Statistical Analysis of Reservoir Pool Elevations

Addicks Reservoir
Barker Reservoir

2008 Summary Report

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Executive Summary

The core of this study is a reanalysis of stage-duration curves and stage-frequency curves. The reanalysis is an initial step of the Dam Safety Study for Addicks and Barker Reservoirs, Houston, Texas.

Methodology, discussion, and results consist of three phases: stage-frequency analysis, stage-duration analysis, and risk-reliability analysis.

The resulting stage-frequency curves provide a means to accurately forecast stage-probability with associated confidence bands of uncertainty.

Quantifying the reservoir pool elevation frequencies is a fundamental step in understanding and communicating water inundation risks to stakeholders located in and around the reservoirs. While the reservoirs are designated as flood control structures, major thoroughfares crossing through the reservoirs are subject to inundation, which is probable for more frequent than 1-% annual chance events. These thoroughfare inundations may lead to significant adverse economic consequences in addition to transportation inconveniences. Similarly, for both Addicks and Barker Reservoirs, there are significant residential encroachments within the footprints of the maximum reservoir flood pools.

The potential benefits of this study are improved communication with local stakeholders and improved reservoir operation during impoundment periods.

Credit goes to Harris County Flood Control District (HCFCD) for furnishing their recent final hydrology reports for Addicks and Barker Reservoirs for comparison purposes, quality checks.

1.0 Introduction

In order to determine the adequacy of Addicks and Barker Dams with respect to safety and functional reliability, it is important to reexamine the hydrology associated with the watershed, namely utilizing stage-duration and stage-frequency techniques with foci of risk-based analysis. The following section provides a general introduction.

1.1 AUTHORITY

Dr. Sterling to provide authority… public law number…

1.2 PURPOSE OF STUDY

The purpose of Addicks and Barker Reservoirs are to prevent downstream flooding of Buffalo Bayou in City of Houston. The reservoirs were authorized under the Rivers and Harbors Act of June 20, 1938, which were modified by the Flood Control Acts of August 11, 1939; September 3, 1954; and October 27, 1965.

This study is a partial response to a dam safety evaluation in which both dams were rated in Dam Safety Action Class (DSAC) II, which requires urgent and compelling action. The review panel commented that the increased urbanization of the surrounding watersheds since that period requires revalidation of the data.

Emphasis is placed on determining reservoir elevation-duration curves (stage-duration) and reservoir elevation-frequency curves (stage-frequency). Empirical evidence suggests that the pool elevations have reached their highest levels more frequently in the past decade. Reanalysis of this data provides a solid basis for public communications about the dams as well as support for future technical decisions concerning engineering and operations of the dams. The top ten pools for Addicks and Barker Reservoirs are found in *Appendix A – Dam Data*.

1.3 WATERSHEDS AND LOCATIONS

Addicks and Barker Reservoirs are located in the Buffalo Bayou watershed of the San Jacinto River Basin approximately 17-miles west of downtown City of Houston in Harris County, Texas, approximately fifty-miles north of the Gulf of Mexico. The Buffalo Bayou Watershed, Barker Watershed, Addicks Watershed, and Cypress Creek Watershed are described as follows:

Buffalo Bayou Watershed:
Buffalo Bayou is a tributary of the San Jacinto River. The Buffalo Bayou watershed lies primarily in Harris and Fort Bend Counties in southeast Texas. The basin is bounded on the north by Cypress Creek, on the east by the San Jacinto River; on the south by Clear Creek; and on the west by the Brazos River. Barker Dam is located on Buffalo Bayou about 1.5-miles above the confluence of South Mayde Creek. Addicks Dam is located on South Mayde Creek about one-mile above the confluence with Buffalo Bayou.

Barker Reservoir Watershed:
Buffalo Bayou watershed above Barker Dam lies within Harris, Waller, and Fort Bend Counties. The watershed, a roughly trapezoidal area of approximately 130-square-miles, is about 23-miles long with an average width of 6-miles. Natural ground elevations vary from 200-feet mean-sea-level (MSL) at the upstream divide to about 71-feet MSL at Barker Dam. Natural stream flow gradients in the basin are very uniform at about 5-feet per mile sloping in a southerly direction.

Addicks Reservoir Watershed:
Addicks Reservoir Watershed includes South Mayde Creek and its tributaries. The watershed above Addicks Reservoir lies within Harris County. The watershed is roughly 15-miles long, 10-miles wide, and has a drainage area of approximately 136-square-miles. Natural ground elevations in the basin vary from 200-feet MSL at the upstream divide to 73-feet MSL at Addicks Dam.

Cypress Creek Watershed:
The 130-square-mile watershed of Cypress Creek upstream of United States Highway-290 lies north of and adjacent to the Addicks Reservoir-South Mayde Creek Watershed. The general land slope of Harris and Waller Counties in this area are in a southerly direction while the Cypress Creek channel flows in an easterly direction to its outlet into the San Jacinto River in eastern Harris County. Consequently, the flood plain for Cypress Creek is relatively shallow with a poorly defined divide to the south; floodwaters from the larger floods flow southward across the divide into the Addicks Reservoir Watershed.

1.4 RESERVOIRS AND LOCATIONS

Construction on Addicks Dam and Reservoir began in May 1946 and was completed in December 1948. Construction of Barker Dam and Reservoir began in February 1942 and was completed in February 1945. Due to seepage, a slurry trench was placed through the top of both dams (up to 70-feet deep) in 1977 through 1979. In 1986 through 1989, both dams were upgraded to comply with modern design criteria, under the Dam Safety Assurance Program. The main embankments of the dams were raised to achieve needed freeboard requirements. Erosion protection was then added to the lower ends of the dams to protect the overflow spillways in case of a catastrophic event.

