improvements include the use of rain gage data, not as a calibration tool for radar rainfall estimates, but as a back-up in the event of a radar station failure or malfunction. Unfortunately, the fourth largest city in the United States is only sufficiently covered by one NEXRAD radar station – the KHGX radar station in Dickinson, TX.

Figure 3.6 illustrates the “new layout” of the FAS2, with both already implemented and planned changes highlighted in light blue. The research presented in the following chapters will focus on specific components of the overall FAS2 system, their effectiveness at improving lead-time and accuracy, and their role in improving overall system operation.
Figure 3.6: Schematic of the new FAS2 system with improvements highlighted in light blue.
Chapter 4

Evaluation of the Accuracy and Effectiveness of a Short-Term Quantitative Precipitation Forecast (QPF) Algorithm from a Watershed Perspective

4.1 Introduction

A hydrologic model transforms spatially averaged or spatially distributed precipitation amounts into a time series of river stages, river discharges, or runoff volumes. Forecasting precipitation is thus a natural prerequisite for a flood warning system whenever the required lead-time of the forecast exceeds the response time of the watershed. This requirement is especially true for flash flood forecasts which provide information for emergency response and reservoir control (Collier and Krzysztofowicz 2000). Recall that as discussed in Chapter 1, flash floods are defined as floods which follow shortly (on the order of a few hours) after a heavy or excessive rainfall event. Therefore, under flash flood conditions in quickly responding watersheds, the available lead-time for alert systems without advanced warning of precipitation can be very short. Despite this fact, for the greater part of the 20th century, operational river forecasts were based solely on precipitation already measured on the ground, with the implicit assumption of zero precipitation beyond the time of the final observation (Georgakakos 1986; Sweeney 1992). Quantitative Precipitation Forecasts, or QPFs, represent a class of forecasting tools that attempt to end this “precipitation stops now” approach to flood forecasting.

Until recently, there has been a lack of widespread acceptance of QPFs as input into hydrologic models for two primary reasons. First, precipitation is one of the most
difficult meteorological predictands, even for very short-ranged forecasts on the order of a few hours. Second, in those situations where precipitation can be predicted at an accepted skill level for application, the quality of the forecast drops rapidly as a function of forecast time. With respect to flood forecasting, this rapid decrease in forecast skill results in a "diminishing returns" scenario as the response time of the basin for which forecasts are being developed increases. As flood warning systems were first developed for larger, slower responding basins, it seemed the minimal benefit was not worth the effort. For example, a QPF that has been proven successful at providing relatively accurate 1-hour forecasts for precipitation would provide a 25% increase in lead-time for a basin with a response time of 4 hours. In contrast, a large basin with a response time of 20 hours would only see a corresponding 5% increase in effective lead-time.

Nevertheless, research efforts in the QPF field by both meteorologists and hydrologists have been on-going for the last forty years. QPFs suited to the requirements of hydrological forecasting are becoming operationally feasible, at selected time and spatial scales, all over the world. Although future research is undoubtedly necessary, research progress has accelerated due to a variety of developments including: the increased understanding of physical and statistical properties of precipitation processes, the improvement of numerical weather prediction models, the deployment of modern weather radars such as the NEXRAD system, the application of sophisticated statistical tools, the advances in information technology, and the ever-increasing interest of meteorologists and hydrologists in the QPF problem. It is now clear that QPFs offer a threshold of opportunity for improving flood alert systems (Collier and Krzysztofowicz 2000).
The goal of this chapter is to evaluate the performance of a particular Quantitative Precipitation Forecast (QPF) algorithm known as the Growth and Decay Storm Tracker (GDST) from a hydrologic perspective. The primary research objective is to determine if the model can successfully be used to extend alert level lead-times at the smaller, urban watershed scale. Specific objectives include:

- Record and archive GDST data over a specified period of record.
- Develop GDST performance evaluation/skill methodology.
- Evaluate GDST forecasts at various forecast times and basin sizes.
- Determine if results support an optimum basin size / forecast time.

The impetus for this research is two-fold. First, the GDST algorithm, as its name implies, was not originally designed as a precipitation forecast tool. Despite this fact, it is currently being utilized at numerous locations around the United States for various applications requiring short-term forecast rainfall amounts. Second, it was observed that while the original FAS provided about 2 hours of lead time from a strictly hydrologic perspective, system users were deriving qualitative estimates of rainfall in the future from observed storm motion in the radar image loops. The combination of a reliable QPF system with the existing FAS infrastructure could possibly reduce some of the error associate with these qualitative estimates of future rainfall.

4.2 Methodology

This discussion focuses on the GDST QPF model and the methodology used to evaluate its performance. A general overview of the model algorithm is presented first for completeness. The following sections discuss the data used as well as its recording, archiving and formatting prior to analysis. The meteorological and hydrological performance criteria used in the data analysis are also presented.
4.2.1 The Growth and Decay Storm Tracker Model

The Growth and Decay Storm Tracker Model (GDST) was developed by Lincoln Laboratory at the Massachusetts Institute of Technology as part of the Integrated Terminal Weather System (Evans and Ducot 1994; Wolfson, Forman et al. 1999). The algorithm uses traditional cross-correlation tracking to forecast mesoscale storm events, but improves on this method by using scale separation filtering (by way of an elliptical filter of varying size and orientation) to separate smaller scale cells from the larger storm cells prior to correlation. This enables better tracking of both the overall storm envelope as well as smaller storm cells within it, many of which are often shorter lived and vary slightly from the larger storm’s mean direction and velocity. As a result, the developers claim that the GDST can account for systematic growth and decay in organized storms, but cannot predict large changes in storm spatial extent, envelope pattern or predict the onset of new storms.

The GDST was originally designed to forecast the progression of linear storm systems near airports for the purpose of improving air traffic control and routing during severe weather events (Forman, Wolfson et al. 1999). Preliminary testing of the algorithm for this purpose was completed at four major airports throughout the United States (Theriault, Wolfson et al. 2000).

4.2.2 Quantitative Precipitation Forecast Data

The GDST provides forecasts of 16-level precipitation at grid scales as small as 1 km². GDST data has been obtained through Vieux and Associates, Inc. (VAI). The data product provided by VAI, called PreVieux, provides up to 60-minute forecasts (or
extrapolations based on radar images) for each radar volume scan. Forecasts are provided in 5 minute bins; therefore, each radar scan has 12 associated forecast images or datasets beginning with the t+5 minute scan and continuing with t+10, t+15 and so forth up to t+60 minutes. The algorithm originally used 16-level, base reflectivity, lowest radar tilt data, but has recently been modified to utilize 256-level data; however, the later data is not analyzed in this report. It will likely be analyzed in the future.

Figure 4.1 provides an example of the GDST data as provided by VAI. The figure shows the progression of a frontal storm as predicted by the algorithm. The grid
values are intensities in inches/hour and are superimposed on the subwatersheds of Brays Bayou.

While the data is available in gridded format as seen above, for the purposes of this study, the data was provided in subbasin averaged rainfall format. Figure 4.2 shows an example of this basin averaged data for a storm event on April 7th, 2003, during which

![Figure 4.2: GDST and DPA data for a storm cell moving west to east across Brays Bayou on April 7th, 2003 (Color schemes for each legend are not shown)](image)

an isolated storm cell moved from west to east across Brays Bayou. The images on the left are a PreVieux™ product operating in real-time and show the cumulative predicted rainfall expected over a 60 minute period in inches. Snapshots of the basin averaged values were taken at 15 minute intervals. The image in the lower right corner shows the same data accumulated over 60 minutes but in the 1 km² grid format. The image on the right is the radar image displayed on the current FAS website, which shows the Digital Precipitation Array product. The DPA exhibits rainfall (in inches) that has fallen over the previous 60 minutes in a 16 km² grid format. While it is not the intention of this research to compare these two different radar products, it is significant because of the differences in precipitation amounts being shown. Rainfall amounts associated with this storm cell as recorded by ALERT rain gages were in the 1 – 2 inch range.

4.2.2.1 QPF Data Collection and Processing

QPF data was collected in the PreVieux format for 38 separate rainfall events between May 2002 and December of 2003. As the goal of this research was to analyze the performance of the QPF algorithm during potential flood events, only storms of significance were analyzed in detail. Both a minimum rainfall average (1.5 inches over the watershed) and minimum bayou peak discharge value (15,000 cfs) criteria were established to identify three storms of hydrologic significance. Table 4.1 illustrates the twelve storm events that satisfied the minimum rainfall criteria and their corresponding peak bayou flow rates.
<table>
<thead>
<tr>
<th>Date of Storm Event</th>
<th>Average Rainfall (inches)</th>
<th>Peak Bayou Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/17/2003</td>
<td>4.96</td>
<td>25,500 *</td>
</tr>
<tr>
<td>8/15/2002</td>
<td>4.76</td>
<td>17,900 *</td>
</tr>
<tr>
<td>10/9/2003</td>
<td>3.23</td>
<td>16,000 *</td>
</tr>
<tr>
<td>7/13/2002</td>
<td>2.54</td>
<td>12,750</td>
</tr>
<tr>
<td>10/28/2002</td>
<td>2.29</td>
<td>7,260</td>
</tr>
<tr>
<td>9/19/2002</td>
<td>2.03</td>
<td>5,800</td>
</tr>
<tr>
<td>9/21/2003</td>
<td>1.72</td>
<td>5,300</td>
</tr>
<tr>
<td>11/3/2002</td>
<td>1.70</td>
<td>6,970</td>
</tr>
<tr>
<td>12/12/2002</td>
<td>1.69</td>
<td>4,980</td>
</tr>
<tr>
<td>8/3/2002</td>
<td>1.65</td>
<td>7,130</td>
</tr>
<tr>
<td>9/12/2003</td>
<td>1.56</td>
<td>10,445 *</td>
</tr>
<tr>
<td>5/17/2002</td>
<td>1.50</td>
<td>4,740</td>
</tr>
</tbody>
</table>

Table 4.1: Storm events for which QPF data was collected along with average watershed rainfall and corresponding peak bayou discharge. (*These events were used in calibration/validation of RTHEC-1 hydrograph model discussed in Chapter 5.)

The PreVieux data is provided by VAI in Extensible Markup Language (.XML) format, which is converted to readable text files for import into EXCEL. Each radar scan series of twelve 5-minute QPFs is stored in a separate directory under a root folder named after the date of the volume scan. Units for the data are in inches and represent the accumulation of rainfall over each of 46 subwatersheds in Brays Bayou over that prediction time. For example, the first 5-minute data file associated with a particular volume scan represents the amount of rainfall over the 5-minute period starting from the time of the volume scan. The second 5-minute data file contained data representing the rainfall over the 10-minute period from the time of the volume scan. This continues until the twelfth 5-minute data file, which represents the cumulative rainfall expected to occur over each subbasin over the 60-minutes following the time of the volume scan. A sample series of QPF .xml files for the KHGX radar volume scan dated June 23rd, 2003 at time 19:04:37 UTC (7:04:37 PM UTC) is shown below.
A methodology was developed to compare the QPF data at various forecast time intervals (+15, +30, +45, and +60) to the actual radar data on an incremental basis. The QPF data product’s first available dataset for comparison purposes is the +5 minute data. This +5 minute, or “near real-time” data was used as the comparison against the other forecast intervals in order to ensure that only the performance of the QPF algorithm was being evaluated (see Figure 4.3). It is felt that the +5 minute data should approximate the actual radar data (at time +0) sufficiently for this study. As illustrated in Figure 4.3, the +15, +30, +45, and +60 minute data sets belonging to the 19:04:37 volume scan are to be compared to the summation of the +5 minute data sets of the appropriate volume scans so as the prediction times overlap. For example, the +60 minute data set of the 19:04:37 volume scan is to be compared to the summation of the twelve +5 minute data sets belonging to the twelve volume scans between 19:04:37 and 19:59:37 inclusive. The various criteria used for QPF model performance will be discussed in Section 4.2.3.

Figure 4.3: Sample series of QPF data files for one radar volume scan
A significant amount of data processing was required prior to data analysis. First, as both cumulative and incremental data comparisons were to be completed, it was necessary to reformat the data in a manner allowing such comparisons. The data were “decumulated” into their respective five minute bins and then collated into a format where incremental comparisons could be made. A python script was developed to perform the data formatting and is included in Appendix A for review.

Figure 4.4 illustrates the data layout after formatting. The figure shows example volume scans labeled A-L....Z. The data for each volume scan was layered in a diagonal format so that the resulting array placed all twelve predictions for the desired interval of five minutes to be analyzed on the same row. This method facilitated incremental comparisons between the +5 minute data for a respective volume scan, and the +15,+30 and +60 predictions for that time interval made by earlier scans. This is illustrated in the yellow shaded cells on row Volume Scan L (VSL) in Figure 4.4. Ideally, with perfect predictions by the QPF model VSL+5 should equal VSL+15, VSG+30, and VSA+60.

This data format also facilitated comparisons of predicted accumulated rainfall values over the range of +5 through +60 minutes. Again, Figure 4.4 illustrates an example comparison for accumulated rainfall predictions. The diagonal light blue cells represent the predicted rainfall amount over the next 45 minutes resulting from Volume Scan A (VSA). Ideally, this value should equal the summation of the horizontal light blue cells, representing the summation of the +5 minute data from the VSA scan and the following eight scans.

Another significant data formatting hurdle was to identify and account for “missing” radar volume scans. As discussed in Chapter 2, radar data scans during heavy
rainfall periods are typically 5-7 minutes apart; however, data scans can be missed either at the radar processing stage or at the QPF processing stage. An additional

<table>
<thead>
<tr>
<th>Vol Scan A (VSA)</th>
<th>VSA+5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol Scan B (VSB)</td>
<td>VSB+5 VSA+10</td>
</tr>
<tr>
<td>Vol Scan C (VSC)</td>
<td>VSC+5 VSB+10 VSA+15</td>
</tr>
<tr>
<td>Vol Scan D (VSD)</td>
<td>VSD+5 VSC+10 VSB+15 VSA+20</td>
</tr>
<tr>
<td>Vol Scan E (VSE)</td>
<td>VSE+5 VSD+10 VSC+15 VSB+20 VSA+25</td>
</tr>
<tr>
<td>Vol Scan F (VSF)</td>
<td>VSF+5 VSE+10 VSD+15 VSC+20 VSB+25 VSA+30</td>
</tr>
<tr>
<td>Vol Scan G (VSG)</td>
<td>VSG+5 VSF+10 VSE+15 VSD+20 VSC+25 VSB+30 VSA+35</td>
</tr>
<tr>
<td>Vol Scan H (VSH)</td>
<td>VSH+5 VSG+10 VSF+15 VSE+20 VSD+25 VSC+30 VSB+35 VSA+40</td>
</tr>
<tr>
<td>Vol Scan I (VSI)</td>
<td>VSI+5 VSH+10 VSG+15 VSF+20 VSE+25 VSD+30 VSC+35 VSB+40 VSA+45</td>
</tr>
<tr>
<td>Vol Scan J (VSJ)</td>
<td>VSJ+5 VSI+10 VSH+15 VSG+20 VSF+25 VSE+30 VSD+35 VSC+40 VSB+45 VSA+50</td>
</tr>
<tr>
<td>Vol Scan K (VSK)</td>
<td>VSK+5 VSJ+10 VSI+15 VSH+20 VSG+25 VSF+30 VSE+35 VSD+40 VSC+45 VSB+50 VSA+55</td>
</tr>
<tr>
<td>Vol Scan L (VSL)</td>
<td>VSL+5 VSK+10 VSJ+15 VSI+20 VSH+25 VSG+30 VSF+35 VSE+40 VSD+45 VSC+50 VSB+55 VSA+60</td>
</tr>
<tr>
<td>Vol Scan Z (VSZ)</td>
<td>VSZ+5 VSL+10 VSK+15 VSH+20 VSG+25 VSF+30 VSE+35 VSD+40 VSC+45 VSB+50 VSZ+60</td>
</tr>
</tbody>
</table>

**Figure 4.4**: Sample series of QPF data files for one radar volume scan and those files selected for comparison (although not illustrated for brevity, comparisons were also made for the +30 and +45 minute datasets).

A python script was developed to identify and account for these missing scans. Approximately 95% of the missing scan periods consisted of either one or two scans. In this situation, a simple averaging was performed between the last and next available radar scans. For example, if VSB in Figure 4.4 was in fact a missing scan, the data for that scan would be approximated by interpolation, using the values for VSA and VSC for each prediction time. Thus, VSB+15 would be the average of VSA+15 and VSC+15. If the missing scan covered two time periods, for example VSB and VSC, the data for the two missing scans would be determined by linearly interpolating the data from VSA and
VSD. If the missing scan period was greater than 14 minutes, the data comparison was discontinued at that time period and resumed when data was once again available.

4.2.2.2 Storm Event Case Studies

As presented in Section 4.2.2.1, three of the twelve storm events for which QPF data were collected met the minimum rainfall and streamflow criteria established to qualify as storms of hydrologic significance. The storm events analyzed are discussed in this section from both a hydrologic and meteorological perspective.

Event A: August 15th, 2002:

While tropical systems are frequently the cause of significant rainfall amounts during the month of August in the Houston area, this was not the case in 2002. Heavy rains were caused throughout the month by easterly moving, upper level atmospheric disturbances interacting with moist air masses from a high pressure system that had settled over the Gulf of Mexico. August 15th was a particularly active day with respect to precipitation over the Houston and coastal regions of southeast Texas.

This storm event consisted of several disorganized, short-lived rainfall cells that moved from west to east across the region. This resulted in highly variable rainfall amounts across the region with the majority of heavy rainfall occurring near coastal areas such as Galveston. Brays Bayou also received significant rainfall that day, consisting of two major rainfall periods. The first period commenced early in the morning and dropped 1-2 inches of rain over a two-hour period from 0630-0830 (CDT). Intermittent rainfall continued throughout the day until a second heavy period of rainfall resulted in an additional 1-2 inches over another two-hour period from 1500-1700 (CDT).
The cumulative and incremental rainfall amounts for this event are displayed in Figures 4.5a, 4.5b and 4.5c. Values shown are average amounts over the upper, middle and lower portions of Brays Bayou. The two periods of heavier rainfall are clearly discernible as well as the easterly motion of the storms. The rainfall pattern resulted in a double-peaked hydrograph for Brays Bayou at Main Street with a peak observed flow of 17,900 cfs. As the real-time operational framework of the FAS2 system was not in place at the time of this storm, a detailed DPA radar image cannot be shown as is done for the following two storm events. Nevertheless, the storm provided an excellent opportunity for calibration of the RT-HEC1 model discussed later in this study.

**Event B: October 9th, 2003:**

The smallest of the three case study storm events was due to deep tropical moisture moving over the region from the Gulf of Mexico. This set the stage for numerous showers in the early and middle portion of October 9th, 2003 followed by severe thunderstorms throughout the late afternoon and early evening. Again, the primary motion of the convective cells was toward the east. The earlier showers provided from 0.5 to 1.0 inches of rainfall across Brays Bayou. This antecedent rainfall saturated the soil for the primary rainfall event, which dropped another 1.5 to 2 inches of rainfall from approximately 5:00 PM – 8:00 PM (CDT). This storm event produced a peak observed flow rate of 16,000 cfs at the Main Street gage of Brays Bayou. Figures 4.6a and 4.6b illustrate a storm cell associated with this event passing over Brays Bayou. The rapid decay of the storm cell was indicative of many of the cells during this storm event.
Event C: November 17th, 2003:

By far the largest of the three storm events studied for this section was caused by a combination of strongly divergent jet stream patterns and a weak low level boundary aligned from the southwest to northeast generally along the U.S. Highway 59 corridor. A strong 500 mb upper level trough moving from west to east across the southern plains caused the polar jet stream associated with this trough to dip into West Texas and then turn sharply to the northeast near Central Texas. The subtropical jet stream was simultaneously oriented west to east across deep South Texas, causing increased low level moisture along the Texas coast along with rapidly increasing upper level winds. This combination of wind speed and directional sheer, along with the weak low level boundary allowed for the formation of intense tornadic thunderstorms throughout the day and well into the evening of November 17th, 2003. The axis of heaviest rainfall was
coincident with the nearly stationary boundary along U.S. 59, with repeated thunderstorm formation and northeasterly passage across the southeast Texas and coastal region.

The portion of this storm event affecting Brays Bayou was primarily due to two convective cells that were very well organized and fairly consistent with respect to rainfall intensity, storm cell velocity, and direction. The first cell impacted the upper half portion of Brays (see Figure 4.7a), dropping approximately 4 inches of rain over a 3-hour period from 1130-1430 (CST). The maximum one-hour rainfall recorded was 3.3 inches from 1130-1230 (CST) over HCOEM Gage 485. The storm cell velocity was initially 20 miles per hour, but diminished somewhat over Harris County to about 15 miles per hour. The second cell impacted the lower two-thirds of Brays Bayou (see Figure 4.7b), dropping approximately 3 inches of rain over a 1.5 hour period from 1430-1600. The cumulative and incremental rainfall amounts for this event are displayed in Figures 4.5a, 4.5b and 4.5c. (shown at end of chapter). Values shown are average amounts over the

![Figure 4.7a: NEXRAD DPA image of first storm cell associated with Event C on November 17th, 2003](image1)

![Figure 4.7b: NEXRAD DPA image of second storm cell associated with Event C on November 17th, 2003](image2)
upper, middle and lower portions of Brays Bayou. This storm event generated an observed peak flow of 25,500 cfs at Main St.

4.2.3 Model Performance Criteria

A complete analysis of QPF forecasts requires a combination of meteorological and hydrological statistics. This enables a better understanding of the spatial and temporal accuracy of the forecasted rainfall. Additionally, the performance criteria should also consider not only spatial accuracy (as in accurately predicting the location of a storm cell), but the accuracy of the predicted rainfall intensity. These criteria are of equal importance from a hydrologic / flood forecasting perspective, as slight errors in future storm cell direction could be equally detrimental to the accuracy of a flood prediction as errors in the predicted intensity of a storm event. This is especially true when forecasting for smaller, urban watersheds where a slight course change in the overall direction of the storm cell envelope could result in the storm cell missing the watershed entirely.

Model performance criteria for the QPF data collected for the three storms listed focus on quantitative comparison measures. Examples of quantitative measures used in this research include: Mean Absolute Error (MAE) analysis, R-Squared Correlation analysis, and Threshold-Based Critical Success Index (TCSI) analysis. These measures will be discussed in detail in the following sections.

The central hypothesis for the research in this section is that the performance of the QPF algorithm might be improved for a given forecast time interval by increasing the basin size over which the forecast data are averaged. This approach, while reducing the locational / spatial accuracy of rainfall prediction, should enable longer predictions to be
made for a given performance criteria – thereby increasing the lead-time provided by the system. In other words, the increased basin size, or "target", should enable longer forecast times at the expense of a variable reduction in spatial accuracy that may not be required based on the end application. Figure 4.8 illustrates a hypothetical example of the affect of increasing basin size for the prediction of the future location of a storm cell. The figure illustrates six subwatersheds in Lower Brays Bayou. Both images show the same predicted (white arrow) and actual (red dashed arrow) of a hypothetical storm cell. In the image above, the prediction is considered a "miss", while the aggregation of the subwatersheds in the lower image allows for the prediction to be considered a "hit" as discussed in Chapter 2 of this report (see discussion of Critical Success Index). If the spatial accuracy of the predicted rainfall is not needed at the resolution of the subwatershed level, this method should improve the overall performance of the QPF

Figure 4.8: Hypothetical example of increasing basin size over which predicted rainfall data are averaged. Increasing basin size may compensate for errors in prediction vector but NOT predicted precipitation intensity.
algorithm within the context of a lumped parameter hydrologic model like RTHEC-1 and the operation of a flood alert system, dependent on its performance.

This approach was adopted for Brays Bayou and the QPF data which was provided at the subbasin averaged level. Performance criteria data were collected for four subwatersheds of approximately equal size at different locations across the bayou. These four subwatersheds (D100B, D100I, D100K, and D100Q) are illustrated in Figure 4.9. The figure also illustrates the aggregation of subbasins to form larger basins for comparative analysis. The original four subbasins were chosen according to the following criteria: insuring coverage of each area of the watershed (upper, middle and lower), their proximity to a recording rain gage, and similarity in area to avoid unnecessary weighting of data. Table 4.2 (included at the end of the chapter) shows the subwatershed groupings (L1-L3) and their corresponding areas used in this study. Two additional larger subwatershed groupings were included for only the TCSI portion of this study. They include L4, the combination of the upper two-portions of Brays Bayou resulting in an 86 mi² region and L5, Brays Bayou as a whole – approximately 128 mi².

![Figure 4.9: Subbasin groupings for analysis of QPF data averaged over basins of varying sizes. (See Table 4.2 for a detailed listing of subbasin aggregations)](image-url)
4.2.3.1 Time-Series Comparisons of QPF Data

Time-series comparisons of QPF data were performed by plotting predicted and observed rainfall accumulations for various prediction time lengths. Observed rainfall data in this comparison should be considered as the +5 minute (or near real-time QPF radar data) discussed earlier in this chapter (see Section 4.2.2.1.). It is important to note that the comparisons in this chapter focus on QPF to QPF (ie radar to radar) for the purpose of determining the extrapolation skill of the QPF algorithm. Comparisons of this data to rain gages will likely not be performed. This is due to the fact that this would not assist in measuring the skill of the methodology as a whole, but rather would include inherent errors in radar estimation of rainfall, which have already been studied at length in the literature as discussed in Chapter 2.

Comparisons were performed on accumulated data at the +15, +30, +45 and +60 minute time periods for each of the subwatershed groupings shown in Table 4.2. Comparisons were first performed for the highest intensity rainfall period within each particular storm event.

Figures 4.10a and 4.10b show an example of the time-series comparisons between the QPF data, near-real time radar data, and rain gage data. These figures provide a both a qualitative and quantitative comparison of how the QPF algorithm performed during a high-intensity rainfall event. It is important to note that these graphs display one-hour summations of expected rainfall (in the case of QPF data) or measured rainfall (in the case of rain gage data). This type of analysis is important from the perspective of the end use of the QPF algorithm. Flood alert system operators and users will be interested in the total amount of future rainfall expected over a given time period. This analysis seeks to
Figures 4.10a: Comparison of Rain Gage, Radar and QPF Data at the Small Subbasin Scale (D100B) for the November 17th, 2003 storm event. Rain gage data is from HCOEM gage #485.

Figures 4.10b: Comparison of Rain Gage, Radar and QPF Data at the Large Subbasin Scale (Upper Brays) for the November 17th, 2003 storm event. Rain gage data represents a Thiessen weighted average of HCOEM gages #485, #470, and #490.
address the appropriateness of that use. Additional comparison graphs for various subbasin groupings and the each of the storm events studied are available in Appendix B.

4.2.3.2 Mean Error and Mean Absolute Error Analysis

Both mean error (ME) and mean absolute error (MAE) analysis were conducted on the entire set of QPF data. This analysis compared the near real-time radar data to each five minute incremental set of QPF data. The ME is computed as the difference between the observed (near real-time radar data) 5-minute incremental rainfall at time \( t+5 \) and the predicted 5-minute incremental rainfall at times \( t+10, t+15, \ldots, t+60 \). Values of ME closest to zero indicate the best overall agreement. ME is a beneficial performance criteria because the overall sign indicator, positive or negative, indicates whether the algorithm is overpredicting or underpredicting future rainfall amounts. An increase in the ME as the forecast time increases is expected due to the extrapolation nature of the QPF algorithm. However, ME has a significant drawback in that when averaging ME values over large data sets, the positive and negative differences may cancel each other out. Hence, an ME analysis may yield a small error while the data set actually has a large range of scatter (McCuen, 1992). For this primary reason, the ME should be used in conjunction with other data analysis and statistical measures. The equation used to calculate Mean Error is shown below in Equation 4.1, where \( X \) is defined as the observed rainfall value and \( Y \) as the predicted rainfall value. An example ME analysis chart is provided in Figure 4.11.

\[
ME = [X - Y]
\]  
(Equation 4.1)
Figure 4.11: Mean Error Analysis for Level I Subbasin Data for the November 17th, 2003 storm event.

The mean absolute error (MAE) is often used to complement the mean error because it is able to indicate a better overall performance measure for a model or prediction algorithm. The MAE is calculated by taking the absolute value of the difference between the observed rainfall and the predicted rainfall. The absolute value removes the negating differences in positive or negative error values and therefore provides a good indication of the scatter or spread of error. The equation used to calculate MAE is shown below in Equation 4.2, again where X is defined as the observed rainfall value and Y as the predicted rainfall value. An example MAE analysis chart is provided in Figure 4.12. Each data column represents the MAE between the particular forecast time data and the near-real time +5 minute forecast radar data. The five minute incremental rainfall periods were compared out to +60 minutes. Data comparisons for
the MAE analysis were only run on the highest rainfall period of each storm event in order to minimize the false error reducing effects of no rainfall periods.

\[ MAE = \text{ABS} \left| X - Y \right| \]  

(Equation 4.2)

Mean Absolute Error (MAE) for Level 1 Subbasin Data (Oct 9th, 2003)

Figure 4.12: Mean Absolute Error Analysis for all Level I Subbasin Data for the October 9th, 2003 storm event.

4.2.3.3 R-Squared Correlation Analysis

Correlation analysis provides a means of drawing inferences about the strength of the relationship between two or more variables. The (linear) Correlation Coefficient (r) is a quantitative index of the degree of common variation between two variables, and as such, is used as a measure of the goodness of fit between the results of a prediction mechanism or equation and the data sample being analyzed, provided the relationship between the two variables varies linearly. An r-squared correlation analysis was
performed in this study between the predicted and observed rainfall values accumulated over various forecast times. The r-squared coefficient, known as the Coefficient of Determination, is often used in place of the correlation coefficient. The equation for r-squared correlation is shown below in Equation 4.3. An example r-squared correlation analysis for a set of 60-minute and 15-minute accumulated rainfall data is shown in Figures 4.13a and 4.13b for subbasin D100B during the November 17th, 2003 storm event.

$$r^2 = \left( \frac{n(\sum XY) - (\sum X)(\sum Y)}{\left[ n\sum X^2 - (\sum X)^2 \right]^{\frac{1}{2}} \left[ n\sum Y^2 - (\sum Y)^2 \right]^{\frac{1}{2}}} \right)^2$$ (Equation 4.3)

4.2.3.4 Threshold-Based Critical Success Index Analysis

As discussed in Section 2.2 of this study, the Critical Success Index (CSI) is a statistical measure often used in the atmospheric sciences to quantitatively describe the accuracy of a forecasting system (Wilks 1995). A variation of the CSI was used in this research to provide a comparative, quantitative measure of performance while varying basin sizes and forecast times. This variation is referred to as the Threshold-Based Critical Success Index (TCSI). The equation for calculating the CSI is shown in Equation 4.4.

$$CSI = \frac{H}{(H + M + FA)}$$ (Equation 4.4)

Where: $H = \text{Number of Hits}$
\[ M = \text{Number of Misses} \]

\[ FA = \text{Number of False Alarms} \]

**Figure 4.13a:** Correlation between 15-Minute Accumulated QPF Data and 15-Minute Accumulated Observed Rainfall Data (Small Scale - D100B - Nov 17th, 2003)

**Figure 4.13b:** Correlation between 1-Hour Accumulated QPF Data and 1-Hour Accumulated Observed Rainfall Data (Small Scale - D100B - Nov 17th, 2003)

The TCSI equation remains unchanged from Equation 4.4 with the exception that a hit, miss, and false alarm are defined as follows:
\[ \text{Hit} = \text{Predicted rainfall within } +/- \text{ threshold } \% \text{ of observed} \]
\[ \text{Miss} = \text{Predicted rainfall} < (\text{observed} - \% \text{ threshold window}) \]
\[ \text{False Alarm} = \text{Predicted rainfall} > (\text{observed} + \% \text{ threshold window}) \]

This modification permits the creation of a variable threshold window around the observed rainfall data point. This change is required as the CSI is normally used in situations where an event either occurs or does not occur. For example, the normal CSI equation could be used without modification to measure the prediction skill of a system designed to predict whether or not rainfall would occur. As we are dealing with variable precipitation amounts, the TCSI must be used instead.

TCSI values range from 0 (poor prediction) to 1 (perfect prediction). An initial threshold of 30\% was used on the analysis of the three storm events at every basin scale. It was expected that TCSI values would be greater for shorter prediction times and would increase as the basin scale was increased. Results supported this expectation and are discussed in detail in Section 4.3.3.

This approach improves upon the approach used by Van Horne et al. by providing both an upper and lower threshold bound around the observed target rainfall value. The Van Horne study only used a lower limit threshold, thereby not accounting for undershoot error. For example, in the Van Horne study, a 50\% threshold was established for "medium intensity" rainfall events. If both the predicted and observed rainfall amounts exceeded this threshold, a "hit" was scored. Theoretically, there could be up to a 49\% error between the observed and predicted values in this scenario, with a hit still counting toward a higher CSI. The theoretically possible error band increases with this
approach as the threshold is lowered. For example, the Van Horne study used a 0% threshold where “hits” were achieved where a rainfall amount was predicted and any rainfall occurred during that time, regardless of the amount – in essence, a rain/no-rain prediction. While this approach may be useful in quantifying the skill of the algorithm for this particular scenario, it does not refine the analysis for maximum benefit when coupled with a hydrologic model or hydrologic analysis of any kind.

4.3 Results and Discussion

This section will provide results and discussion of each of the comparison methods outlined above. The discussion will begin with a summary of the correlation analysis performed, which initially revealed the possible operational benefits of increasing basin size toward the application of the QPF algorithm. Following this discussion, results from the MAE analysis will be presented, quantifying from an error perspective the benefits of increased basin size and increased forecast times. The results of the TCSI analysis are then presented.

4.3.1 Correlation Analysis

The r-squared correlation analysis performed in this study was the first to be completed after the QPF data was collected and ready for analysis. This was performed in order to provide some initial confidence in the hypothesis that increasing basin size would improve QPF performance.
Ideally, stronger correlations between the QPF data and the near real-time radar data should be noted for larger basin sizes as well as for shorter forecast times. Figures 4.14a-d through 4.16a-d support the hypothesis by illustrating consistently increased Coefficients of Determination from the lesser correlated data (small basin and one hour forecast times) to the more greatly correlated data (large basin and 15-minute forecast times) for all three case study storm events.

Results for the November 17th storm event are shown in Figures 14a-d for data from 1100-1800 local time. As discussed earlier, the well-organized storm cells associated with this event (see Figure 4.7a) resulted in excellent correlations across the spectrum of basin sizes and forecast times. The storm event is an excellent case study as both large and small rainfall events were experienced over a prolonged period of time (nearly seven hours). An $R^2$ value of 0.64 was calculated for the small basin, D100B, for accumulated rainfall totals over one hour. An improved $R^2$ value of 0.88 was noted for the same period using the Upper Brays (L3) basin averaged data. This value of 0.88 was very close to the $R^2$ value of 0.90 for the D100B basin using 15-minute accumulated data, indicating that it could be possible to improve forecast times at the expense of spatial resolution, an important indicator supporting the original hypothesis. A strong $R^2$ value of 0.97 resulted for the 15-minute, large basin data comparison. Additional correlation comparisons for various forecast times are included in Appendix C.

Results for the October 9th storm event do not exhibit as strong a correlation as the Nov 17th event for the one hour forecast accumulations. $R^2$ coefficients of 0.39 and 0.55 for the one-hour small basin and one-hour large basin respectively may indicate poorer performance of the QPF algorithm during this storm event. As discussed and illustrated
in Section 4.2.2.2., this event was characterized by rapidly growing and decaying storms, a scenario under which this particular QPF model does not perform as adequately (Wolfson et al. 1999; Van Horne 2002; Vivoni et al 2002). However, the correlation increases once the basin size is increased, again supporting the original hypothesis. It should be noted here that the number of data points for this storm event is significantly less than the other case studies due to the fact that only one significant burst of rainfall occurred during the event.

Results for the August 15th, 2002 storm event follow the same pattern as the previous storm events, with increasing correlation while increasing basin size and decreasing forecast times. A more significant increase in the $R^2$ correlation is noted after reducing forecast times than compared to increasing basin size.

![Correlation between 1-Hour Accumulated QPF Data and 1-Hour Accumulated Observed Rainfall Data (Small Scale - D100B - Nov 17th, 2003)](image)

$R^2 = 0.6419$

Figure 4.14a
Correlation between 1-Hour Accumulated QPF Data and 1-Hour Accumulated Observed Rainfall Data
(Large Scale - Upper Brays - Nov 17th, 2003)
1100-1800 Local

$R^2 = 0.8753$

---

Correlation between 15-Minute Accumulated QPF Data and 15-Minute Accumulated Observed Rainfall Data
(Small Scale - D100B - Nov 17th 2003)
1100-1800 Local

$R^2 = 0.8974$

---

Figure 4.14b

Figure 4.14c
Correlation between 15-Minute Accumulated QPF Data and 15-Minute Accumulated Observed Rainfall Data (Large Scale - Upper Brays - Nov 17th 2003) 1100-1800 Local

\[ R^2 = 0.975 \]

Figure 4.14d

Correlation between 1-Hour Accumulated QPF Data and 1-Hour Accumulated Observed Rainfall Data (Small Scale - D100B - Oct 9th, 2003) 1500-1800 Local

\[ R^2 = 0.3941 \]

Figure 4.15a
Figure 4.15b

Figure 4.15c
Correlation between 15-Minute Accumulated QPF Data and 15-Minute Accumulated Observed Rainfall Data
(Large Scale - Upper Brays - Oct 9th 2003)
1500-1800 Local

\[ R^2 = 0.9545 \]

Figure 4.15d

Correlation between 1-Hour Accumulated QPF Data and 1-Hour Accumulated Observed Rainfall Data
(Small Scale - D100Q - Aug 15th, 2002)
0500-1730 Local

\[ R^2 = 0.5766 \]

Figure 4.16a
Figure 4.16b

Correlation between 1-Hour Accumulated QPF Data and 1-Hour Accumulated Observed Rainfall Data
(Large Scale - Lower Brays - Aug 15th, 2002)
0500-1730 Local

Figure 4.16c

Correlation between 15-Minute Accumulated QPF Data and 15-Minute Accumulated Observed Rainfall Data
(Small Scale - D100Q - Aug 15th 2002)
0500-1730 Local

R^2 = 0.6828

R^2 = 0.8689
4.3.2 Mean Error and Mean Absolute Error Analysis

The Mean Error (ME) and Mean Absolute Error (MAE) analyses were performed in order to directly determine the effectiveness of the QPF algorithm at various forecast times and basin sizes. Results for the ME analysis revealed varying degrees of both overprediction and underprediction for the various storm events. As discussed in Section 4.2.3.2, this often resulted in the positive and negative results canceling each other out when the data were averaged for comparison purposes. It still remains possible to analyze individual subbasin results for ME on a case by case basis since the data exists; however, only MAE results will be discussed in detail in this section. The MAE results were sufficient in supporting the improved performance of the QPF algorithm at larger basin sizes. The question of whether or not this improvement is sufficient to make an
impact on the overall system operation remains after this analysis. This will be addressed later in Section 4.3.3.