Substantial residential neighborhoods and commercial developments are located upstream and adjacent to the federal project lands as well as along the channel below the dams and throughout the Buffalo Bayou watersheds. The tremendous growth rate of City of Houston is accountable for the extensive suburban development of these watersheds, which were previously in an undeveloped condition. The federal project lands are within City of Houston. Descriptions and location overviews of Addicks and Barker Reservoirs are as follows:

Addicks Reservoir:
Addicks Reservoir is formed by a rolled earthen dam 61,666-feet long with a maximum height of 49.6-feet above the streambed. A 12-foot wide gravel road extends along the top of the dam. The top of the dam has a maximum elevation of 122.7-feet above the National Geodetic Vertical Datum (NGVD). Five gated conduits, 8-feet wide by 6-feet high by 252-feet long, serve as the outlet works. The discharge passes through a 43.5-foot long spillway into a 40-foot long by 60-foot wide stilling basin.

The area of Addicks Reservoir to be studied is roughly bounded by West Little York Road on the north, West Beltway-8 on the east, Interstate-10 on the south, and Barker Cypress Road on the west. State Highway-6 bisects the reservoir from north to south. Addicks Dam is located on South Mayde Creek approximately one-mile above the confluence with Buffalo Bayou. The main inflow contributors to Addicks Reservoir are South Mayde Creek, Bear Creek, and their tributaries: Horsepen Creek, Dinner Creek, and Langham Creek.

Barker Reservoir:
Barker Reservoir is formed by a rolled earthen dam 71,900-feet long with a maximum height of 38.7-feet above the streambed. A 12-foot wide gravel road extends along the top of the dam. The top of the dam has a maximum elevation of 114.7-feet above the NGVD. Five gated conduits, 9-feet wide by 7-feet high by 190.5-feet long, serve as the outlet works. The discharge passes through a 55.5-foot long spillway into 50-foot long by 60-foot wide stilling basin.

The area of Barker Reservoir to be studied is roughly bounded by Interstate-10 on the north, State Highway-6 on the east, Westpark Tollway on the south, and Grand Parkway on the west. Barker Reservoir is located on Buffalo Bayou, approximately 50-miles from its mouth and approximately 0.2-miles upstream of State Highway-6.

1.5 OPERATIONS

The two reservoirs, and corresponding two dams, are similar structures consisting of long earthen embankments with each dam having five gated conduits capable of discharging flood waters into downstream channels. The two flood control dams are operated by the USACE South West Division, Galveston District (SWG) to reduce flooding along Buffalo Bayou through City of Houston. Layout and feature data for Addicks and Barker Reservoirs are found in *Appendix B – Facility Data*.

In the original design for both dams, four of the five conduits were to be un-gated. However, with increasing urban development and encroachment along the discharge conduit, gates were added to the conduits and maximum discharges were reduced.

Table 01: Changes in Addicks and Barker Operational Release Targets shows the changes in combined discharge maximums per date. The latest restrictions were added in 1972 due to continued encroachment along the bayou, increased complaints of periodic flooding, and bank erosion impacting the foundation stability of properties.

Table 01: Changes in Addicks and Barker Operational Release Targets

Date	Number of Gated Conduits	Combined Discharge Maximum (cfs)
Original Design	1 of 5 on each reservoir	15,000
1948	3 of 5 on each reservoir	7,900 (uncontrolled)
1963	5 of 5 on each reservoir	4,000 (normal operating limit) 6,000 (non-damaging limit)
1972	5 of 5 on each reservoir	2,000 (normal operating limit)

Under normal conditions, the gated structures at both Addicks and Barker Dams are set to allow the unimpeded passage of low-flow water down Buffalo Bayou; this will prevent the unnecessary impoundment of water behind the dams. If severe weather is predicted or occurring that could cause excessive flows in Buffalo Bayou down stream of the dams, the dams will be closed until the threat of flooding has passed. After the threat has passed, the dams will be opened to allow any impounded waters to pass down Buffalo Bayou – through City of Houston – in a controlled manner until the reservoirs are once again empty. The decision on when and how much to open or close the dams is a team effort of the staff of USACE SWG, including water control personnel and the staff of the Addicks Field Office; these decisions are based on data obtained from rain gauges, stream gauges, and information from various agencies including the National Weather Service.

1.6 CLIMATOLOGY

Temperature:
The average annual temperature for the Houston area is 68.7-degrees Fahrenheit (National Climatic Data Center, 2008). Seasonal averages are as follows:

Winter: 56.2-degrees Fahrenheit;
Spring: 75.1-degrees Fahrenheit;
Summer: 81.8-degrees Fahrenheit;
Fall: 61.6-degrees Fahrenheit.

Temperature extremes range from 109 (2000) to 7-degrees Fahrenheit (1989).

Precipitation:
The climate of Harris County is predominantly maritime with relatively high humidity. The average relative humidity for the AM and PM are 90 and 63-%, respectively. The normal annual precipitation for the Houston area is 47.84-inches. Rainfall occurs on 106-days of the year on average. The greatest annual amount on record is 72.86-inches recorded in 1900 and the least was 17.66-inches recorded in 1917. There is no seasonal bias in precipitation amounts, the averages by season being as follows:

Winter:	10.02-inches;
Spring:	14.10-inches;
Summer:	11.34-inches;
Fall:	12.38-inches.

Storms and Floods:
Prior to construction of Addicks and Barker Reservoir, the maximum known flood on Buffalo Bayou occurred in December 1935. During this flood, considerable overflow occurred from Buffalo Bayou south into Brays Bayou. A peak flow rate of 40,000-cubic-feet-per-second (CFS) has been estimated for Buffalo Bayou at Waugh Drive, located about 25-stream-miles below the reservoirs (USACE, 1940).

Since establishment of stream gage stations, the maximum flood which has occurred on Buffalo Bayou was that of August 1945 when a peak discharge of 10,900-CFS was recorded above White Oak Bayou about 28-stream-miles below the reservoirs.

Post construction of Addicks and Barker Reservoir, the largest combined discharge occurred in June 1960 when an outfall of 5,800-CFS was estimated.

1.7 PREVIOUS STUDIES

Two previous studies provide benchmark hydrologic and hydraulic analyses of the Addicks and Barker Reservoirs. The first is Report of 2000, which is a summary of Report of 1998 (operations foci) and Report of 1999 (urbanization foci). The second is Report of 1977, which is a restudy due to apparent urbanization of the watersheds. Report of 2000 and Report of 1977 are summarized as follows:

Report of 2000:
Buffalo Bayou and Tributaries, Texas
Addicks and Barker Reservoirs
Operation of Addicks and Barker Reservoirs
United States Army Engineer District, Galveston
United States Army Corps of Engineers
Galveston, Texas
January 2000

When originally constructed in the 1940's, Addicks and Barker Dams were located about 17-miles west of the city limits; the reservoir lands were not a part of City of Houston. Substantial residential neighborhoods and commercial development located upstream and adjacent to the federal project lands as well as along the channel below the dams and throughout the Buffalo Bayou Watershed.

Optimal operating policies for Addicks and Barker Reservoirs are extremely important because:

- Extensive urban development occurred adjacent to the government owned lands upstream of the dams as well as along the channel downstream of the dams.
- As demonstrated by the studies cited in Report of 2000, stage-frequency relationships were sensitive to reservoir operating practices.

Report of 2000 summarizes conclusions regarding reservoir operations derived from investigations conducted by the Harris County Flood Control District (HCFCD). Recommendations are presented for further evaluation of operating procedures focusing on addressing flooding risks upstream of the dams as well as downstream.

Detailed revaluation of the procedures followed by USACE District, Galveston (SWG) in determining releases from Addicks and Barker Reservoirs is recommended. The risk of flooding properties located upstream of the government-owned lands is a primary consideration in a comprehensive evaluation of operating policies and practices. Both normal and emergency operations are addressed.

Period reevaluation of operating procedures is prudent practice for any major reservoir project. Reevaluation and modification of project operations in response to changing conditions and objectives is a well established policy within USACE. Reevaluation of release policies for Addicks and Barker Reservoirs is particularly important. Significant changes occurred since the reservoir projects were constructed and the regulation plans were developed. The risk of flooding residential and commercial properties located upstream of the dams is a major concern.

In the past, USACE studies of operating policies for Addicks and Barker Reservoirs focused on setting the allowable flow rate in the downstream channel, which was originally 6,000-CFS and was adjusted to 2,000-CFS at the Piney Point gage station. Future refining of release procedures should focus on the timing of gate openings and closures. Stage-frequency relationships are sensitive to the timing of gate operations. Closing gates early in a storm to reduce the risk of flooding downstream may result in significant increases in reservoir stages. The effects of early gate closures become increasingly more significant as the watersheds are urbanized. Extreme reservoir storage levels typically result from the cumulative effects of multiple rain storms occurring over several weeks. Waiting longer than necessary to open the gates after a storm ends results in more water in storage at the beginning of the next rain and thus higher peak stages. Improved flood forecasting capability could be pertinent in addressing these issues.

Optimal balancing of the storage between the two reservoirs warrants further consideration since the probability of the stage exceeding the limits of the government-owned land is greater at Barker Reservoir than at Addicks Reservoir. This could involve release results for the existing facilities of a conveyance structure between the reservoirs.

Release decisions are based on storage content and inflows, rather than downstream flows, during extreme conditions with stages approaching or exceeding designated critical levels. A detailed updated regulation schedule should be developed for use during extreme flooding conditions involving stages that could approach or exceed the limits of government-owned land. The reservoir system has not experienced a flood of this magnitude to-date. However, when such an extreme event does occur, a well designed current regulation schedule properly reflecting the risk of flooding properties upstream as well as downstream of the dams will be essential.

Report of 1977:
Buffalo Bayou and Tributaries, Texas
Addicks and Barker Reservoirs
Hydrology
United States Army Engineer District, Galveston
United States Army Corps of Engineers
Galveston, Texas
August 1977

Addicks and Barker Dams were constructed in 1948 and 1945, respectively, by USACE for flood control purposes only. Report of 1977 presents a detailed description and analysis of the general hydrology necessary to determine the adequacy of the two dams with respect to safety and functional reliability. Report of 1977 is a restudy deemed necessary because it was apparent that urbanization of the subject watersheds would soon reach levels in excess of those considered in the original design; further, an updated hydrologic criteria prescribed more severe design standards than those addressed in the original hydrologic investigation.

2.0 Methodology

This section discusses the methods of gathering and analyzing raw and derived data. Methodologies for analysis consist of three phases: stage-duration analysis, stage-frequency analysis, and risk-reliability analysis. Results and discussions are provided in *Section 3.0 Results and Discussions*.

2.1 DATA COLLECTION

Recorded stage data are extracted and derived from daily morning reports. For Addicks and Barker Reservoirs, daily morning reports (consisting of reservoir inflow and outflow computations and corresponding reservoir stages) are available for a 20-year time period, 1988 to 2007. Data from the daily morning reports are supplemented with 2008 peak stage data from United States Geological Survey (USGS). The combination of daily morning reports and USGS data results in a 21-year time period. The period of record is assumed to represent current development conditions within the watershed.

United States Army Corps of Engineers (USACE) is the responsible entity for upkeep to the daily morning reports by producing daily reservoir routing computations; RELQA, a FORTRAN-type program, is employed during reservoir routing computations and gate opening determinations. It should be noted, the results of the daily morning reports depict the results of operating procedures and reservoir inflows, i.e. the data provided within the daily morning reports are read from gage stations, and the gage station outputs are a direct result of gate operations.

The four primary United States Department of the Interior (USDI): USGS gage stations utilized and their corresponding drainage basin areas (in square-miles) are shown in **Table 02: USGS Gage Stations**.

Table 02: USGS Gage Stations

USGS Gage Station Description (location)	USGS ID (number)	Drainage Area (mi^2)
Buffalo Bayou at Piney Point, Texas	08073700	299
Buffalo Bayou at West Belt Drive, Houston, Texas	08073600	290
Addicks Reservoir near Addicks, Texas	08073000	136
Barker Reservoir near Addicks, Texas	08072500	128

The daily morning reports consist of 6-hour stage recordings and corresponding gate settings. There are over 58,000 6-hour stage recordings available for stage-duration analysis (percent of time exceeded) and for determining yearly peak stages for stage-frequency analysis.