Figures 4.17a-d (whole storm comparisons) display the MAE results for subbasin levels 1 through 3 (smallest to largest) for the largest rainfall episode associated with each storm event. This was performed in order to minimize the effects of no rainfall periods on the error analysis. The values plotted were obtained by averaging the MAEs for each of the individual subbasins. The three storm average MAE is also shown and was obtained by averaging the MAEs for each storm event. It is important to note that the value of the MAE is in inches per 5 minute increment; therefore, an MAE of 0.02 inches is not as insignificant as it may first seem apparent, as this error would translate to 0.24 inches of error if the trend continued for one hour.

The forecast error steadily increases as the forecast time increases for two of the three storm events. The August 15th, 2002 is the only event that does not exhibit the steady increase, with the MAE stabilizing after the +30 minute forecast. The larger error associated with the November 17th event is likely due to the more intense rainfall experienced over the time period analyzed. Average MAE’s for the Level 1 subbasins ranged from 0.028 inches at +15 minutes up to 0.041 inches at the +60 minute forecast. The largest range was noted for the October 9th storm with an MAE of 0.026 inches at +15 minutes and 0.046 inches at +60 minutes.

The most important result of the MAE analysis is the noticeable reduction in the MAE as the subbasin size increases. This is illustrated in Figures 4.17a-d and summarized in Figure 4.18. There are two important points to discuss regarding the results shown in these figures. First, the similar reduction in MAE observed from
increasing the basin size from L1 (approximately 1.6 mi2) to L2 (approximately 16.6 mi2) and increasing the basin size from L2 to L3 (approximately 42.7 mi2). This would suggest a diminishing return from increasing basin size that will be investigated later.

Second, is the leveling off of the MAE reduction observed after the ±40 minute forecast time. This also suggests a diminishing return to increasing basin size.

MAE analysis was also performed on each of the storm events using rain rate percentiles as the cutoff for comparisons. Rainfall rate thresholds used were the 80th, 50th, and 20th percentiles. This means that an analysis using the 80th rainfall rate percentile would only include those 5-minute datasets with a rainfall rate greater than 80% of that observed during the entire storm event. This was performed in order to eliminate any bias in the analysis that may have resulted from only looking at the peak rainfall episode within the entire storm event. It was also performed to determine if the algorithm performed differently for various rainfall intensities. Figures 4.19a-19c illustrate the results for the 80th, 50th, and 20th rain rate percentile MAE analysis for the October 9th event. The results illustrate that the overall trend in MAE increase as forecast time increases remains; however, one notable difference is the reduced effect of increasing basin size on reducing the MAE at forecast times larger than 30 minutes. This can be explained by the increased likelihood of small intensity storm cells either growing or decaying within the 30 to 60 minute period. Additionally, it is also likely that smaller storm cells not associated with the original storm cell being tracked may have contributed to the rainfall amount.
The 80th percentile analysis results are included for the August 15th and November 17th storm events for completeness, in Figures 4.20 and 4.21. Additional results for these storm events are listed in Appendix D.

Figure 4.17a
Mean Absolute Error (MAE) for Level 2 Subbasin Data (All Storms - Peak Event)

- Average Level 2 Nov 17 2003
- Average Level 2 Oct 9th 2003
- Average Level 2 Aug 15th 2002
- Overall L2 Average

Forecast Time (minutes)

Error in Rainfall Prediction Over 5-minute Interval (inches)

Figure 4.17b

Mean Absolute Error (MAE) for Level 3 Subbasin Data (All Storms - Peak Event)

- Average Level 3 Nov 17 2003
- Average Level 3 Oct 9th 2003
- Average Level 3 Aug 15th 2002
- Overall L3 Average

Forecast Time (minutes)

Error in Rainfall Prediction Over 5-minute Interval (inches)

Figure 4.17c
Figure 4.19a

Mean Absolute Error (MAE) for all Levels of Subbasin Data
October 9th, 2003

Figure 4.19b

Mean Absolute Error (MAE) for all Levels of Subbasin Data
October 9th, 2003
Mean Absolute Error (MAE) for all Levels of Subbasin Data
October 9th, 2002

Figure 4.19c

Mean Absolute Error (MAE) for all Levels of Subbasin Data
August 15th, 2002

Figure 4.20
4.3.3 Threshold Critical Success Index Analysis

The Threshold Critical Success Index (TCSI) analysis was performed in order to obtain a comparative measure of the performance of the QPF algorithm at the desired forecast times and basin sizes. The results of the TCSI analysis are shown on a storm by storm basis in Tables 4.3-4.5. Table 4.6 provides an average result from the three storms. In general, the TCSI validated the results found in the MAE analysis discussed above, with improved performance observed for shorter forecasts and larger basin sizes (see Figure 4.22).

As before, the analysis was performed on varying intensities of rainfall, using the 20th, 50th, and 80th percentiles for rainfall rates observed in each storm. It can be noted that improved TCSI values are illustrated for the more intense rainfalls. This supports the use of this type of forecast algorithm for rainfall events that are likely to cause significant flooding. All data was presented in the tables for completeness; however, for the
purpose of applying this forecast algorithm within the framework of a flood alert system, the most important results are for the >80\textsuperscript{th} percentile data. Nevertheless, the >50\textsuperscript{th} and >20\textsuperscript{th} percentile TCSI results could be significant when considering the possible application of this algorithm in situations where less intense rainfall predictions are relatively more important. Examples of these types of applications would include storm sewer operations, systems attempting to predict minor street flooding, and/or using the algorithm for short-term planning of outdoor operations including repairs to utilities, construction and even sports-related activities.

It is important to understand what the TCSI numbers indicate. To clarify, the >80\textsuperscript{th} percentile data for the November 17\textsuperscript{th}, 2003 storm event indicates that at the largest basin size of L5, 92\% of the +15 minute predicted data were within +/- 30\% of the observed rainfall value. Likewise, only 36\% of the +60 minute predicted data were within +/- 30\% of the observed rainfall value. The TCSI is intended to provide a comparative means of analysis; therefore, the final determination of a "good" or "satisfactory" TCSI will depend greatly on the end user’s application and needs. However, there should theoretically exist a TCSI “lower limit” that would indicate the QPF algorithm’s prediction skill is effectively no better than other methods of prediction, including persistence as well as the subjective “educated guess” by observers of real-time radar data. Additional study may be required to determine this lower limit threshold.
### TCSI (30% Threshold)  August 15th, 2002 (Table 4.3)

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### TCSI (30% Threshold)  October 9th, 2003 (Table 4.4)

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Figure 22 illustrates a discernible trend in the effect of increasing basin size on TCSI as the forecast time increases, a greater than doubling of the TCSI as basin increases from L1 to L5. There is a significantly greater increase in the TCSI at the 15 and 30 minute forecasts in the L1 – L3 range; however, the 45 and 60 minute forecasts “catch up” to the earlier forecasts in the L4 and L5 basin size analyses. Table 4.7 shows the percentage increase in TCSI when increasing basin size from L1 to all other basin sizes. It should be kept in mind that while the percentage analysis is important, the relatively lower TCSIs at the 45 and 60 minute forecasts may preclude their use for certain applications.

Surprisingly, the data trended as expected with two exceptions, there was observed a greater percentage increase in TCSI for the 60 minute forecasts as compared to the 45 minute forecasts for the L1 to L3 and L1 to L4 basin increase analysis. This “unexpected” result may be an anomaly brought about by the August 15th, 2002 data not displaying a continuing decrease in TCSI as forecast time increases (see Figures 4.23a-e). This storm was the only one of the three storms to not exhibit the expected performance of continued decreasing TCSI with forecast time increases. Additional storms should be studied as the operational FAS2 system gathers data to determine if this was indeed an anomaly. Regardless, the relatively low TCSIs at the 45 and 60 minute forecasts render the larger percentage increase at 60 minutes practically irrelevant when taking actual operational uses of the system into account. This may provide some guidance to determining the useful lower limit of the TCSI as discussed above.
Figures 23a-e display the TCSI scores by subbasin size on an individual basis for each of the three storm events. Comparing the five graphs illustrates that the storm event exhibiting the greatest correlation at each forecast time, November 17th, also displayed the highest TCSI across the board. Level 1 subbasin TCSIs for the >80th percentile
ranged from 0.22 at 60 minutes to 0.48 at 15 minutes. Level 5 subbasin TCSIs improved to 0.36 at 60 minutes and 0.92 at 15 minutes. Although the methodology is not directly comparable as discussed in Section 4.2.3.4, the average TCSIs calculated by Van Horne et al. (Van Horne, Entekhabi et al. 2002) ranged from 0.28 to 0.40 at 60 minutes for an area approximately equal to this study’s L3 basin size (~ 40 km²). Again, considering that the Van Horne study only had a lower limit threshold, slightly improved CSI scores should be expected over those found in this study. Consistent scores in the 0.5 to 0.7 range were not observed for the 60 minute forecast, as observed by Cartwright et al (Cartwright, Wolfson et al. 1999) as this earlier study was over a 434 km² basin and was limited to a “rain / no rain” criteria, thereby not taking any variation in rainfall intensity into account, as discussed earlier. Additional figures shown below illustrate how the TCSI varied from storm event to storm event at the same subbasin size (Figures 4.24a-c) and how the TCSI varied at different subbasin sizes for the same storm event.
Figures 4.23a – 23e
Figures 4.24a – 24c
4.3.4 Generalization of TCSI Results

Although only three storms were studied in the TCSI QPF analysis, the data revealed sufficient trends to allow a generalization of the dataset within the range of the parameters investigated. The above TCSI data was combined and integrated to generate Figures 4.25a and 4.25b. These figures allow a user to determine an expected performance level of the QPF algorithm for significant rainfall events (>80% rainfall rate percentile) for a specified basin size and forecast time. The maximum basin size was limited to that studied in Section 4.3.3. or approximately 128 square miles (the area Brays Bayou). The longest forecast time was also equal to the longest forecast time used in the above section.

It should be noted that despite the trends exhibited in the data, the limited range of this study does not allow for the determination of the best method for fitting trend lines to the data. The figures provide two approaches at fitting the data, using linear relationships as well as a second power curve. Exponential data fitting did not perform as well as either of these two approaches. Within the limits of the data studied (interpolation), neither approach differs significantly; however, significant differences would be expected if the data were extrapolated beyond one hour or 128 square miles.
Figure 4.25a

Figure 4.25b
Figures 4.5a: Incremental and cumulative lowest tilt radar rainfall amounts over the lower, middle, and upper portions of Brays Bayou for the August 15th, 2002 event.
Figures 4.5b: Incremental and cumulative lowest tilt radar rainfall amounts over the lower, middle, and upper portions of Brays Bayou for the October 9th, 2003 event.
Figures 4.5.c: Incremental and cumulative lowest tilt radar rainfall amounts over the lower, middle, and upper portions of Brays Bayou for the November 17th, 2003 event.
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<th>Mid-Level Subbasin Scale - Level II (L2)</th>
<th>Large Subbasin Scale - Level III (L3)</th>
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D129A  
D100A (16.78 mi²)  
D122A  
D126A  
D100C | D100B  
D129A  
D100A  
D122A  
D126A  
D100C |
| **Middle** (Green and Blue Shaded Basins in Figure 4.7) | D100I (1.71 mi²) | D100I  
D133A  
CityA  
D100H (16.99 mi²)  
D100G  
D118E  
D140C  
D140B | D100K  
D115A  
D100J | D139A  
D112B  
D100I  
D133A  
CityA  
D100H (43.47 mi²)  
D100G  
D118E  
D140C  
D140B  
D142A  
D100F  
D118D  
D140A  
D112A |
| **Lower** (Yellow Shaded Basins in Figure 4.7) | D100Q (1.60 mi²) | D100Q  
D100R  
D103A (16.52 mi²)  
D100P  
D105A | D100Q  
D100R  
D103A  
D100P  
D105A |

Table 4.2: Subbasin groupings for QPF data analysis and comparison.
Chapter 5

Development and Evaluation of a Lumped-Parameter Hydrologic Model for Real-Time Application within a Flood Alert System

5.1 Introduction

As stated in Chapter 4, a hydrologic model transforms spatially averaged or spatially distributed precipitation amounts into a time series of river stages, river discharges, or runoff volumes; additionally, a hydrologic model used within the context of a real-time flood alert system must perform this transformation both quickly and accurately. A hydrologic model, and in particular the real-time operation of this model, is the "heart" of any flood alert system that seeks to make the most beneficial use of the latest available precipitation data, such as radar, and dissemination systems, such as the internet. Since radar-based precipitation data, QPFs based on this data, and dissemination of information via the internet are now all available in real-time, the time used in hydrologic calculation and prediction may be one of the most critical aspects of producing a timely flood warning. Of course, this speed should not come at the expense of accuracy. The hydrologic model used in this study is the U.S. Army Corps of Engineers Hydrologic Engineering Center's HEC-1 Flood Hydrograph Package, one of the most widely used and commonly available flood event modeling programs throughout the United States.

The overall objective of this chapter will be to present the development and evaluation of a lumped-parameter hydrologic model updated to utilize real-time
precipitation data and generate real-time prediction hydrographs for Brays Bayou that can be readily disseminated through the internet or other communication methods. Specific goals and challenges associated with this objective include:

- Develop and implement a real-time operational structure that supports HEC-1 models,
- Calibrate an existing HEC-1 model provided by the Harris County Flood Control District to a storm of significance – the August 15th, 2002 storm event,
- Validate and analyze the Real-Time HEC-1 (RTHEC-1) performance during actual storm events within the context of an operational flood alert system, replacing the older version’s nomograph based approach,
- Determine if the model is providing useful, timely and accurate information to end users.

5.2 Methodology

This discussion focuses on the RTHEC-1 model and the methodology used to develop it as well as analyze its performance. An overview of the HEC-1 Flood Hydrograph Package is presented for completeness. The following section provides a brief overview of the real-time structure developed for the Brays Bayou HEC-1 model and its importance to the flood alert system improvements. Finally, the calibration methodology and the methods used to incorporate the model within the new alert system structure are discussed.

5.2.1 HEC-1 Flood Hydrograph Package

The HEC-1 Flood Hydrograph Package was originally produced by the U.S. Army Corps of Engineers in 1967. The first model was published in October, 1968 and the first model available for the personal computer was published later in 1984. The most recent version was released in June of 1998. According to the U.S. Army Corp of Engineers, “The HEC-1 model is designed to simulate the surface runoff response of a
river basin to precipitation by representing the basin as an interconnected system of hydrologic and hydraulic components. Representation of a component requires a set of parameters which specify the particular characteristics of the component and mathematical relations which describe the physical processes. The result of the modeling process is the computation of streamflow hydrographs at desired locations in the river basin.” Thus for computer modeling purposes, HEC-1 divides the watershed into subwatersheds and reaches. Each subwatershed and reach uses averaged values (parameters) over the area or stream length for the mathematical coefficients for the hydrologic and hydraulic computations. For these reasons, and as discussed in detail in Chapter 2, HEC-1 is referred to as a “lumped-parameter” model.

HEC-1 is also a single event based simulator that emphasizes the modeling of the direct runoff hydrograph over a period of time limited to the precipitation event plus the amount of time required for the hydrograph to return to baseflow conditions. This is opposed to continuous streamflow simulation models such as the Hydrologic Simulation Program – FORTRAN (HSPF) developed in 1980, the Storm Water Management Model (SWMM) developed in 1988, and several others still used today, that maintain a continuous accounting of water storage in a watershed over extended periods of time.

A HEC-1 model for a simple or complex river basin has basic components for subbasin runoff, channel and reservoir routing, and hydrograph computation and combination. The subwatershed boundaries are delineated so that lumped precipitation loss and watershed parameters can be used. Historical or design rainfall is transformed to runoff via a variety of unit hydrograph methods. The reader is referred to Bedient and Huber, 2002 for a detailed discussion of the unit hydrograph methods used by this model,
while the specific method used in this work, the Clark Method, will be discussed in further detail later in this chapter. Discharge from each of the subwatersheds is computed at the outlet of each subarea and may be combined if required (Figure 5.1).

![Diagram of HEC-1 watershed processes]

**Figure 5.1 : Schematic representation of HEC-1 watershed processes.**

The routing component in HEC-1 requires input parameters to define the specific routing characteristics of a river reach or reservoir. Output consists of an outflow hydrograph at the downstream station. Hydrograph combining at key locations is essential for the overall system logic in HEC-1 and allows for an optimal use of computer storage in the model. HEC-1 is a general flood hydrograph package with the following capabilities:
1. Simulation of watershed runoff and stream flow from historical or design rainfall;
2. Use of unit hydrograph, loss rate, and streamflow routing parameters from measured data;
3. Computation of damage frequency curves and expected annual damages for various locations and multiple flood control plans;
4. Simulation of reservoir and channelization flood controls.

HEC-1 is one of the most widely used methods for watershed simulation and flood event analysis in the United States. Again, the reader is referred to Bedient and Huber, 2002 as well as the appropriate user manuals developed by the Hydrologic Engineering Center (HEC 1968; HEC 2000) for a complete discussion of the features of the HEC-1 modeling package.

**5.2.2 HEC-HMS: HEC’s Next Generation Hydrologic Modeling System**

The U.S. Army Corps of Engineers’ HEC-HMS is a Windows-based program with notable improvements over its predecessor, HEC-1. The first version of HEC-HMS (version 1.0) was released in March of 1998. The latest version (version 2.2.2) was released in May of 2003.

The Windows-based format allows for the program’s most notable improvement, a highly effective graphical user interface (GUI) illustrated in Figure 5.2. This interface permits easier input and manipulation of the various hydrologic elements discussed earlier. The characteristics of each of these elements can be readily modified via pull-
down menus. Results can also be more easily viewed at any point along a schematic of icons representing specific portions of the modeled watershed (see Figure 5.2). The

Figure 5.2: Graphical User Interface (GUI) for the newer HEC-HMS modeling program.
much improved graphics capabilities allow for the quick generation of easier-to-read hydrographs. Most importantly for existing HEC-1 models in use throughout the United States, an import feature permits the transfer of existing HEC-1 programs to the updated HEC-HMS format.

Another significant improvement of HMS is its method of organizing and storing data. The modeling data is organized into three separate sub-models: the basin model, the meteorological model, and the control model. Each sub-model is required for a specific overall model run. The basin model contains pertinent information regarding the hydrologic system connectivity and other physical data describing the basin. It is the sub-model within which the watershed schematic is constructed and manipulated. Loss rates, hydrograph transformation method (such as the Clark Method), and baseflow data are added or adjusted within the basin model (HEC 2000). The meteorological model contains the precipitation and evapotranspiration data necessary to simulate an historical or design rainfall event. The control model contains the time parameters for execution of the model runs, such as starting and ending dates and times as well as the computational time step for the specific run.

Despite these significant improvements in the interface of the computer modeling programs as compared to HEC-1, this updated Windows-based version has continuously been plagued by a variety of programming and stability problems that persist to this date. Additionally, real-time programming of the HEC-1 hydrograph package proved more feasible due to its open-source and straight-forward coding. The source code of the HEC-HMS program, while available, is complicated due to the GUI and interdependence of the various sub-programs listed above. Thus, an existing HEC-1 model provided by
the Harris County Flood Control District was used for this study to attempt to implement in real-time. Despite using HEC-1, none of the operational benefits of the HEC-HMS are lost as the models can be readily transferred between both formats. Therefore, a model may be calibrated and adjusted using historical data in the easier to use HEC-HMS format, then transferred back to HEC-1 for real-time application. The following section describes the real-time operational structure used to create RTHEC-1.

5.2.3 Real-Time Operational Structure for HEC-1 (RTHEC-1)

The RTHEC-1 system was developed as a modular subsystem to the FAS2 by Anthony Holder and Jude Benavides from the summer of 2002 to the early part of 2003. The overall responsibility of this subsystem is to operate HEC-1 in real-time, using a live radar data feed to generate real-time hydrographs for Brays Bayou at the Main Street crossing near the Texas Medical Center and Rice University. The system displays a 24-hour snapshot of observed and predicted streamflow data, displaying a 12-hour future look and a 12-hour past look. Figure 5.3 provides a sample of the RTHEC-1 output data display.

The system consists of four major subcomponents: a HEC-1 handler process written in Java, an HCOEM handler process written in Java, and two configuration files (one for each handler process). The following sections will briefly describe each of the subcomponents for the purpose of understanding system operation. The actual Java Beans lines of code are provided in Appendix E for completeness.
Figure 5.3: Sample output graphic for the RTHEC-1 hydrograph component of the FAS2 system. The figure displays an adjustable time-scale, with this illustration showing a 24-hour period of data (12 hours in yellow showing future / predicted data and 12-hours in white showing data in the past. The red horizontal line is the "now-line", the blue line represents predicted (calculated) flow data, the red line represents observed streamflow data by streamgage, and the gray bar graphics represent a general depiction of the average rainfall intensity over the Brays Bayou watershed.

5.2.3.1 HEC-1 Handler Process and Preference Files

The HEC-1 handler process is the heart of the RTHEC-1 system, responsible for a wide variety of application calls and actions. In short, the HEC-1 handler reads preformatted rainfall data, creates a HEC-1 input file, outputs that file to the HEC-1 program run on a Macintosh system (via VirtualPC), reads the output "punch" file created by the HEC-1 program that contains the output hydrograph, then generates the .PNG (Portable Network Graphics) file seen in Figure 5.3 and publishes to the website via the existing JavaFAS system used for the original flood alert system. This process is
completed each time new radar data is detected, which is approximately every 5-7
minutes based on the scan pattern of the radar during rainfall events.

The HEC-1 handler creates HEC-1 precipitation cards that function as simulated
"rain gages", representing each of the 46 subbasins in the watershed. The cards are
populated with rainfall data that has been formatted by Vieux and Associates, Inc. as
subwatershed averaged rainfall. These PC cards are then inserted into “placeholders” in
the HEC-1 input file prior to running. The PC cards consist of 60 hours worth of
previous DPA data, translating to 2.5 days of prior rainfall for each HEC-1 run. The 60-
hour limitation was decided upon based upon the high confidence of this period capturing
even long-duration storm events, while simultaneously reducing the computation time
required for each run.

Currently, the system is using Digital Precipitation Array (DPA) data discussed
earlier in this dissertation in Chapter 3. This limits the rainfall time-distribution
incrementing to 60 minutes. It was hoped that real-time LEVEL 2 rainfall data would
become available sooner than Spring of 2004 so that the system could be adjusted to
accommodate the 5-minute increment new data. Now that this data is available in real-
time, the system can readily be adjusted to accept the new data. The limitation imposed
on the hydrologic streamflow calculations caused by the 60-minute incremental DPA
data has proven significant and will be illustrated and discussed later in this chapter.

The HEC-1 handler runs the HEC-1 program when new data becomes available
and watchdogs the system for runtime completion. Upon completion, the HEC-1
program creates a “punch card” that consists of a DOS type representation of the
calculated hydrograph. The HEC-1 handler converts this old format file to a more readily
used .txt file named MainStHydrograph.txt. The output image file, hec1.png, is created from this text file and is posted to the website along with time stamping and archiving. The HEC-1 output data is shown in Figure 5.3 as the blue line that extends from previous data through the 12-hour prediction portion of the image. This blue line changes both in overall maximum peak and time-to-peak as additional rainfall is detected across the watershed. Only rainfall from subwatersheds upstream of the Main St. bridge is used in the calculation of the hydrograph.

The preference file for the HEC-1 handler process enables the user to change a variety of settings associated with data gathering, input, run-time, archiving, and display. One of the most important features included in this file is the ability to accommodate the additional subdivision or joining of subdivisions of Brays Bayou, either increasing or reducing the current number of 46 subwatersheds. This is an important capability given the current revision of the Brays Bayou HEC-1/HEC-HMS hydrologic model being conducted by the Tropical Storm Allison Recovery Project. The system can readily be changed to accept the new HEC-HMS model once it has been converted to the HEC-1 format. The capability to do this has been provided by DAVID FORD Consultants, Inc. The newly released TSARP model and its eventual incorporation to the FAS2 system will be discussed later in this chapter.

Other important preference settings include changing the 60 hour rainfall data set duration of the model, when to archive representative graphics and data for post-event analysis, and other more minor preferences such graphics size, color and website interfacing. The archive is currently set to begin capturing data once 0.5 inches have fallen over any one particular subwatershed in the basin. It is set to continue archiving
for 24 hours after the cessation of rainfall – providing ample time to capture the falling/recession limb of the hydrograph. The 60 hour rainfall dataset may need to be changed once Level 2 data is incorporated into the system, depending on the computational resources available to the programmer.

5.2.3.2. **HCOEM Handler Process and Preference Files**

The HCOEM handler process is primarily responsible for querying the Harris County Office of Emergency Management’s website (www.hcoem.org) and obtaining an observed stage height from Stream Gage 419 located at the Main St. crossing of Brays Bayou. This data is used for the purpose of measuring the performance and accuracy of the hydrologic prediction. This enables both real-time observation of the level of performance of the system as the storm progresses, as well as a detailed dataset for post-event analysis.

The HCOEM handler polls the stream gage for a stage height every 5 minutes. The obtained stage height is then converted to a flow rate by the handler via a rating curve at the Main St. bridge developed by the USGS. The data is stored temporarily for one week and if required, archived permanently (as in the case for large storm events).

The HCOEM handler uses this stored data and the most recently obtained stream data to create a real-time observed flow dataset that is converted to a format that is readily added to the hec1.png file discussed above. This data is shown in Figure 5.3 as a red line that is visible only through the past 12-hour portion of the image.

As is often the case with both rain gages and stream gages, Gage 419 often either fails outright or allows large portions of time to pass without issuing an update. The system is designed to continue issuing updated PNG image files even without input from
the stream gage. If the data lag was attributed to HCOEM website transfer issues, the page is updated with the newly delivered data when it becomes available - resulting in a continuous set of data without interruption; however, if the data lag is due to a mechanical or electrical failure (such as physical "sticking" of the float sensor in the stilling well of the gage), the data will likely not represent the real change in flow rate and possibly misrepresent the current stream flow. A system of filters that can be changed by the operator prevents spurious data from displaying on the website image. The preference file for the HCOEM handler includes is at this point limited to simple graphical changes to the output data and changes to the filter to eliminate spurious streamflow data posting.

5.2.4. Brays Bayou HEC-1 Model

The Brays Bayou HEC-1 Model used in this study was originally provided by the Harris County Flood Control District (HCFCD). The model was created in the 1990's and was last updated by a Letter of Map Revision (LOMR) in 2002. The model included all diversion and detention options in place at that time (see Appendix F).

The model subdivides Brays Bayou in 46 subwatersheds ranging in size from 0.50 mi² to 7.16 mi², with subwatershed divides provided by both elevation maps and man-made structures including major highways and other structures that would impede or redirect overland flow. The base model has successfully been used in the original Flood Alert System, providing input for the nomograph subsystem of the FAS. Table 5.1 lists the subwatersheds and their respective acreage. Figure 5.4 shows the location of each of these subwatersheds. Figure 5.5 shows a HEC-HMS schematic of the HEC-1 model dataset for illustrative purposes.
Figure 5.4: Brays Bayou subwatershed locations with main channel and tributaries.

Figure 5.5: HEC-HMS schematic of Brays Bayou showing subwatersheds, junctions, and reaches along with a stream and watershed background map.
<table>
<thead>
<tr>
<th>Subwatershed ID</th>
<th>Basin Size (mi²)</th>
<th>Subwatershed ID</th>
<th>Basin Size (mi²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D100B</td>
<td>1.48</td>
<td>CITYA</td>
<td>1.19</td>
</tr>
<tr>
<td>D129A</td>
<td>3.22</td>
<td>D100H</td>
<td>0.50</td>
</tr>
<tr>
<td>D100A</td>
<td>6.79</td>
<td>D100G</td>
<td>1.33</td>
</tr>
<tr>
<td>D122A</td>
<td>2.98</td>
<td>D118E</td>
<td>2.67</td>
</tr>
<tr>
<td>D126A</td>
<td>1.73</td>
<td>D140C</td>
<td>2.87</td>
</tr>
<tr>
<td>D100C</td>
<td>0.58</td>
<td>D140B</td>
<td>2.20</td>
</tr>
<tr>
<td>D129B</td>
<td>1.35</td>
<td>D142A</td>
<td>2.35</td>
</tr>
<tr>
<td>D100D</td>
<td>1.22</td>
<td>D100F</td>
<td>0.79</td>
</tr>
<tr>
<td>D100E</td>
<td>2.17</td>
<td>D118D</td>
<td>2.43</td>
</tr>
<tr>
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<td>2.43</td>
<td>D140A</td>
<td>3.63</td>
</tr>
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<td>2.19</td>
<td>D112A</td>
<td>1.01</td>
</tr>
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<td>D120A</td>
<td>1.49</td>
<td>D100Q</td>
<td>1.60</td>
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<td>2.13</td>
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<td>2.71</td>
<td>D105A</td>
<td>5.14</td>
</tr>
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<td>D100K</td>
<td>1.53</td>
<td>D100O</td>
<td>7.16</td>
</tr>
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<td>3.60</td>
<td>D109A</td>
<td>4.95</td>
</tr>
<tr>
<td>D100J</td>
<td>6.25</td>
<td>D100N</td>
<td>4.56</td>
</tr>
<tr>
<td>D139A</td>
<td>1.55</td>
<td>D100M</td>
<td>0.91</td>
</tr>
<tr>
<td>D112B</td>
<td>3.34</td>
<td>D111A</td>
<td>2.28</td>
</tr>
<tr>
<td>D100I</td>
<td>1.71</td>
<td>D100L</td>
<td>3.80</td>
</tr>
<tr>
<td>D133A</td>
<td>4.52</td>
<td>D113A</td>
<td>1.40</td>
</tr>
</tbody>
</table>

### 5.2.4.1. Model Parameters

As discussed in the Chapter 2, HEC-1 models are lumped-parameter models that use one single parameter value for every subdivision (subwatershed) defined in each specific model. As there are 46 subwatersheds defined for Brays Bayou, there exist 46 sets of parameters for the purpose of hydrologically characterizing each subwatershed. These subwatershed parameters include hydrograph transformation method and loss rate method. Additionally, routing of flood water from subwatershed to subwatershed is also parameterized by a specific method, assigning a set of values to each routing “reach”
defined in the model. The following sections briefly describe the methods of
subwatershed and reach parameterization and the specific parameters used for each
element.

5.2.4.2. **Subwatershed Hydrograph Transformation – The Clark
Method**

The hydrograph transformation method used in the Brays Bayou RTHEC-1 model
is called the Clark Method. Before discussing this method in detail, it is important to
discuss the basic theory behind the transformation of rainfall to runoff within a watershed
– the unit hydrograph.

The concept of the unit hydrograph was originally introduced by Sherma in a
paper published in 1932 (Dooge, 1973). By definition, a unit hydrograph is the direct
runoff hydrograph that results from one inch of rainfall excess generated over a
watershed at a uniform rate for a specified period of rainfall excess duration (Bedient and
Huber 2002; Chow et al. 1998). The essential assumption that underlies all of unit
hydrograph theory is that the relationship between rainfall excess and runoff is linear and
time-invariant (Dooge, 1973). Although this assumption is known to be incorrect, it
allows for a considerable reduction in computational effort and for most engineering
applications, the accuracy of the results obtained is sufficient. The reader is referred to
Bedient and Huber for a detailed discussion of how to determine the unit hydrograph for
a given subwatershed that has the requisite measurements in the form of both rainfall and
streamflow gages.

The unit hydrograph (UH), once determined, is assumed to be characteristic of the
watershed and not storm dependent. Therefore, an analysis of several different storms of
the same duration is generally performed in order to obtain an average UH. The UH for a specific watershed and for a given duration may be used to obtain the total storm Direct Runoff Hydrograph (DRO Hydrograph) for that watershed given any desired rainfall excess distribution discretized in time by an amount equal to D by the process of unit hydrograph convolution. Again the reader is referred to Bedient and Huber for further information on the determination of the DRO hydrograph as well as limitations of this approach.

Following the development of UH theory, researchers became interested in methods of applying the theory to ungaged basins since these tended to make up the bulk of watersheds. According to Dooge (1973), research in this area developed along two main lines. The first line of development assumed that each watershed had associated a unique unit hydrograph. Methods based on this reasoning are an extension of the time-area method. For example, Clark (1943) proposed that the runoff response of a watershed could be obtained by routing the time-area-concentration curve through a hypothetical linear reservoir located at the basin outlet to represent the storage characteristics of the watershed. The second line of development assumed that unit hydrographs for all watersheds could be represented by a single curve or family of curves. This type of approach led to the well known dimensionless UH proposed by the then Soil Conservation Service (SCS, 1972) that represents the UH by a gamma function.

Regardless of the approach taken, all synthetic UH methods assume that the runoff response of a watershed may be related to the physical characteristics of the basin, namely: size, shape, and slope. Typically, a relationship is given between the time-of-peak or the time-of-rise of the hydrograph and the length and slope of the main drainage
channel. An additional correlation is generally made between the peak flow and the basin area. These relationships are empirically derived.

Due to its wide acceptance and the availability of a large amount of historical data from a number of studies, the Clark UH method is the method recommended by the HCFCD for runoff analysis in the Houston area (HCFCD, 1994). In using the Clark method, three parameters are required to determine the UH: 1) the time of concentration, TC, which is equivalent to the time base of the time-area-concentration diagram and should correspond to the maximum time required for a rainfall drop to travel from the most remote portion of a watershed to the basin outlet, 2) a routing coefficient, R, that is used to relate basin outflow to storage, and 3) a time-area curve expressed as a proportion of TC. A number of researchers have developed empirical expressions for TC and R for application in the particular locale in which they were working.

In 1983, the HCFCD published a flood hazard study of Harris County, Texas (HCFCD, 1983). This study included the analysis of a number of watersheds in the Texas Gulf Coast region. One of the goals of these analyses was the development of expressions for the Clark unit graph parameters, which could then be applied to estimate the runoff response of ungaged watersheds in the region. Regression analyses were performed on unit graph coefficients determined through the HEC-1 optimization of computed hydrographs using 38 recorded storm hydrographs at 19 separate stream gage locations coupled with similar optimization data obtained from previous studies. The data were separated into that which represented undeveloped watersheds, fully developed watersheds, and finally, partially developed watersheds. The empirical relationships and
expressions obtained by this study are shown in Appendix G for completeness. The reader is referred to Fisher, 1993 for further details on the Clark UH method.

Table 5.2 shows the Tc and R values used for each of the 46 subwatersheds in the RTHEC-1 model. These values were obtained by the method discussed above and are available for a large number of areas around the United States – especially in floodprone areas with established flood control districts and subsequently, sufficient gauging.

| Brays Bayou Subwatershed TC and R Values (Table 5.2) |
|----------------|----------------|----------------|----------------|----------------|----------------|
| Subwatershed ID | TC (hrs) | R  | Subwatershed ID | TC (hrs) | R  |
| D100B           | 0.65     | 16.57 | CITYA           | 0.51     | 2.12 |
| D129A           | 1.02     | 3.51  | D100H           | 0.24     | 2.42 |
| D100A           | 1.64     | 8.14  | D100G           | 0.49     | 2.94 |
| D122A           | 1.04     | 4.21  | D118E           | 0.67     | 3.97 |
| D126A           | 0.75     | 3.14  | D140C           | 0.78     | 3.30 |
| D100C           | 0.44     | 2.54  | D140B           | 0.59     | 2.78 |
| D129B           | 0.49     | 2.13  | D142A           | 0.87     | 2.46 |
| D100D           | 0.69     | 6.24  | D100F           | 0.40     | 3.81 |
| D100E           | 0.53     | 3.06  | D118D           | 1.04     | 3.36 |
| D124A           | 0.54     | 2.07  | D140A           | 1.07     | 4.05 |
| D122B           | 0.37     | 2.15  | D112A           | 0.26     | 3.01 |
| D120A           | 0.61     | 3.15  | D100Q           | 0.61     | 1.99 |
| D120B           | 0.52     | 2.53  | D100R           | 0.82     | 3.11 |
| D118C           | 0.60     | 4.11  | D103A           | 1.05     | 6.52 |
| D118B           | 1.15     | 5.96  | D100P           | 1.14     | 3.20 |
| D118A           | 1.39     | 12.94 | D105A           | 0.77     | 6.72 |
| D100K           | 0.62     | 2.40  | D100O           | 0.64     | 2.27 |
| D115A           | 2.05     | 5.91  | D109A           | 0.74     | 6.64 |
| D100J           | 1.01     | 3.29  | D100N           | 1.71     | 3.42 |
| D139A           | 0.67     | 1.81  | D100M           | 0.26     | 1.77 |
| D112B           | 0.74     | 2.90  | D111A           | 0.81     | 5.67 |
| D100I           | 0.50     | 2.41  | D100L           | 1.18     | 3.64 |
| D133A           | 1.43     | 3.73  | D113A           | 0.76     | 5.00 |
5.2.4.3. Subwatershed Abstraction – The Initial and Constant Loss Method, Exponential Loss Method, or No Losses

The abstraction methods used in the Brays Bayou RTHEC-1 model included the initial and constant loss method, the exponential loss method, and no losses. Each of these methods was investigated as part of the primary calibration method of the RTHEC-1 model. The final model set-up that is currently a part of the FAS2 operational structure uses one model set up with no losses and another model that uses the initial and constant loss method.