2.2 STAGE-DURATION ANALYSIS

With Microsoft Excel Visual Basic macros, computations for stage-duration curves are performed by year and by quarterly season. Quarterly seasons consist of the following:

Winter:	January, February and March;
Spring:	April, May and June;
Summer:	July, August and September;
Fall:	October, November and December.

USACE Statistical Analysis of Time Series Data (STATS) program is used to perform various analyses of time-series data. The STATS program performs the following analyses: duration curves, annual maximum and minimum events, depart of monthly and annual values from respective means, and annual volume-duration exchange of high and low events. STATS is utilized for setup and comparison purposes only; the additional macro is used in lieu of STATS. The macro incorporates a smaller time increment of 6-hours (compared to 1-day with STATS) into the results. As many as two-hundred class-intervals may be used for a duration analysis with the additional macro.

2.3 STAGE-FREQUENCY ANALYSIS

Stage-frequency analysis consists of gathering peak stage data, modeling infrequent events, and graphing stage-frequency.

USACE Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS) Version 3.3 computer modeling software is used to perform hypothetical frequency analyses of hydrologic data for the 10, 2, 1, and 0.2-% annual chance events. USACE HEC Statistical Software Package (SSP) Version 1.0 computer modeling software is used to perform graphical frequency analysis based on Weibull plotting position distributions. A description of Weibull plotting position is as follows:

Weibull plotting is a graphical technique for determining if a data set comes from a population that would logically be fit by a two-parameter Weibull distribution. The Weibull plot has special scales that are designed so that if the data do in fact follow a Weibull distribution, the points will be linear (or nearly linear). The least squares fit of this line yields estimates for the shape and scale parameters of the Weibull distribution. (Engineering Statistics Handbook, 2008).

Modeling Infrequent Events:
To extend the stage-frequency curve beyond the Weibull ordinates, hypothetical frequency storm events are examined. USACE HEC-HMS is used to determine fully-developed flows.

For Addicks Reservoir, the Tropical Storm Allison Recovery Project (TSARP) HEC-HMS model is utilized to compute the 10, 2, 1, and 0.2 % annual chance events. The model accounts for overflows from the Cypress Creek Watershed into Addicks Reservoir. Respective pool elevations are derived from the hypothetical storms by converting the routed flood hydrograph storage to acre-feet and using the equations from RELQA. For hypothetical storms, an assumption is made that reservoir gates are closed and outflows are zero. The assumption corresponds to the criterion: *If severe weather is predicted or occurring that could cause excessive flows in Buffalo Bayou downstream of the dams, then the dams are to be closed until the threat of flooding has passed.*

For Barker Reservoir, the HEC-HMS model used for hypothetical storm events is the Corps Water Management System (CWMS) model based on the Modclark transform parameter and gridded precipitation. CWMS is an automated information system used by USACE to support the water control management mission; CWMS is utilized for encompassing the flows of Addicks and Barker Reservoirs through the intricate water control structures within the Houston area. The model is inactive for real-time storm forecasting; however, the model is calibrated with the storm events of October 2002, November 1998, and October 1994. For this analysis, the model is converted to Clark's transform parameters with hypothetical rainfall-frequency. The model is utilized to compute the 20, 10, 4, 2, 1, 0.4, and 0.2-% annual chance events. Minor amounts of overflow run-off volume into Mason Creek and Caney Creek from South Mayde Creek in Addicks Reservoir are directly added to the run-off volume of the routed hydrographs at Barker Reservoir. The assumption is made that reservoir gates are closed and outflows are zero.

As previously stated, the Barker Reservoir CWMS model is calibrated with the storm events of October 2002, November 1998, and October 1994. To simulate hypothetical rainfall-frequency, it was necessary to replace the gridded rainfall format with hypothetical rainfall-frequency and to use the regular Clark transform parameters, TC and R. TC and R parameters are not altered for this analysis. To be consistent with the rainfall-frequency procedures from Harris County Flood Control District (HCFCD), the same rainfall-frequency is used in this study. To estimate the impervious parameter for the different sub-watersheds, the entire watershed is superimposed on Google Earth and estimates for percent impervious are based on development shown on Google Earth. A workmap of Barker Watershed superimposed on Google Earth is found in *Appendix C – Workmaps*. TC and R parameters, infiltration loss rates, and routing parameters are adjusted as necessary to calibrate the model with emphasis on the hydrograph run-off volumes for the 20, 10, and 4-% annual chance events in order to match the Weibull plotting points of the graphical frequency curve. Once the respective hypothetical frequency storm ordinates agree with the graphical curve, the HEC-HMS model is changed back to Modclark with gridded rainfall and once more checked with the three historic storms. With this procedure, the graphical frequency curves provide reasonable forecasts of stage-frequency for a range of events, up to the 0.2-% annual chance event.

The Barker Reservoir model is based on the National Geodetic Vertical Datum (NGVD) 1929, 1973 Adjustment (73 ADJ). Similar to the current analysis, the Report of 2000 and the Report of 1997 utilize NGVD 1929 (73 ADJ), which provides an ideal basis for comparison purposes, quality checks. In difference to NGVD 1929 (73 ADJ), the Department of Homeland Security (DHS): Federal Emergency Management Agency's (FEMA) and TSARP recent reports utilize North American Vertical Datum (NAVD) 1988 with vertical height adjustments in 2001. Both reports are referenced in this study.

Graphing Stage-Frequency:
Improved representations of the stage-frequency curves are established with supplemental data points from Weibull plotting positions and HEC-HMS hypothetical storm events.