The exponential loss method is only available in the HEC-1 version of the HEC hydrograph package and was not incorporated in the newer HEC-HMS version of the package. The method was used initially due to the fact that the original model provided by HCFCD used it; however, the method was abandoned due to difficulties in effective parameterization and its unnecessary complexity. Interestingly, the exponential loss method proved quite effective with early uses of the model. The reader is referred to HEC, 1968 for a further discussion of the exponential loss method.

The initial and constant loss method is available in both HEC-1 and HEC-HMS models and is widely used throughout many regions of the United States because of its combination of utility and effectiveness. The initial and constant loss method utilizes one initial loss amount for a specified time period, followed by a constant loss rate for the following time steps. The initial loss amount is always greater than the constant loss amount, representing the increased loss due to the filling of pore spaces and saturation of the soil. Typical loss rates for the mostly clay soils of the Harris County area are 0.5 inches of precipitation for the first hour of rainfall, followed by 0.05 inches of rainfall
every following hour. This method has proven very effective for modeling storm events
with little to no antecedent rainfall. The reader is referred to Bedient and Huber, 2002 for
more information on the initial and constant loss method.

The no loss option is used when there has been a significant amount of antecedent
rainfall over the Brays Bayou watershed. It is used in one of the hydrologic model runs
in real-time to provide an upper bound on the predicted hydrograph – assuming that all
rainfall over the bayou eventually flows past the Main St. bridge and Gage 419 (near the
TMC).

5.2.4.4. Flow Routing Methodology – The Modified Puls Method

The flow routing methodology used in the RTHEC-1 model is known as the
modified Puls method. Flow routing is a procedure to determine the timing and
magnitude of flow at a point on a particular portion of the stream (known as a reach)
from known or assumed hydrographs at one or more points upstream. This is necessary
to account for timing and attenuation changes in the flood wave as it travels through the
reach.

The modified Puls method is a hydrologic (vice hydraulic) and reservoir (vice
river) routing method. It is a storage indication method using the finite-difference form
of the continuity equation. The method combines this equation with a storage indication
curve. The basic equations are illustrated below in equations 4.1 through 4.3.

\[ I - Q = \frac{\Delta S}{\Delta t} \]  \hspace{1cm} (Equation 4.1)

\[ \frac{1}{2} (I_1 + I_2) - \frac{1}{2} (Q_1 + Q_2) = \frac{(S_2 - S_1)}{\Delta t} \]  \hspace{1cm} (Equation 4.2)
\[(I_n + I_{n+1}) + \left(\frac{2S_n}{\Delta t} - Q_n\right) = \left(\frac{2S_{n+1}}{\Delta t} + Q_{n+1}\right)\]  
(Equation 4.3)

Equation 4.1 above is the general storage form of the continuity equation, where:

I = inflow,
O = outflow,
\(\Delta S\) = change in storage in the reach or reservoir,
\(\Delta t\) = change in time.

Equation 4.1 can be written in finite-difference form as Equation 4.2, where \(\Delta t\) is referred to as the routing time period and subscripts 1 and 2 denote the beginning and end of the time period, respectively. In turn, Equation 4.2 can be re-written in the form shown in Equation 4.3, in which the only unknowns are \(S_{n+1}\) and \(Q_{n+1}\) on the right-hand side. The variable I is known for all n, and \(S_n\) and \(Q_n\) are known for the initial time step; therefore, the right-hand side of Equation 4.2 can be calculated. Values of \(S_{n+1}\) and \(Q_{n+1}\) are then used as input on the left-hand side and the calculation is repeated for the second time interval and so on.

A storage-indication curve, the components of which are \(2S/\Delta t + Q\) versus Q, is used to read follow on values of Q to solve the \(S,Q\) portion of the left side of Equation 4.3. This storage-indication relationship is determined either by a water-surface profile that is computed by a hydraulic model such as HEC-2 or HEC-RAS (River Analysis System), or historical observations of flow and stage when available. The reader is referred to Bedient and Huber as well as Fisher for a more detailed discussion of the modified Puls method.

The RTHEC-1 model modified puls data can be found in Appendix F for each reach in the Brays Bayou model. This data was obtained as part of the HEC-1 model
provided by HCOEM. The data represents the latest changes to channel configuration as of 2002. It should be noted that some minor changes have occurred since that time and major changes are planned in the future as part of the Brays Bayou Federal Flood Control Project in the form of channel improvements and widening. The most recent routing data is being transferred from the new TSARP HEC-HMS model to the real-time operational RTHEC-1 model currently operating in FAS2.

5.3 Results and Discussion

This section will present the results of the calibration and validation efforts for the RTHEC-1 model used as part of the FAS2 system; additionally, it will illustrate the observed improvements over the older nomograph approach used in the original FAS. The section will also highlight the performance of the real-time interface created for this study – one of the more important results of this work.

5.3.1. Replacing the Original FAS Flow Nomograph

As discussed briefly in Chapter 3, the original FAS relied upon a flow nomograph that was created from the results of over 2,000 hydrologic model runs using an earlier version of the Brays Bayou HEC-1 model. The flow nomograph is a simple, graphical representation of the peak flows that are computed from observed rainfall intensities during a storm event. The nomograph is based on the hydrologic modeling of hypothetical storms. All model runs were performed with constant, uniform rainfall intensities ranging from 0.1-4 in./hr and storm durations of 1-10 hours. Each individual
hydrologic model run calculates a specific peak flow value at Main Street, which was used to create the isoflow contours on the nomograph.

The isoflow lines represent points of equal peak flow in the Bayou corresponding to different combinations of rainfall intensity and duration. Figure 5.6 illustrates these contours as well as the NEXRAD estimates of peak intensity and duration for Tropical Storm Allison (shown in circles).

![Figure 5.6: The Brays Bayou FAS Flow Nomograph with peak results shown for Tropical Storm Allison in June, 2001.](image)

The flow nomograph was the primary method for predicting flow for over XXXXXX storm events from 1998-2002 and is still functioning as a back-up to the new RTHEC-1 system. Figure 5.7 illustrates the performance of the nomograph for 38 events between the years 2000 and 2002.
Figure 5.7: Performance of the Flow Nomograph for 38 storm events observed from 2000 - 2002.

Although the flow nomograph updates in real-time based on uniform rainfall over the watershed, it is important to emphasize that the results displayed are based on the previously run hypothetical storms mentioned earlier. The lack of a real-time hydrologic modeling system that is not reliant upon previously run models and can account for the distribution of rainfall in both time and space, resulted in system underprediction on a regular basis as observed in Figure 5.7. Equally important is the fact that the flow nomograph provided absolutely no indication of lead-time to the end-user. Both of these
deficiencies can theoretically be corrected by a real-time hydrologic model using spatially and temporally distributed rainfall as input.

**5.3.2. RTHEC-1 Model Calibration**

Initial model calibration was completed on the August 15\textsuperscript{th}, 2002 storm event discussed in Chapter 4 (Section 4.2.2.2.). As discussed, the storm provided an excellent opportunity for calibration as it was a "double-peaked" event consisting of two intense, but separate periods of rainfall. The resulting hydrograph illustrated the classic double peaking resulting from this rainfall pattern – an event type infamously difficult to match.

The initial model run was expected to perform adequately but with some underprediction, as the model, provided by HCFCD, had been previously calibrated by that organization to prior storm events and had been used in conjunction with the flow nomograph in the original FAS. The hydrograph did not match observed streamflow values within 20% of either flow peak. The model resulted in significant underprediction for both peaks (approximately 30% for the first, and 25% for the second). Additionally, a time lag on both peaks was observed of approximately 90 minutes for each peak. The rising limb of the hydrograph was also approximately 90 minutes late. After a brief sensitivity analysis involving the adjustment of TC and R values, routing parameter changes, and loss changes, it was observed that loss rate adjustments had the most significant effect on predicted values.

Loss rates were reduced from the model settings of a watershed wide 0.75 inches for the initial hour of rainfall and 0.075 inches for each hour thereafter to various amounts depending on the location of the watershed. Approximately the upper third of the subwatersheds loss rates were reduced somewhat to 0.6 inches initial and 0.06
inches/hour. The remainder of the subwatershed's loss rates were reduced to 0.5 inches initial and 0.05 inches/hour. Some minor adjustments were made to TC and R values in the middle portion of the bayou, in order to reduce storage effects and attempt to more closely match the timing of the observed streamflow data.

The end result of the calibration effort is illustrated in Figure 5.8. The matching of both peaks was successfully accomplished with respect to flow values. A time-lag still remained of approximately one hour. The time lag could not be corrected without compromising the small error in flow peak matches. Volume comparisons for the observed and predicted data were within 5%.

Figure 5.8: RTHEC-1 calibration run results during the August 15th, 2002 storm event.
5.3.3. RTHEC-1 Real-Time Model Run Results and Discussion

This section illustrates the performance of the RTHEC-1 model within the operational framework of the FAS2 system for three separate storm events in the fall of 2003. The figures shown consist of real-time “snapshots” of data feed provided to end users via the internet as discussed in Chapter 3. Each storm event has two corresponding figures, one illustrating the results as determined by the nomograph (uniform rainfall assumption) approach and the other illustrating the performance of the RTHEC-1 model. The figures are presented for comparison purposes and clearly exhibit the improved performance of the RTHEC-1 model over the nomograph approach. It is important to note that the timestamps with each figure and radar data input to each approach are the same, ensuring equitable comparisons between the two approaches. It is also extremely important to recall that the system is currently using unadjusted radar rainfall approximations; therefore, accurately predicting peak flows within +/- 15% should be deemed as acceptable (Vieux and Bedient 1998). As an additional result of using uncalibrated radar data, it should be emphasized that the only two of the three comparison metrics for observed and measured hydrographs will be studied. Time-to-peak and peak flow accuracy far outweigh the third measurement parameter of total volume in terms of relevance to FAS effectiveness.

5.3.3.1. September 12th, 2003 Event Results and Discussion

This event was the only storm event not to be analyzed with both the RTHEC-1 model and the QPF algorithm. The reason for this was the rainfall timing and distribution that caused the observed 10445 cfs flow in Brays Bayou at Main St. Only approximately 1.5 inches of rainfall fell over the basin on a watershed average basis. The rainfall was
highly localized to the middle portion of the bayou and had nearly 75% of that amount fall within 60 minutes. This localized, heavy burst of rainfall near the TMC resulted in a very rapidly rising (steep sloped) hydrograph. The nomograph approach has historically underpredicted these types of rainfall patterns and it underpredicted the observed flow by nearly 50% (see Figure 5.9). The maximum predicted flow according to the nomograph

![Nomograph diagram]

**Figure 5.9**: Flow Nomograph peak flow results for the September 12th, 2003 storm event.

was just over 5000 cfs, with the system officially recording 5000 cfs and a close analysis of the nomograph at local time 0907 shows a maximum flow of approximately 6000 cfs. As a reminder, the nomograph approach does not provide any indication of the timing of when this predicted peak flow will occur so an analysis of timing error is not possible.

In contrast, the RTHEC-1 system predicted a much more accurate peak flow of 11958 cfs, resulting in an overprediction of approximately 14.5%; however, the time lag
was significant at just over two hours late (see Figure 5.10). The late prediction is obviously of significant concern with respect to the issuance of flood warnings; nevertheless the peak flow prediction was made 90 minutes prior to the peak event actually occurring. It is important to address timing issues with respect to peak flow predictions in context of both hydrologic prediction error and lead-time maximization and accuracy. This chapter will focus on the discussion of the former, while Chapter 6 will focus on the later by considering the FAS2 system operation as a whole.

The overprediction of 14.5% was deemed as acceptable in this situation, primarily due to the fact that some antecedent rainfall had resulted in a minor increase in flowrate through the system on Sept 11th, 2003. The falling limb of the predicted hydrograph resulting from this minor event had not yet completed. This can be observed in Figure 5.10 at the “minus 7” hour period of the hydrograph as shown. A difference of

![Graph showing flow rates and observed hydrograph results](image)

**Figure 5.10**: RTHEC-1 predicted and observed hydrograph results for the September 12th, 2003 storm event.
approximately 1,250 cfs is observed and when taken into consideration for a peak analysis, the hydrologic error with respect to peak flow was reduced to an overprediction of only 2.4%. Due to this result, it was decided that no significant calibration adjustments should be made to the hydrologic model with respect to storage, loss rates and/or routing; however, the event raised the concern of the effectiveness of system performance as a whole during multi-storm event periods.

5.3.3.2. October 9th, 2003 Event Results and Discussion

This event was of much greater significance than the previous event with respect to the both the amount of rainfall and the flow rate generated at Main St., with approximately 3.25 inches of watershed average rainfall resulting in an observed peak flow rate of 16,000 cfs. The spatial distribution of the rainfall was much more widespread over the watershed as compared to the September event and, just as importantly, the timing was very unique. The storm consisted of three small bursts of rainfall approximately one hour apart and consisting of approximately 60 minutes each. This was followed by the major rainfall period, which last approximately 2.5 hours and comprised nearly 75% of the total rainfall associated with this event. The reader is referred to Figure 4.5b in this study for a detailed illustration of the timing and spatial distribution of rainfall for this event.

The nomograph again severely underpredicted the peak flow associated with this event, predicting a peak flow of just over 5,000 cfs (see Figure 5.11). In this case, this resulted in an underprediction error of nearly 69%. This extreme underprediction could not be directly attributed to a single cause as the rainfall distribution was evenly
distributed across the watershed and the timing should not have presented such difficulties.

The RTHEC-1 model encountered some difficulty with the antecedent, periodic rainfall bursts, resulting in some moderate error in the shape and timing of the rising limb of the hydrograph; nevertheless, the peak flow rate was only underestimated by 15.6% (see Figure 5.12). Again, a time lag was exhibited between the observed and predicted peak flow estimates – in this case, approximately 85 minutes. With this second result, two separate factors were identified as contributing to the time delay of the forecast peak flow:

1) First, the use of the Digital Precipitation Array (DPA) product, which outputs the average of the last sixty minutes of rainfall experienced over a 16 km² area, would naturally result in a delay of anywhere from a few minutes to the maximum of 60 minutes, depending on the duration of the rainfall event. This timing error will be eliminated, or at least significantly reduced, by the use of Level II radar data in real-time that provides the last 5-minutes of rainfall over 1 km² areas every 5 minutes. The Level II data is now available at the KHGX radar station and will soon be incorporated as a feed to the RTHEC-1 system. In the interim, a temporary adjustment was made to the system by adjusting the timing ordinate of the predicted hydrograph – in essence, “moving up” the hydrograph 30 minutes prior to plotting.

2) Second, by analyzing both Figures 5.10 and 5.12, it can be seen that the response time of the rising limb of the hydrograph was too slow. This was
Figure 5.11: Flow Nomograph peak flow results for the October 9th, 2003 storm event.

Figure 5.12: RTHEC-1 predicted and observed hydrograph results for the October 9th, 2003 storm event.

deemed to be caused by routing errors in the middle portions of the
watershed. Therefore, an adjustment was made to the routing parameters in the middle reaches of the model by changing the storage-outflow relationship – allowing for a faster translation of the flood wave.

As a result of the underprediction, minor changes were again made to the initial and constant loss rates. Losses in the upstream portions of the watershed were reduced to 0.55 inches in the first hour and 0.05 inches thereafter.

5.3.3.3. November 17th, 2003 Event Results and Discussion

This event was by far the most significant of all those studied in terms of both rainfall and resulting peak flow past Main St. The event is described in detail in Section 4.2.2.2., additionally, rainfall distribution and incremental / cumulative accumulations are graphically displayed in Figure 4.5c and radar snapshots of the event are illustrated in Figures 4.5a and 4.5b. A watershed average of nearly 5 inches of rainfall fell in two major bursts, resulting in an observed peak flow of 25,500 cfs. This proved to a major storm event that resulted in a classic “case study” example of system operation as a whole. The integrated system operation of FAS2 for this particular storm event will be discussed in Chapter 6.

The nomograph results represented a significant improvement as compared to the prior two storm events, with a predicted maximum flow of 21,000 cfs resulting in an underprediction of 17.6%. As can be seen in Figure 5.13, this was the only of the studied events to enter an alert warning zone – in this case, yellow between 20,000 and 24,000
Figure 5.13: Flow Nomograph peak flow results for the November 17\textsuperscript{th}, 2003 storm event.

Figure 5.14: RTHEC-1 predicted and observed hydrograph results for the November 17\textsuperscript{th}, 2003 storm event.
cfs. These alert warnings have been revised as a result of this case study and communication with the TMC and will be discussed in further detail in Chapter 6.

Figure 5.14 illustrates that the previous adjustments made to the RTHEC-1 model resulted in a markedly improved predicted hydrograph, with a predicted maximum flow rate of 25,000 cfs resulting in a minor underprediction of 2.0%. Additionally, the rising limb of the hydrograph was in very close agreement with the observed hydrograph, matching the slope of the rising limb nearly perfectly. A minor time lag of approximately 30 minutes remains throughout the rising limb and to the peak flow prediction.

The unique shape of the upper portion of the predicted hydrograph needs to be addressed in this discussion. The flattened out portion represents an approximation of the near out-of-bank storage-discharge relationships near the middle portion of the bayou. An approximation was necessary as detailed out-of-bank information was not provided with the original model. Additionally, prior studies during major storm events such as TS Allison and TS Frances illustrated the need to provide additional storage in the upper banks of the main channel. Figure 5.14 illustrates that additional work needs to be performed in this area in order to maximize the performance of the model during extremely high-flow events. Nevertheless, the same logic used in arguing that volumetric comparisons are not as significant for flood alert purposes holds true here as well. Once sufficient rainfall has occurred over the basin for predicted flows to exceed 24,000 cfs, the job of the alert system is essentially complete. This circumstance is another factor in the re-determination of the alert level criteria for FAS2 and will be discussed further in Chapter 6.
5.3.3.4. **Summary of Event Study Results**

The above results have been summarized for the RTHEC-1 model in Table 5.3. The calibration run, as well as subsequent validation runs, have been listed with time-to-peak and peak flow errors listed in absolute terms. It should be noted that the errors shown for the calibration run are post calibration as discussed earlier.

**Table 5.3 : Summary of results for the RTHEC-1 model for Brays Bayou, including calibration and validation runs.**

<table>
<thead>
<tr>
<th>Storm Event</th>
<th>Rainfall Amount (in) / Peak Observed Flow (cfs) At Main Street</th>
<th>Time to Peak (min)</th>
<th>Peak Flow (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/15/2002 Calibration</td>
<td>4.76 in 17,900 cfs</td>
<td>50 minutes late</td>
<td>+200 cfs*</td>
</tr>
<tr>
<td>09/12/2003 Validation</td>
<td>1.56 in 10,445 cfs</td>
<td>120 minutes late</td>
<td>+1,510 cfs</td>
</tr>
<tr>
<td>10/9/2003 Validation</td>
<td>3.23 in 16,000 cfs</td>
<td>85 minutes late</td>
<td>-2,500 cfs</td>
</tr>
<tr>
<td>11/17/2003 Validation</td>
<td>4.96 in 25,500 cfs</td>
<td>30 minutes late</td>
<td>-500 cfs</td>
</tr>
</tbody>
</table>

* Post calibration. Initial model runs resulted in 90 minute lag and -5,400 cfs (first peak).

5.3.4. **Continuous Collection of Data for Future Analysis and Calibration/Validation**

Besides the direct results of fully predicted hydrographs, the RTHEC-1 model provides a system that generates a continuous dataset of rainfall to runoff relationships that are archived for every storm event beyond a user-determined setting. The importance of this data in providing the potential for continuous calibration / validation
of a hydrologic model for a watershed cannot be overstated. Once operated for a similar period of time as the older nomograph approach, a graph similar to that in Figure 5.7 will be generated for the RTHEC-1 model. Given the greater detail of rainfall data distribution and a fully illustrated hydrograph, the potential for further research in the lumped-parameter model approach is significant.
Chapter 6

Operational Issues for the Flood Alert System and the Texas Medical Center: Improving Overall System Effectiveness

6.1 Introduction

The effective operation of a flood alert system depends on numerous variables, but these may be grouped into three major areas: rapid and accurate data collection, data processing, and information dissemination. The former two of these have been addressed to some extent in previous chapters. The latter will be introduced in this chapter with specific attention paid to improving dissemination through more carefully defined alert action levels. A specific example of the overall performance and usage of the system will be presented by illustrating real-time snapshots of system output and TMC actions during the previously discussed November 17th, 2003 storm event.

A complete discussion regarding the flood threat to the Texas Medical Center and operation of the FAS is not possible without discussing the Harris Gully outlet and its confluence with Brays Bayou. This chapter commences with a brief discussion of how flooding conditions may occur in the TMC and how the improved FAS2 has been and will continue to be modified to provide warning for these conditions. It continues with a presentation of the analysis of historical rainfall and the corresponding level in the Harris Gully outlet, which is critical to flood conditions at the TMC. This leads to a discussion of the revamping of the alert action levels to incorporate the results of this historical data with real-time data provided by the FAS2 system with the aim of providing additional
lead-time for the TMC. Implicit in this discussion is a brief overview of the current TMC flood damage mitigation policies and actions during an actual storm event and how these may be improved based on the above mentioned results.

The chapter continues with a discussion of the November 17th, 2003 FAS2 output. The system was nearly fully operational by the time of this event, which served as a classic example of how equally important it is to predict if flooding will not occur in addition to if and when it will occur. Snapshots of the various data products available to end-users will be shown at critical times from the commencement of rainfall over the watershed through the end of rainfall and the observation of lowering flow levels in the bayou. Alert action level triggers and notifications of the TMC of the flood threat were documented and are presented herein. One critical element of this section that was not run in real-time was the coupling of the RTHEC-1 system (discussed in Chapter 5) with the QPF data (discussed in Chapter 4). This direct link was not completed as the spatial accuracy of the QPF was proven not to be sufficient at the subwatershed scale required to warrant this work; however, an attempt to indirectly link the two via revised alert levels and an alert level nomograph will be shown near the end of the chapter.
All of the elements discussed above are illustrated in Figure 6.1 (repeated from Chapter 2 for emphasis). This flood forecast element timeline should be referenced throughout this chapter to illustrate changes to the operational effectiveness and improvement of lead-time in the overall system. Changes to the timeline and improvements in specific sections shown on the timeline should be noted as the discussion progresses.

6.2 Harris Gully and Flood Alert Actions for the TMC

The Harris Gully subwatershed of Brays Bayou contains both Rice University and the entire Texas Medical Center, with both of these important institutions located near the confluence of the outlet of this subwatershed with the Brays Bayou channel. As such, the subwatershed plays a vital role in determining the flood threat condition to the area for which both the original FAS and the new FAS2 were designed to provide flood notifications. Figures 6.2 through 6.5 illustrate the unique challenge the location of these...
institutions within Harris Gully provides with respect to flood warning. Figure 6.2 shows a digital elevation model of the gully, emphasizing that the area of interest is at the lowest elevation areas of the subwatershed and that all overland flow from the gully must pass through the TMC prior to reaching Brays Bayou. Figure 6.3 shows the current underground storm sewer network, again illustrating that this critical region is important with respect to storm sewer flow – with nearly the entire system relying on the Harris Gully box culvert outlet to reach Brays Bayou. Figure 6.4 shows a photograph of the Harris Gully / Brays Bayou confluence with the TMC in the immediate foreground and Rice University just behind it. Shown extending past Rice University is a large region of the nearly 5 mi² subwatershed. Figure 6.5 shows a close up of the Harris Gully twin 15 by 15 foot box culverts as shown by the FAS2 system Bayou Cam. Shown in this picture is the staff gage marked with white numbers that shows water level in feet above the invert elevation of the culvert. Additionally, the sensor line for the HCOEM Stream Gage 403 can be seen just inside the right box culver, from which a significant amount of historical data has been collected and analyzed. The results of this analysis are an important part of the new alert action levels created for the system and are discussed later in this chapter.
Figure 6.2: Digital Elevation Model for Harris Gully, a subwatershed within Brays Bayou. Note the downstream locations of both Rice University and the Texas Medical Center near the confluence of Harris Gully and the bayou.
Figure 6.3: The City of Houston storm sewer network for Harris Gully as shown in their GIS management system. Note how a significant portion of the subwatershed storm sewer network drains toward the Harris Gully box culvert to the southeast of the TMC.
Figure 6.4: Aerial view of the Harris Gully/Brays Bayou Confluence, along with the TMC (foreground) and Rice University.

Figure 6.5: BayouCam close-up of the Harris Gully box culvert outlets.
After studying Figures 6.2 through 6.5, it should be clear what hydrologic mechanisms play a role determining the flood threat to Rice University and the TMC. They consist of either one or a combination of the following three possibilities:

1. Massive flooding of the Rice/TMC area due to flooding caused by out-of-bank flow conditions in Brays Bayou;

2. Flooding within Harris Gully due primarily to excessive rainfall and ensuing runoff principally over the subwatershed, overwhelming the storm sewers and streets capability to carry direct runoff;

3. Flooding within Harris Gully due to the reduced capacity of the storm sewer system caused by the backwater effect of elevated stream levels in Brays Bayou, thus surcharging the box culverts and reducing its carrying capacity to nearly 20% of the flow carried during normal runoff conditions (Holder et al. 2002).

Of the above three mechanisms, only the first was directly addressed by the original FAS. The nomograph, and the associated flood action levels triggered by nomograph predicted flows, was designed for predicting out-of-bank flooding only. While the newer FAS2, and its associated real-time hydrologic models are still only directly predicting out-of-bank flow conditions in the Bayou, the system as a whole makes it possible to begin to address both of the latter mechanisms.
6.2.1 Original Flood Alert Action Levels (FAS)

As was alluded to in Chapter 5, the original FAS relied upon a system of flood alert action levels based on predetermined flow values to communicate a change in flood threat to end-users via a change in a color-coded set of alert lights. The alert status is based on nomograph-predicted flows as discussed in Chapter 3. A flood caution (yellow) was issued for predicted flows between 20,000 ft³/s and 24,000 ft³/s. A heightened alert status (orange) was issued for predicted flows between 24,000 ft³/s and 28,000 ft³/s, when out-of-bank flooding was considered possible given the prospect of additional rainfall over the watershed. A final alert status (red) was issued for predicted flows greater than 28,000 ft³/s, signifying that severe flooding at the TMC was probable given the combination of currently existing flow in the bayou and already experienced rainfall amounts as measured by radar. These levels were color-coded into the nomographs displayed as part of the FAS as illustrated in the nomograph images in Chapter 5.

After extensive analysis of the performance of the FAS and also communication with TMC personnel, it was determined that the existing flood action alert levels must be reconfigured on three counts. First, the alert levels were too liberal and provided insufficient warning for many actions required to be taken by TMC personnel and security managers (Personal Communication, Hank Rietz 2004). Second, the alert levels only addressed out-of-bank bayou flooding and it had been observed that significant street flooding and minor building flooding had occurred due to conditions 2 and 3 listed above. And third, there needed to exist some reliable method of incorporating the new QPF data into the FAS operation on a quantitative basis, readily discernable by TMC personnel.
As a result, the TMC decided to augment these alert action levels with additional action levels linked directly to the level in the Harris Gully box culvert and other directly measured metrics. Actions taken by security personnel, member hospitals and “tunnel dwellers” were linked to these conditions – with these member institutions agreeing to take specific flood protection actions when notified that the Harris Gully box culvert level had reached 7 ft and 10 ft. The 7 ft benchmark is the trigger point for the Priority One actions that include securing the periphery of the TMC – namely parking garage entrances, outer ring flood logs and water tight doors. The 10 ft benchmark is the trigger point for the Priority Two and Three actions that include all parking garage exits and all other active flood control measures including all water tight doors, flood logs and final preparation of dewatering equipment including garage pumps.

The Harris Gully alert action levels of 7 feet and 10 feet “at the box” were preliminary estimates based on a limited historical study of rising water levels in the box during past storm events. These initial estimates were put into policy as a matter of necessity, but have always warranted further study. With the database provided by the HCOEM stream and rain gages, as well as the advent of finer resolution radar data and QPF data, a more robust system of alert levels combining Brays Bayou flow levels and Harris Gully alert levels has been developed. The following section discusses the methodology used in determining these new box culvert action levels.

6.2.2 Methodology for Improving Flood Action Alert Levels at the Harris Gully Box Culverts

Historical rain gage and streamflow data from the Harris County Office of Emergency Management’s (HCOEM) Automated Local Evaluation in Real-Time
(ALERT) system were collected for the period of record from 1993-2002 and analyzed to identify significant storm event periods. Six rain gages and one stream gage were chosen out of the available data for analysis. The rain gages were chosen based on their location in the watershed and their completeness of coverage for the identified storms. The stream gage, Gage 403, is the stream gage corresponding to water levels at the Harris Gully outlet. Gage locations are illustrated in Figure 6.6. The individual periods of record for the rain gages vary based on the time they were installed, but were preferentially used over radar data as most provided data before 1994 – the first available period of data for NEXRAD.

![Map of selected rain and stream gage locations](image)

**Figure 6.6: Selected rain and stream gage locations for analysis.**

The primary purpose of an ALERT system is to provide real-time data for analysis; therefore, historical data obtained from these systems needed to be extensively processed and quality checked prior to its use in hydrologic analysis. Rain gages occasionally stop recording or record incorrect readings that must be identified and corrected. The same applies to stream gage data. Several MATLAB scripts were created for the purpose of processing the data before analysis. The scripts are included in Appendix H for completeness and review.
Rain gage data have been analyzed and corrected for “spikes”. A spike is a
variably defined threshold set to disregard excessive jumps in the cumulative rain gage
data. Negative jumps in the data are automatically disregarded, while the threshold for a
positive jump is normally set to the equivalent of 10 inches per hour. Figure 6.7 shows
sample rain gage data for gage 460 before (black) and after (red) the initial processing of
the data for the year 1991. Note the data “gap” that still exists just after julian date 100.
Data gaps such as these can only be compensated for when compared to other nearby rain
gages or radar data if available (only after 1994). Data gaps in the rain gage data were
compensated for by averaging locally available rain gages that were accurately recording
data.

Stream gage data correction has proven to be more complicated as the data often
exhibit datum jumps when the data is viewed collectively over a long-time period.
Figure 6.8 illustrates this occurrence showing Gage 403 stream level data over its period
of record. Compensation for these datum jumps was accomplished by locally adjusting
levels to the new datum once the datum shift was verified. Unfortunately, there are far
fewer stream gages than rain gages, and analysis options are more limited when they
mechanically fail. The data gap observed from 1995 to 1996 can only be filled in by
analyzing an upstream or downstream gage. Attempts to fill in these types of data gaps
were not successful due to the quick response time of the bayou and the inability to
account for the true propagation of the flood wave between stream gages; however, this
did not adversely affect the resulting data to a great extent.
Figure 6.7: Sample rain gage data before (black) and after (red) processing

Figure 6.8: Gage 403 stream level data for 1993-2001
6.2.3 Results of Improving Flood Action Alert Levels for Harris Gully

A preliminary frequency study was conducted on the stream gage data for the purpose of identifying the number of times specific threshold levels were exceeded. The selected thresholds and the number of times they were exceeded are shown in Table 6.1. Recall that 7 feet is the current alert level established by the TMC to initiate the first round of emergency action procedures. This corresponds to the outlet being just short of half full. Additional levels were chosen based on the following: 9 ft, 10 ft, and later 12 ft were chosen to determine if the alert level could be safely raised. 15 ft represents box full conditions where the culvert becomes surcharged and its flow capacity becomes drastically reduced (Holder et al. 2002). 17 ft and higher levels historically have represented massive street flooding in the TMC.

An analysis of each of the identified storm events in Table 6.1 has been completed and was used as the basis for further statistical study. Rainfall data were plotted from all six HCOEM ALERT gages that contained data from 1993-2001. In addition, the stage (ft) at Harris Gully was plotted versus time. Within each plot, several levels and time periods of interest were identified. Figures 6.9 through 6.12 illustrate sample data plots for three storm events of interest during the study period. The blue dot and corresponding line indicate when the box first reached the 7 ft level. The red dot and line identified the peak stage and time for that event. The green dot and line indicate when the level in the box returned to 7 ft. Having documented these critical levels and times, along with their corresponding rainfall timing and distribution over the watershed, it was possible to begin statistical analysis of the data.
Table 6.1: Harris Gully Culvert Outlet Level Frequency Data (1993-2002)

<table>
<thead>
<tr>
<th>Date</th>
<th>Peak Level *</th>
<th>Level at Outlet</th>
<th>&gt;7</th>
<th>&gt;9</th>
<th>&gt;10</th>
<th>&gt;15</th>
<th>&gt;17</th>
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<td>x</td>
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<td></td>
<td></td>
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</table>

Number of Times Level was Exceeded: 20 11 8 4 1

Statistical information is provided in the lower right hand side of Figures 6.9 through 6.12 for that particular event. The data listed include: date of event, peak stage, time to peak (defined in this case as the time from 7 ft in the culvert to the peak stage), time above 7 ft, and a variety of rainfall statistics.

This type of analysis has been completed for all identified storm events and the resulting data plots for these events are included in Appendix 1. Table 6.2 shows a summary of results for the data analyzed. Two storms were omitted due to incorrect or questionable stage data as discussed earlier.
Table 6.2: Harris Gully Culvert Outlet Level Statistical Data (1993-2002)

<table>
<thead>
<tr>
<th>Date</th>
<th>Peak Stage</th>
<th>Total RF Prior to 7 ft</th>
<th>Total RF</th>
<th>Total RF divided by RF prior to 7 ft</th>
<th>RF 1 hr after 7 ft</th>
<th>RF 2 hrs after 7 ft</th>
<th>Hourly Intensity after 7 ft (2hrs)</th>
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<td>6/9/2001</td>
<td>19.2</td>
<td>1.75</td>
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<td>16.8</td>
<td>2.58</td>
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<td>1.80</td>
<td>0.47</td>
<td>0.69</td>
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</tr>
<tr>
<td>10/17/1994</td>
<td>16.6</td>
<td>1.38</td>
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<td>0.64</td>
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</tr>
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<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
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</table>

** Events for 9/17/96 and 11/13/98 are not included due to missing data

This data analysis was conducted with the aim of updating the existing flood action alert levels and possibly developing a real-time metric that would aid TMC observers with predicting if these levels would be exceeded as soon as possible. It can be seen in Table 6.2 that a clear distinction exists between the storms with peaks of 9.0 ft or less as compared to the more intense storms. The ratio of the total rainfall for the storm to the rainfall observed prior to 7 ft is near one for storms that did not peak higher than 9 ft. While this result may be intuitive, and does not serve as a useful real-time metric because the total storm rainfall would not be known a priori, it represented an excellent starting place for further analysis.
It is known from a preliminary timing study done on Harris Gully levels for these same storms (results and data not shown), that the average time for the gully to increase from 7 ft to 15 ft is approximately 1 to 2 hours; however, this is highly dependent on the spatial and temporal distribution of rainfall. Further work was conducted to investigate the use of the observed rainfall intensities over the next 1 to 2 hours after the gully reaches 7ft as part of a real-time metric. The average rainfall over the first hour after 7ft in the gully for storms peaking higher than 9 ft is 0.32 inches as compared to the average of 0.05 inches for storms peaking at 9ft or less. The same trend holds for rainfall over the next two hours, as the averages are 0.53 and 0.08 respectively.

Results of this analysis show that the initial alert level for Harris Gully can be safely raised from 7 feet to 9 feet given a number of caveats. First, the average rainfall over the middle and upper portions of Brays Bayou must not exceed 3 inches in the three hour period prior to the box reaching 7 ft. If this condition is violated, then it is likely that the culvert level will exceed 9 ft solely as a result of runoff from the watershed and any additional rainfall over either the Harris Gully subwatershed or upstream Brays Bayou subwatersheds. The QPF feature of FAS2 should be used to assist the end-user in determining the potential for and amount of future rainfall. This will be clarified in the November 17th, 2003 case study discussion.

Although raised to 9ft, the 7 ft benchmark remains important. If reached, careful monitoring of future rainfall intensity is required via the use of radar rainfall totals and the QPF component of FAS2. No alert actions (Priority One, Two, or Three) need be taken if the box culvert reaches 7 ft and both of the following conditions are met:
1. QPF data shows that the next hour of average rainfall over the upper and middle portions of Brays Bayou will be less than 0.25 inches.

2. RTHEC-1 hydrograph does not show a predicted flow exceeding 15,000 cfs over the next 4 hours resulting from previous rainfall.

If either of the two conditions are violated then it is likely that 9ft will be exceeded based on the historical study; therefore, all Priority One actions should be ordered at the earlier time.

Should the box culvert levels continue to rise and actually exceed the 9 ft level then the Priority Two and Three actions should be taken if any of the following conditions are met:

1. RTHEC-1 hydrograph shows that flow levels in the Bayou will continue to increase (ie still on the rising limb of the hydrograph);

2. Any additional rainfall is being observed by FAS2 radar imaging over the Harris Gully watershed.

3. Any additional rainfall is predicted over the next hour by QPF over any contributing portion of Brays Bayou.

It is expected that the increase in the initial flood action level from 7 ft to 9 ft under the above specified circumstances should significantly reduce the number of false alarms initiated by the TMC to its member institutions. Although the period of record for this analysis is admittedly brief at 8 years of data, had the increase been implemented over that time, the initial alert level would have been triggered only 55% of the time without a decrease in the level of flood protection provided to the TMC.
Data for this analysis continues to be collected such as over the more recent storm events during 2002 to the present. This will be necessary to analyze the potential need for further changes to these alert levels as the period of record increases.

06/05/01

Figure 6.9: Harris Gully alert level analysis data. Stream and rain gage data for first wave of Tropical Storm Allison – 06/06/2001.
Figure 6.10: Harris Gully alert level analysis data. Stream and rain gage data for the February 12th, 1997 event.
Figure 6.11: Harris Gully alert level analysis data. Stream and rain gage data for the April 4th, 1997 event.
Figure 6.12: Harris Gully alert level analysis data. Stream and rain gage data for the September 11th, 1998 event.
The above data analysis permitted the revamping of the alert action levels for the TMC based on Harris Gully box culvert levels. The following section will discuss, by way of the November 17th, 2003 storm event case study, the changes made to the Brays Bayou "out-of-bank" flood alert action levels recommended for the FAS2 system.

6.3 FAS2 Performance during the November 17th, 2003 Storm Event and Flood Alert Actions for the TMC

This section presents a discussion of the November 17th, 2003 FAS2 output. This event, during which the system was nearly fully operational, provided an excellent opportunity for analysis of system performance from an operational perspective. System data was archived and snapshots of this data are shown in this section. The event also provided the opportunity to critically analyze the previous Brays Bayou flood action alert levels – the color-coded levels used in conjunction with the FAS nomograph. The improved detail provided by the RTHEC-1 output and the real-time QPF data have warranted a revamping of these alert levels just as in the case of the Harris Gully box culvert alert levels. The event also provided an opportunity to critique system effectiveness and each of the component's performance individually as well as collectively.

The section begins with an overview discussion of the system snapshots – highlighting critical time periods during which notification decisions were made and actions were taken by the TMC. The ensuing subsection presents a discussion of the lead-time issues currently present with the RTHEC-1 system as it is operating now and what improvements may be made to refine lead-time predictions. The impact of system
operation on improving the lead-time and accuracy as compared to the original FAS is
then discussed – emphasized by how the system changes Figure 6.1. Lastly, the updated
alert action levels for Brays Bayou are presented.

6.3.1 FAS2 Real-Time Results during the November 17th, 2003 Storm Event

Figures 6.13 through 6.27 illustrate a series of snapshots taken from the actual
output of the FAS2 during this storm event. The figures are not actual screen shots as
shown on the webpage, but rather a collection of the various component outputs so that
their collective operation can be more readily observed and analyzed. As a reminder, the
November 17th, 2003 storm event was also used in the QPF analysis (Chapter 4) of this
dissertation and a brief summary of the meteorological and hydrologic characteristics of
this event are presented therein.

Starting at the top-left corner of each figure and continuing counter-clockwise,
Figures 6.13 through 6.27 illustrate the following components of the FAS2 system:

1. Harris County zoom of DPA radar illustrating the average last 60 minutes of
   accumulated rainfall over each 4 km by 4 km grid.
2. Scale of rainfall accumulation (inches over previous 60 minutes);
3. Reduced size, regional zoom of the same DPA radar data discussed above;
4. RTHEC-1 real-time hydrograph output showing predicted and observed
   hydrographs at Main St. (upper right-hand corner);
5. Nomograph prediction of peak flow (lower right-hand corner);
6. Average accumulated rainfall over the middle and upper portions of Brays Bayou;

7. Both BayouCam images (lower left-hand corner);

8. Located just below the regional DPA image is an graphic representation of Brays Bayou divided into Upper, Middle, and Lower sections. This graphic is used for illustrating spatially averaged QPF (PreVieux) data for the predicted next 60 minutes of rainfall. Note: The color scheme follows the same as that shown for the DPA radar data.

9. Date and time stamp for all data products illustrated (center).

The time period covered is from 10:00 A.M. through approximately 4:30 P.M. in roughly half-hour increments. A final snapshot of the system data is shown at 7:00 P.M., illustrating that the peak had passed and the falling limb of the hydrograph had commenced. Exact half-hour increments were not possible based on the fluctuations in NEXRAD data delivery (every 5-7 minutes) as discussed in Chapter 2. The data between 4:30 P.M. and 7:00 P.M. was not illustrated for the purpose of brevity and because the HCOEM stream gage (red line in the RTHEC-1 hydrograph) did not update between that time due to telemetry / data delivery difficulties. (Suter 2003).

Figures 6.13 through 6.16 show the approach of the first of the strong convective cells associated with the storm event. At 10:00 A.M (Figure 6.13), no rainfall has yet to fall over the Brays Bayou watershed and the PreVieux image is forecasting no rainfall within the next 60 minutes; however, over the next 90 minutes (Figures 6.14 through 6.16), the storm cell can be seen to fluctuate in intensity and according to the PreVieux
estimate, will impact the upper portion of Brays Bayou. First notification to the TMC was made at 11:15 A.M., due to the fact the storm cell had been observed to be generating nearly 3 inches/hour of rainfall and seemed to be tracking steadily toward upper Brays. The notification consisted of a “heads-up” alert to security personnel to ensure proper monitoring of the system was taking place as only a light drizzle was being observed over the TMC at the time; additionally, the NWS had only issued a thunderstorm watch for Harris County advising of the possibility of widespread rainfall totals of 1-2 inches, and isolated rainfall totals of 2-3 inches.

By 12:00 noon (Figure 6.17), very heavy rainfall can be seen over the upper portion of Brays Bayou. The QPF data is indicating 2.5 to 3 inches over the upper portion of the bayou, with decreasing amounts predicted downstream. Additionally, both the RTHEC-1 and the nomograph are registering the rainfall amount and corresponding flow predictions are rapidly increasing. It is interesting to note that the excellent performance of the QPF algorithm can be seen graphically as well as by comparing the predicted amounts in Figure 6.17 (an upstream and midstream average of approximately 2 inches over the next hour) with the two inches observed in the cumulative rain chart in Figure 6.19. Also note that the HCOEM stream gage had not updated for nearly 4 hours; however, minimal flow was visible in the BayouCam for both the main channel and the Harris Gully box culvert.

At 1:00 P.M. (Figure 6.19), a second storm cell with the potential for impacting Brays Bayou was identified over the Colorado River. While that particular storm cell was not predicted to impact Brays within the next 60 minutes or 2:00 P.M., the steady direction of the storm cell movement indicated that it would likely impact the bayou
within the next 2 to 3 hours. The combination of this estimate of a possible additional 2-3 inches of rainfall over the following 2 to 3 hours along with the RTHEC-1 prediction of a peak flow of 10,000 cfs (resulting from rainfall having already occurred) in approximately 3 hours, was sufficient to alert the TMC to begin its Priority One flood protection actions. The TMC was officially notified of this recommendation at 1:10 P.M. (Hank Rietz 2003).

By 2:00 P.M. (Figure 6.21), the second storm cell was about to impact Brays Bayou, with the QPF algorithm predicting it would more heavily impact the lower portion of the bayou; however, upstream predictions remained as high as one additional inch at that time. It is important to point out that the RTHEC-1 hydrograph was predicting a peak flow of 12,000 cfs to occur at approximately 4:15 P.M. as a result of the previous storm cell. It should be emphasized that this hydrograph prediction is based on the assumption of no additional rainfall. Should the expected additional rainfall occur, the resulting peak flow would not only increase in magnitude but could possibly happen sooner than 4:15 P.M., depending on the location of the rainfall within the watershed. This highlights a point to be discussed later in this chapter – that of the importance of combining the QPF data with the RTHEC-1 model to produce Quantitative Flood Forecasts. Another important observation in Figure 6.21 is that the Harris Gully box culvert level remains below 1 foot and the streamflow in Brays Bayou is just beginning to increase, yet remains below 5,000 cfs.

By 2:15 P.M. the peak predicted flow had increased to 16,000 cfs. Based on the prediction of additional rainfall, the out-of-bank flooding alert level was raised to Yellow in anticipation of exceeding 20,000 cfs flow in the Bayou. Additionally, an average of 3
inches of rainfall had fallen over the upper and middle portions of the bayou within the last 3 hours. The TMC was notified at 2:20 P.M. to commence all available flood protection actions in anticipation of the box culvert levels exceeding the 10 foot benchmark which existed at that time. In turn, we were notified that all Priority One protective actions had been completed by the TMC at approximately 2:15 P.M.

At approximately 2:30 P.M., the predicted peak flow was 19,000 cfs according to the RTHEC-1 model and the observed stream flow was seen to be tracking the predicted rising limb of the hydrograph quite well. The nomograph was predicting a peak of only 16,000 cfs, with an underprediction expected as per its historical performance. The box culvert level was barely 1 foot at this time. It is important to point out that the QPF prediction did not fair as well for the second storm cell, which seemed to intensify and shift slightly more toward the north-north east than its previous northeasterly track. This resulted in greater rainfall over the middle and upper portions of the Bayou than predicted by PreVieux at 2:30 P.M.

The critical decision point in this storm event with respect to the final estimate of whether or not out-of-bank flooding would or would not occur came at approximately 2:50 P.M. The RTHEC-1 hydrograph began to show a leveling off of the peak flow in the Bayou just under 25,000 cfs. This plateau was a result of increased storage in the upper portions of the Brays Bayou channel implemented in the model after TS Allison. Although the QPF was predicting an additional 1 to 1.5 inches of rainfall over the contributing portions of the bayou, this rapidly began to drop off over the next 30 minutes. DPA radar images confirmed that the storm cell was passing quickly to the east and the final call that out-of-bank flooding would not occur was made at 3:20 P.M., based
on continuing strong agreement between the predicted and observed hydrographs as well as the expectation of quickly diminishing rainfall intensity. At this point, flow in both the bayou and the Harris Gully culvert was increasing very rapidly and it is likely that without the aid of the predictive components of this system that out-of-bank flooding would have been anticipated. The TMC was notified at 3:20 that although the expected flow in Brays Bayou might just exceed 24,000 cfs (the benchmark for initiating an alert level of Orange), the alert level would remain at Yellow based on the expectation of rapidly diminishing rainfall over the bayou (Hank Rietz 2003).

By 4:00 P.M. (Figure 6.25), future rainfall predictions by radar observation and QPF algorithm were negligible. Additionally, an inflection point in the observed streamflow data was also noticed. Unfortunately, the stream gage did not update again until almost 7:00 P.M.; however, the BayouCams served their intended purpose well – showing a leveling out of flow in the Bayou throughout that time. By 7:00, the update on the stream gage confirmed what was already known – that the threat of out-of-bank flooding had passed. The maximum observed flow of 25,500 cfs occurred from 4:30 P.M. until approximately 5:45 P.M., indicating the need for fine tuning the upper storage-discharge relationships for the Bayou.
Figures 6.13 and 6.14: Rainfall intensity and flow data for Nov 17th, 2003 at 10:00 a.m. and 10:31 a.m. respectively.
Figure 6.23

Fig. 6.23: Graph showing rainfall intensity and duration for Nov 17th, 2003, 3:00 p.m.

Figure 6.24

Fig. 6.24: Graph showing rainfall intensity and duration for Nov 17th, 2003, 3:27 p.m.
6.3.2 Operational Lead-Time Issues with respect to the RTHEC-1 Component of FAS2

One of the primary concerns that arose from the analysis of the November 17\textsuperscript{th}, 2003 storm event was that of the accuracy of lead-time predictions that could be obtained from the RTHEC-1 output. As mentioned above, the RTHEC-1 algorithm displays the predicted flow from rainfall that has already fallen over the watershed; therefore, the time-to-peak from the “now-line” to the peak of the predicted hydrograph would only accurately represent the available lead-time in the event no further rainfall occurred. If additional rainfall occurred over the watershed, both the peak intensity and time-to-peak
would change; therefore, caution must be used in estimating the lead-time available to end-users despite the "precise" estimates provided by a real-time hydrograph.

Figures 6.28 and 6.29 illustrate the effect that additional rainfall may have on lead-time availability as predicted by time-to-peak estimates from the RTHEC-1 hydrograph. At 2:37 P.M. (Figure 6.28), the predicted hydrograph estimated that a flow of 20,000 cfs would occur in approximately 1 hour and 45 minutes, or about 4:22 P.M. It can be seen in Figure 6.29 that additional rainfall over the middle portion of Brays Bayou (and therefore a time of concentration of less than 1 hour and 45 minutes), that the observed flow of 20,000 cfs actually occurred at approximately 3:20 P.M, or nearly one hour before the prediction in Figure 6.28.

Returning to the flood alert warning forecast timeline originally presented by Singh, it can be seen that the two primary methods of increasing lead-time are to:

1. Reduce the time used by observation lag, forecasting operations and calculations, and communications, or;

2. Begin the forecast assessment prior to the commence of rainfall over the watershed.

The RTHEC-1 system, radar data collection and processing, and the combination of all communications improvements inherent in FAS2 have greatly diminished the time involved with item one above; however, much stands to be gained by the linkage of the RTHEC-1 system and a QPF algorithm such as PreVieux in terms of additional lead-time improvements – particularly in quickly responding watersheds.

The planned switch from DPA NEXRAD radar data to real-time Level II radar data would also improve lead-time prediction. Although it would not directly provide
additional lead-time, the switch should eliminate much of the lag seen in many of the RTHEC-1 hydrograph runs, and thus provide more accurate lead-time estimates.

Figure 6.28: RTHEC-1 output showing 20,000 cfs estimate to occur at approximately 4:30 P.M.

Figure 6.29: RTHEC-1 output showing that 20,000 cfs actually occurred at 3:22 P.M. due to additional rainfall over Brays Bayou.
6.4 New Alert Levels for Out-of-Bank Flooding in Brays Bayou at Main Street

Improving the lead-time and accuracy of a flood alert system necessitates the revamping of existing flood warning action levels – especially given the components listed previously in this dissertation. Additionally, and perhaps more importantly, it is essential to consider the limitations of these new technologies as they are implemented within the system framework and received by end-users in terms of response.

This section presents a new set of alert levels that will incorporate these new technologies along with finally addressing an area that is often overlooked in the world of deterministic hydrologic modeling, the incorporation of error. While each of the components (RTHEC-1, QPF, Radar estimation of rainfall) could each have an individual error analysis associated with them, it would be difficult to assess the combined total error associated with a final flood prediction due to the large number of interdependent variables. This is the primary reason that deterministic hydrologic approaches have nearly always avoided error analyses (Krzysztofowicz 2001).

One method to address this important need is by incorporating the most important error factors in the final result of the analyses, which in this case is the establishment of alert levels or trigger points for required actions on behalf of the end-user. The following example provides a unique situation developed for the needs of the TMC; however, the approach is applicable with minor variations to any watershed and any end-user – with the end-user deciding between the trade off of increase accuracy or increased lead-time.

The approach illustrated and discussed here has not yet been fully implemented within the real-time framework of FAS2; however, it should be easily accomplished in
the near future as it uses nothing more than existing datasets and would operate within the FAS2 infrastructure utilizing similar programming codes as those used for the flow nomograph, PreVieux data assimilation, and RTHEC-1.

The establishment of new alert levels for Brays Bayou flooding centers around the following key points:

1. New, lower flow levels for each previous alert level;
2. The incorporation of RTHEC-1 output;
3. On-the-fly comparison of this output to streamflow measurements for error determination;
4. The incorporation of QPF data;
5. On-the-fly comparison of this data to real-time rain gages for an error estimate of both the QPF algorithm and current radar rainfall data if available or an error estimate based on consecutive predictions.

Figure 6.30 illustrates the improved flood action alert levels resulting from the combination of reduced overall levels for increased lead-time and the incorporation of QPF data averaged over the upper and middle portions of Brays Bayou. The new baseline alert levels given no additional rainfall are seen on the left side of the graph with 15,000 cfs corresponding to the yellow alert level setting, 20,000 cfs to the orange alert level setting, and 25,000 cfs to the red alert level setting. The lowering of these levels was completed for two primary reasons: first, to increase the lead-time to end-users and second, to accommodate for error in the RTHEC-1 flow prediction. Historically, predicting a peak flow within 10-15% has been considered “good” given the large
number of variables involved in such a prediction; therefore, a prediction of 25,000 cfs is within the error range of 29,000 cfs given even this “best” margin of error. The yellow alert level was reduced significantly from 20,000 cfs to 15,000 cfs in order for this alert level to serve as more of an advanced warning or “heads-up” to end-users. This change was made as a direct result of communications with TMC personnel observing the “noted lack of change of alert lights” for the older FAS (Personal Comm, Hank Rietz 2003).

Figure 6.30 shows how the alert level criteria change with the incorporation of QPF data over the watershed. As increasing rainfall amounts are predicted over the contributing portion of the watershed, the threshold flow levels decrease correspondingly. These curves were derived from the FAS flow nomograph and a number of newer RTHEC-1 model runs for validation. It is important to point out that this data depends on the assumption of averaged, uniform predictive rainfall. While this assumption was proven to be the source of significant error in Chapter 5 with respect to rainfall having already fallen over the watershed, it must be carefully noted that this does not apply to predictive rainfall by virtue of the performance limitations of the QPF algorithm highlighted in Chapter 4. The QPF algorithm could not sufficiently predict rainfall out to one hour at the small basin size and performed somewhat better at 60 minutes for the larger basin sizes. Therefore, the assumption of uniform predictive rainfall is considered valid and used to determine the lower flow thresholds required under future rainfall conditions. It should be noted that the QPF algorithm was observed to perform significantly better for 30-minute forecasts as compared to 60-minute forecasts; therefore, this serves only as an example of how this data could be compiled and illustrated in real-time. Time permitting, a similar improved alert level criteria chart will be completed for
the 30-minute predictive rainfall data. It is understood, however, that the 30-minute data set curves will be less conservative than those shown in Figure 6.30.

The graph presented in Figure 6.30 readily accommodates predictions of flow, QPFs, and error estimation in real-time. Figure 6.31 shows an example of what the graph would have shown for the November 17th, 2003 event had the system been operational during the storm. The example begins at 1130 that morning with a box centered at the peak estimated flow rate as read from the RTHEC-1 hydrograph (y-axis) and the average of the three previous QPF predictions averaged over the upper and middle portions of the bayou. The errors in the y-axis direction are derived from the error observed in the RTHEC-1 output between the observed streamflow measurement and the predicted peak flow value. If no data is available from the streamgage, or the data provided is sufficiently outdated, a minimum of +/- 10% of the peak flow estimate is used. For example, at 12:30 P.M. the peak flow rate predicted by RTHEC-1 was approximately 8,500 cfs and the streamgage 419 had not updated for four hours and was still showing less than 300 cfs; therefore, a box approximately 1,700 cfs wide was centered at 8,500 cfs.

The x-axis box center and error approximation is gathered from the previous 3 QPF data estimates. This was chosen in order to compensate for periodic shifts in the direction of the storm cell motion and the resulting variation in the QPF rainfall prediction. The center is located at the average of the three QPF estimates, with the error ranging from the maximum to the minimum observed over that dataset. When the data becomes available, real-time rain gage data will be used to augment this error estimate.
The result of the above methodology is shown in Figure 6.31. The first major period of concern would have been shortly after the 1200 time frame, where the large amount of future rainfall predicted by the QPF algorithm alone was sufficient to nearly trigger a yellow alert level. By 1230, the increased flow predicted by RTHEC-1 combined with a widely varying QPF assessment (hence the significantly wide box in the x-axis direction associated with the 1230 estimate) would have triggered a yellow or flood caution alert. This would have been a full 1 hour and 45 minutes prior to the time at which the yellow alert warning was actually provided to the TMC. Thus, the purpose of the yellow alert serving as a "heads-up" to the TMC would have been met – especially if the warning was called at 1200 as could have been done as seen in Figure 6.31.

The next significant time period shown is that of 1430, where again increasing flow and the prediction of an additional one inch of rainfall over the watershed are sufficient to warrant an orange alert level warning and the possible consideration of soon issuing a red alert level warning. By 1500, this methodology revealed the possibility of out-of-bank flooding had the predicted rainfall by the QPF actually occurred.

It is important to keep in mind that this type of data chart would update in real-time every 5-7 minutes. For clarity, Figure 6.31 is showing only a limited number of data snapshots; however, it is easy to imagine what the interspersed data would look like by envisioning a set of boxes (varying in size in the x and y-direction to some degree due to error estimate changes) slowly tracking from one snapshot to the other.

It can be seen that the alert level criteria are significantly more conservative as compared to the timeline of actions presented earlier in this chapter. This again was a direct request from personnel at the TMC. In fact, this system would have provided
observable and quantifiable evidence to take flood protection actions earlier.

Additionally, the predictions shown were reasonably accurate.

It is interesting to point out that incorporating the RTHEC-1 model data with the QPF data may result in fluctuations in the alert level. Of course, any automated alert system would have to be carefully designed to incorporate at least a cursory review by an experienced hydrologist in order to validate the claims made by this type of predictive tool. Nevertheless, this type of system seems to hold significant promise by marrying two very powerful tools with the result of making the earliest and most accurate flow predictions possible.

Figure 6.30: Improved flood action alert levels that incorporate Quantitative Precipitation Forecasts averaged over the runoff contributing portions of Brays Bayou.
Figure 6.31: A sample of the operational framework for predicting alert level triggering using RTHEC-1 and QPF predictions from the November 17\textsuperscript{th}, 2003 event. Note the varying size of the boxes indicating estimated error from both predictions.
Chapter 7

Conclusions and Future Research

7.1 Summary of Conclusions

The research and results presented in previous chapters have provided insight into the improvement of several of the most critical performance factors of flood alert systems including: accuracy, lead-time and effectiveness. The research was focused specifically on improving alert systems for quickly responding, urban watersheds that have demonstrated the most need for the improvements that the investigated technologies promised to provide. The original FAS provided the perfect starting point for the analysis of these technologies. Additionally, the Brays Bayou study area served as the perfect backdrop for methods to implement these technologies. This chapter will summarize the conclusions discussed in Chapters 4, 5 and 6 of this dissertation. It will also present a discussion of some of the areas in which future research may further improve flood alert systems.

Evaluation of the Accuracy and Effectiveness of a Short-Term Quantitative Precipitation Forecast Algorithm from a Watershed Perspective

The analysis of a Quantitative Precipitation Forecast algorithm was completed by a variety of means including Mean Absolute Error analysis, correlation analysis, and the Threshold Critical Success Index (TCSI) analysis. Results supported the initial hypothesis that the algorithm would exhibit performance limitations at the forecast times
and basin scales being investigated. The results of this section are summarized in bullet format below:

- There was a strongly noted trend between increased forecast times and decreased algorithm performance.
- A pronounced correlation between increasing basin size or prediction "target area" and improved algorithm performance was successfully proven.
- The Threshold Critical Success Index (TCSI) is a fundamentally sound methodology to determine algorithm performance, displaying expected trends under numerous storm events that included various precipitation patterns.
- The QPF algorithm performed adequately to the 30 minute forecast time period at the middle to large basin sizes investigated (80 – 128 square miles).
- The data was marginally sufficient to generalize the TCSI data analysis of the QPF algorithm, allowing a user over a range of basin sizes to estimate the performance level of the QPF over a range of basin sizes and forecast times.
- Additional work should include continuing the TCSI study after increasing the basin size beyond 128 square miles and the forecast time to approximately 2-3 hours.
- Further analysis must be completed to determine if the performance of the QPF algorithm at the +45 and +60 minute forecast times denotes any
statistically significant improvement from a less robust prediction method such as persistence or a more simplified radar extrapolation scheme.

- Future work should be attempted to determine the relationship between threshold and algorithm performance. This study was limited to a +/- 30% threshold simply due to time constraints, but an analysis of a 10% and/or 50% threshold window will be completed soon.

- Other applications for the QPF algorithm should be investigated, especially those with lesser spatial detail requirements. These would include storm sewer operations, intelligent traffic systems that would use input for street closure or re-routing of traffic and/or emergency vehicles, and field work crews working in weather sensitive related areas such as water quality sampling or even electrical repair teams.

**Development and Evaluation of a Lumped-Parameter Hydrologic Model for Real-Time Application within a Flood Alert System**

The development of a real-time interface for the widely-used lumped-parameter hydrologic model was completed and tested under numerous storm events. The results from the real-time data output were evaluated and used to further refine the model parameters. A successful validation run was completed in the late Fall of 2003. Specific results and future research possibilities are highlighted below:

- A real-time operational structure was successfully developed to support the widely used HEC-1 hydrologic models.
• The HEC-1 model was shown to be an effective hydrologic model for quickly responding, urban watersheds when properly calibrated, despite the limitations of the Digital Precipitation Array radar product.

• RTHEC-1 data output, in the form of continuously updating basin hydrographs, provides a powerful tool for calculating the time-to-peak and peak flow for spatially and temporally variable rainfall.

• The real-time hydrographs provide an excellent starting point for the estimation of the “hydrologic” lead-time available for end user action based on current rainfall patterns over the bayou.

• The system was successfully validated under three different storm events and is considered robust from an operational standpoint.

• The RTHEC-1 model denotes a marked improvement over the older nomograph-based approach at approximating peak flows.

• The RTHEC-1 system is readily adaptable to and implemented in any urban basin throughout the United States as both the requisite radar data and baseline models are likely to already exist due to the wide coverage of the NEXRAD system and the widespread use of the HEC-1 / HEC-HMS model.

• Further work needs to be conducted to establish an interface between this structure and the newer HEC-HMS models; however, it is a trivial matter to transfer between the two model types.

• Future work would be to polish the real-time interface so it may be extracted to exportable software for ready use.
• The RTHEC-1 system should be upgraded to accept the latest Level II radar data in order to properly eliminate the observed time-lag in the predicted hydrographs. The system has been programmed to readily accept any new radar data feeds.

• The use of real-time Level II radar data will permit the use of real-time rain gage data in order to calibrate the radar data “on-the-fly”. Vieux and Associates, Inc. is awaiting permission for access to the HCOEM’s rain gage network in real-time in order to accomplish this task.

• The latest hydrologic model created as a result of the TSARP work should be converted from HEC-HMS to HEC-1 format and incorporated into the system. This should only be done after sufficient validation of the model has been completed. It would be feasible to run the system using both models for a period of time.

• Perhaps the area with the greatest potential for future research would be the linkage of the QPF data presented in Chapter 4 with the RTHEC-1 model methodology discussed in this section to create Quantitative Flood Forecasts that incorporate predictive rainfall. The methodology should carefully consider the benefit gained from this linkage as the QPF performance would be limit it to larger basins (greater than 128 square miles) with relatively fast response times. The latter criteria being necessary to not compete with flood wave based alert systems.
Operational Issues for the Flood Alert System and the Texas Medical Center:

Improving Overall System Effectiveness

The overall system effectiveness of the FAS was improved by a number of methods including the incorporation of the above discussed technologies and methodologies, as well as the development of newer flood protection action levels based on the results of their implementation. The late fall 2003 storm event provided an excellent opportunity to test the overall operation and effectiveness of the new FAS2, identifying both strengths and weaknesses of the new technologies. Specific results and future research possibilities are listed below:

- Historical rain gage and streamflow gage data was successfully processed in order to perform a statistical analysis of the Harris Gully box culvert levels. This in turn allowed for the development of improved flood protection action levels based on historical patterns combined with RTHEC-1 and QPF data. These new levels maintain the same flood protection to the TMC while providing a lesser chance of false alarms and thus reducing operation interference costs to the member institutions.

- Future work in this area should include the analysis of more recent and future storm events to further validate or possibly adjust the new Harris Gully box culvert alert levels.

- A framework was proposed for indirectly linking (by way of a new nomograph) the RTHEC-1 peak flow predictions and QPF data by incorporating their real-time output into modified flood protection action
levels for out-of-bank Brays Bayou flooding. This approach, while
developed specifically for Brays Bayou, could be applied to any watershed
if the HEC-1 model was run under a sufficiently wide variety of
precipitation patterns to develop the curves displayed in Figure 6.30.

- Future work for this portion would include creating the real-time interface
  for plotting the position on the alert level nomograph as a storm event
  progressed.

- The FAS2 system performed successfully from an operational standpoint,
  utilizing the tools discussed above to provide improved lead-time and
  accurate flood level predictions to the TMC during the November 17\textsuperscript{th},
  2003 storm event. The system has been operational since that time and
  continues to provide real-time information when required.
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Chapter 9

Appendices

Appendix A: Python and PERL Scripts for QPF Data Formatting and Averaging

The following Python script was written by J. Cameron Cooper, under the direction of Jude A. Benavides, for the purpose of formatting the QPF data prior to analysis. The subsequent PERL script was written by Dr. Jerry Fowler, under the direction of Jude A. Benavides, for the purpose of averaging QPF data according to larger basin sizes shown in Table 4.2 in this dissertation.

Python "Decumulation" Script:

```python
#!/usr/bin/env python
#
# ^ on MacOS X, this works with Python installed by fink or apt-get
# should work with other BSDish unices. other platforms need to change this or use 'python collater.py'

"""PreVieux data collater in Python
authors: J Cameron Cooper and Jude A. Benavides
started: 8 Jan 2003
v1.0 rc1: 24 Jan 2003

Creates a set of TSV files for each sub-watershed containing data collected from a directory full of directories full of XML files containing predictions of rainfall in appx 5 min increments for said sub-watersheds.

Silently skips files or directories that don't fit the established scheme.

While only tested with the data in 5-min increments and predicted an hour ahead, the program is by no means bound to those conditions. It should happily deal with whatever size prediction it is given, or with any time increments as specified, with the notable exception of the various statistics generated. It is also not too closely bound to the various naming conventions and file formats, although any change may bork it to no end.
```
Usage: %(program)s [options] event_directory1 event_directory2 ...

Options:

-h, --help print this message.
-v, --verbose verbosity level. Turn it up for more detail on what the program is doing.
Default: %%(VERBOSITY)s
-q, --quiet specify no output at all (same as setting verbosity to -1)
-i, --interval expected interval of observations, in seconds.
Default: %%(INTERVAL)s (%%(INT_in_minutes)s min)
-b, --before seconds prior to interval where an interval is still accepted.
Default: %%(WINDOW_BEFORE)s
-a, --after seconds subsequent to interval where an interval is still accepted.
Default: %%(WINDOW_AFTER)s
-l, --local whether to read directory names as local (else UTC)
Default: %%(LOCALTIME)s
-d, --decmulate whether to read rainfall as cumulative and convert to incremental
Default: %%(DECMULATE)s
-p, --precision number of digits of precision to print
Default: %%(PRECISION)s
-g, --gap number of missing entries to interpolate
Default: %%(MAXGAP)s

### Useful LINKS ###
# Python library reference
# http://python.org/doc/current/lib/lib.html

# Python tutorial
# http://python.org/doc/current/tut/tut.html

# Python language reference
# http://python.org/doc/current/ref/ref.html

# Python module index
# http://python.org/doc/current/modindex.html

### DEFINITIONS ###
# (it being helpful to name the various directory and file types the program uses)

# event : a directory full of observation directories. Usually named for the date when the
# data was recorded

# observation : a directory full of xml files containing predictions made some time.
import os, sys, getopt, string, time, calendar
from xml.dom.minidom import parse  # a lightweight, simple implementation of the Document Object Model
    # requires Python 2.0 or later

program = sys.argv[0]
vars = vars()  # used by 'usage()', done because 'vars()' must be called from top scope

### CONFIGURATION ###

# level of messages to show (shows all messages labeled less than this)
VERBOSITY = 2

# padding in seconds used to recognize a sample interval
WINDOW_BEFORE = 5
WINDOW_AFTER = 95

# number of seconds in the target interval between observations
INTERVAL = 5*60
INT_in_minutes = INTERVAL/60  # for interface purposes only

# whether to use local or GMT
LOCALTIME = 0

# digits of precision
PRECISION = "%.3f"

# whether to subtract cumulations to produce incremental
DECUMULATE = 1

# whether to interpolate missing values and how many to accept
INTERPOLATE = 1
MAXGAP = 2

DEMARICATION_CHAR = "\t"

### CLASSES ###

# none

### GLOBAL VARIABLES ###

BASIN_ELEMENT = "basin"
BASIN_ATTRIBUTE_ID = "id"
BASIN_ATTRIBUTE_VALUE = "value"

### FUNCTIONS ###

def report(msg, level=1, basin="D100K"): 

    """Report information to the user."

    Report information somehow (terminal) iff the reported interest level is less than or equal to the set verbosity level. A verbosity level of 1000 should show all messages; a level of 0 only the most important, and a negative setting none at all. Indents the message with 'level' number of spaces. Must be given a string.

    """
    if basin != "D100K":
        return

    if level <= VERBOSITY:
        print string.rjust(msg,len(msg)+level)

def usage():

    """Prints command-line usage information."""
    print __doc__ % vars

def cmd_line():

    """Parse command line using the getopt library""
    global VERBOSITY  # must do this to change global variables
    global WINDOW_AFTER
    global WINDOW_BEFORE
    global INTERVAL
    global DECUMULATE
    global LOCALTIME
    global PRECISION
    global INT_in_minutes
    global MAXGAP
    global INTERPOLATE
report("Parsing command-line arguments...",0)
try:
    # options will be in opts, arguments (path to event subdir, in this case) will be in args
    opts, args = getopt.getopt(sys.argv[1:], "hqv:b:a:i:l:d:p:g:",
    ["help", "quiet", "verbose", "before", "after", "interval", "decumulate", "localtime", "precision", "gap”])
    except getopt.GetoptError:
        usage()
        sys.exit(1)

if len(args) == 0:
    usage()
    sys.exit(0)

# look through the options
quit = 0
for o, a in opts:
    if o in ("-h", "--help"):
        usage()
        sys.exit()
    if o in ("-v", "--verbose"):
        VERBOSITY = int(a)
        report("setting verbosity=%s"%a,4)
    if o in ("-q", "--quiet"):
        VERBOSITY = -1
        report("setting quiet (verbosity at -1)",5)
    if o in ("-a", "--after"):
        if a < 0:
            print "ERROR: window after interval cannot be negative"
            quit = 1
        WINDOW_AFTER = int(a)
        report("setting window_after=%s"%a,5)
    if o in ("-b", "--before"):
        if a < 0:
            print "ERROR: window after interval cannot be negative"
            quit = 1
        WINDOW_BEFORE = int(a)
        report("setting window_before=%s"%a,5)
    if o in ("-i", "--interval"):
        if a < 1:
            print "ERROR: interval cannot be set 0 or negative"
            quit = 1
        INTERVAL = int(a)
INT_in_minutes = INTERVAL/60
report("setting interval=%s"%a,5)
if o in ("-p", "--precision"):
    if a < 1:
        print "ERROR: precision cannot be set 0 or negative"
        quit = 1
    PRECISION = "%." + a + "f"
    report("setting precision=" + PRECISION,5)
if o in ("-l", "--local"):
    if a < 1:
        print "ERROR: local is negative, was it a typo?"
        quit = 1
    if (int(a) == 0):
        LOCALTIME = 0
    else:
        LOCALTIME = 1
        report("setting local=%s"%a,5)
if o in ("-d", "--decumulate"):
    if a < 1:
        print "ERROR: decumulate is negative, was it a typo?"
        quit = 1
    if (int(a) == 0):
        DECUMULATE = 0
    else:
        DECUMULATE = 1
        report("setting decumulate=%s"%a,5)
if o in ("-g", "--gap"):
    if a < 0:
        print "ERROR: gap cannot be set negative"
        quit = 1
    MAXGAP = int(a)
    INTERPOLATE = 1
    report("setting gap=%s"%a,5)
if quit:
    sys.exit(quit)

return args

def ordered_listdir(event):
    """Return a list of subdirectories as in os.listdir, but ordered numerically, thus by time."
   "
    # we may not need such a hardcore sorter as sorted_copy, but better safe than sorry
    return sorted_copy(os.listdir(event))

def sorted_copy(alist):
    """Sort strings in numeric order."""
# Uses code from Python cookbook
# http://aspn.activestate.com/ASPN/Cookbook/Python/Recipe/135435
indices = map(_generate_index, alist)  # apply _generate_index against every member
of alist
decorated = zip(indices, alist)  # create a list of tuples (indices[n],alist[n])
decorated.sort()  # sort it, by first member of tuple (from indices)
return [item for index, item in decorated]  # return the second member of the tuples in
decorated

def _generate_index(str):
    """Splits a string into alpha and numeric elements, to be used as an index for sorting.

    Used by sorted_copy, as part of the recipe.
    """
    # index built progressively using the inline _append function
    index = []
    def _append(fragment, alist=index):
        if fragment.isdigit():
            fragment = long(fragment)  # function might be int(), but our dates are 12-place
            integers
            alist.append(fragment)

    # initialize loop
    prev_isdigit = str[0].isdigit()
    current_fragment = "
    # group a string into digit and non-digit parts
    for char in str:
        curr_isdigit = char.isdigit()
        if curr_isdigit == prev_isdigit:
            current_fragment += char
        else:
            _append(current_fragment)
            current_fragment = char
        prev_isdigit = curr_isdigit
        _append(current_fragment)
    return tuple(index)

### MAIN ###
def main():
    """Called as the main function of the script by code in the top scope.

    Drives the whole thing. Pretty obvious, I think.
    """

    largest_gap = 0
# take care of how we were called
args = cmd_line()

# loop through the list arguments/events
for event in args:
    report("Processing event in %s" % event, 1)
    report("Analyzing observation directories...", 2)
    contents = ordered_listdir(event)
    basetime = 0  # interval is calculated by this (here set to default)
    timedict = {}  # we create an empty dictionary of minute_index : pyttime
    subdirdict = {}  # we create an empty dictionary of minute_index :
    subdirectory_path
    holes = []  # make empty list of indexes where a discontinuity occurs
    unpatched_discontinuities = []  # make empty list of indexes where a discontinuity occurs
    recoverables = []  # make empty list of indexes believed to be recoverable
    counter = 0  # index (subscript) of time
    basin_dict = {}  # dictionary on basin_id:observation_dict (not the one above)
    # An essay on my oh-so-clever data structure:
    # A dictionary is a mapping structure between a key and value, so that if we say
    # dict[key] = value
    # we can ask the dictionary 'dict[key]' and it will return 'value'.
    # Here, the basin_dict has key:basin_id (as got from xml) and value: {}, another dictionary.
    # That new dictionary has key:observation_index (the observations numbered in order) and
    # value: {} (yet another empty dictionary).
    # That third dictionary has key:prediction_index (the predictions numbered in order)
    # value: rainfall, the rainfall that prediction in that observation predicts in that basin.
    # Thus, we can say basin_dict['CITYA'][4][0] to mean the rainfall predicted in
    # CITYA to
    # occur 5 minutes after the observation made during the fourth observation. Neat, huh?
    