USACE HEC Flood Damage Analysis (FDA) Version 1.2 computer modeling software is used to determine engineering performance for Addicks and Barker Reservoirs. Resulting graphical stage-frequency curves are entered into HEC-FDA as stage-frequency probability functions with an equivalent period of record in order to compute the plus and minus two standard deviations of stage uncertainty for the confidence bands. The derivation of the equivalent period of record is based on guidance from EM 1110-2-1619, Table 4-5. More detail of engineering performance is provided in *Sub-Section 2.4: Risk-Reliability Analysis*.

2.4 RISK-RELIABILITY ANALYSIS

The third phase of analysis is risk-reliability analysis. Risk-reliability analysis consists of determining an equivalent period of record and engineering performance.

Equivalent Period of Record:
To determine an equivalent period of record for the Addicks Reservoir graphical frequency curve and associated stage uncertainty, a 30-year period of record is adopted using the guidance from EM-1110-2-1619, Table 4-5. The 30-year period of record corresponds to a rainfall-runoff-routing model calibrated to several short-interval events. For Barker Reservoir, the actual period of record is used from the same category of the respective table; this is due to the model being calibrated with three historical storms within a short period of record. Equivalent period of records are used in the HEC-FDA program to compute corresponding stage uncertainty for the graphical frequency curves.

Engineering Performance:
USACE policy requires all flood-damage reduction plans to be evaluated using a risk-based framework; the risk-based framework is to account for the uncertainties associated with the key hydraulic parameters of stage and discharge. Non-economic performance of a plan is displayed in terms of engineering performance. Engineering performance is determined from HEC-FDA program computations. The indices described herein represent some aspects of the non-economic performance of

alternative plans; the indices include annual exceedance probability, long-term risk, and conditional annual non-exceedance probability.

Note: Addicks and Barker Reservoirs are located within the 100-year floodplain as shown on the FEMA Flood Insurance Rate Map (FIRM) panel number 48201C0610L, 48201C0630L, 48201C0615L, 48201C0620L, 48201C0640L, 48201C0785L, 48201C0805L, and 48201C0810L for Harris County, Texas, dated June 2007. For further information, see FEMA Flood Insurance Study (FIS): Harris County, Texas and Incorporated Areas.

3.0 Results and Discussion

This section discusses the results of applying the raw and derived data to the methodology computations. Discussions follow *Section 2.0 Methodologies* by exploring the results via three phases: stage-duration analysis, stage-frequency analysis, and risk-reliability analysis.

3.1 STAGE-DURATION ANALYSIS

The results of period of record analysis consist of stage-duration curves. **Figure 01: Addicks Reservoir Duration Curves** and **Figure 02: Barker Reservoir Duration Curves** illustrate the stage-duration curves for the respective reservoirs based on seasons.

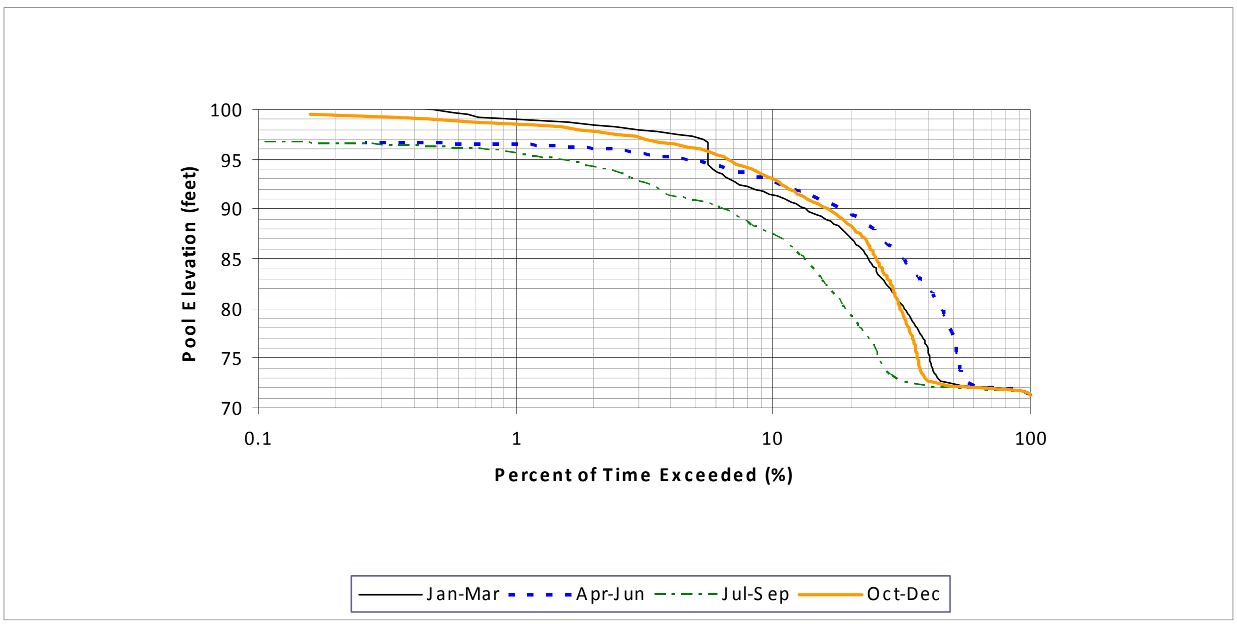

Figure 01: Addicks Reservoir Duration Curves

US Army Corps of Engineers

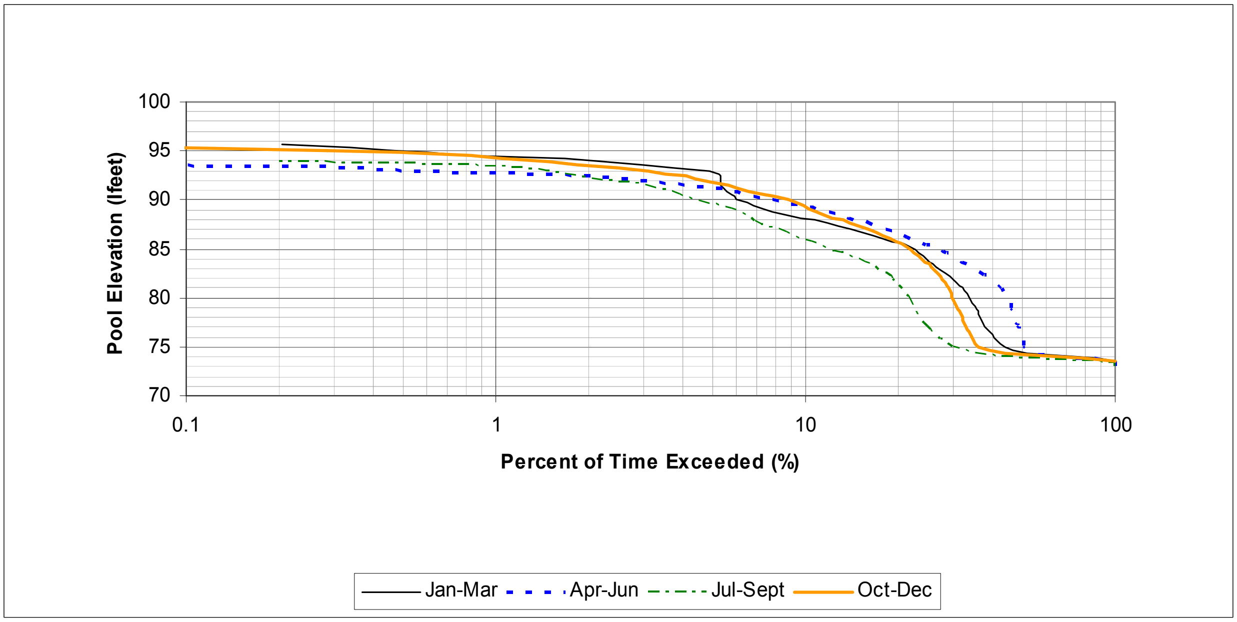

Figure 02: Barker Reservoir Duration Curves

The stage-duration curves are based on a horizontal axis of *percent of time stage exceeded* and a vertical axis of *pool elevation*. The similarities in curve shapes indicate parallel behaviors between Addicks and Barker Reservoirs. That is, both sets of curves illustrate an empty stage, two turning-points, a noise stage, and a level-out stage. The empty stage represents a static state (x changes; y constant) and is indicated by a slope approaching zero; it is located in the bottom right of the figures, approximately. The two turning-points represent a change from static state to dynamic state (x changes; y changes) and are indicated by a noticeable change in overall slope. The noise stage represents the dynamic state between the two turning points and is indicated by a parabolic-type shape. The level-out stage is normally approaching a static state (slope approaching zero) due to limitations in data. That is, the period of record does not experience a significant maximum peak stage.

Figure 01: Addicks Reservoir Duration Curves:
The empty stage is at approximately 72-feet in pool elevation, which occurs 71, 75, 58, and 62-percent of time during Winter, Spring, Summer, and Fall, respectively. The turning points are determined where the greatest difference in percent of time exceeded occurs. The noise stage is from approximately 72 to 97-feet in pool elevation. Within the noise stage, the 10-percent of time exceeded occurs at approximately 91, 93, 88, and 93-feet during Winter, Spring, Summer, and Fall, respectively. The limitations of the graph are in the level-out stage, which is due to the period of record. For example, the maximum design water surface is 114.0-feet; the period of record does not breach a pool elevation of 101-feet. As a result, the level-out stage approaches a slope of zero at a lower stage.

Figure 02: Barker Reservoir Duration Curves:
The empty stage is at approximately 74-feet in pool elevation, which occurs 62, 64, 65, and 53-percent of time during Winter, Spring, Summer, and Fall, respectively. The turning points are determined where the greatest difference in percent of time exceeded occurs. The noise stage is from approximately 74 to 94-feet in pool elevation. Within the noise stage, the 10-percent of time exceeded occurs at approximately 88, 89, 86, and 89-feet during Winter, Spring, Summer, and Fall, respectively. The maximum design water surface is 105.4-feet; the period of record does not breach a pool elevation of 96-feet. As a result, the level-out stage approaches a slope of zero at a lower stage.

Note: Graphical summaries depicting annual and seasonal data versus peak stage recordings for Addicks and Barker Reservoirs are shown in *Appendix D – Additional Data*.

3.2 STAGE-FREQUENCY ANALYSIS

The results of probability analysis consist of stage-frequency curves.

For summary purposes, static elevations determined for selected recurrence intervals for Addicks and Barker Reservoirs are shown in **Table 03: Summary of Reservoir Elevations**.

Table 03: Summary of Reservoir Elevations

Flooding Source	Peak Elevation NAVD29-73 (feet)			
	10% Annual Chance	2% Annual Chance	1% Annual Chance	0.2% Annual Chance
Addicks Reservoir	99.6	101.5	103.4	108.2
Barker Reservoir	95.0	96.2	97.3	100.10

The stage-frequency curves for Addicks and Barker Reservoirs are shown in **Figure 03: Addicks Reservoir – Probability versus Stage (with Uncertainty)** and **Figure 04: Barker Reservoir – Probability versus Stage (with Uncertainty)**. The stage-frequency curves are supplemented with data points from Weibull plotting positions and Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS) hypothetical storm events.