    # loop through the list of data directories (observations) in an event
    firsttime = 0
    for subdir in contents:
        # we ignore non-directories (like zip files)... 
        if os.path.isdir(os.path.join(event, subdir)):
            # extract the time from the dirname, looking at the timestamp after the first
substring = "brefl="
subtime = subdir[string.index(subdir,substring)+len(substring):] # remove before time
subtime = subtime[:14] # remove everything after time

# convert to a Python time

## We would like to use
# timeformat = "%Y%m%d%H%M%S"
# ptime = time.strptime(subtime, timeformat)
## but strftime uses the std C library, which seems absent on Mac and probably Windows.
## So, we do it the hard way... (look up the tuple format in Python library docs)
pytuple = (int(subtime[0:4]), int(subtime[4:6]), int(subtime[6:8]),
int(subtime[8:10]),
    int(subtime[10:12]), int(subtime[12:14]), 1, 1, -1)
# Note that we're supplying hardcoded values [1] to mktime for day of week and Julian
# day. It seems to be okay with that, but you can test any particular implementation
# by doing 'time.gmtime(ptime)' and comparing the tuples.
if (LOCALTIME == 1):
    ptime = time.mktime(pytuple)
else:
    ptime = calendar.timegm(pytuple)

report("[" + `counter` + "] " + subtime + ":" + `ptime` + ",",4)

# we assume everything is in chronological order and number the observations
timedict[counter] = ptime

# skip if this is the first through...
if (firsttime == 0):
    firsttime = ptime

if basetime != 0:
timediff = ptime - firsttime
pint = basetime + INTERVAL # the predicted (desired) interval
report("basetime=" + `time.asctime(time.gmtime(basetime))`,6)
report("predict =" + `time.asctime(time.gmtime(pint))`,6)
report("realtime=" + `time.asctime(time.gmtime(ptime))`,6)

delta = ptime-pint # calculate the delta
report("d=" + `ptime-pint` + "s",6)

# determine if delta is within acceptable limits or not
if not ((delta >= -WINDOW_BEFORE) and (delta <= WINDOW_AFTER)):
    if (INTERPOLATE == 0):
        holes.append(counter)
    else:
        # insert all the appropriate missing intervals
        while (delta > -WINDOW_BEFORE):
            if (delta <= WINDOW_AFTER):
                report("Breaking at " + `counter` + ": " + `delta`,0)
                break
            # rewrite timedict to desired interval, not real
            report("HOLE " + `counter` + " by " + `pytime-pint` + "s" + ": " + `timediff`,0)
            holes.append(counter)
            timedict[counter] = pint
            pint = pint + INTERVAL
            delta = delta - INTERVAL
            counter = counter + 1
        else:
            pass
        # adjust for decrement below. ugh.
        # counter = counter + 1
        # counter = counter - 1

    report("New " + `counter` + ": " + `timediff`,0)
    timedict[counter] = pytime # redundant if (!INTERPOLATE)

    # check for recoverability
    deltamod = delta % INTERVAL # the modulus of delta with interval
    if (deltamod <= WINDOW_AFTER) or ((INTERVAL-deltamod) <= WINDOW_BEFORE):
        recoverables.append(counter)
        report("may be RECOVERABLE at " + `delta/INTERVAL` + " intervals out",4)
        # note that two observations at the same time will be marked
        recoverable,
        # but can easily be caught by a negative div result check

        subdirdict[counter] = os.path.join(event,subdir)
        counter = counter + 1
        basetime = pytime

    # report what we found
    ##for a in obsdict.keys():
```python
# report("[" + `a` + "]" + `obsdict[a]"
report("discontinuities: " + str(holes), 3)
report("recoverables: " + str(recoverables), 3)

# we look at the first prediction in the first observation to set up the basin dictionary
observation = subdirdict[0]
predictions = ordered_listdir(observation)
prediction = os.path.join(observation, predictions[0])  # the path to the xml file
dom1 = parse(prediction)  # open and parse the XML file. This returns a
Doc
ument.

# minidom works like any other DOM. Javascript programmers should recognize
this easily
basinelts = dom1.getElementsByTagName('BASIN_ELEMENT')
firstbasin = basinelts[0].getAttribute('BASIN_ATTRIBUTE_ID')  # used below

for elt in basinelts:
    # the basin dictionary has an entry made the basin name as key and an empty dict
    # as value
    basin_dict[elt.getAttribute('BASIN_ATTRIBUTE_ID')] = {}
dom1.unlink()  # clean up. this is minidom specific

# READ and INPUT the whole event into memory. there's probably some less-
memory-intensive
# ways to do this, but I don't think that's a big enough concern to bother with
# (plus this way is way more extendable for different outputs)
# we do it just like above, but looping looping looping
report("Reading Input...", 6)
for index, observation in subdirdict.items():
    report("in observation " + `index`, 3)
    # create empty dictionaries for predictions
    for basin in basin_dict.keys():
        basin_dict[basin][index] = {}
        # this might be sped up by use of built-in functions (say, map()), but this is
        # easier to understand, and shouldn't be too slow

predictions = ordered_listdir(observation)
a = 0
for prediction in predictions:
    if prediction[-3:] == "xml":  # if it has an xml file extension
        report("reading prediction " + prediction, 8)
predpath = os.path.join(observation, prediction)
dom1 = parse(predpath)
basinelts = dom1.getElementsByTagName('BASIN_ELEMENT')
for elt in basinelts:
    rainfall = elt.getAttribute('BASIN_ATTRIBUTE_VALUE')
```
# convert rainfall to a number (it is currently a string)
# note that behaviour of float() varies based on the underlying C library
# however, the input format is so common, there shouldn't be any trouble
rainfall = float(rainfall)
# we'll truncate in the output section

basin_dict[elt.getAttribute(BASIN_ATTRIBUTE_ID)][index][a] = rainfall

report("+["+elt.getAttribute(BASIN_ATTRIBUTE_ID)+"]"["+\`index`+"]["+`a`+"]="
   + rainfall`,6)
a = a + 1

sys.exit;

num_predictions = len(basin_dict[firstbasin][0])

if (INTERPOLATE == 0):
    unpatched_discontinuities = holes
else:
    for basin_name, obs_dict in basin_dict.items():
        report("Interpolating " + basin_name,1)

# do the mainstream reporting
ceiling = 0
lastvalid = 0
p51hsum = []
missing = 0
for index, pytime in timedict.items():

    # interpolate into discontinuities
    if index in holes:

        enddisc = -1
        for oind in range(index + 1, lastvalid + MAXGAP + 2):
            if oind not in holes:
                enddisc = oind
                break

        if enddisc == -1:
            report("Unpatched " + `index`,1,basin_name)
            missing = index - lastvalid - 1
        else:
            missing = 0
basin_dict[basin_name][index] = {}

trange = enddisc - lastvalid
tfraction = index - lastvalid

    pend = basin_dict[basin_name][enddisc][0]
    pstart = basin_dict[basin_name][lastvalid][0]

    report("Hole " + `index' + ` range:" + `lastvalid' + `-" + `enddisc` + ", " + `tfraction` + "/`range` + `. " + `pstart` + " + `pend`.0,basin_name)

    for predno in range(num_predictions):
        rainsum = basin_dict[basin_name][enddisc][predno] +
        basin_dict[basin_name][lastvalid][predno]

        basin_dict[basin_name][index][predno] = (tfraction*rainsum)/trange

    else:
        report("Fill " + `index`.0,basin_name)

        if (missing > 0):
            unpatched_discontinuities.append(index)
        if (missing > largest_gap):
            largest_gap = index - lastvalid - 1

        report("Gap of length " + `index - lastvalid - 1` + ` index - 1`.0,basin_name)

        missing = 0
        lastvalid = index

# OUTPUT what we now have in memory to TSV files
# we will output to a list of lists first, then output those as files
report("Generating Output...",2)

num_predictions = len(basin_dict[firstbasin][0])
ps = range(INT_in_minutes, (num_predictions+1)*INT_in_minutes,
INT_in_minutes)
ss = map(lambda num: "S"+`num`, ps)
ps = map(lambda num: "P"+`num`, ps)

if (INTERPOLATE):
    gap = "Gap"
else:
    gap = "Gap End"

headline = ["Observation_End","H/R Time (UTC)","-","-","Index", gap] + ps +
["P5_Sum"] + ss

doctored = 0;
for basin_name, obs_dict in basin_dict.items():
    report("Formatting " + basin_name,3)
outlist = []
outlist.append(headline)
# do the mainstream reporting
celling = 0
lastindex = 0
p51hsum = []

for index, pytime in timesdict.items():
    d = ""
    # edge reporting: discontinuities
    # I don't understand why this is displaying off-by-one
    if ((index-1) in holes) and INTERPOLATE:
        d = "#"  # overridden next line if hole is unpatched
    if (index-1) in unpatched_discontinuities:
        d = "*"  # if you change this, change the pred5_1hrsum determination of
        discont.

    # JCC TODO: can this/should this be factored out?
    for index2 in range(lastindex, lastindex + num_predictions - 1):
        nlist = []
o = index2
p = 0

        for x in range(num_predictions):
            if (o >= lastindex) or (o < ceiling) or (o not in
basin_dict[basin_name].keys()):
                #nlist.append("("+`o`+","+`p`+)")
                nlist.append(""")
            else:
                #nlist.append(`o`+","+`p`)
                if (DECUMULATE == 0 or p == 0):
                    prevrain = 0
                else:
                    prevrain = basin_dict[basin_name][o][p-1]
                rainnow = basin_dict[basin_name][o][p] - prevrain
                nlist.append(PRECISION%rainnow)

                o = o - 1
p = p + 1

        line = ["","","","",""] + nlist + ["",""]
        outlist.append(line)
        report(`line`,6)
        ceiling = lastindex

    # o and p are coordinates in our dictionary structure, for observation and
prediction
o = index - 1
p = 0
nlist = []
slist = []
for x in range(num_predictions):
    if (o < ceiling) or (o not in basin_dict[basin_name].keys()):
        nlist.append("\"+\"o\"+\",\"+\"p\"+\")
        nlist.append("")
    else:
        nlist.append(\"o\"+\",\"+\"p\")
    if (DECUMULATE != 0 or p == 0):
        prevrain = 0
    else:
        prevrain = basin_dict[basin_name][o][p-1]
        rainnow = basin_dict[basin_name][o][p] - prevrain
        nlist.append(PRECISION%rainnow)
        slist.append(PRECISION%basin_dict[basin_name][o][p])

o = o - 1
p = p + 1

### generate statistics

if ((index-1) not in basin_dict[basin_name].keys()):
    doctored = 11
    nlist.append("#")
else:
    # pred5 1hr sum - total of 5min prediction for an hour

    if d == "#":  # ie, if this observation is discontinuous
        doctored = 11

    p51hsum.append(basin_dict[basin_name][index-1][0])
    if len(p51hsum) == 12:
        sum = 0
        for x in p51hsum:
            sum = x + sum
        if (doctored > 0):
            nlist.append("\"\"")
            nlist.append(PRECISION%sum)
            del(p51hsum[0])    # remove oldest
        else:
            nlist.append("\"")
            doctored = doctored - 1

    if (DECUMULATE):
nlist = nlist + slist

line = ["time.asctime(time.gmtime(pytime))", "index", d] + nlist
outlist.append(line)
report("line", 6)

lastindex = index  # for use with edge cases

# edge reporting: finish out after the end
# finding o works subtly different here
for index in range(lastindex, lastindex + num_predictions - 1):
    nlist = []
o = index
p = 0
for x in range(num_predictions):
    if (o >= lastindex) or (o < ceiling):
        nlist.append("\"+\"o\"++\"+\"p\"+");
        nlist.append("\"")
    else:
        nlist.append("o\"++\"+\"p\")
    if (DECUMULATE == 0 or p == 0):
        prevrain = 0

    prevrain = basin_dict[basin_name][o][p-1]
    rainnow = basin_dict[basin_name][o][p] - prevrain
    nlist.append("PRECISION\%rainnow")

    o = o - 1
    p = p + 1

line = ["", ",", ",", ",", "] + nlist + ["", "]
outlist.append(line)
report("line", 6)

report("Writing " + basin_name, 3)
tsvfile = file(os.path.join(event, basin_name+".full.tsv"), "w")
for list in outlist:
    outline = string.join(list, DEMARCATION_CHAR)+"\n"  # join must be given
    tsvfile.write(outline)
tsvfile.close()

if (INTERPOLATE):
    report("Largest gap " + \"largest_gap\")

# magic to make the 'main()' above execute on run like a C or Java 'main()'
if __name__ == "__main__":
    main()
    report("Done.",1)

**PERL Basin Averager Script:**

#!/usr/bin/perl

use File::Spec;

$guide = shift;

unless ($guide) {
    print q(Usage:
        average.pl listfile [dir] [start] [end] [format]
        listfile a file that looks like
    Basin1
        subbasin1 weight
        subbasin2 weight
    Basin2
        subbasin3 weight
        subbasin4 weight
    ..
    <weight> is optional (straight average without it)
    and can be expressed with decimals, if desired
    [dir] directory to find subbasins in and put results in
    [start] index to begin on (default 12)
    [end] index to end on (default 9999)
    [format] number of decimal digits to print
    );
    exit 0;
}

$log = $guide;
@times = split /s/, scalar localtime();
($oclock) = $times[3] =~ /(.\*:[^\:]*)+;/
$timestamp = "$times[$#times]-$times[1]-$times[2] $oclock";
$log =~ s/\([!^\.]*\)$/$log;$/;
$log = "$log.log";

$dir = shift or $dir = ".";
$start = shift or $start = 12;
$end = shift or $end = 99999;
$format = shift or $format = "6";
$format = sprintf("%%%0%d.%df", $format+2, $format);
$comment = "\n";$

open LISTER, ">", $guide or die ("Failed to open basin list "$guide": $!
");
open LOG, ">", $log or die ("Failed to open logfile $log: $!
");

use Cwd;
$cdir = getcwd();
print LOG "Current directory: $cdir\nprog: $0\nData directory $dir (lines $start to $end) format $format\nRan at ". scalar localtime() . "\n";

@basins = ();
@thisbasin = ();
while (<LISTER>) {
  next unless $_
  next if /$comment/o;
  if (/\S+/) {
    if (defined $basinname) {
      push @{$basins{$basinname}}, @thisbasin;
    }
    $basinname = $1;
    @thisbasin = ();
  } elsif (/\s+\(\S+\)\s+\(\d*\?\d+\)/) {
    push @thisbasin, $1;
    $weight{$basinname} {$1} = $2;
  } elsif (/\s+\(\S+\)/) {
    push @thisbasin, $1;
    $weight{$basinname} {$1} = 1;
  } else {
    if (defined $basinname) {
      push @{$basins{$basinname}}, @thisbasin;
    }
  }
}
close LISTER;

#debug
#for $key (keys %basins) {print "$key\n"; for $subbasin (@{$basins{$key}}) {print "\t$subbasin\n";}}

sub filename {
  my $basin = shift;

  return "$basin.full.tsv";
}
for $basinkey (sort keys %basins) {
    print LOG "$basinkey\n";
    @basin = ();
    my $subcount = 0;
    my $indj = 0;
    my $totalweight = 0;
    for $subbasin (@{basins {$basinkey}}) {
        my $weight = $weight{$basinkey} {$subbasin};
        $totalweight += $weight;

        $file = File::Spec->catfile("$dir", filename($subbasin));
        open BIN, "<", $file or die("Bad open of $dir/$subbasin: $!");
        print LOG "Itsubbasin $subbasin (weight $weight)\n";
        $header = <BIN>;
        for ($indj = 0; (<BIN>); $indj++) {
            chomp;
            @line = split /\t/, $_;
            ($date, $index, $status) = @line[0..2];
            next if ($index < $start or $index > $end);
            if (defined $basin[$indj][0]) {
                die "$basin[$indj][0] ne $date" if ($basin[$indj][0] ne $date);
                die "$basin[$indj][1] ne $index" if ($basin[$indj][1] ne $index);
                die "$basin[$indj][2] ne $status" if ($basin[$indj][2] ne $status);
            } else {
                push @$basin[$indj], @line[0..2];
            }
            for (my $i = 3; $i < @line; $i++) {
                $basin[$indj][$i] += $line[$i]*$weight if (defined $line[$i]);
            }
        }
        # if ($basin[$indj][1] == 112) {print join ("\t", "$file: ", @$basin[$indj], "\n");}
    }
    $subcount++;
}
next unless $totalweight;

for ($i = 0; $i < $indj; $i++) {
    if ($basin[$i][1] == 112) {print join ("\t", "$basinkey: ", @$basin[$i], "\n");
    map { if ($_ =~ /^0$/|\d*\d+/) {$_ = sprintf($format, $_/$totalweight); } } @$basin[$i];
    if ($basin[$i][1] == 112) { print join ("\t", "Again: ", @$basin[$i], "\n"); }
}
```perl
$file = File::Spec->catfile("$dir", filename("$basinkey-Avg"));
open BOUT, ">", $file or die("Bad open of $file");
print LOG "$basinkey: total weight $totalweight, $indj lines, $subcount files
(@{$basins{$basinkey}}) in $file
";
print BOUT "$header
";
for ($i = 0; $i < $indj; $i++) {
    print BOUT join("", @{$basin[$i]})."\n" if (defined $basin[$i]);
}
close BOUT;
```
Appendix B: Additional Time-Series Comparison
Graphs of QPF and Rain Gage Data for Brays Bayou
Appendix C: Additional Correlation Graphs
Documenting QPF Performance at Various Basin Sizes and Forecast Times

November 17th 2003 Storm Event:

Correlation between 1-Hour QPF Data and Observed Real-Time Radar Data - D100K - Level 1

\[ R^2 = 0.725 \]

Correlation between 45-Minute QPF Data and Observed Real-Time Radar Data - D100K - Level 1

\[ R^2 = 0.781 \]
Correlation between 30-Minute QPF Data and Observed Real-Time Radar Data - D100K - Level 1

$R^2 = 0.885$

Correlation between 15-Minute QPF Data and Observed Real-Time Radar Data - D100K - Level 1

$R^2 = 0.956$
Correlation between 1-Hour QPF Data and Observed Real-Time Radar Data - D100K - Level 2

R² = 0.8417

Correlation between 45-Minute QPF Data and Observed Real-Time Radar Data - D100K - Level 2

R² = 0.8683
Correlation between 30-Minute QPF Data and Observed Real-Time Radar Data - D100K - Level 2

$R^2 = 0.9156$

Correlation between 15-Minute QPF Data and Observed Real-Time Radar Data - D100K - Level 2

$R^2 = 0.9702$
Correlation between 1-Hour QPF Data and Observed Real-Time Radar Data - D100K - Level 3

\[ R^2 = 0.9207 \]

Correlation between 45-Minute QPF Data and Observed Real-Time Radar Data - D100K - Level 3

\[ R^2 = 0.9272 \]
Correlation between 30-Minute QPF Data and Observed Real-Time Radar Data - D100K - Level 3

\[ R^2 = 0.9464 \]

Correlation between 15-Minute QPF Data and Observed Real-Time Radar Data - D100K - Level 3

\[ R^2 = 0.9771 \]
Appendix D: Additional MAE Graphs for QPF Data at Various Forecast Times and Basin Sizes

Mean Absolute Error (MAE) for Level 1 Subbasin Data (Nov 17th, 2003)

Mean Absolute Error (MAE) for Level 1 Subbasin Data (Oct 9th, 2003)
Mean Absolute Error (MAE) for Level 2 Subbasin Data
(Oct 9th, 2003)

Mean Absolute Error (MAE) for Level 2 Subbasin Data
(Aug 15th, 2002)
Mean Absolute Error (MAE) for Level 3 Subbasin Data
(Nov 17th, 2003)

Mean Absolute Error (MAE) for Level 3 Subbasin Data
(Oct 9th, 2003)
Mean Absolute Error (MAE) for Level 3 Subbasin Data
(Aug 15th, 2002)

Error in Rainfall Prediction over 5-minute Interval (inches)

Forecast Time (minutes)
Appendix E: RTHEC-1 JavaBeans Code for HEC-1 Handler and HCOEM Handler

The following Java processes were written in conjunction with Mr. Anthony Holder in order to process data and information exchange related to the RTHEC-1 program. It should be noted that these two basic processes, while the heart of the system, constitute only a handful of the Java processes and scripts required to run RTHEC-1 as part of an overall Flood Alert System. The scripts call on many of the Java processes originally part of the JavaFAS system developed by Anthony Holder during the original FAS development.

**HEC-1 Handler:**

```java
package org.floodalert.fas.tasks;

import org.floodalert.fas.FASDriver;
import org.floodalert.fas.exception.*;
import org.floodalert.fas.util.*;

import org.floodalert.fas.controllers.*;
import org.floodalert.fas.controllers.inputs.*;
import org.floodalert.fas.controllers.outputs.*;
import org.floodalert.fas.controllersprefs.*;
import org.floodalert.fas.server.*;

import java.util.Vector;
import java.io.*;
import java.util.StringTokenizer;
import java.util.Enumeration;
import java.util.Iterator;

import javachart.chart.*;
import java.awt.image.BufferedImage;
import java.awt.Image;

import org.floodalert.fas.simulation.Date;
import java.text.SimpleDateFormat;

import java.awt.Graphics;
```
import java.awt.Color;
import java.awt.Font;

import com.sun.jimi.core.Jimi;
import com.sun.jimi.core.JimiException;
import com.sun.jimi.core.JimiWriter;
import com.sun.jimi.core.options.PNGOptions;

/**
 * HEClHandler:
 * Outputs a HECl input file for the Watershed.
 * Once the file is created, the handler calls HEC-1 via VirtualPC,
 * waits for it to finish, and reads the output of PUNCH, a file
 * created
 * by HEC-1 containing the output hydrograph. This hydrograph is
 * plotted
 * for the website.
 */
public class HEClHandler extends TaskHandler {

    private String lastDataFileUsed = "0";
    private Vector heclVector = new Vector();
    private Vector heclGageOrder = new Vector();
    private Vector hydrograph = new Vector();
    private Vector hcoemData = new Vector();
    private Vector avgRainfall = new Vector();
    private String heclStartTimeStr = "0";

    protected Archiver heclOutArchiver;
    protected Archiver hydroArchiver;
    private Date endDate;
    boolean initialized = false;
    private String heclOut = watershed.getRadarCurrentOutputPath() +
    getHandlerOutput().get("hecloutput");
    private String hydroOut = watershed.getRadarCurrentOutputPath() +
    getHandlerOutput().get("hydrooutput");
    private String hcoemGage =
    (String)getHandlerInput().get("hcoemGage");
    private String heclInputFile =
    (String)getHandlerInput().get("heclInputFile");
    private String filename =
    (String)getHandlerOutput().get("filename");
    private String dateFileName =
    (String)getHandlerOutput().get("datefilename");

    static protected SimpleDateFormat dateFormat = new 
    SimpleDateFormat("dd MMM yy, HH:mm");
    // private Gage vcp;
    private int hoursToHECl;

    /**
     * HEClHandler constructor
     * @param d the FASDriver for this TaskHandler
     * @param p the prefs for this TaskHandler
     */
* @param w the Watershed for this TaskHandler
* @exception thrown if instantiation fails
*/

public HEC1Handler(FASDriver d,Prefs p,Watershed w) throws FASException {
    super(d, p, w);
    String fname = "hecl" + File.separator + heclInputFile;
    // vcp = (Gage)watershed.getInput("VCP");
    File heclFile = new File(FAS.getFASConfigPath(fname));
    if (!heclFile.exists()) {
        LogHandlerEvent(heclFile.getName() + " does not exist.",
                        Logger.SYSTEM, Logger.S_ERROR);
        throw new FASException(heclFile.getName() + " does not exist.");
    }

    // Read the file, split it into parts, where it encounters------
    // INSERTTEXT,IN,IOCardsHERE------------------------ lines
    // The rainfall data will be put into those places, and an output
    file will be made, and used to run HEC1
    // HEC1 cannot read groups of gages as claims in the manual very
    well, so we break the
    // file into parts for each gage. The gage number is in the file,
    preceded by "PR"
    // replace the PR line with the rainfall data.
    // Note, can have up to 2000 time steps. Must have less than or
    equal to number of timesteps on IT card.
    // Only 10 timesteps per line. Must use same dt as last IN card.
    // For now, IN card will specify 60 minutes. Once NativeRes comes
    in, we can reduce this.
    // Can use comma-separated values.

    // The result of this file needs to be a Vector of Vector of
    String. The lines are Strings, and each section is a Vector of Strings.
    BufferedReader heclReader;

    try {
        heclReader = new BufferedReader(new FileReader(heclFile));
    } catch (java.io.FileNotFoundException e) {
        return;
    }
    Vector heclGroup = new Vector();
    String heclLine;

    int dividerCount = 0;
    // heclLine=heclReader.readLine();
    try {
        while ((heclLine=heclReader.readLine()) != null) {
            System.out.println(heclLine);
            if (heclLine.startsWith("PR")) {
                heclVector.insertElementAt(heclGroup.clone(),dividerCount);
                dividerCount = dividerCount+1;
                heclGroup.setSize(0);
                heclGageOrder.add(heclLine.substring(2));
            } else {
                // do something with the line
            }
        }
    }
}
// System.out.println("+++++++++++++ " + hec1Line);
} else if (hec1Line.startsWith("-----")) {

hec1Vector.addElementAt(hec1Group.clone(), dividerCount);
dividerCount = dividerCount+1;
hec1Group.setSize(0);
// System.out.println("+++++++++++++ " + hec1Line);
} else {
    hec1Group.add(hec1Line);
}
// hec1Line=hec1Reader.readLine();
} hec1Vector.addElementAt(hec1Group.clone(), dividerCount);
hec1Reader.close();
} catch (java.io.IOException ioe) {LogHandlerEvent("Error Reading " + hec1File.getName(),
    Logger.SYSTEM, Logger.S_ERROR);
    throw new FASEException("Error Reading " + hec1File.getName());
}

endDate = watershed.getLastData();
// System.out.println(hec1Vector.toString());
initialized = true;
}

protected void refreshSubclass() throws FASEException {

    // if the taskhandler needs more than one archiver, create them in refreshSubclass.
    // Use this same basic code, with appropriate names. The rest can be the same.
    // Be sure to declare the variables in the class definition, though.

    if (getHandlerArchiving() && (hec1OutArchiver == null)) {

hec1OutArchiver = new Archiver("Task archiver (" + getWatershedUniqueID() + "_." + getHandlerName() + " for HEC1 Output)",
    getWatershedID() + File.separator +
    getHandlerName(),
    getArchiveTypes(), getWatershedUniqueID());
    AddLogEntry(hec1OutArchiver.getName() + " started with types: " +
    getArchiveTypes().toString() + " and directory: " + getWatershedID() +
    File.separator + getHandlerName(),
    Logger.SYSTEM, getWatershedID(),
    Logger.S_VERBOSE);
    } else if (!getHandlerArchiving() && (hec1OutArchiver != null)) {
hec1OutArchiver = null;
}
if (getHandlerArchiving() && (hydroArchiver == null)) {
    hydroArchiver = new Archiver("Task archiver " +
              getWatershedUniqueID() + "_" + getHandlerName() + " for HEC1 Output",
              getWatershedID() + File.separator +
              getHandlerName(),
              getArchiveTypes(), getWatershedUniqueID());
    AddLogEntry(hydroArchiver.getName() + " started with types: " +
              getArchiveTypes().toString() + " and directory: " + getWatershedID() +
              File.separator + getHandlerName(),
              Logger.SYSTEM, getWatershedID(),
              Logger.S_VERBOSE);
} else if (!getHandlerArchiving() && (hydroArchiver != null)) {
    hydroArchiver = null;
}

//add secondary and tertiary archivers, for the hec1 output, and
//for any graphics
//without having to create a new taskhandler to do it.

    //do nothing
}

public void asyncHandle() throws FASEException {
    // System.out.println("Start Of asyncHandle");
    if (!initialized) return;

    // System.out.println("Start Of asyncHandle - initialized");
    if (lastDataFileUsed == null) lastDataFileUsed = "0";
    String watershedLastData = watershed.getLastDataFile();

    // for debugging, I commented out these lines. I want the HEC1 to run a
    // lot until I figure out what's up.

    if (watershedLastData.equals(lastDataFileUsed)) return;

    lastDataFileUsed = watershedLastData;
    endDate = watershed.getLastData();

    // Object gages_temp = prefs.getPref(FAS.HANDLER_HEC1_GAGES);
    // Vector gages = new Vector();
    // if (gages_temp instanceof String)
    //     gages.addElement((String)gages_temp);
    // else
    //     gages = (Vector)gages_temp;

    Vector data = new Vector();
    hoursToHEC1 =
              Integer.parseInt((String)prefs.getPref(FAS.HANDLER_HEC1_HOURS));

    hec1StartTimeStr = dateFormatter.format(new
          Date(endDate.getTime() -hoursToHEC1*3600000));
Input westOfMain = watershed.getInput( "brays_wm" );
avgRainfall = findInputData(westOfMain, hoursToHEC1);

// String heclNowTimeStr = endDate.toString();

/*
 * try {
 * maxHole = Integer.parseInt(firstInput());
 * }
 * catch(NumberFormatException e) {
 * LogHandlerEvent("max_missing_data isn't a number. Defaulting
to 6000",
 * Logger.SYSTEM, Logger.S_ERROR);
 * maxHole = 6000;
 * }
 * */

// LogHandlerEvent("hecl Test - before findInputData.",
Logger.SYSTEM, Logger.S_NORMAL);

// comment everything from here to 'read hydrograph' for testing

for (int j = 0; j < hec1GageOrder.size(); j++) {
    Input thisInput = watershed.getInput(
(String)hec1GageOrder.elementAt(j));
data.addElement( findInputData(thisInput, hoursToHEC1) );
}

try {
    FileWriter test = new
FileWriter(watershed.getRadarCurrentOutputPath() + filename);

    // writes regular data to a local file
    PrintWriter dataOutput = new PrintWriter(test);
    // LogHandlerEvent("hecl Test - before generateHEC1Cards.",
Logger.SYSTEM, Logger.S_NORMAL);
    // String[] hec1 =
    OutputUtil.Singleton.generateHEC1Cards(hec1GageOrder, data, hec1Vector,
hec1StartTimeStr, endDate);
    String[] hec1 = generateHEC1Cards(data);
    for (int j=0; j < hec1.length; j++)
        dataOutput.println(hec1[j]);
dataOutput.close();
test.close();
}

} catch(IOException e) {

LogHandlerEvent("Error (" + e.getMessage() + ") on write to temporary HEC1 file.", Logger.SYSTEM, Logger.S_ERROR);
}

try {
    FileWriter test2 = new FileWriter(watershed.getRadarCurrentOutputPath() + dateFileName);
    // writes regular data to a local file
    PrintWriter dateFile = new PrintWriter(test2);
    dateFile.println(hec1StartTimeStr + " " + endDate);
    dateFile.close();
    test2.close();
}

catch(NoSuchElementException e) {
    LogHandlerEvent("Error (" + e.getMessage() + ") on write to HEC1 date file.", Logger.SYSTEM, Logger.S_ERROR);
}

// have VirtualPC run HEC1, concatenate the date file with the MainStHydrograph file, then delete the filename + "e" file.
    // when this file is gone, we will know that hec1 is done, and that the output file can be read.