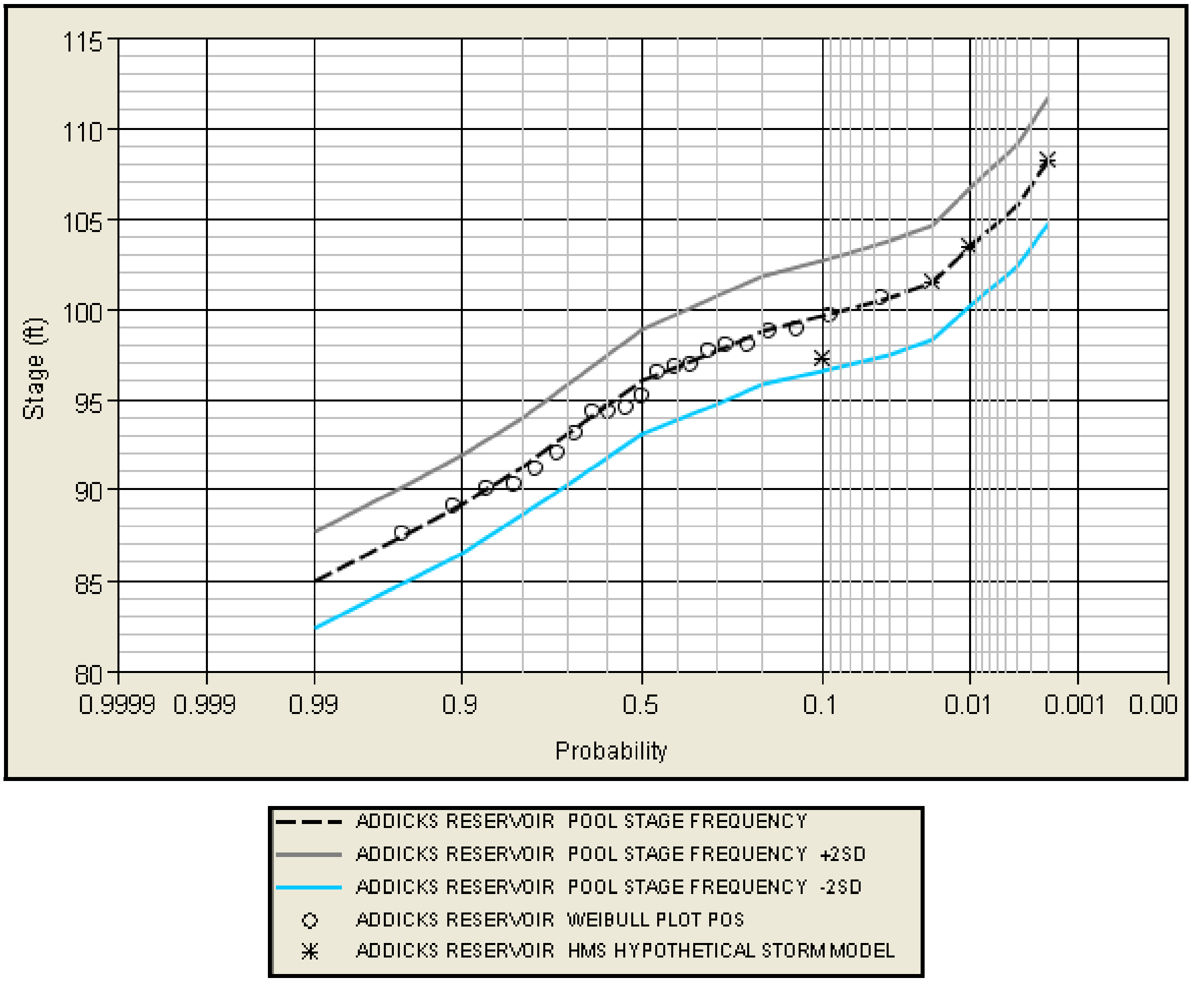

Figure 03: Addicks Reservoir – Probability versus Stage (with Uncertainty)