    // Now that we've made the hec1 file, we need to run it and read the output and create a graph of some sort.
    //String[] cmd1 = {"/usr/bin/osascript", ",-e", " tell application "Virtual PC" to activate "};
    //String[] cmd2 = {"/usr/bin/osascript", ",-e", " tell application "Virtual PC" to execute "c:\\hec1runs\\hec1run.bat " + watershed.getID() + "\\CurrentStatus\\\\" + watershed.getWatershedRadar() + "\\ in virtual machine "Win2k" " };
    // System.out.println(cmd0.toString());
    // System.out.println(cmd1.toString());
   
    try {
        Process p1 = Runtime.getRuntime().exec(cmd1,null);
        p1.waitFor();
        Process p2 = Runtime.getRuntime().exec(cmd2,null);
        p2.waitFor();
        /* System.out.println("Error Messages -- ");
        BufferedReader br = new BufferedReader(new InputStreamReader(p.getErrorStream()));
        System.out.println(br.readLine());
        System.out.println("Input Stream -- ");
*/
BufferedReader bri = new BufferedReader(new InputStreamReader(p.getInputStream()));
System.out.println(bri.readLine());
/*
// ByteArrayOutputStream bro =
(ByteArrayOutputStream)p.getOutputStream();
// System.out.println(bro.toString());
*/
} catch (Exception ioe) {
    System.out.println("Exception! " + ioe);
}

boolean finishedHEC1 = false;

File dateFile = new File(watershed.getRadarCurrentOutputPath() + dateFileName);
for (int i = 0; i<45; i++) {
    if (dateFile.exists()) {
        System.out.println("sleeping for 10 to wait for HEC1
to finish");
        try {
            Thread.sleep(10000);
        } catch (InterruptedException ie) {};
    } else {
        System.out.println("HEC1 Complete");
        hydrograph = readHec1Output();
        finishedHEC1 = true;
    }
    if (finishedHEC1)
        continue;
}
if (!finishedHEC1) {
    LogHandlerEvent("Ran out of time on write to HEC1 png file.",
        Logger.SYSTEM, Logger.S_ERROR);
    return;
}
System.out.println("hcoemGage = " + hcoemGage);
System.out.println("(FASServer)driver +
((FASServer)driver).getTask(hcoemGage).toString() ");

hcoemData =
((HcoemDataHandler)((FASServer)driver).getTask(hcoemGage)).getHcoemData();
// System.out.println(hydrograph);
// System.out.println(hcoemData);

BufferedImage myGraph = drawHydrograph();
//hydrograph,endDate,hcoemData
uploadImage(myGraph);
myGraph.flush();

LogHandlerEvent("Uploaded HEC1 image.",

//archiving with secondary archivers must be set manually
archiveFile(heciOutArchiver,new File(heciOut));
//archiving with secondary archivers must be set manually
archiveFile(hydroArchiver,new File(hydroOut));

String archivefile = watershed.getRadarCurrentOutputPath() + filename;

/*archiveFile(new File(archivefile));
this.enableArchive();
grabDate(archivefile);*/

archiveHandler(archivefile);
}

protected void do_archiving() {

/**
* Creates a row containing error elements.
* Returns a <code>Vector</code> representing HEC1 PC Cards containing "n/a" elements
* in the columns. This method places <code>name</code> into the first column, and then
* places "n/a" in <code>length</code> number of columns and returns the <code>Vector</code>. *
* @param name the name to place in the first column
* @param length the number of "n/a" columns to add
*/
private Vector returnErrorVector(int length) {
    Vector output = new Vector();
    for (int i=0; i<length; i++)
        output.addElement("0.0");
    return output;
}

/**
* Creates a row of data for an <code>Input</code>.
* Returns a Vector representing the data for the <code>Input i</code>.  
* It uses <code>OutputUtil.getTotalRainfall</code> in order to calculate
* the past <code>hours</code> total rainfall, and writes the result to
* the output <code>Vector</code>.
* @param i the Input for which to calculate the data
* @param hours the hours which to calculate data for
* @return Vector containing the data rows
*/
private Vector findInputData(Input i, int hours) {
    Vector data = new Vector();
    String myDF = (String)
prefs.getPref(FAS.HANDLER_HEC1_DECIMAL_FORMAT);
    //LogHandlerEvent("hec1 Test - inside findInputData - before
    getCumulativeRainfall." + i.getTitle().toString(), Logger.SYSTEM,
    Logger.S_NORMAL);

data.addAll(OutputUtil.Singleton.getCumulativeRainfall(i.getData(),
hours+1, myDF));

    return data;
}

/**
* Creates a Vector containing the contents of the HEC1 Output
* File.
* Returns a Vector representing the last row of the HEC1 PC Card,
* containing a
* timestamp. This method simply returns the representation of the
* last row
* of an HTML table, with a given <code>colSpan</code>, containing
* only
* a timestamp.
* *
* @param colSpan the number of columns for the cell to span
* @param i the <code>Controller</code> which called this output
* @return Vector containing the timestamp
*/
private Vector readHec1output() throws FASException {

    BufferedReader outReader;
    Vector hydrograph = new Vector();
    String outLine;
    Vector tmpData = new Vector();

    // System.out.println(hec1Out);

    try {
        outReader = new BufferedReader(new FileReader(hec1Out));
    } catch (java.io.FileNotFoundException e) {
        return hydrograph;
    }

    String tmpIntStr;

    // hec1Line=hec1Reader.readLine();
    try {
        while ((outLine=outReader.readLine()) != null) {
            System.out.println(outLine);
            // System.out.println(hec1Line);
            if (outLine.startsWith("QI")) {

for (StringTokenizer st = new StringTokenizer(outLine.substring(2)); st.hasMoreElements(); ) {
    tmpIntStr = st.nextToken();
    // System.out.println(tmpIntStr);
    // System.out.println(Integer.decode(tmpIntStr));
    hydrograph.addElement(Double.valueOf(tmpIntStr));
}

heclLine=heclReader.readLine();
}
outReader.close();
} catch (java.io.IOException io) {LogHandlerEvent("Error Reading " + heclOut,

Logger.SYSTEM, Logger.S_ERROR);
    throw new FASException("Error Reading " + heclOut);
}

return hydrograph;
}

private BufferedImage drawHydrograph() throws FASException {
    //Vector hydrograph, Date endDate, Vector hcoemData

    Vector flowsToPlot = new Vector();
    int dt = 5;
    int startHydrograph = -12;
    int endHydrograph = 12;
    int xTicks = 12;
    double baseFlow = 200d;
    Date updated = watershed.getLastData();

    Vector hcoemDates = new Vector();
    Vector hcoemFlows = new Vector();
    Vector hcoemStages = new Vector();
    double doubleStart = (double)(startHydrograph*3600*1000);
    double doubleEnd = (double)(endHydrograph*3600*1000);
    double hr;

    int hcoemMaxFlow = 0;
    Date hcoemMaxFlowDate = new Date();

    for (Enumeration enum = hcoemData.elements();
        enum.hasMoreElements(); )
    {
        RatedStreamDateTime rsdt =
(RatedStreamDateTime)(enum.nextElement());
        hr = (double)(rsdt.getTime().getTime() - updated.getTime());
        if (hr > doubleStart & hr < doubleEnd) {
            hcoemDates.addElement(new Double(hr/3600/1000));
            hcoemFlows.addElement( new Double(rsdt.getFlow() ) );
            hcoemStages.addElement(new Double(rsdt.getData() ) );
        }
    }
if ( (int)rsdt.getFlow() > hcoemMaxFlow)
{
    hcoemMaxFlow = (int) rsdt.getFlow();
    hcoemMaxFlowDate = (Date)rsdt.getTime();
}

// System.out.println(hcoemDates.lastElement() + " " + hcoemFlows.lastElement() + " " + hcoemStages.lastElement());
}

int plotStartIndex = (hoursToHEC1 + startHydrograph) * 60/dt;
int plotEndIndex = (hoursToHEC1 + endHydrograph) * 60/dt;
int plotNowIndex = hoursToHEC1 * 60/dt;

//System.out.println(hydrograph.size());

// System.out.println("pSI " +plotStartIndex + ", pEI " + plotEndIndex + ", pNI " + plotNowIndex);

int hec1MaxFlow = hcoemMaxFlow;
int tmpFlow;
Date hec1MaxTime = updated;
for (int i=plotStartIndex; i<= plotEndIndex; i++){
    tmpFlow = (int)((Double)hydrograph.elementAt(i)).doubleValue() + baseFlow;
    flowsToPlot.addElement(new Double(tmpFlow));
    // System.out.println(hydrograph.elementAt(i));
    if ( tmpFlow > hec1MaxFlow )
    {
        hec1MaxFlow = tmpFlow;
        // System.out.println(hydrograph.elementAt(i));
        hec1MaxTime = new Date(updated.getTime() + (long)((-hoursToHEC1 + (double)i*(double)dt/60d)*3600d*1000d));
    }
}
tmpFlow = (int)Math.ceil(hec1MaxFlow/5000d);
// System.out.println(hec1MaxFlow/5000d);
double maxFlow = (double)(tmpFlow*5000d);
int yTicks;
if (tmpFlow < 3) {
    yTicks = tmpFlow * 5;
} else if (tmpFlow < 5) {
    yTicks = tmpFlow * 2;
} else {
    yTicks = tmpFlow;
}

// System.out.println(hec1MaxFlow + ", " + maxFlow + ", " + tmpFlow + ", " + yTicks);
//System.out.println(hydrograph);
LineChart myChart = new LineChart();

    // these allow FAS to manually scale/set ticks of the axes
    myChart.getXAxis().setAutoScale(false);
    myChart.getYAxis().setAutoScale(false);
    
    // these set up the axes (start, end, and ticks)
    myChart.getXAxis().setAxisStart(startHydrograph);
    myChart.getXAxis().setAxisEnd(endHydrograph);
    double maxFlow = 35000d;
    myChart.getYAxis().setAxisStart(0);
    double y = getNum((double)2.5, FAS.HANDLER NOMOGRAPH_HEIGHT);
    myChart.getYAxis().setAxisEnd(maxFlow);
    x = getNum(10, FAS.HANDLER NOMOGRAPH_LENGTH_TICKS);
    myChart.getXAxis().setNumLabels(xTicks);
    myChart.getXAxis().setNumMajTicks(xTicks);
    y = getNum(5, FAS.HANDLER NOMOGRAPH_HEIGHT_TICKS);
    myChart.getYAxis().setNumLabels(yTicks);
    myChart.getYAxis().setNumMajTicks(yTicks);

    // these set up the grid
    myChart.getXAxis().setGridVis(true);
    myChart.getYAxis().setGridVis(true);
    myChart.getXAxis().setNumGrids(1);
    myChart.getYAxis().setNumGrids(1);

    // these set up the position of the chart on the image
    y = getNum((double)0.125, FAS.HANDLER NOMOGRAPH_LOWERLEFT_X);
    myChart.getPlotarea().setLlx(0.125);
    y = getNum((double)0.125, FAS.HANDLER NOMOGRAPH_LOWERLEFT_Y);
    myChart.getPlotarea().setLly(0.125);
    y = getNum((double)0.92, FAS.HANDLER NOMOGRAPH_UPPERRIGHT_X);
    myChart.getPlotarea().setUrX(0.92);
    y = getNum((double)0.92, FAS.HANDLER NOMOGRAPH_UPPERRIGHT_Y);
    myChart.getPlotarea().setUrY(0.92);

    // these set up the labels on the axes
    String title =
    (String)prefs.getPref(FAS.HANDLER NOMOGRAPH_X_TITLE) +
    String title = "HEC-1 Model Output" +
    " - " + updated.toString();
    myChart.getXAxis().setTitleString(title);
    title = (String)prefs.getPref(FAS.HANDLER NOMOGRAPH_Y_TITLE);
    title = "Flow (cfs)";
    myChart.getYAxis().setTitleString(title);

    // these set up the position of the legend on the graph
    // put into prefs file ?
    myChart.getLegend().setVerticalLayout(false);
    myChart.getLegend().setLlx(0.3);
    myChart.getLegend().setLly(0.925);
    myChart.setLegendVisible(true);

    // this retrieves the width and height of the nomograph image
    int width = getNum(550, FAS.HANDLER NOMOGRAPH_PIXEL_WIDTH);
int height = getNum(380, FAS.HANDLER_NOMOGRAPH_PIXEL_HEIGHT);

int width = 550;
int height = 380;

// draw!
BufferedImage output = new BufferedImage(width, height, BufferedImage.TYPE_INT_RGB);
Graphics g = output.getGraphics();
myChart.resize(width, height);

double[] blank = new double[0];

// set line colors
myChart.addDataSet("HEC1 Flow", blank, blank);
myChart.addDataSet("HCOEM Observed Flow", blank, blank);
myChart.getDatasets()[0].getGc().setLineColor(new Color(0).blue);
myChart.getDatasets()[1].getGc().setLineColor(new Color(0).red);

myChart.drawGraph(g);

int l1x = (int)((getNum((double)0.125, FAS.HANDLER_NOMOGRAPH_LOWERLEFT_X))*width);
int l1y = (int)((getNum((double)0.125, FAS.HANDLER_NOMOGRAPH_LOWERLEFT_Y))*height);
int urx = (int)((getNum((double)0.92, FAS.HANDLER_NOMOGRAPH_UPPERRIGHT_X))*width);
int ury = (int)((getNum((double)0.92, FAS.HANDLER_NOMOGRAPH_UPPERRIGHT_Y))*height);

int l1x = (int)(0.125*width);
int l1y = (int)(0.125*height);
in urx = (int)(0.92*width);
int ury = (int)(0.92*height);

double length = getNum((double)10, FAS.HANDLER_NOMOGRAPH_LENGTH);
double range = getNum((double)2.5, FAS.HANDLER_NOMOGRAPH_HEIGHT);

double length = (double)(endHydrograph - startHydrograph);
double range = maxFlow;

int yTicks = getNum(5, FAS.HANDLER_NOMOGRAPH_HEIGHT_TICKS);
double yHeight = getNum((double)2.5, FAS.HANDLER_NOMOGRAPH_HEIGHT);

double xWidth = length;

double yHeight = maxFlow;

// create y-values of points on grid on the graph
int[] yValues = new int[(ury-l1y)/2];
int[] xValues = new int[(urx-l1x)/2];
int[] yValues2 = new int[yTicks-1];
int[] xValues2 = new int[xTicks-1];
int counter = 0;
for (int i = lly; i < ury; i=i+2) {
    yValues[counter] = i;
    counter++;
}
yValues[counter-1] = ury-1;

counter = 0;
for (int i = llx; i < urx; i=i+2) {
    xValues[counter] = i;
    counter++;
}
xValues[counter-1] = urx-1;

counter = 0;
double interval = yHeight/yTicks;
    // System.out.println("interval " + interval);
for (double i = interval; i < yHeight; i=i+interval) {
    yValues2[counter] = (int)(height - (((i/yHeight) * (ury - lly) + lly));
    // System.out.println("yValues2[" + counter + "] " +
yValues2[counter]);
    counter++;
}

counter = 0;
double xInterval = xWidth/xTicks;
    // System.out.println("interval " + xInterval);
for (double i = xInterval; i < xWidth; i=i+xInterval) {
    xValues2[counter] = (int)((i/xWidth) * (urx - llx) + llx));
    // System.out.println("xValues2[" + counter +
*] " + xValues2[counter]);
    counter++;
}

// create the pixel values of the plot lines
Vector now = new Vector();
now.addElement(new Double(0d));
    // System.out.println("now.size() = " + now.size());
    //int[] nowInt =
convertToXPixels(now,length,startHydrograph,llx,urx);
    int[] nowInt =
GraphTools.convertToPixels(now,startHydrograph,endHydrograph,llx,urx);
    int[] xAxisIsInt =
GraphTools.convertToPixels(GraphTools.createHEC1XValues((double)dt/60d,
startHydrograph, endHydrograph),
    startHydrograph, endHydrograph, llx, urx);
    // int[] hec1ModelFlow = convertToYPixels(flowsToPlot, range, lly, ury, height);
    int[] hec1ModelFlow = GraphTools.convertToPixels(flowsToPlot, 0d, maxFlow, height-lly+1, height-ury+1);
    // vertical, because lly actually is the top of the graph.
System.out.println("maxFlow = " + maxFlow + ", ury = " + ury + ", lly = " + lly);
System.out.println(flowsToPlot);
int[] obsTimes = convertToXPixels(hcoemDates, length, startHydrograph, llx, urx);
int[] obsFlows = convertToYPixels(hcoemFlows, range, lly, ury, height);
int[] obsTimes = GraphTools.convertToPixels(hcoemDates, startHydrograph, endHydrograph, llx, urx);
int[] obsFlows = GraphTools.convertToPixels(hcoemFlows, 0d, maxFlow, height-lly+1, height-ury+1);
int dataLength = xAxisint.length;
int obsLength = obsTimes.length;
System.out.println(dataLength + " <- axis: data-> " + hec1ModelFlow.length);
System.out.println(dt);
System.out.println(obsTimes[0] + ", obsLength = " + obsLength);
for (int i=0; i<obsLength; i++)
    System.out.println("obsTimes[" + i + "] = " + obsTimes[i] + ", obsFlows[" + i + "] = " + obsFlows[i]);

counter=0;
double[] avgRainfallPlot = new double[-startHydrograph];
double maxAvgRF = 0d;
for (int i = hoursToHEC1+startHydrograph; i< hoursToHEC1;i++) {
    avgRainfallPlot[counter] =
    Double.parseDouble((String)(avgRainfall.elementAt(i) + ")") -
    Double.parseDouble((String)(avgRainfall.elementAt(i) + ");
    if(maxAvgRF < avgRainfallPlot[counter]) {
        maxAvgRF = avgRainfallPlot[counter];
    }
    counter ++;
}

int ceilMaxAvgRF = (int)Math.ceil(maxAvgRF);

int[] xAxisRF =
    GraphTools.convertToPixels(GraphTools.createHEC1XValues(1d, startHydrograph, 0d),
    startHydrograph, endHydrograph, llx, urx);
int[] yAxisRF =
    GraphTools.convertToPixels(avgRainfallPlot, 0d, ceilMaxAvgRF,
    height-lly+1, height-ury+1);

g.setColor(new Color(0).black);
Font hec1Font = new Font("TimesRoman", Font.BOLD, 13);
g.setFont(hec1Font);
g.drawString(Integer.toString(ceilMaxAvgRF) , urx + 5, height - ury + 5);
g.drawString("in/hr", urx + 5, 
    height - ury + 5 + 16);

g.setColor(new Color(0).lightGray);

    for (int i=0; i<startHydrograph;i++) {
        // System.out.println("i" + i + " y0= " + (height - lly + 1) + " yRF=" + yAxisRF[i] + " rf=" + avgRainfallPlot[i]);
        if(yAxisRF[i] < height-lly & maxAvgRF > 0) {
            // System.out.println("drawing: i=" + i + " y0= " + (height - lly + 1) + " yRF=" + yAxisRF[i] + " rf=" + avgRainfallPlot[i]);
            g.fillRect(xAxisRF[i],height-lly,xAxisRF[i]-xAxisRF[i]+1,yAxisRF[i]-(height-lly));
        }
    }

    // System.out.println("Drawing HEC1");

g.setColor(new Color(0).yellow);
g.fillRect(nowint[0], height - yValues[yValues.length-1], urx-
nowint[0], yValues[yValues.length-1] - yValues[0]);

    // draw y-axis lines vertical grid lines
    g.setColor (new Color(0).gray);
    for (int i = 0; i < xValues2.length; i++)
        // for (int j = 0; j < yValues.length; j++)
            g.drawLine(xValues2[i], height - yValues[0], xValues2[i],
height - yValues[yValues.length-1]);

    // System.out.println("ht = " + height + " y0 = " + yValues[0]
    + " y1 = " + yValues[yValues.length-1]);

    // draws x-axis lines horizontal grid lines
    // for (int i = 0; i < xValues.length; i++)
    for (int j = 0; j < yValues2.length; j++)
        g.drawLine(xValues[0], yValues2[j], xValues[xValues.length-1],
yValues2[j]);

    g.setColor (new Color(0).red);
g.drawLine(nowint[0], height - yValues[0], nowint[0], height -
yValues[yValues.length-1]);
    // draw lines
    g.setColor(Color.blue);
g.drawPolyline(xAxisInt, hec1ModelFlow, dataLength-1);
g.setColor(Color.red);
    if (obsTimes.length > 0) g.drawPolyline(obsTimes, obsFlows,
obsLength);

    // draw points
    // for (int i = 0; i < dataLength-1; i++) {
    //    g.setColor(Color.black);
g.drawRect(xAxisint[i]-3, hec1ModelFlow[i]-3, 6, 6);
g.setColor(Color.blue);
g.fillRect(xAxisint[i]-2, hec1ModelFlow[i]-2, 5, 5);
}

//add text to Nomograph
int maxDuration =
streetlight.getMaxFlowduration(gageID(gage)).intValue();
double maxFlowrate =
streetlight.getMaxFlowrate(gageID(gage)).intValue();
Date maxTime = ((DateTime)maxAllData.elementAt(maxDuration-1)).getTime();

double tempxplace = getNum((double)0.19,
FAS.HANDLER_NOMOGRAPH_TEXT_X);
int xplace = (int)(tempxplace * width);
double tempyplace = getNum((double)0.15,
FAS.HANDLER_NOMOGRAPH_TEXT_Y);
int yplace = (int)(tempyplace * height);
double tempseparation = getNum((double)13.0,
FAS.HANDLER_NOMOGRAPH_TEXT_SEPARATION);
int separation = (int)tempsparation;

int xplace = (int)(0.20d * width);
int yplace = (int)(0.15d * height);
int separation = 16;

g.setColor(new Color(0).black);
g.setFont(hec1Font);

if (hcoemMaxFlow > 500 | hec1MaxFlow > 500) {

g.drawString("Max observed flow: " + hcoemMaxFlow + " cfs",
xplace, yplace);
g.drawString("Peak Observed Flow at: " , xplace, yplace + separation);
g.drawString(hcoemMaxFlowDate.toString() , xplace, yplace + 2*separation);
g.drawString("Max modeled flow: " + hec1MaxFlow + " cfs",
xplace,
yplace + 3*separation);
g.drawString("Peak Modeled Flow at: " , xplace, yplace + 4*separation);
g.drawString(hec1MaxTime.toString() , xplace, yplace + 5*separation);
}

if (hec1MaxFlow > baseFlow + 500 &
((Double)hydrograph.elementAt(plotNowIndex)).doubleValue() > baseFlow + 50 ) {

    // & hydrograph.elementAt(plotNowIndex) > 100
Iterator e = ((FASServer)driver).watershedCollection().iterator();
while (e.hasNext()) {
    Watershed w = (Watershed)e.next();
    if (w.getUniqueID().startsWith(watershed.getID())) {
        //System.out.println("Gage Up, Archiving, watershed " +
        w.getUniqueID());
        FAS.setArchiveUntil(w.getID(), w.getWatershedRadar(),
        60*60*1000);
    }
}

return output;

private double getNum(double d, String prefString) {
    double attempt = d;
    try {
        attempt = Double.parseDouble((String)prefs.getPref(prefString));
    }
    catch(NumberFormatException n) {
        LogHandlerEvent(prefString = " is not a number. Using a
default of " +
        d + ".", Logger.SYSTEM, Logger.S_WARNING);
    }
    return attempt;
}

/**
 * createXAxis:
 *
 * @param set double[]
 * @return Vector
 */
private Vector createXAxis(int dt, int start, int end ) {
    Vector output = new Vector();
    int numPts = (int)((end - start) * 60 / dt) + 1;
    for (int i = 0; i < numPts; i++)
        output.addElement( new Double((double)start+((double)i)*((double)dt)/60d) );
    return output;
}

private void uploadImage(BufferedImage output) throws FASException {
    String errorMessage = "error creating final hecl image.";
}
try {
    JimiSync.singleton.makePNGFromImage(hydroOut, output);
}

} catch(JimiException j) {
    LogHandlerEvent("Jimi " + errMessage, Logger.SYSTEM, Logger.S_ERROR);
    throw new FASException("Jimi " + errMessage + " Exception message: " + j.getMessage());
}

} catch(FileNotFoundException f) {
    LogHandlerEvent("File " + errMessage, Logger.SYSTEM, Logger.S_ERROR);
    throw new FASException("File " + errMessage + " Exception message: " + f.getMessage());
}

/**
 * convertToXPixels:
 *
 * @param linex Vector
 * @param length double
 * @param start int
 * @param end int
 * @return int[]
 */
private int[] convertToXPixels(Vector linex, double length, int startData, int startPix, int endPix) {
    int linexLen = linex.size();
    int[] line = new int[ linexLen + 1 ];

    for (int k=0; k < linexLen; k++)
        line[k] = (int) (( (Double)linex.elementAt(k)).doubleValue() - startData)/length) * (endPix - startPix) + startPix;
    line[linexLen] = endPix;

    return line;
}

/**
 * convertToYPixels:
 *
 * @param liney Vector
 * @param height double
 * @param start int
 * @param end int
 * @param imageheight int
 * @return int[]
 */
private int[] convertToYPixels(Vector liney, double height, int start, int end, int imageheight) {
    int lineyLen = liney.size();
    int[] line = new int[ lineyLen + 1 ];

    for (int k=0; k < lineyLen; k++)
        line[k] = (int) (( (Double)liney.elementAt(k)).doubleValue() - startData)/length) * (endPix - startPix) + startPix;
    line[lineyLen] = endPix;

    return line;
}
for (int k=0; k < lineyLen; k++)
    line[k] = (int) (imageheight - (((Double)liney.elementAt(k)).doubleValue() /height) * (end - start) + start));
    line[lineyLen] = imageheight - end + 1;

    return line;
}

/**
 * generateHEC1Cards:
 * This method creates the HEC1 cards for the gages
 * It will be modified to add a parameter for the rest of the
 * HEC1 file, and will add that to its output.
 * 
 * @param data Vector
 * @param gages Vector
 * @return String[]
 */
public String[] generateHEC1Cards(Vector data) {
    //Vector gages, Vector data, Vector heclfile, String startTimeStr, Date endTime
    //hec1GageOrder, data, heclVector, hec1StartTimeStr, endDate

    Vector cards = new Vector();
    int thisGage;
    int modelDT = 5;
    int rainfallDT = 60;
    int numTS = 1200;
    //    cards.addElement("KM Insert HEC1 Header Here");
    cards.addAll((Vector)heclVector.elementAt(0));
    cards.addElement("ID Last Data at: " + endDate.toString());
    cards.addElement("IT," + modelDT + "," + hec1StartTimeStr + ", "+numTS);
    cards.addElement("IO,5,0,0");
    cards.addElement("IN," + rainfallDT + "," + hec1StartTimeStr);
    cards.addAll((Vector)heclVector.elementAt(1));
    // need to add the IT, IO, and IN lines here.
    // format: IT, model dt, date, time, nsteps
    // IO,5,0,0
    // IN,rainfall dt, date, time
    // need to format the date as ddMMyy and time as HHmm
    // going to add a new argument for the method, with the
    // date-time string ddMMyy,HHmm

    //heclfile is a Vector of Vector of String
    for (int i=0; i < hec1GageOrder.size(); i++){
cards.addElement("KM Rainfall :" + i + "+" +
(String)heclGageOrder.elementAt(i));
cards.addElement("PB 0");
cards.addAll((Vector)generateHEC1PCCards((Vector)data.elementAt(i)));
cards.addAll((Vector)heclVector.elementAt(i+2));
}

return (String[])cards.toArray(new String[0]);
}

/**
 * generateHEC1PGPCCards:
 * This method creates one PG/PC Card set using the
 * elements of the Vector data input as each of the PC card
 * data. Each of the elements are converted to String representation
 * using the toString() method. The PG card is created using
 * 
 * @param data Vector
 * @param gage String
 * @param gageReplaces String
 * @return Vector
 */
public Vector generateHEC1PCCards(Vector data) {
    Vector cards = new Vector();
    StringBuffer temp = new StringBuffer("";
    for (int i=0; i <= (data.size()-1)/10; i++){
        temp.setLength(0);
        int numLeft = data.size() - 10*(i);
        if (numLeft > 10) numLeft=10;
        temp.append("PC");
        for (int j=0; j<numLeft; j++){
            temp.append(""," + data.elementAt(i*10+j).toString());
        }
        cards.addElement(temp.toString());
    }
    return cards;
}
HCOEM Handler:

package org.floodalert.fas.tasks;

import org.floodalert.fas.FASDriver;
import org.floodalert.fas.server.FASServer;
import org.floodalert.fas.util.*;
import org.floodalert.fas.alert.AlertHandler;
import org.floodalert.fas.exception.*;

import org.floodalert.fas.controllers.prefs.*;
import org.floodalert.fas.controllers.*;
import org.floodalert.fas.controllers.inputs.*;
import org.floodalert.fas.controllers.outputs.*;

import java.io.*;
import java.util.Enumeration;
import java.util.Collection;
import java.util.Hashtable;
import java.util.Vector;
import java.util.Iterator;
import org.floodalert.fas.simulation.Date;
import java.util.Calendar;
import java.util.GregorianCalendar;
import java.util.StringTokenizer;

import java.net.URL;
import java.net.MalformedURLException;

import java.text.SimpleDateFormat;

/**
 * HcoemDataHandler:
 * Reads stream level data from HCOEM website and prepares it for FAS website
 * Will need a separate handler for rain gage data if we ever get it.
 */
public class HcoemDataHandler extends TaskHandler {

    private Vector coefficients = new Vector();
    private RatedStreamGage rsGage;
    private Date lastDataReceived;
    private Vector flowData = new Vector();
    private boolean initialized = false;
    static protected SimpleDateFormat dateReader = new SimpleDateFormat("MM/dd/yyyy HH:mm:ss");
    private String hcoemfile = this.getHandlerName() +
    getHandlerOutput().getProperty("fileExtension");
    private String ricefile = (String) getHandlerInput().get("input");
    private double topOfBank =
    Double.parseDouble((String) this.getHandlerInput().get("topOfBank"));
private double bottomOfChannel =
Double.parseDouble((String) this.getHandlerInput().get("bottomOfChannel"));
private double minArchive =
Double.parseDouble((String) this.getHandlerInput().get("minArchive"));
private double datumAdjust =
Double.parseDouble((String) this.getHandlerInput().get("datumAdjust"));

public HcoemDataHandler(PASDriver d, Prefs p, Watershed w) throws FASException {
    super(d, p, w); // does a refresh

    String tempcoef = (String)getHandlerInput().get("coefficients");

    for (StringTokenizer st = new StringTokenizer(tempcoef, ","); st.hasMoreElements();)
        coefficients.addElement(new Double(st.nextToken()));

    rsGage = new RatedStreamGage(this.getHandlerName(),
this.getHandlerName(), w, coefficients);
    initialized = true;
}

protected void refreshSubclass() throws FASException {
    // do nothing, for now
    /* There is nothing here that can't be done in the refresh of super.
    */
}

/**
 * Handles updating
 * @exception Exception to signal an error w/ the update.
 * @return The File object representing the file updated.
 */
public void asynch_handle() throws FASException{
    if (!initialized) return;

    /** makes the assumption that the first URL and first Output are
     * the relevant ones.
     * there is little reason that this should not be so, based on
     * structure of the prefs file
     */
    if (hcoemfile == null) {
        throw new FASException("HcoemData: no output file specified");
    }
    if (ricefile == null) {
        throw new FASException("HcoemData: no inputfile specified");
    }

    String text;
URL url;
try {
    url = new URL(this.firstURL() + "" + ricefile);
text = this.httpGet(url);
} catch(MalformedURLException e) {
    throw new FASEException("Malformed URL " + this.firstURL());
} catch(IOException e) {
    throw new FASEException("HcoemData IOException: " + e.getMessage());
}

/**
 * StringWriter (in conjuction with StringTokenizer) was used
 * because
 * the tokenizing needed was a bit too lightweight to do with
 * StreamTokenizer, since the only delimiters were " " and "\n"
 */

boolean infoRetrieved = false;
boolean inDataSection = false;

if (rsGage.getLastTime() == null) {
    lastDataReceived = new Date(01);
} else {
    lastDataReceived = rsGage.getLastTime();
}

String temp = "";
Vector tmpData = new Vector();
Vector data = new Vector();
Vector dataStrings = new Vector();
Date tmpdate = null;

for (StringTokenizer st = new StringTokenizer(text, "\r\n", false);
    st.hasMoreTokens() && !infoRetrieved;) {
    String line = st.nextToken();
    if (line.indexOf("raw_data") > 0) {
        inDataSection = true;
        temp = line.substring(line.indexOf(">")+1);
        // System.out.println("First," + temp + ",");
        // data.addElement(parseData(temp));
        // dataStrings.addElement(getDataString((Vector)data.lastElement()));
        if(temp.length() >= 26) {
            tmpdate = new Date(dateReader.parse(temp.substring(0,19),
java.text.ParsePosition(0)).getTime();
    // System.out.println("LastDataReceived = " +
    lastDataReceived + ", tmpdate = " + tmpdate);
    // if (lastDataReceived == null ||
    tmpdate.after(lastDataReceived)) // don't change order of 'or'
    // {
    //     System.out.println("Data String is: " +
    temp.substring(19,26));
    //     System.out.println("Data Double is: " +
    Double.parseDouble(temp.substring(19,26)));
    tmpData.addElement(new
    DateTime(Double.parseDouble(temp.substring(19,26)) + datumAdjust, tmpdate)
    );
    // }
    // else
    //     infoRetrieved = true;
    } else if (inDataSection && line.indexOf("<") > 0) {
    inDataSection = false;
    infoRetrieved = true;

    if (line.indexOf("<") >= 26) {
    // System.out.println("Last," +
    line.substring(0,line.indexOf("<")-1) + ",");
    // data.addElement(parseData(line.substring(0,line.indexOf("<")-1)));
    // dataStrings.addElement(getDataString((Vector)data.lastElement()));
    tmpdate = new Date(dateReader.parse(line.substring(0,19),
    new
    java.text.ParsePosition(0)).getTime());
    // if (lastDataReceived == null ||
    tmpdate.after(lastDataReceived)) {
    //     System.out.println("Inside is new");
    //     System.out.println("Data String is: " +
    line.substring(19,26));
    //     System.out.println("Data Double is: " +
    Double.parseDouble(line.substring(19,26)));
    try {
    tmpData.addElement(new
    DateTime(Double.parseDouble(line.substring(19,26)) + datumAdjust, tmpdate)
    );
    } catch (java.lang.NumberFormatException nfe) {
    // do nothing, it will work itself out.
    System.out.println(" ");
    System.out.println("end :" + line);
    System.out.println(text);
    }
    // }
    // else
    infoRetrieved = true;
```java
else if (inDataSection && !infoRetrieved) {
    if (line.length() >= 26) {
        //
        System.out.println("Inside," + line + ",");
        //
        data.addElement(parseData(line));
        //
        dataStrings.addElement(getDataString((Vector) data.lastElement()));
        tmpdate = new Date(dateReader.parse(line.substring(0, 19),
                new java.text.ParsePosition(0)).getTime());
        //
        if (lastDataReceived == null ||
            tmpdate.after(lastDataReceived)) {
            //
            System.out.println("Data String is: " +
                    line.substring(19, 26));
            //
            System.out.println("Data Double is: " +
                    Double.parseDouble(line.substring(19, 26)));
            try {
                tmpData.addElement(new
                        DateTime(Double.parseDouble(line.substring(19, 26)) + datumAdjust, tmpdate));
            } catch (java.lang.NumberFormatException nfe) {
                //do nothing, it will work itself out.
                inDataSection = false;
                infoRetrieved = true;
                //
                System.out.println("");
                //
                System.out.println("mid:" + line);
                //
                System.out.println(text);
            }
            //
        } else
            //
            infoRetrieved = true;
            //
    }
}

int lastDone = tmpData.size();
if (lastDone == 0) {
    return;  // if lastDone = 0, then there wasn't any data, and
    // we'll just try again next time.
    } else {  
            //
            System.out.println("i = " + i + ", tmpData.size() = " +
                    tmpData.size());
            //
            System.out.println(((DateTime) tmpData.elementAt(i)).toString() +
                    ", boc= " + bottomOfChannel + ", tob= " +
                    topOfBank + ", i = " + i);
            //
            data.addElement(parseData((String) tmpData.elementAt(i)));
            if (((DateTime) tmpData.elementAt(i)).getData() >
                    bottomOfChannel &&
                    ((DateTime) tmpData.elementAt(i)).getData() <
                    topOfBank + 10d) {
                //
                System.out.println(((DateTime) tmpData.elementAt(i)).toString() +
```
// , boc= " + bottomOfChannel + ",
tob= " + topOfBank +
// , i= " + i + ", size = " +
(tmpData.size() ));
    if (i < tmpData.size()-2) {
    // System.out.println(((DateTime)tmpData.elementAt(i)).toString() +
    // , boc= " + bottomOfChannel + ",
tob= " + topOfBank +
    // , i= " + i + ", pre1 = " +
    ((DateTime)tmpData.elementAt(i+1)).getData()
    // + " , pre2 = "
    +((DateTime)tmpData.elementAt(i+2)).getData());
        if ( ((DateTime)tmpData.elementAt(i)).getData() < ((DateTime)tmpData.elementAt(i+1)).getData() + 1 &
            ((DateTime)tmpData.elementAt(i)).getData() < ((DateTime)tmpData.elementAt(i+2)).getData() + 1 &
            ((DateTime)tmpData.elementAt(i)).getData() > ((DateTime)tmpData.elementAt(i+1)).getData() - 1 &
            ((DateTime)tmpData.elementAt(i)).getData() > ((DateTime)tmpData.elementAt(i+2)).getData() - 1)
    {
        // System.out.println("mid "+
        (DateTime)tmpData.elementAt(i));
        if (lastDone > i+2) {
            for (int j = 2; j>0; j--)
                {
                    if (lastDataReceived == null ||
                     (((DateTime)tmpData.elementAt(i+j)).getData()).after(lastDataReceived))
                        {
                            // System.out.println("extras "+
                            (DateTime)tmpData.elementAt(i+j));

                            rsGage.refresh(((DateTime)tmpData.elementAt(i+j));
                        }
                }
        } if (lastDataReceived == null ||
        (((DateTime)tmpData.elementAt(i)).getData()).after(lastDataReceived) )
        {
            // System.out.println("new "+
            (DateTime)tmpData.elementAt(i));

            rsGage.refresh(((DateTime)tmpData.elementAt(i));
        }
        lastDone = i;
    }
}
}
tmpData.setSize(0);
FileWriter fw;
PrintWriter output;
File outfile = new File(watershed.getCurrentPath() + hcoemfile);
   // System.out.println(watershed.getCurrentPath() + hcoemfile);
try {
   fw = new FileWriter(outfile);
   output = new PrintWriter(fw);
}
catch(IOException e) {
   throw new FASEException("Output file doesn't exist");
}

try {
   for (Enumeration enum = rsGage.getFlows().elements(); 
    enum.hasMoreElements(); ) {
      output.println((String)((RatedStreamDataTime)enum.nextElement()).toString());
   }
   output.close();
   fw.close();
}
catch(IOException e) {
   throw new FASEException("Error writing to output file " + hcoemfile);
}

/* Note that the above depends on the data received from the URL being in a very
   * specific format, as did the Perl script from which this derives. Changing the data
   * WILL require a change in the above values for token gathering.
   */

   // check to see if the last 3 data points are above the archiving threshold. If so,
   // set archiving for an extra hour for all watershed/radar pairs with matching radars.

   if
      (OutputUtil.Singleton.lastThreeExceedThreshold(rsGage.getData(),minArchive)) {
         Iterator e =
            ((FASServer)driver).watershedCollection().iterator();
            while (e.hasNext()) {
               Watershed w = (Watershed)e.next();
               if (w.getUniqueID().startsWith(watershed.getID())) {

                  //System.out.println("Gage Up, Archiving, watershed " + w.getUniqueID());
                   FAS.setArchiveUntil(w.getID(), w.getWatershedRadar(),
                   60*60*1000);
               }
            }
   }
archiveFile(outfile);
}

/**
 * Uses up 'num' unneeded tokens from the given StringTokenizer
 */
private void burn_tokens(StringTokenizer st, int num) {
    String useless_data;
    for(int i = 0; i < num; i++)
        useless_data = st.nextToken();
}

protected void do_archiving() {

private Vector parseData(String data) {
    if ((data == null) || (data.length() == 0)) return null;
    Vector to_return = new Vector();
    // to_return.addElement(DateFormat.parse(data.substring(0,18)));
    double temp = Double.parseDouble(data.substring(19));
    double tempFlow = 0.000046152229d*this.getPower(temp,6) -
    0.00960282774d*this.getPower(temp,5) +
    0.815433439301d*this.getPower(temp,4) -
    36.20810647918d*this.getPower(temp,3) +
    917.111880452079d*this.getPower(temp,2) - 12124.6341763097d*temp +
    63430.5431708006d;
    to_return.addElement(new Double(temp));
    to_return.addElement(new Double(tempFlow));
    return to_return;
}

private double getPower(double base, int exponent) {
    if (exponent == 0) return 1d;
    if (exponent > 0) return base*this.getPower(base,exponent-1);
    if (exponent < -1) return base*this.getPower(base,exponent+1);
    return 1d/base;
}

private String getDataString(Vector data) {
    String to_return;
    to_return = data.elementAt(0) + ", Stage = " +
    data.elementAt(1).toString() + ", Flow = " +
    data.elementAt(2).toString();
    return to_return;
}

/*
 * public Vector getHcoemData()
 * @return a Vector of RatedStreamDateTime objects
 */
public Vector getHcoemData() {
    return rsGage.getFlows();
}

Appendix F: HEC-1 Model for Brays Bayou Used as Baseline Model for RTHEC-1

The following HEC-1 model was provided by the Harris County Office of Emergency Management (HCOEM) office for the purpose of providing an initial, baseline hydrologic model from which to begin further calibration and validation for this research. Note the "PI" cards for each subwatershed. They contain 60 data values (one value for each hour of data) provided by radar data.

*FREE
*NLIST
IDIT 5 1JAN83 0000 1200
IDIO 5 0 0
IDIN60,1JAN83,0000
ID August 2002 Storm with PI and LE
IT,5,14Aug02, 1400, 1200
IO,5,0,0
IN,15,14Aug02, 1400
KKD100A
KM Rainfall :0 D100A
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.002,0.006,0.006,0.012,0.085,0.391,0.172,0.047,0.043
PI,0.045,0.044,0.047,0.026,0.008,0.009,0.055,0.017,0.000,0.000
PI,0.005,0.021,0.055,0.005,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.027,0.038,0.001,0.003,0.003,0.003,0.022,0.030
PI,0.042,0.045,0.136,0.245,0.210,0.087,0.018,0.003,0.011,0.005
PI,0.000,0.000,0.001,0.001,0.001,0.002,0.005,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.001,0.000,0.000,0.000,0.000,0.000
PI,0.006,0.009,0.000,0.000,0.001,0.004,0.004,0.002,0.001,0.001
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.002,0.007,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.022,0.019,0.000
BA6.79
BF0.0,-0.1,1.05
LU0.5,0.05,9.12
UC 1.64   8.14
KKD100#2 ROUTE FROM D100#1 TO D100#2
KM   STATION 1494+61 TO STATION 1424+57
RS4,STOR,-1
SV  0  53  90  125  235  595  910
SQ  0  770 1540 2310 3080 3850 4620
KKD100B
KM Rainfall :1 D100B
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.073,0.041,0.069,0.042,0.015,0.001,0.040,0.039,0.001,0.000
PI,0.012,0.054,0.182,0.012,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.007,0.015,0.002,0.005,0.006,0.000,0.004,0.016
PI,0.014,0.040,0.055,0.201,0.096,0.104,0.029,0.005,0.008,0.005
PI,0.000,0.000,0.002,0.007,0.002,0.001,0.006,0.001,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.007,0.008,0.001,0.002,0.005,0.010,0.007,0.004,0.002,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.030,0.060,0.000
BA1.48
LU0.7,0.05,9.12
UC  0.65  16.57
KKD100#2 COMBINE HYDROGRAPHS
HC2
KKD100#3 ROUTED FROM D100#2 TO D100#3
KM   STATION 1424+57 TO STATION 1375+37 (UPSTREAM OF D129-00-00)
RS2,STOR,-1
SV  0   47   79  108  247  552  781

KKD100#3 ROUTED FROM D129#1 TO D100#3
KM STATION 61+19 TO STATION 0+00
RS3,STOR,-1
SV 0 43 72 98 194 375 485
SQ 0 740 1480 2220 2960 3700 4440
KKD129B
KM Rainfall :4 D129B
PB 0
PI,0.005,0.003,0.000,0.001,0.003,0.006,0.006,0.004,0.001,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PA,0.015,0.095,0.013,0.007,0.0353,0.197,0.152,0.254
PI,0.166,0.064,0.081,0.081,0.045,0.005,0.019,0.043,0.003,0.000
PI,0.006,0.120,0.141,0.073,0.000,0.000,0.006,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.001,0.010,0.003,0.002,0.007,0.001,0.003,0.016
PI,0.015,0.034,0.038,0.191,0.109,0.179,0.056,0.007,0.007,0.005
PI,0.000,0.000,0.000,0.011,0.006,0.005,0.007,0.002,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.006,0.065,0.001
BA1.35
LU0.7,0.05,34.71
UC .49 2.13
KKD100#3 COMBINE HYDROGRAPHS AT MOUTH OF D129-00-00
HC2
KKD100#3 COMBINE HYDROGRAPHS DOWNSTREAM OF D129-00-00
CONFLUENCE
HC2
KGD100#4 ROUTED FROM D100#3 TO D100#4
KM STATION 1375+37 TO STATION 1319+90
RS4,STOR,-1
SV  0  70  110  148  303  1459  2436
SQ  0  1330  2670  4000  5340  6670  8000
KGD100D
KM Rainfall :5 D100D
PB  0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.001,0.001,0.002,0.002,0.001,0.001,0.001,0.001,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA1.22
LU0.7,7,05,4,0
UC  0.69  6.24
KGD100#4 COMBINE HYDROGRAPHS
HC2
KGD100#5 ROUTED FROM D100#4 TO D100#5
KM STATION 1319+90 TO STATION 1247+02 (UPSTREAM OF D126-00-00)
RS3,STOR,-1
SV  0  75  127  178  255  424  730
SQ  0  1490  2980  4480  5970  7460  8950
KGD100E
KM Rainfall :6 D100E
PB  0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.001,0.003,0.003,0.002,0.002,0.001,0.002,0.003,0.001,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.202,0.161,0.505,0.312,0.094,0.094,0.026,0.063,0.016,0.001
PI,0.000,0.030,0.180,0.069,0.000,0.000,0.000,0.001,0.001,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.002,0.000,0.000,0.003,0.007
PI,0.002,0.003,0.001,0.003,0.003,0.004,0.004,0.004,0.005,0.004,0.004,0.004
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000

BA2.17
LU07,0.05,19,16
UC .53 3.06
KKD100\#5 COMBINE HYDROGRAPHS UPSTREAM OF D126-00-00
HC2
KKD126A
KM Rainfall:7 D126A
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.002,0.003,0.002,0.003,0.004,0.003,0.002,0.003,0.001,0.001
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.123,0.111,0.222,0.143,0.063,0.036,0.035,0.053,0.008,0.000
PI,0.001,0.085,0.197,0.029,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.006,0.006,0.009,0.001,0.004,0.021
PI,0.038,0.053,0.075,0.150,0.082,0.179,0.143,0.011,0.041,0.011
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.007,0.008,0.001,0.004,0.007,0.009,0.007,0.004,0.004,0.001
PI,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.016,0.057,0.000
BA1.73
LU07,0.05,26,17
UC .75 3.14
KKD100#5 COMBINE HYDROGRAPHS DOWNSTREAM OF D126-00-00
HC2
KKD100#6 ROUTED FROM D100#5 TO D100#6
KM STATION 1247+02 TO STATION 1201+02 (UPSTREAM OF D124-00-00)
RS2,STOR.-1
SV 0 62 109 153 220 327 461
SQ 0 1760 3520 5270 7030 8790 10550
KKD124A
KM Rainfall :8 D124A
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,
PI,0.001,0.002,0.001,0.001,0.000,0.001,0.001,0.001,0.000,0.000,0.000,0.000,0.000,0.000,
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,
PI,0.253,0.185,0.829,0.513,0.061,0.146,0.031,0.062,0.017,0.002
PI,0.000,0.013,0.077,0.097,0.005,0.000,0.004,0.010,0.000,0.000
PI,0.000,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.024,0.060,0.172,0.154,0.090,0.219,0.467,0.077,0.019,0.005
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.002,0.001,0.001,0.002,0.001,0.001,0.002,0.002,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.004,0.040,0.001
BA2.43
LU0.4,0.05,34.73
UC .54 2.07
Kkd100#6 COMBINE HYDROGRAPHS DOWNSTREAM OF D124-00-00
HC2
Kkd100#7 ROUTED FROM D100#6 TO D100#7
KM STATION 1201+02 TO STATION 1163+02 (UPSTREAM OF D122-00-00)
RS1,STOR.-1
SV 0 55 98 138 194 267 650
SQ 0 2060 4130 6190 8260 10320 12380
KK WEIR
KO 5 1 1000 0
Dtd50006
* DIVERSION OVER WEIR INTO D500-06-00 DETENTION FACILITY
* FLOW VALUES FROM SIDE FLOW WEIR PROGRAM (HCFCD REPORT - SEPT 1994)
DI 0 2400 2600 2800 3000 4000 5000 6000 7000 8000
DI 9000 9300 10000 20000
DQ 0 0 40 140 245 860 1470 2120 2800 3480
DQ 4150 4290 4300 4300
KKPOND-I
* RETRIEVE DIVERTED HYDROGRAPH AND ROUTE THROUGH D500-06-00 RESERVOIR
DRD50006
KKPOND-O
KO 5 1 1000 0
* WEIR RATING CURVE FOR D500-06-00 RATING CURVE FOR BRAYS
SEC 116302
* (FROM HCFCD REPORT SEPT 1994) (FROM HEC-2 STORAGE-OUTFLOW MODEL)
* Q   ELEV ABOVE WEIR   Q   ELEV
* 50  60.62   0  46.4
* 200  61.00  2060  57.4
* 800  61.88  4130  62.0
* 1500  62.60  6190  65.4
* 2500  63.43  10-YR [7170] [67.5]
* 4000  64.44  8260  69.8
* 6000  65.57  10320  72.3
* 8000  66.54  12380  73.6
*
* DETENTION RESERVOIR SIZING FROM HCFCD REPORT SEPT 1994
RS1. STOR -1.
SA0. 3.25  7.31  11.38  13.41  13.80  14.32  14.85  15.37  15.90
SA16.42 16.94  17.47  17.99  18.05
SE51.2 52.  53.  54.  54.5  56.  58.  60.  62.  64.
SE66. 68.  70.  72.  72.2
* DUMMY WEIR WHICH SIMULATES FLOW RETURNING BACK OVER REAL WEIR INTO
* CHANNEL ONCE MAXIMUM CAPACITY OF POND IS REACHED.
RETURN FLOWS ARE
* DESIGNED BEGIN TO OCCUR WHEN THE RESERVOIR REACHES THE 10-YR CHANNEL
* STAGE. OSCILLATIONS OCCUR WHEN A TIME STEP OF 15 MINUTES IS USED,
* AND WERE ELIMINATED WITH A 5 MINUTE TIME STEP.
SL51.7 1.00 .1 .5
SS66.5 1000. 2.7  1.5
KKD100#7 COMBINE RETURNED FLOW FROM D500-06-00 WITH UNDIVERTED FLOW FROM CHAN
KO 5 1 1000 0
HC2
KKD122A
KM Rainfall :9 D122A
PB 0
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.001,0.000,0.001,0.001,0.002,0.001,0.001,0.002,0.001,0.001,0.001
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.077,0.114,0.126,0.063,0.034,0.009,0.042,0.034,0.004,0.000,0.000
P1,0.002,0.060,0.116,0.006,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.015,0.008,0.000,0.004,0.006,0.000,0.003,0.013
P1,0.051,0.050,0.084,0.101,0.090,0.172,0.100,0.015,0.027,0.013
P1,0.000,0.000,0.001,0.006,0.002,0.002,0.005,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.003,0.002,0.004
P1,0.004,0.005,0.001,0.001,0.003,0.006,0.005,0.004,0.003,0.001
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.104,0.054,0.000
BA 2.98
LU 0.6,0.05,18.8
UC 1.04 4.21
KKD100#7 ROUTED FROM D122#1 TO D100#7
KM STATION 111+88 TO STATION 2+00
RS 4,STOR,-1
SV 0 69 118 169 282 490 868
SQ 0 820 1640 2460 3280 4100 4920
KKD122B
KM Rainfall :10 D122B
PB 0
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.004,0.005,0.004,0.004,0.006,0.005,0.004,0.005,0.002,0.001
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.133,0.282,0.882,0.321,0.051,0.037,0.042,0.073,0.011,0.000
P1,0.000,0.015,0.151,0.072,0.002,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.003,0.000,0.008,0.006,0.001,0.006,0.039
P1,0.047,0.092,0.203,0.157,0.092,0.199,0.390,0.069,0.071,0.009
P1,0.000,0.001,0.001,0.007,0.010,0.006,0.013,0.001,0.000,0.000
P1,0.000,0.000,0.000,0.000,0.000,0.000,0.003,0.005,0.005,0.006
KDD100#7 COMBINE HYDROGRAPHS AT MOUTH OF D122-00-00
HC2
KDD100#7 COMBINE HYDROGRAPHS DOWNSTREAM OF D122-00-00 CONFLUENCE
HC2
KDD100#8 ROUTED FROM D100#7 TO D100#8
KM STATION 1163+02 TO STATION 1111+02 (UPSTREAM OF D120-00-00)
RS2,STOR,-1
SV 0 89 155 214 306 688 1647
SQ 0 2760 5510 8270 11020 13780 16540
KDD100F
KM Rainfall :11 D100F
PB 0
PI,0.006,0.005,0.002,0.003,0.004,0.004,0.004,0.006,0.004,0.001
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.002,0.001,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.001,0.002,0.001,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.014,0.012,0.000
BA2.19
LU0.7,0.05,28.1
UC .37 2.15
KDD100F
KM Rainfall :11 D100F
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.003,0.003,0.003,0.001,0.002,0.002,0.003,0.004,0.002,0.001
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.029,0.016,0.465,0.120,0.100,0.279,0.310,0.067,0.114,0.015
PI,0.001,0.001,0.001,0.007,0.007,0.006,0.012,0.003,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.003,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.002,0.000
BA0.79
LU0.7,0.05,12.75
UC .40 3.81
KKD100#8 COMBINE HYDROGRAPHS UPSTREAM OF D142-00-00 AND D120-00-00
HC2
KKD142A
KM Rainfall :12 D142A
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.001,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001
PI,0.000,0.000,0.000,0.012,0.044,0.024,0.054,0.070,0.288,0.394
PI,0.283,0.108,0.567,0.674,0.059,0.054,0.027,0.070,0.019,0.001
PI,0.000,0.017,0.055,0.078,0.033,0.003,0.002,0.004,0.000,0.000
PI,0.002,0.006,0.000,0.000,0.000,0.000,0.003,0.007,0.003,0.000,0.005
PI,0.024,0.115,0.429,0.127,0.083,0.239,0.445,0.130,0.054,0.014
PI,0.001,0.000,0.001,0.010,0.011,0.009,0.019,0.008,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA2.35
LU0.5,0.05,31.52
UC .87 2.46
KKD120A
KM Rainfall :13 D120A
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.001,0.002,0.000,0.001,0.004,0.002,0.002,0.002,0.000,0.002,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
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PI,0.000,0.000,0.000,0.000,0.006,0.008,0.018,0.024,0.065,0.222,0.192
PI,0.077,0.363,0.352,0.098,0.056,0.024,0.045,0.044,0.005,0.000
PI,0.000,0.019,0.108,0.018,0.001,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.005,0.007,0.001,0.003,0.001,0.000,0.011,0.019
PI,0.088,0.075,0.210,0.064,0.075,0.233,0.263,0.061,0.070,0.015
PI,0.000,0.000,0.000,0.002,0.005,0.003,0.003,0.006,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
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<td>BA1.49</td>
<td>LU0.5,0.05,18.84</td>
<td>UC .61</td>
<td>3.15</td>
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<tr>
<td>KKD100#8 ROUTED FROM D120#1 TO D100#8</td>
<td>KM STATION 120+88 TO STATION 2+00</td>
<td>RS4,STOR,-1</td>
<td></td>
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<td>SV 0 59 94 125 176 304 474</td>
<td>SQ 0 652 1304 1956 2608 3260 3912</td>
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<td>KKD120B</td>
<td>KM Rainfall :14 D120B</td>
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<td>PB 0</td>
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<td>PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000</td>
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<td>PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000</td>
<td>PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000</td>
<td>PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000</td>
<td>PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000</td>
<td>PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000</td>
<td>PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000</td>
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<tr>
<td>BA2.05</td>
<td>LU0.7,0.05,25.51</td>
<td>UC .52</td>
<td>2.53</td>
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<tr>
<td>KKD100#8 COMBINE HYDROGRAPHS AT MOUTH OF D120-00-00</td>
<td>HC2</td>
<td></td>
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<tr>
<td>KKD100#8 COMBINE HYDROGRAPHS AT DOWNSTREAM OF D142-00-00 AND D120-00-00</td>
<td>HC3</td>
<td></td>
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<tr>
<td>KKD100#9 ROUTED FROM D100#8 TO D100#9</td>
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KM   STATION 1111+02 TO STATION 1050+92 (UPSTREAM OF CITY DITCH, US 59)
RS2,STOR,-1
SV   0   145   239   318   466   1323   2261
SQ   0   3470  6940  10400  13870  17340  20810
KKD100G
KM Rainfall :15 D100G
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA1.33
LU0.7,0.05,26.22
UC    .49  2.94
KKD100#9 COMBINE HYDROGRAPHS UPSTREAM OF CITY DITCH
HC2
KKCITYA
KM Rainfall :16 CITYA
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.041,0.162,0.429,0.081,0.097,0.231,0.226,0.080,0.124,0.030
PI,0.002,0.001,0.001,0.005,0.006,0.005,0.015,0.006,0.002,0.002
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA1.19
LU0.5,0.05,33.7
UC .51  2.12
KKD100#9 COMBINE HYDROGRAPHS DOWNSTREAM OF CITY DITCH
HC2
KKD100#10 ROUTED FROM D100#9 TO D100#10
KM STATION 1050+92 TO STATION 1011+42 (UPSTREAM OF D118-00-00)
RS1,STOR,-1
SV 0  63  118  169  263  767  1484
SQ 0  3470  6940  10400  13870  17340  20810
KKD100H
KM Rainfall :17 D100H
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.001,0.000,0.000,0.000,0.001,0.004
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA0.50
LU0.7,0.05,34.17
UC .24  2.42
KKD100#10 COMBINE HYDROGRAPHS UPSTREAM OF D118-00-00 (KEEGANS BAYOU)
HC2
KKD118A
KM Rainfall :18 D118A
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.001,0.001,0.000,0.002,0.001
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.006,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA2.71
LU0.7,0.05,11.37
UC 1.39 12.94
KKD118#2 ROUTE FROM D118#1 TO D118#2
KM STATION 350+85 TO STATION 258+83
RS6,STOR,-1
SV 0 85 148 380 895 1406 1861
SQ 0 746 1492 2238 2984 3730 4476
KKD118B
KM Rainfall :19 D118B
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.002,0.002,0.002,0.002,0.003,0.002
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.065,0.019,0.000
BA2.71
LU0.7,0.05,11.37
UC 1.39 12.94
PI,0.000,0.000,0.014,0.004,0.002,0.001,0.000,0.001,0.016,0.016
PI,0.130,0.115,0.226,0.036,0.063,0.301,0.189,0.114,0.091,0.015
PI,0.000,0.000,0.001,0.002,0.005,0.002,0.001,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
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PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.003,0.000,0.000,0.000,0.000
PI,0.213,0.017,0.000
BA5.56
LU0.5,0.05,20.89
UC 1.15 5.96
KKD118#2 COMBINE HYDROGRAPHS
HC2
KKD118#3 ROUTE FROM D118#2 TO D118#3
KM STATION 258+83 TO STATION 126+37
RS5,STOR,-1
SV 0 129 223 567 1125 1894 2564
SQ 0 1184 2368 3552 4736 5920 7104
KKD118C
KM Rainfall :20 D118C
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.085,0.493,0.763,0.072,0.006,0.005,0.052,0.063,0.015,0.001
PI,0.000,0.035,0.109,0.045,0.042,0.000,0.000,0.000,0.000,0.000
PI,0.044,0.000,0.001,0.002,0.003,0.011,0.003,0.000,0.013,0.035
PI,0.170,0.347,0.313,0.027,0.033,0.087,0.148,0.211,0.244,0.037
PI,0.000,0.000,0.000,0.000,0.006,0.002,0.003,0.000,0.005,0.001
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA5.06
LU0.7,0.05,29.44
UC 0.6  4.11
KKD118#3 COMBINE HYDROGRAPHS
HC2
KKD118#4 ROUTE FROM D118#3 TO D118#4
KM STATION 126+37 TO STATION 89+44
RS1,STOR,-1
SV 0  30  54  101  166  227  287
SQ 0  1508  3016  4524  6032  7540  9048
KKD118D
KM Rainfall :21 D118D
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.023,0.185,0.219,0.368,0.170,0.073,0.066,0.120
PI,0.103,0.580,0.453,0.075,0.006,0.004,0.033,0.040,0.035,0.007
PI,0.000,0.035,0.013,0.005,0.004,0.001,0.003,0.000,0.000,0.000
PI,0.036,0.000,0.003,0.017,0.004,0.015,0.004,0.000,0.007,0.018
PI,0.099,0.256,0.225,0.031,0.036,0.142,0.121,0.217,0.420,0.156
PI,0.001,0.000,0.001,0.001,0.003,0.002,0.001,0.001,0.015,0.002
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.005,0.000,0.000
BA2,43
LU0.5,0.05,26.86
UC 1.04  3.36
KKD118#4 COMBINE HYDROGRAPHS
HC2
KKD100#10 ROUTE FROM D118#4 TO D100#10
KM STATION 89+44 TO STATION 0+00
RS2,STOR,-1
SV 0  75  120  172  394  829  1294
SQ 0  1624  3248  4872  6496  8120  9744
KKD118E
KM Rainfall :22 D118E
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.002,0.002
KKD100#10 COMBINE HYDROGRAPHS AT MOUTH OF KEEGANS BAYOU (D118-00-00)

HC2

KKD100#10 COMBINE KEEGANS BAYOU AND BRAYS BAYOU HYD ABOVE GESSNER RD

HC2

KKD100#11 ROUTED FROM D100#10 TO D100#11 WITH D500-05-00

ADDITIONAL VOLUME

KM    STATION 1011+42 TO STATION 930+33 (UPSTREAM OF D133-00-00, D140-00-00)

RS2,STOR,-1

* STORAGE WITHOUT D500-05-00:

* SV  0  135  244  292  347  556  1171  2285

SV  0  141  280  342  385  564  1171  2285

SQ  0  5010  10030  12320  15040  20060  25070  30084

KKD100I

KM Rainfall :23 D100I

PB 0
BA1.71
LU0.7,0.05,28.73
UC .5 2.41
KKD100#11 COMBINE HYDROGRAPHS UPSTREAM OF D140-00-00 AND D133-00-00
HC2
KKD133A
KM Rainfall :24 D133A
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.001
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.004,0.003,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.002,0.082,0.164,0.148,0.165,0.105,0.098,0.216
PI,0.438,0.266,0.265,0.568,0.291,0.039,0.010,0.042,0.032,0.008,0.004,0.000,0.000,0.000,0.000
PI,0.014,0.048,0.000,0.000,0.000,0.000,0.004,0.011,0.004,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.027,0.098,0.349,0.055,0.182,0.442,0.230,0.100,0.104,0.038
PI,0.005,0.001,0.000,0.004,0.005,0.006,0.014,0.008,0.002,0.003
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA4.52
LU0.5,0.05,31.34
UC 1.43 3.73
KKD140A
KM Rainfall :25 D140A
PB 0
PI,0.000,0.000,0.000,0.000,0.001,0.001,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.002,0.002
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.193,0.663,0.246,0.054,0.004,0.008,0.025,0.040,0.038,0.029
PI,0.000,0.033,0.003,0.023,0.018,0.002,0.022,0.000,0.000,0.001
PI,0.022,0.000,0.002,0.024,0.007,0.026,0.004,0.003,0.024,0.029
PI,0.074,0.158,0.113,0.047,0.038,0.311,0.065,0.194,0.423,0.269
PI,0.009,0.000,0.001,0.004,0.000,0.000,0.000,0.006,0.024,0.002
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.005,0.000,0.000
BA3.63
LU0.5,0.05,17.25
UC 1.07 4.05
KKD140#2 ROUTE FROM D140#1 TO D140#2
KM STATION 242+12 TO STATION 109+29
RS9,STOR,-1
SV 0 111 253 449 714 945 1752
SQ 0 784 1568 2352 3136 3920 4704
KKD140B
KM Rainfall :26 D140B
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.001,0.001,0.000,0.000,0.000,0.005,0.003
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.148,0.684,0.180,0.223,0.140,0.114,0.157,0.577
PI,0.331,0.756,0.486,0.087,0.013,0.004,0.020,0.035,0.028,0.051
PI,0.002,0.023,0.009,0.038,0.055,0.015,0.068,0.000,0.000,0.000,0.000
PI,0.034,0.000,0.000,0.010,0.008,0.036,0.007,0.002,0.069,0.123
PI,0.030,0.091,0.070,0.045,0.211,0.159,0.062,0.124,0.176,0.259
PI,0.042,0.001,0.002,0.066,0.001,0.000,0.002,0.011,0.032,0.006
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
KKD140#2 COMBINE HYDROGRAPHS
HC2
KKD100#11 ROUTE FROM D140#2 TO D100#11
KM STATION 109+29 TO STATION 0+00
RS9,STOR,-1
SV 0 97 205 476 653 772 2159
SQ 0 900 1800 2710 3620 4520 5420
KKD140C (INCLUDES DRAINAGE AREA FOR D112-02-00 AND D112-09-00)
KM Rainfall :27 D140C
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.003,0.002,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.006,0.003
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.001,0.006,0.004,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.094,0.682,0.280,0.124,0.128,0.058,0.058,0.072,0.543
PI,0.308,0.693,0.508,0.131,0.033,0.002,0.014,0.036,0.031,0.023
PI,0.003,0.014,0.013,0.014,0.026,0.020,0.113,0.005,0.000,0.000,0.000
PI,0.026,0.003,0.000,0.009,0.011,0.018,0.007,0.002,0.017,0.130
PI,0.032,0.113,0.064,0.040,0.344,0.144,0.161,0.071,0.181,0.197
PI,0.038,0.001,0.003,0.005,0.001,0.001,0.004,0.006,0.029,0.008
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA2.87
LU0.5,0.05,32.58
UC .78 3.30
KKD100#11 COMBINE HYDROGRAPHS AT MOUTH OF D140-00-00
HC2
KKD100#11 COMBINE HYDROGRAPHS AT DOWNSTREAM OF D133-00-00 AND D140-00-00
HC3
KKD100#12 ROUTE FROM D100#11 TO D100#12
KM STATION 930+33 TO STATION 824+73
RS2,STOR,-1
SV 0 202 340 470 853 2776 9022
SQ 0 6440 12890 19330 25780 32220 38660
KKD100J
KM Rainfall :28 D100J
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.003,0.002,0.000,0.000,0.000,0.000,0.000
PI,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.004,0.003
PI,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA6.25
LUO.7,0.05,33.12
UC 1.01 3.29
KKD100#12 COMBINE HYDROGRAPHS UPSTREAM OF D139-00-00
HC2
KKD1039A
KM Rainfall :29 D139A
PB 0
PI,0.000,0.000,0.000,0.000,0.008,0.063,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.007,0.003
PI,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.002,0.008,0.011,0.003,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.209,0.210,0.054,0.133,0.072,0.083,0.427
PI, 0.569, 0.717, 0.590, 0.274, 0.048, 0.019, 0.012, 0.025, 0.033, 0.023
PI, 0.007, 0.002, 0.006, 0.007, 0.046, 0.095, 0.111, 0.009, 0.000, 0.000
PI, 0.023, 0.007, 0.000, 0.004, 0.009, 0.021, 0.013, 0.001, 0.008, 0.153
PI, 0.032, 0.067, 0.067, 0.030, 0.305, 0.368, 0.175, 0.020, 0.097, 0.167
PI, 0.099, 0.003, 0.002, 0.008, 0.002, 0.001, 0.002, 0.008, 0.031, 0.016
PI, 0.001, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
BAI, 55
LUO, 0.5, 0.05, 34.55
UC, 0.67, 1.81
KO, 5, 1, 1000, 0
KKD100#12 COMBINE HYDROGRAPHS AT DOWNSTREAM OF D139-00-00
HC2
KKD100#13 ROUTED FROM D100#12 TO D100#13 (UPSTREAM OF D112-00-00, D113, D115)
KM STATION 824+73 TO STATION 740+88 (AT D112-00-00)
RS2,STOR,-1
SV, 0, 170, 293, 410, 1378, 5257, 12217
SQ, 0, 6520, 13030, 19550, 26060, 32580, 39096
KKD100K
KM Rainfall :30 D100K
PB, 0
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI,0.000,0.000,0.000,0.000,0.011,0.001,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000
BA1.53
LU0.7,0.05,34.62
UC .62 2.40
KKD100#13 COMBINE HYDROGRAPHS UPSTREAM OF D112-00-00, D113-00-00
AND D115-00-00
HC2
KKD112A (EXCLUDES DRAINAGE AREA FOR D112-02-00 AND D112-09-00)
KM Rainfall:31 D112A
PB 0
PI,0.000,0.000,0.000,0.000,0.008,0.019,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.009,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.006,0.018,0.010,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.371,0.656,0.683,0.164,0.014,0.002,0.023,0.024,0.031,0.041
PI,0.060,0.003,0.005,0.022,0.034,0.027,0.143,0.002,0.000,0.000
PI,0.042,0.002,0.000,0.022,0.026,0.055,0.020,0.007,0.036,0.028
PI,0.019,0.096,0.051,0.029,0.295,0.242,0.091,0.129,0.179,0.357
PI,0.093,0.001,0.001,0.009,0.003,0.002,0.006,0.010,0.037,0.011
PI,0.002,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA1.01
LU0.7,0.05,35.00
UC .62 3.01
KO 5 1 1000 0
KKD112#2 ROUTED FROM D112#1 TO D112#2
KM STATION 159+84 TO STATION 0+00
KS6,STOR,-1
SV 0 69 125 194 503 919 1962
SQ 0 746 1492 2238 2984 3730 4476
KKD112B
KM Rainfall:32 D112B
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
KK D112#2 COMBINE HYDROGRAPHS AT THE MOUTH OF WILLOW WATERHOLE D112-00-00

HC2

KKD100#13 COMBINE HYDROGRAPHS DOWNSTREAM OF D112-00-00

HC2

KKD115A

KM Rainfall : 33 D115A

PB 0
PL 0.000, 0.016, 0.036, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PL 0.000, 0.000, 0.000, 0.000, 0.000, 0.018, 0.025, 0.000, 0.000, 0.000, 0.003
PL 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
BA3.60
LU0.7, 0.05, 32.29
UC 2.05 5.91
KKD113A
KM Rainfall: 34 D113A
PB 0
PL 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PL 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.002, 0.012, 0.000
PL 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PL 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PL 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PL 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.002, 0.168, 0.278
PL 0.000, 0.181, 0.146, 0.214, 0.062, 0.082
PL 0.040, 0.460, 0.361, 0.267, 0.330, 0.174, 0.019, 0.018, 0.030, 0.033
PL 0.015, 0.000, 0.013, 0.001, 0.030, 0.096, 0.160, 0.083, 0.000, 0.000
PL 0.001, 0.006, 0.002, 0.000, 0.003, 0.009, 0.015, 0.015, 0.002, 0.031
PL 0.056, 0.050, 0.078, 0.052, 0.066, 0.481, 0.226, 0.081, 0.183, 0.134
PL 0.054, 0.006, 0.002, 0.000, 0.008, 0.004, 0.000, 0.001, 0.022, 0.013
PL 0.001, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
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PI 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
BA1.40
LU0.7, 0.05, 31.83
UC 0.76 5.0
KKD100#13 COMBINE HYDROGRAPHS DOWNSTREAM OF D112-00-00, D113-00-00, D115-00-00
HC3
KKD100#14 ROUTED FROM D100#13 TO D100#14
KM STATION 740+88 TO STATION 638+35 (UPSTREAM OF D111-00-00)
RS2,STOR,-1
SV 0 216 379 529 1454 2648 8023
SQ 0 7050 14100 21160 28210 35260 42310
KKD100L
KM Rainfall: 35 D100L
PB 0
PI 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.013, 0.032, 0.054
PI 0.001, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
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PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.011,0.005
PI,0.002,0.001,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.011,0.006
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.011,0.001
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PI,0.001,0.001,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001
PI,0.084,0.109,0.165,0.673,0.557,0.053,0.021,0.006,0.026,0.026
PI,0.033,0.007,0.052,0.000,0.002,0.355,0.163,0.026,0.027,0.094
PI,0.012,0.012,0.001,0.014,0.172,0.070,0.024,0.031,0.010,0.035
PI,0.037,0.024,0.119,0.206,0.353,0.595,0.171,0.070,0.062,0.047
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PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA4.56
LU0.5,0.05,24.36
UC1.71 3.42
KKD100#16 COMBINE HYDROGRAPHS UPSTREAM OF D109-00-00
HC2
KKD109A
KM Rainfall :39 D109A
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.010,0.025,0.005,0.000,0.000,0.000,0.000,0.000,0.001
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PI,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.010,0.015,0.011
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.000,0.000,0.000,0.000
PI,0.000,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.065,0.058,0.051,0.079,0.158,0.104,0.090
PI,0.099,0.242,0.042,0.074,0.365,0.191,0.066,0.015,0.012,0.051
PI,0.017,0.005,0.008,0.006,0.006,0.122,0.343,0.117,0.005,0.002
PI,0.004,0.007,0.006,0.000,0.029,0.112,0.030,0.015,0.012,0.013
PI,0.043,0.022,0.063,0.157,0.160,0.480,0.168,0.083,0.055,0.078
PI,0.022,0.010,0.002,0.002,0.002,0.002,0.000,0.000,0.000,0.000,0.022,0.020
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PI,0.000,0.000,0.000,0.000,0.002,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000
BA4.95
LU0.5,0.05,35.00
UC0.74 6.64
KKG100#16 COMBINE HYDROGRAPHS DOWNSTREAM OF D109-00-00 -- KO
Card that follows prints hydrograph to PUNCH
HC2
KO 2 1 1000 2
KKG100#17 ROUTED FROM D100#16 TO D100#17
KM STATION 511+28 TO STATION 372+25
RS2,STOR,-1
SV 0 343 613 858 1241 2213 5581
SQ 0 8160 16310 24470 32620 40780 48940
KKG100O
KM Rainfall : 40 D100O
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.033,0.023,0.006,0.002,0.005,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.002
PI,0.002,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.002,0.001
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.001,0.000,0.000,0.000
PI,0.002,0.001,0.001,0.000,0.000,0.001,0.001,0.000,0.000,0.000
PI,0.002,0.028,0.001,0.014,0.069,0.152,0.121,0.096,0.071,0.057
PI,0.061,0.062,0.115,0.418,0.794,0.108,0.046,0.026,0.012,0.022
PI,0.027,0.017,0.057,0.012,0.000,0.180,0.209,0.026,0.011,0.183
PI,0.036,0.006,0.006,0.001,0.168,0.225,0.100,0.057,0.033,0.004
PI,0.011,0.011,0.092,0.246,0.188,0.457,0.246,0.141,0.103,0.028
PI,0.039,0.025,0.001,0.005,0.005,0.000,0.000,0.001,0.029,0.035
PI,0.018,0.005,0.000,0.000,0.001,0.000,0.000,0.000,0.000,0.000
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PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000
BA7.16
LU0.4,0.05,32.94
UC0.64 2.27
KKG100#17 COMBINE HYDROGRAPHS
HC2
KKG100#18 ROUTED FROM D100#17 TO D100#18
KM STATION 372+25 TO STATION 220+65 (UPSTREAM OF D105-00-00)
RS3,STOR,-1
SV  0  580  953  1305  1807  2453  3177
SQ  0  8380  16750  25130  33500  41880  50260
KKD100P
KM Rainfall :41 D100P
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
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PI,0.012,0.003,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.120,0.029,0.008,0.042,0.105,0.114,0.101,0.081,0.070
PI,0.073,0.059,0.066,0.558,0.617,0.223,0.076,0.079,0.014,0.012
PI,0.015,0.021,0.051,0.067,0.000,0.068,0.250,0.029,0.025,0.098
PI,0.054,0.004,0.006,0.000,0.058,0.446,0.348,0.090,0.028,0.006
PI,0.002,0.004,0.061,0.198,0.177,0.328,0.244,0.209,0.097,0.021
PI,0.008,0.010,0.001,0.006,0.008,0.002,0.000,0.000,0.023,0.046
PI,0.021,0.005,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
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PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA4.00
LU0.4,0.05,32.45
UC1.14  3.20
KKD100#18 COMBINE HYDROGRAPHS UPSTREAM OF D105-00-00
HC2
KKD105A
KM Rainfall :42 D105A
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
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PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA5.14
LU0.7,0.05,34.53
UC0.77 6.72
KKD100#18 COMBINE HYDROGRAPHS DOWNSTREAM OF D105-00-00
HC2
KKD100#19 ROUTED FROM D100#18 TO D100#19
KM STATION 220+65 TO STATION 110+00 (UPSTREAM OF D103-00-00)
RS2,STOR.-1
SV 0 583 831 1101 1528 1969 2574
SQ 0 8770 17540 26320 35090 43860 52630
KKD100Q
KM Rainfall 43 D100Q
PB 0
PI,0.000,0.000,0.000,0.000,0.000,0.001,0.001,0.001,0.000,0.002,0.001,0.001
PI,0.000,0.000,0.000,0.000,0.000,0.006,0.008,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.029,0.007,0.005,0.007,0.007,0.002,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.005,0.137,0.068,0.070,0.154,0.090,0.066,0.116,0.084
PI,0.057,0.031,0.038,0.265,0.390,0.604,0.222,0.170,0.018,0.004
PI,0.005,0.030,0.027,0.132,0.003,0.066,0.277,0.018,0.040,0.035
PI,0.026,0.023,0.001,0.000,0.035,0.413,0.366,0.125,0.030,0.002
PI,0.001,0.002,0.069,0.253,0.250,0.360,0.264,0.158,0.257,0.041
PI,0.009,0.011,0.004,0.002,0.007,0.009,0.003,0.001,0.028,0.049
PI,0.026,0.008,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
BA1.60
LU0.7,0.05,32.19
UC0.61 1.99
KKD100#19 COMBINE HYDROGRAPHS UPSTREAM OF D103-00-00
HC2
KKD103A
KM Rainfall :44 D103A

PB 0

PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.001,0.000,0.000,0.000,0.000,0.001,0.002,0.003,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.002
PI,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.022,0.005,0.001,0.001,0.001,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.074,0.114,0.021,0.036,0.140,0.175,0.125,0.082,0.079
PI,0.077,0.085,0.040,0.465,0.917,0.329,0.061,0.083,0.027,0.009
PI,0.013,0.018,0.006,0.068,0.001,0.030,0.288,0.039,0.052,0.096
PI,0.046,0.003,0.013,0.001,0.003,0.271,0.549,0.153,0.053,0.012
PI,0.001,0.003,0.042,0.197,0.166,0.206,0.162,0.232,0.088,0.019
PI,0.010,0.005,0.001,0.005,0.009,0.004,0.000,0.000,0.014,0.042
PI,0.018,0.006,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000

BA3.65
LU0.5,0.05,33.07
UC1.05 6.52

KKD100#19 COMBINE HYDROGRAPHS DOWNSTREAM OF D103-00-00
HC2
KKD100#20 ROUTED FROM D100#19 TO D100#20
KM STATION 110+00 TO STATION 0+00
RS2,STOR,-1
SV 0 843 959 1100 1425 1626 1952
SQ 0 9132 18264 27396 36528 45660 54792
KKD100R
KM Rainfall :45 D100R
PB 0

PI,0.000,0.001,0.001,0.000,0.000,0.000,0.000,0.000,0.001,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.004,0.005,0.005,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.015,0.021,0.013
PI,0.027,0.008,0.005,0.009,0.003,0.000,0.000,0.000,0.000,0.000,0.000,0.000
PI,0.000,0.002,0.110,0.109,0.046,0.203,0.121,0.059,0.095,0.098
PI,0.056,0.044,0.023,0.239,0.375,0.794,0.239,0.279,0.040,0.005
PI,0.005,0.030,0.078,0.206,0.013,0.034,0.220,0.020,0.059,0.065
PI,0.026,0.020,0.008,0.001,0.000,0.245,0.400,0.279,0.079,0.005
PI,0.003,0.003,0.051,0.306,0.136,0.209,0.148,0.105,0.205,0.044
PI, 0.014, 0.005, 0.006, 0.002, 0.005, 0.011, 0.003, 0.000, 0.015, 0.051
PI, 0.029, 0.010, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.023, 0.014, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000, 0.000
PI, 0.001, 0.002, 0.002
BA2.13
LU0.7, 0.05, 32.06
UC0.82 3.11
KKD100#20 COMBINE HYDROGRAPHS AT THE MOUTH OF BRAYS BAYOU
D100-00-00
HC2
ZZ
Appendix G: Empirical Equations for the Clark Unit Hydrograph TC and R Parameters Used in Harris County, Texas

The Clark Method requires that $(TC + R)$ and TC are computed from the following formulas. $R$ is then found by subtraction of the two, where $R = (TC + R) - TC$.

$$TC + R = C \left( \frac{L}{\sqrt{S}} \right)^{0.706}$$

where

TC = time of concentration (hr),
R = routing constant (hr),
L = length of channel (outflow to basin boundary) (mi),
S = channel slope (ft/mi),

$$C = 4295[\%Dev]^{-0.678}\left[\%Conv\right]^{-0.967}$$

$$C = 7.25 \text{ if } \%Dev \leq 18$$

$$TC = C' \left( \frac{L_{ca}}{\sqrt{S}} \right)^{1.06}$$

where $C'$ is taken from the following for overland slope and $\%Dev$:

<table>
<thead>
<tr>
<th>$S_0$ (ft/mi)</th>
<th>$%Dev$</th>
<th>$C'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 40</td>
<td>0</td>
<td>5.12</td>
</tr>
<tr>
<td>20 $\leq S_0 \leq$ 40</td>
<td>0</td>
<td>3.79</td>
</tr>
<tr>
<td>$\leq$ 20</td>
<td>0</td>
<td>2.46</td>
</tr>
<tr>
<td>&gt;40</td>
<td>100</td>
<td>1.95</td>
</tr>
<tr>
<td>$\leq$ 20</td>
<td>100</td>
<td>0.94</td>
</tr>
</tbody>
</table>

(If the percent development is between 0 and 100, $C'$ is found by linear interpolation.)

where

$L_{ca}$ = length along channel to centroid of area (mi),
$S_0$ = representative overland slope (ft/mi),
$\%Dev$ = percent of area that is developed (%),
$\%Conv$ = % conveyance, the ratio of flow in channel to total flow (%),
Appendix H: MATLAB Scripts for Smoothing and Processing Rain Gage Data and Stream Flow Data Prior to Analysis

The following MATLAB scripts were written in conjunction with Mr. Anthony Holder for the purpose of smoothing historical rain gage and stream flow data provided by the HCOEM ALERT system. These scripts were needed as the analysis was performed on archived “real-time” hydrologic data that often contained spurious or missing data.

Common Data Script:

% This file contains commonly used data
% it could probably be put in as global variables, but I want to
% do it this way. Call the file in any function that needs the
% info.

datroot = 'C:\PhD_Data\RainfallData\';
firstyear = 1986;
lastyear = 2002;
syear=1986;
eyear=2002;
years = [syear:1:eyear];

statti =[
'raw'
'auto_processed'
'processedm1'
'processedm2'
'processedm3'
'processedm4'
];
statti_english = [
'is Raw Data.
'has been Automatically Processed. ' 
'has been Manually Processed Once.  ' 
'has been Manually Processed Twice.  ' 
'has been Manually Processed Three Times.' 
]
'has been Manually Processed Four Times.'
];
%[dataroot 'otherdata\stationIDs.xls']

[stationdata stationIDs] = xlsread([dataroot 'otherdata\stationIDs.xls'],'Gages');

for i=2:length(stationIDs(:,1));
gagelist(i-1,:) = stationIDs{i,3};
temp = stationIDs{i,5};
temp2 = ' ';
temp2(1:length(temp)) = temp;
gagetype(i-1,:) = temp2;
%gagestartyear = str2num(datestr(stationdata(i,7)+datenum('01-Jan-1904'),10));
%stream_matching_rain_gage(i-1,:) = char(stationIDs(i,12));
end
stream_matching_rain_gage = strvcat(stationIDs(2:end,12));
stream_datum = stationdata(2:end,12);

maxriserain = 6; %in
maxdtrain = 60 ; %min
maxrisestream = 1; %ft
maxdtstream = 5 ; %min

BraysRainGages=['0400'
 '0410'
 '0420'
 '0430'
 '0435'
 '0440'
 '0460'
 '0465'
 '0470'
 '0475'
 '0480'
 '0485'
 '0490'];

BraysStreamGages=['0403'
 '0413'
 '0419'
 '0429'
 '0438'
 '0443'
 '0459'
 '0468'];
'0469'
'0474'
'0479'
'0484'
'0489'];

BraysGageNames = [
    'Harris Gully',
    'Lawndale',
    'Main St.',
    'Stella Link',
    'Willow Waterhole',
    'S. Rice',
    'Gessner',
    'Beltway 8',
    'Belle Park',
    'Bellaire',
    'Roark',
    'SH 6',
    'Keegans'];

numRG = length(BraysRainGages(:,1));

gages2use = [1 3 6 7 9 13];

BraysRainGages = BraysRainGages(gages2use,:);
BraysStreamGages = BraysStreamGages(gages2use,:);
BraysGageNames = BraysGageNames(gages2use,:);
numRG = length(BraysRainGages(:,1));

**Start Up Script:**

clear;
CommonData;
year=1999;
gage='0419';
type='Rain';
status = 'raw';

auto = 0;

maxrise = 1; %ft
maxdt = 5; %min
[gage,syear,eyear,initstatus] = selectgage_year(auto);

if auto == 0
    type = deblank(gagetype(strmatch(gage,gagelist,'exact'),:));
    disp(['This is a ' type ' gage.']);
    year = syear;
    while year <= eyear
        newstat=[];
        skip = 0;
        if strcmp(type, 'Stream') == 1
            col = 'b';
        else
            col = 'r';
        end
        fn=fileselect(year,gage,initstatus(year-syear+1));
        [mldate,data]=hcoemload(fn,yeart);
        figure(1);
        clf
        plot(mldate-datenum(year,1,1,0,0,0),data,'k-');
        set(gca,'position',[.05 .05 .95 .90])
        ax=axis;
        axis([0 366 ax(3) ax(4)]);
        title(['Gage ' gage ' ', num2str(year)]);
        hold on;
        plot(mldate-datenum(year,1,1,0,0,0),data,[col '-']);
        zoom on;
        orient landscape;
        disp('Please review the data in Figure 1. ');
        selectedstatus = 0;
        while selectedstatus == 0
            newstat = input([num2str(year) 's data has already been processed ' num2str(initstatus(year-syear+1)-1) ' time(s). Do you want to start from [r]aw data, [n]processed [1,2,3] times data, [n]or [s]kip this year: ',s']);
        end
        prevstatus = initstatus(year-syear+1);
        if isempty(newstat)
            disp('Using latest processed data');
        elseif strcmp(newstat,'r')
            disp('Using raw data')
        elseif strcmp(newstat,'n')
            disp('Using nprocessed data')
        end
    end
end
initstatus(year-syear+1) = 1;
elseif strcmp(newstat,'1')
  disp('Using once processed data')
  initstatus(year-syear+1) = 2;
elseif strcmp(newstat,'2')
  disp('Using twice processed data')
  initstatus(year-syear+1) = 3;
elseif strcmp(newstat,'3')
  disp('Using three times processed data')
  initstatus(year-syear+1) = 4;
elseif strcmp(newstat,'s')
  disp(['Skipping ' num2str(year) '.'])
  skip = 1;
  year = year+1;
else
  disp('Using latest processed data');
end

if initstatus(year-syear+1) < prevstatus
  disp(['Data was processed ' num2str(initstatus(year-syear+1)-1) ' time(s).']);
  disp(['You have chosen to use data from a previous processing step.']);
  deletedata = input(['Do you wish to delete ' num2str(prevstatus - initstatus(year-syear+1)) ' sets of data? [y/n]'],s');
  if isempty(deletedata)
    elseif strcmp(deletedata(1), 'y')
      selectedstatus = 1;
      disp('Deleting data.);
      for s = initstatus(year-syear+1)+1:prevstatus
        delete(fileselect(year,gage,s));
      end
  end
  elseif initstatus(year-syear+1) > prevstatus
    disp('Can't reprocess data that doesn't exist. Try again.');
  else
    selectedstatus = 1;
  end
end
if skip == 0;

fn=fileselect(year,gage,initstatus(year-syear+1));
[mldate,data]=hcoemload(fn,year);

[newmldate,newdata,initstatus(year-syear+1)] = 
process_gage(year,gage,initstatus(year-syear+1),maxrise,maxdt,type,auto);
```matlab
figure(1);
clf
plot(mldate-datum(year,1,1,0,0,0),data,'k-');
hold on;
plot(mldate-datum(year,1,1,0,0,0),data,'k.');
plot(newmldate-datum(year,1,1,0,0,0),newdata',[col '.']);
plot(newmldate-datum(year,1,1,0,0,0),newdata',[col '.']);
set(gca,'position',[.05 .05 .95 .90])
ax=axis;
axis([0 366 ax(3) ax(4)]);
title(['Gage ' gage ', ' num2str(year)]);
zoom
orient landscape;

done = 'n';
while strcmp(done,'n')==1
    if year < eyear
        go = input(['Check your conversion in the figure. \nPress return to continue to ' num2str(year+1) ' \nor enter "r" to re-process this year starting from raw data, \nor enter "p" to re-process starting with the processed data.'],s);
    else
        go = input(['Check your conversion in the figure. \nPress return to quit \nor enter "r" to re-process this year starting from raw data, \nor enter "p" to re-process starting with the processed data.'],s);
    end
    if isempty(go)
        initstatus(year-syear+1) = initstatus(year-syear+1) + 1;
        done = 'y';
        year = year + 1;
    elseif strcmp(go,'p') == 1
        initstatus(year-syear+1) = initstatus(year-syear+1) + 1;
        done = 'y';
    elseif strcmp(go,'r') == 1
        initstatus(year-syear+1) = 1;
        done = 'y';
    else
        disp('Didn\'t understand that input. Try again.');
        done = 'n';
    end
end
end
end
```

end % if auto == 1
Rain Gage Clean-Up Script:

function [clean2mldate,clean2data] = autocleanrain(mldate,data,maxrise,maxdt);
%AUTOCLEAN performs some automated cleaning processes on a gage

maxslope = maxrise/maxdt*1440; %ft/day

difft = diff(mldate);

% toss any data that is before the previous point
keep1 = [1 find(difft > 0)+1 ]';
mldate = mldate(keep1);
data = data(keep1);

numdata = length(data);

difft = diff(mldate);
diffh = diff(data);
diff2h = [data(3:end,:)-data(1:end-2,:)];

% Select rain to see if we should throw out.
% first criterion -- absolute rise > maxrise/10.
% second criterion -- time less than maxdt and no change in rainfall

toss = find(abs(diffh)>maxrise/10 | (difft<maxdt/1440 & diffh==0));

%disp('Keyboard mode: type RETURN to continue running program.')
%keyboard

if isempty(toss) == 1
    toss = [];
cleandate = mldate;
clean.data = data;
else
    % put in a bogus point so we can not have special treatment of the last point.
toss(end+1) = 10000000;
toss2(1) = 0;
count = 1;
for i=1:length(toss)-1
    % if we have two points in a row, and the signs of the delta are different, then toss
    the second one.
    if (toss(i+1) == toss(i)+1) & (sign(difff(toss(i))) == sign(difff(toss(i)+1)))
        toss2(count) = toss(i)+1;
count = count + 1;
    end
end
toss2(count) = 0;
end
end

toss2(count) = 10000000;

% convert from 'toss' to 'keep'.

count = 0;
counttoss=1;
toss3 = unique(toss2);
for i=1:numdata
    if i ~= toss3(counttoss)
        count = count+1;
        keep(count) = i;
    else
        counttoss = counttoss + 1;
    end
end

cleanmldate = mldate(keep);
cleandata = data(keep);
end

% once we have gotten rid of the easy ones (up and down/ down and up), lets work on
tougher ones.

clear keep;
numdata = length(cleandata);

diffh = diff(cleanmldate);
diffh = diff(cleandata);
diff2h = [data(3:end,:)-data(1:end-2,:)];
slp = diffh./diffh;

% find those points with slopes greater than the 'maxslope', first used 6 in/hr
toobig = find(abs(slp)>maxslope|diffh>maxrise);
diffh(toobig) = diffh(toobig)*0;

% if slope gt maxslope, then reset the diffh to zero. Start at point 1 = 0 rainfall, and add
back in the differences.

cleandata(1,1) = 0;
for i=2:length(cleandata)
    cleandata(i,1) = cleandata(i-1,1) + diffh(i-1);
end

diffh = diff(cleandata);

% This time, we're going to eliminate negative differences.
ltzero = find(diffh<0);
diffh(ltzero) = diffh(ltzero)*0;
cleandata(1,1) = 0;
for i=2:length(cleandata)
    cleandata(i,1) = cleandata(i-1,1)+diffh(i-1);
end

toss=[];

% this time, eliminate negative changes in time.
counttoss = 0;
for i=2:length(cleandata)
    if cleanmldate(i) < cleanmldate(i-1)
        counttoss = counttoss + 1;
        toss(counttoss) = i;
    end
end

% again, we have to convert from 'toss' to 'keep'
if counttoss > 0
    count = 0;
    counttoss=1;
toss2 = unique(toss);
toss2(end+1) = 100000000;
for i=1:ndata
    if i ~= toss2(counttoss)
        count = count+1;
        keep(count) = i;
    else
        counttoss = counttoss + 1;
    end
end
else
    keep = [1:1:length(cleanmldate(:,1))];
end
toss2;
clean2mldate = cleanmldate(keep);
clean2data = cleandata(keep);
Stream Flow Gage Clean-Up Script:

function [clean2mldate,clean2data] = autocleanstream(mldate,data,maxrise,maxdt);
%AUTOCLEAN performs some automated cleaning processes on a gage

maxslope = maxrise/maxdt*1440; %ft/day
numdata = length(data);

for i=1:3 % do this three times to be sure it gets done right.

diff = diff(mldate);
keep1 = [1 find(diff > 0)'+1 ];
mldate = mldate(keep1);
data = data(keep1);
end

keep1 = find(data>0);
mldate = mldate(keep1);
data = data(keep1);
numdata = length(data);

diff = diff(mldate);
diffh = diff(data);
diff2h = [data(3:end,:) - data(1:end-2,:)];
diff2t = [mldate(3:end,:) - mldate(1:end-2,:)];
slp = diffh./diff;
slp2 = diff2h./diff2t;

mult = 1;

keep4 = find(~(abs(slp(1:end-1)) > maxslope/mult & abs(slp(2:end)) > maxslope/mult &
abs(diffh(2:end)) > maxrise/2 & sign(slp(1:end-1)) == sign(slp(2:end))))+1;

keep4 = [1 keep4'];
cleanmldate = mldate(keep4);
cleandata = data(keep4);
clean2mldate = cleanmldate;
clean2data = cleandata;
mult = 2;
cleandata = clean2data;
cleanmldate = clean2mldate;
diff2t = diff(cleanmldate);
diffh = diff(cleandata);
diff2h = [cleandata(3:end,:)) - cleandata(1:end-2,:));]
diff2t = [cleanmldate(3:end,:) - cleanmldate(1:end-2,:));
slp = diffh./diff2t;
slp2 = diff2h./diff2t;

keep4 = find((abs(diffh(1:end-2)) > maxrise/mult & abs(diffh(3:end)) > maxrise/mult & (sign(slpm(1:end-2)) =~ sign(slpm(3:end)))));+1;

keep4 = [1 keep4' length(cleanmldate)];
clean2mldate = cleanmldate(keep4);
clean2data = cleandata(keep4);

for i=1:7
    cleandata = clean2data;
cleanmldate = clean2mldate;
diff2t = diff(cleanmldate);
diffh = diff(cleandata);
diff2h = [cleandata(3:end,:)) - cleandata(1:end-2,:));
diff2t = [cleanmldate(3:end,:) - cleanmldate(1:end-2,:));
slp = diffh./diff2t;
slp2 = diff2h./diff2t;

keep4 = find((abs(diffh(1:end-1)) > maxrise/mult & abs(diffh(2:end)) > maxrise/mult & (sign(slpm(1:end-1)) =~ sign(slpm(2:end)))));+1;

keep4 = [1 keep4' length(cleanmldate)];
clean2mldate = cleanmldate(keep4);
clean2data = cleandata(keep4);

end
Find Storms of Significance for Stream Gage 0419 Script:

clear;
CommonData;

Gage419Levels;

stage=27.8;

auto = 0;

% get the gage and start/end years from the user, as well as the processing % status of the data.

%[RainStat,StreamStat]=getGageStatus;

load GageStatus.mat;

gage='0403';
% gage = 'null';
%
% while strcmp(gage, 'null') % keep trying till I get a gage in my list of gages.
% gage=input('Enter Gage Number: ','s');
% if strcmp(isagage(gage), 'null')
% disp('Not a valid Gage Number');
% gage = 'null';
% elseif isempty(strmatch(gage,BraysStreamGages,'exact')) == 1
% disp('No Data for that Stream Gage')
% gage = 'null';
% end
% end

gageno = strmatch(gage,BraysStreamGages,'exact');

type = deblank(gagetype(strmatch(gage,gagelist,'exact'),:));

disp(['This is a ' type ' gage.']);

gagesyear=min(years(find(StreamStat(gageno,:))));
gageeyear=max(years(find(StreamStat(gageno,:))));
year = gagesyear;
storm=1;

AllStimes = [];
AllEtimes = [];
AllPeakTimes = [];
AllPeakStages = [];

mldate=[];
data=[];

while year <= gageeyear
    y = year - syear + 1; % This is the index of the years, from 1:number of years
    skip = 0;
    if strcmp(type, 'Stream') == 1
        col = 'b'; % color of the data for plotting.
    else
        col = 'r';
    end
    % get the data from the file, and plot it, so we can decide whether to process it or not.
    fn=fileselect(year,gage,StreamStat(gageno,y));
    [tmldate,tdata]=hcoemload(fn,year);

    mldate = [mldate' tmldate']';
data = [data' tdata']';
year=year+1;
end

figure(1);
cf
plot(mldate-datenum(gagesyear,1,1,0,0,0),data,'k-');
set(gca,'position',[.05 .05 .95 .90])
ax=axis;
axis([0 366*(gageeyear-gagesyear)+1 ax(3) ax(4)]);
title(['Gage ' gage]);
hold on;
plot(mldate-datenum(gagesyear,1,1,0,0,0),data,[col '.']);
zoom xon;
orient landscape;

[stimes,etimes,peaktimes,peakstages] = getOverStage(mldate,data,stage);

% going to modify getOverStage to take an array of stages, rather than just one.
Description at the end of that .m file.
numStorms = length(stimes);

for rg = 1:numRG
    rgage = BraysRainGages(rg,:)
    rmldate = [];
    rdata = [];
    year = gagesyear;
    while year <= gageeyear
        y = year - syear + 1;  % This is the index of the years, from 1:number of years
        skip = 0;
        if strcmp(type, 'Stream') == 1
            col = 'b';  % color of the data for plotting.
        else
            col = 'r';
        end
        % get the data from the file, and plot it, so we can decide whether to process it or not.
        if(RainStat(rg,y) > 0)
            fn=fileselect(year,rgage,RainStat(rg,y));
            [tmldate,tdata]=hcoemload(fn,year);

            rmldate = [rmldate' tmldate']';
            rdata = [rdata' tdata']';
        end
        year=year+1;
    end

    % uncomment these if you need to save the data.
    % eval(['r' rgage 'mldate = rmldate']);
    % eval(['r' rgage 'mdata = rdata']);

figure(1);
clf
plot(rmldate-datenum(gagesyear,1,1,0,0,0),rdata,'k-');
set(gca,'position',[.05 .05 .95 .90])
ax=axis;
axis([0 366*(gageeyear-gagesyear)+1 ax(3) ax(4)]);
title(['Gage ' gage]);
hold on;
plot(rmldate-datenum(gagesyear,1,1,0,0,0),rdata,[col ' ']);
zoom xon;
orient landscape;
% when I modify getOverStage to take several stages, I'll need to figure out how it will affect this code.
% Need to plot peak stage v. rainfall in X hrs before hit 7, 9, 10, 15, etc.
% Also, include rainfall after it hit the 'magic level'
% Do statistics on whether it hits 10, based on rainfall levels around the time it hits 7.
% include all the older gages. The newer gages don't have enough history.
% need some Thiessen Polygons or something to base rainfall estimates on.
% Need to have processed data to work with, especially for Gage 400 (Harris Gully).

rs(:,rg) = interp1q(rmldate,rdata,stimes);
for dur=1:6
    r_sm(:,dur,rg) = rs(:,rg) - interp1q(rmldate,rdata,stimes-dur/24);
    r_sp(:,dur,rg) = interp1q(rmldate,rdata,stimes+dur/24) - rs(:,rg);
end
clear rmldate rdata;
end

stagestr = num2str(stage);
stagestr = strrep(stagestr,' ','_');
fn=[dataroot 'gage_' gage '_stage_' stagestr '.mat'];
eval(['save ' fn ' stimes etimes peaktimes peakstages ']);
Appendix I: Additional Harris Gully Analysis Plots for
Storms of Significance between 1993 and 2001

10/20/93

First over 7 ft in Box at 20-Oct-1993 15:59:56
Peaked at 20-Oct-1993 16:45:06, 31.67 ft MSL
Time to Peak 0.75 hours
Time above 7 ft: 3.45 hours

Average Rainfall - All: 4.3 DS: 2.3 US: 3.8 in
Average Prior Rainfall - All: 3.0 DS: 3.7 US: 2.5 in
80% RF Prior - Dur: 3.25 RF: 2.5 Intensity: 0.8 in/hr
80% RF All - Dur: 6.50 RF: 3.4 Intensity: 0.5 in/hr
2 hrs After - RF: 0.5 Intensity: 0.3 in/hr
11/16/93

Gage 0403 - Harris Gully
Total = 2.41 in
Prior = 1.97 in

Gage 0420 - Main St.
Total = 3.62 in
Prior = 2.68 in

Gage 0460 - Gessner
Total = 3.58 in
Prior = 2.72 in

Gage 0470 - Belle Park
Total = 1.90 in
Prior = 1.38 in

Gage 0490 - Keegans
Total = 2.48 in
Prior = 1.85 in

First over 7 ft in Box at 16-Nov-1993 09:31:27
Peaked at 16-Nov-1993 10:41:55, 32.46 ft MSL
Time to Peak: 1.17 hours
Time above 7 ft: 6.23 hours
Average Rainfall - All: 3.2 DS: 1.2 US: 2.7 in
Average Prior Rainfall - All: 2.3 DS: 2.8 US: 2.0 in
80% RF Prior - Dur: 3.75 RF: 1.9 Intensity: 0.5 in/hr
80% RF All - Dur: 5.50 RF: 2.6 Intensity: 0.5 in/hr
2 hrs After - RF: 0.1 Intensity: 0.1 in/hr
10/17/94

Gage 0403

Total = 2.16 in
Prior = 0.20 in

Gage 0420 - Main St.

Total = 5.09 in
Prior = 1.36 in

Gage 0460 - Gessner

Total = 5.72 in
Prior = 1.81 in

Gage 0440 - S. Rice

Total = 6.98 in
Prior = 1.80 in

Gage 0440 - Harris Gully

Total = 10.41 in
Prior = 3.96 in

Gage 0470 - Belle Park

Total = 5.40 in
Prior = 1.71 in

Gage 0490 - Keegans

First over 7 ft in Box at 17-Oct-1994 19:56:03
Peaked at 17-Oct-1994 21:26:09, 36.54 ft MSL
Time to Peak 1.50 hours
Time above 7 ft: 7.24 hours
Average Rainfall - All: 5.1 DS: 0.7 US: 5.4 in
Average Prior Rainfall - All: 1.4 DS: 1.0 US: 1.6 in
80% RF Prior - Dur: 9.25 RF: 1.1 Intensity: 0.1 in/hr
80% RF All - Dur: 14.25 RF: 4.1 Intensity: 0.3 in/hr
2 hrs After - RF: 0.8 Intensity: 0.4 in/hr
10/18/94

Gage 0403

Rainfall (in)

0 1 2 3 4
18 21 00 03 06 09 12 15 18
0 10 20 30 40 50

Gage 0420 - Main St.

Total = 2.17 in
Prior = 1.91 in

Rainfall (in)

0 1 2 3 4
18 21 00 03 06 09 12 15 18
18 21 00 03 06 09 12 15 18

Gage 0440 - S. Rice

Total = 7.57 in
Prior = 5.56 in

Rainfall (in)

0 1 2 3 4
18 21 00 03 06 09 12 15 18
18 21 00 03 06 09 12 15 18

Gage 0460 - Gessner

Total = 5.64 in
Prior = 3.82 in

Rainfall (in)

0 1 2 3 4
18 21 00 03 06 09 12 15 18
18 21 00 03 06 09 12 15 18

Gage 0470 - Belle Park

Total = 5.13 in
Prior = 3.07 in

Rainfall (in)

0 1 2 3 4
18 21 00 03 06 09 12 15 18
18 21 00 03 06 09 12 15 18

Gage 0490 - Keegans

Total = 5.62 in
Prior = 3.69 in

Rainfall (in)

0 1 2 3 4
18 21 00 03 06 09 12 15 18
18 21 00 03 06 09 12 15 18

First over 7 ft in Box at 19-Oct-1994 04:13:18
Time to Peak 0.65 hours
Time above 7 ft: 13.92 hours
Average Rainfall - All: 3.8 DS: 0.7 US: 5.5 in
80% RF Prior - Dur: 6.50 RF: 2.9 Intensity: 0.3 in/hr
80% RF All - Dur: 15.00 RF: 4.2 Intensity: 0.3 in/hr
2 hrs After - RF: 0.3 Intensity: 0.1 in/hr
04/25/97

Gage 0403

Total = 2.60 in
Prior = 1.55 in

Gage 0420 - Main St.

Total = 2.50 in
Prior = 1.59 in

Gage 0460 - Gessner

Total = 2.97 in
Prior = 1.89 in

Gage 0440 - S. Rice

Total = 3.16 in
Prior = 2.35 in

Gage 0440 - Harris Gully

Total = 3.83 in
Prior = 2.32 in

Gage 0470 - Bella Park

Total = 2.27 in
Prior = 1.23 in

Gage 0490 - Keegans

First over 7 ft in Box at 25-Apr-1997 17:04:56
Peaked at 25-Apr-1997 19:39:15, 31.64 ft MSL
Time to Peak 2.57 hours
Time above 7 ft. 4.83 hours
Average Rainfall - All: 2.7 DS: 0.9 US: 2.6 in
Average Prior Rainfall - All: 1.7 DS: 2.0 US: 1.6 in
80% RF Prior - Dur: 3.25 RF: 1.4 Intensity: 0.4 in/hr
80% RF All - Dur: 5.25 RF: 2.2 Intensity: 0.4 in/hr
2 hrs After - RF: 0.7 Intensity: 0.3 in/hr
05/24/97

Gage 0403

Total = 1.50 in
Prior = 1.45 in

Gage 0420 - Main St.

Total = 2.46 in
Prior = 2.32 in

Gage 0460 - Gessner

Total = 1.72 in
Prior = 1.44 in

Gage 0440 - S. Rice

Total = 1.57 in
Prior = 1.55 in

Gage 0440 - Harris Gully

Total = 2.64 in
Prior = 2.50 in

Gage 0470 - Belle Park

Total = 1.44 in
Prior = 1.33 in

First over 7 ft in Box at 24-May-1997 18:33:23
Peaked at 24-May-1997 19:24:54, 30.04 ft MSL
Time to Peak 0.86 hours
Time above 7 ft: 2.26 hours
Average Rainfall - All: 1.7 DS: 0.5 US: 1.9 in
Average Prior Rainfall - All: 1.6 DS: 1.5 US: 1.7 in
80% RF Prior - Dur: 1.50 RF: 1.3 Intensity: 0.9 in/hr
80% RF All - Dur: 2.25 RF: 1.4 Intensity: 0.6 in/hr
2 hrs After - RF: 0.0 Intensity: 0.0 in/hr
01/06/98

Gage 0403
Total = 0.86 in
Prior = 0.86 in

Gage 0420 - Main St.
Total = 1.01 in
Prior = 1.01 in

Gage 0440 - S. Rice
Total = 1.94 in
Prior = 1.86 in

Gage 0460 - Gessner
Total = 2.01 in
Prior = 2.01 in

Gage 0470 - Belle Park
Total = 2.20 in
Prior = 1.95 in

Gage 0490 - Keegans

First over 7 ft in Box at 06-Jan-1998 21:50:28
Peaked at 06-Jan-1998 22:17:35, 29.10 ft MSL
Time to Peak 0.45 hours
Time above 7 ft: 0.96 hours
Average Rainfall - All: 1.6 DS: 0.3 US: 2.1 in
Average Prior Rainfall - All: 1.5 DS: 0.9 US: 1.9 in
80% RF Prior - Dur: 2.28 RF: 1.3 Intensity: 0.6 in/hr
80% RF All - Dur: 2.50 RF: 1.3 Intensity: 0.5 in/hr
2 hrs After - RF: 0.0 Intensity: 0.0 in/hr
01/21/98

Gage 0403

Gage 0420 - Main St.
Total = 3.09 in
Prior = 2.12 in

Gage 0460 - Gessner
Total = 2.36 in
Prior = 1.98 in

Gage 0470 - Belle Park
Total = 1.83 in
Prior = 1.77 in

Gage 0490 - Keegans
Total = 1.50 in
Prior = 1.42 in

Gage 0400 - Harris Gully
Total = 4.65 in
Prior = 3.16 in

Gage 0440 - S. Rice
Total = 1.62 in
Prior = 0.76 in

First over 7 ft in Box at 21-Jan-1998 22:19:57
Peaked at 21-Jan-1998 23:33:32, 34.60 ft MSL
Time to Peak 1.23 hours
Time above 7 ft: 4.25 hours
Average Rainfall - All: 2.1 DS: 1.0 US: 1.9 in
Average Prior Rainfall - All: 1.6 DS: 1.4 US: 1.7 in
80% RF Prior - Dur: 3.50 RF: 1.3 Intensity: 0.4 in/hr
80% RF All - Dur: 4.25 RF: 1.7 Intensity: 0.4 in/hr
2 hrs After - RF: 0.4 intensity: 0.2 in/hr
11/13/98

Gage 0403

Gage 0420 - Main St.
Total = 0.15 in
Prior = 0.08 in

Gage 0460 - Gessner
Total = 2.65 in
Prior = 2.22 in

Gage 0490 - Keegans
Total = 3.49 in
Prior = 2.96 in

Gage 0400 - Harris Gully
Total = 4.24 in
Prior = 3.31 in

Gage 0440 - S. Rice
Total = 3.16 in
Prior = 2.67 in

Gage 0470 - Belle Park
Total = 4.14 in
Prior = 3.43 in

First over 7 ft in Box at 13-Nov-1998 03:49:24
Peaked at 13-Nov-1998 07:06:54, 29.56 ft MSL
Time to Peak 3.29 hours
Time above 7 ft: 3.86 hours
Average Rainfall - All: 2.7 DS: 0.1 US: 3.4 in
Average Prior Rainfall - All: 2.3 DS: 1.4 US: 2.9 in
80% RF Prior - Dur: 9.50 RF: 1.9 Intensity: 0.2 in/hr
80% RF All - Dur: 11.50 RF: 2.2 Intensity: 0.2 in/hr
2 hrs After - RF: 0.2 Intensity: 0.1 in/hr
11/14/98

Gage 0403

Total = 0.02 in
Prior = 0.02 in

Gage 0410 - Main St.

Total = 2.69 in
Prior = 2.69 in

Gage 0420 - Gessner

Total = 2.06 in
Prior = 2.06 in

Gage 0440 - S. Rice

Total = 2.13 in
Prior = 2.11 in

Gage 0460 - Keegans

Total = 2.53 in
Prior = 2.43 in

Gage 0470 - Bella Park

Total = 1.24 in
Prior = 1.24 in

First over 7 ft in Box at 14-Nov-1998 07:57:53
Peaked at 14-Nov-1998 08:14:03, 29.82 ft MSL
Time to Peak 0.27 hours
Time above 7 ft: 0.90 hours
Average Rainfall - All: 1.6 DS: 0.0 US: 2.0 in
Average Prior Rainfall - All: 1.6 DS: 1.0 US: 2.0 in
80% RF Prior - Dur: 5.50 RF: 1.3 Intensity: 0.2 in/hr
80% RF All - Dur: 5.50 RF: 1.3 Intensity: 0.2 in/hr
2 hrs After - RF: 0.0 Intensity: 0.0 in/hr
11/12/00

Gage 0403
Total = 2.56 in
Prior = 2.28 in

Gage 0420 - Main St.
Total = 3.18 in
Prior = 2.68 in

Gage 0440 - S. Rice
Total = 2.24 in
Prior = 2.07 in

Gage 0460 - Gessner
Total = 2.56 in
Prior = 2.34 in

Gage 0470 - Bella Park
Total = 2.09 in
Prior = 2.09 in

Gage 0490 - Keegans
Total = 2.56 in
Prior = 2.40 in

First over 7 ft in Box at 12-Nov-2000 20:43:35
Time to Peak: 1.27 hours
Time above 7 ft: 3.25 hours
Average Rainfall - All: 2.5 DS: 1.1 US: 2.4 in
Average Prior Rainfall - All: 2.4 DS: 2.5 US: 2.3 in
80% RF Prior - Dur: 1.25 RF: 2.1 Intensity: 1.7 in/hr
80% RF All - Dur: 1.25 RF: 2.1 Intensity: 1.7 in/hr
2 hrs After - RF: 0.1 Intensity: 0.1 in/hr
06/07/01

Gage 0403
Total = 1.58 in
Prior = 1.56 in

Gage 0420 - Main St.
Total = 1.97 in
Prior = 1.93 in

Gage 0440 - S. Rice
Total = 2.01 in
Prior = 2.00 in

Gage 0460 - Gessner
Total = 3.35 in
Prior = 3.30 in

Gage 0470 - Bella Park
Total = 1.10 in
Prior = 1.08 in

Gage 0490 - Keegans
Total = 2.76 in
Prior = 2.73 in

First over 7 ft in Box at 07-Jun-2001 07:59:52
Peaked at 07-Jun-2001 08:29:11, 29.20 ft MSL
Time to Peak 0.49 hours
Time above 7 ft: 1.27 hours
Average Rainfall - All: 2.2 DS: 0.5 US: 2.4 in
Average Prior Rainfall - All: 2.1 DS: 1.7 US: 2.4 in
80% RF Prior - Dur: 5.00 RF: 1.7 Intensity: 0.3 in/hr
80% RF All - Dur: 5.00 RF: 1.7 Intensity: 0.3 in/hr
2 hrs After - RF: 0.0 Intensity: 0.0 in/hr
06/08/01

Gage 0403

Gage 0420 - Main St.
Total = 11.65 in
Prior = 2.49 in

Gage 0460 - Gessner
Total = 5.39 in
Prior = 2.60 in

Gage 0490 - Keegans
Total = 2.41 in
Prior = 0.91 in

Gage 0440 - S. Rice
Total = 5.58 in
Prior = 1.75 in

Gage 0470 - Bella Park
Total = 2.68 in
Prior = 1.02 in

First over 7 ft in Box at 08-Jun-2001 21:40:27
Peaked at 09-Jun-2001 01:58:12, 41.05 ft MSL
Time to Peak 4.30 hours
Time above 7 ft: 244.86 hours
Average Rainfall - All: 5.5 DS: 3.9 US: 3.5 in
Average Prior Rainfall - All: 1.8 DS: 2.1 US: 1.5 in
80% RF Prior - Dur: 3.00 RF: 1.5 Intensity: 0.5 in/hr
80% RF All - Dur: 6.75 RF: 4.5 Intensity: 0.7 in/hr
2 hrs After - RF: 0.7 Intensity: 0.4 in/hr
12/12/01

Gage 0403 - Stage (ft MSL)

Gage 0440 - Harris Gully
Total = 3.23 in
Prior = 3.17 in

Gage 0420 - Main St.
Total = 2.63 in
Prior = 2.57 in

Gage 0440 - S. Rice
Total = 1.88 in
Prior = 1.75 in

Gage 0460 - Gessner
Total = 2.80 in
Prior = 2.70 in

Gage 0470 - Bella Park
Total = 3.12 in
Prior = 3.06 in

Gage 0490 - Keegans
Total = 3.50 in
Prior = 3.43 in

First over 7 ft in Box at 12-Dec-2001 01:51:00
Peaked at 12-Dec-2001 02:11:08, 30.35 ft MSL
Time to Peak 0.34 hours
Time above 7 ft: 2.15 hours
Average Rainfall - All: 2.8 DS: 0.9 US: 3.1 in
Average Prior Rainfall - All: 2.7 DS: 2.2 US: 3.1 in
80% RF Prior - Dur: 7.00 RF: 2.2 Duration: 0.3 in/hr
80% RF All - Dur: 7.25 RF: 2.2 Intensity: 0.3 in/hr
2 hrs After - RF: 0.0 Duration: 0.0 in/hr