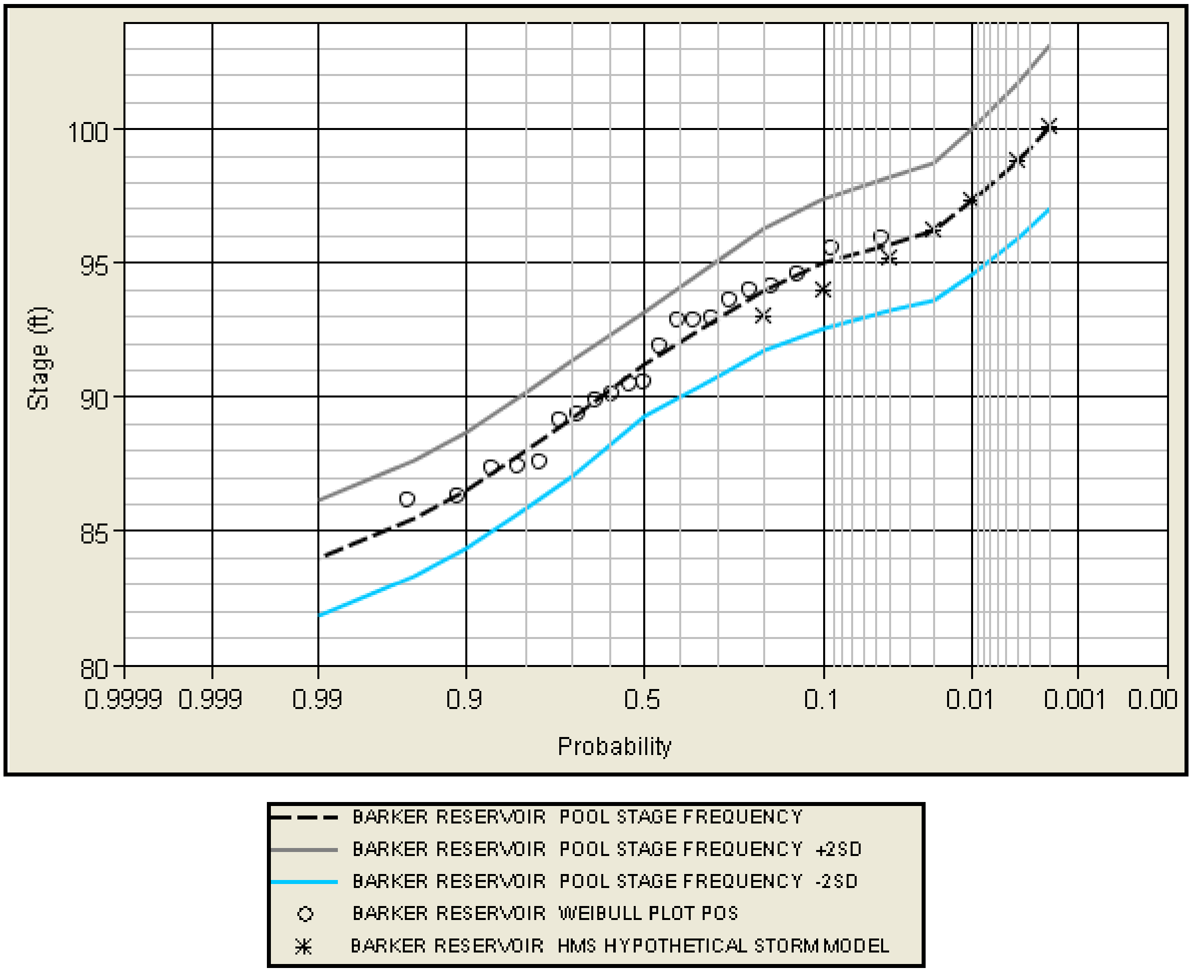

Figure 04: Barker Reservoir – Probability versus Stage (with Uncertainty)

The stage-frequency curves are based on a horizontal axis of *probability* and a vertical axis of *stage*. The similarities in curve shapes, which are roughly linear, indicate parallel behaviors between Addicks and Barker Reservoirs. All Weibull plotting positions and HEC-HMS hypothetical storm events fall within the plus and minus two standard deviations boundary. As a result, the data sets are within confidence and match closely with the frequency curves.

As discussed in *Sub-Section 2.3: Stage-Frequency Analysis*, there are 21-ordinates for Weibull plotting positions and 4-ordinates for percent chance annual events from hypothetical frequency events for Addicks Reservoir and 21-ordinates for Weibull plotting positions and 7-ordinates for percent chance annual events from hypothetical frequency events for Barker Reservoir.

Figure 05: Addicks Reservoir – Probability versus Stage (with 1977 Data) and **Figure 06: Barker Reservoir – Probability versus Stage (with 1977 Data)** compare the results of the current stage-frequency analyses with the results of the past stage-frequency analyses (Report of 1977).

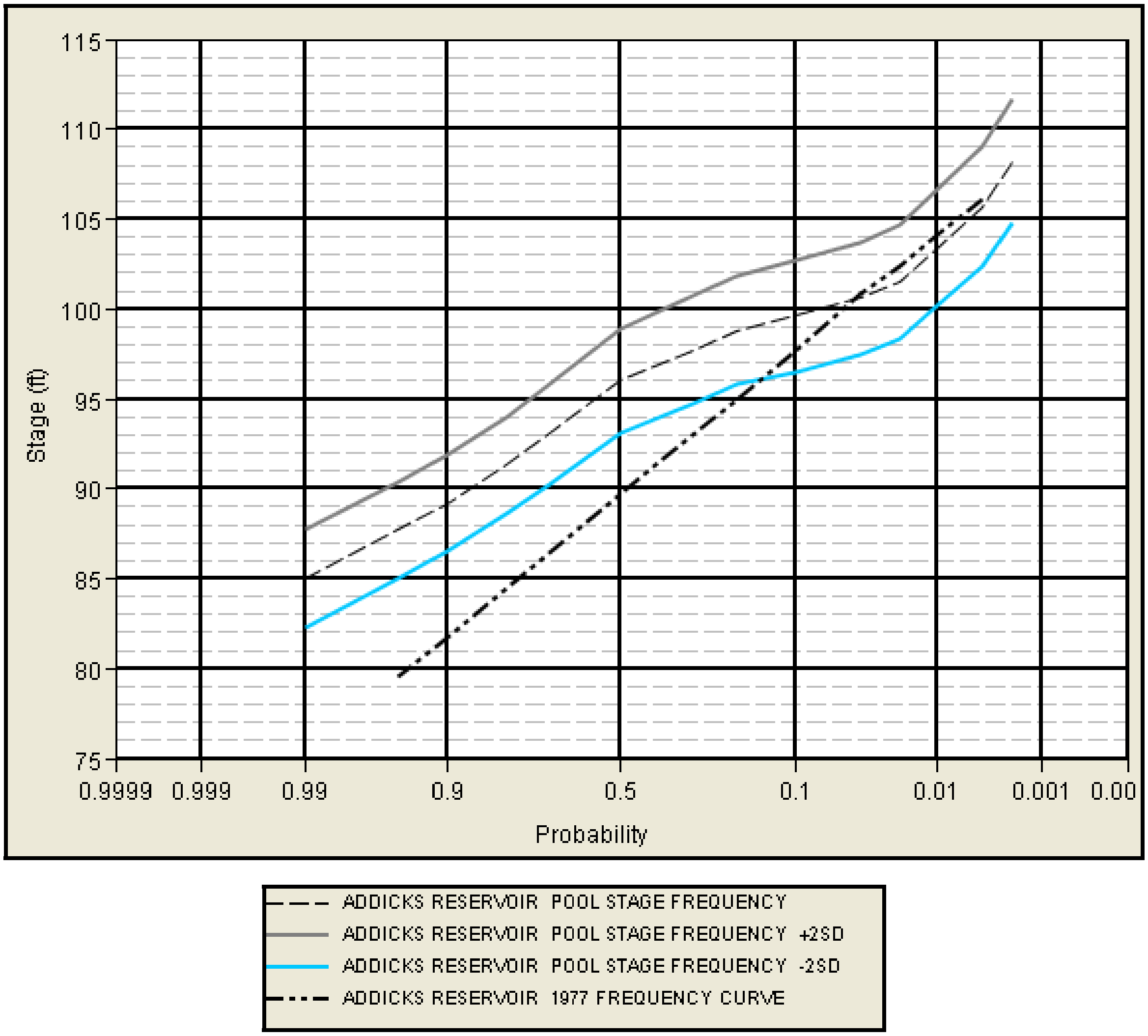

Figure 05: Addicks Reservoir – Probability versus Stage (with 1977 Data)

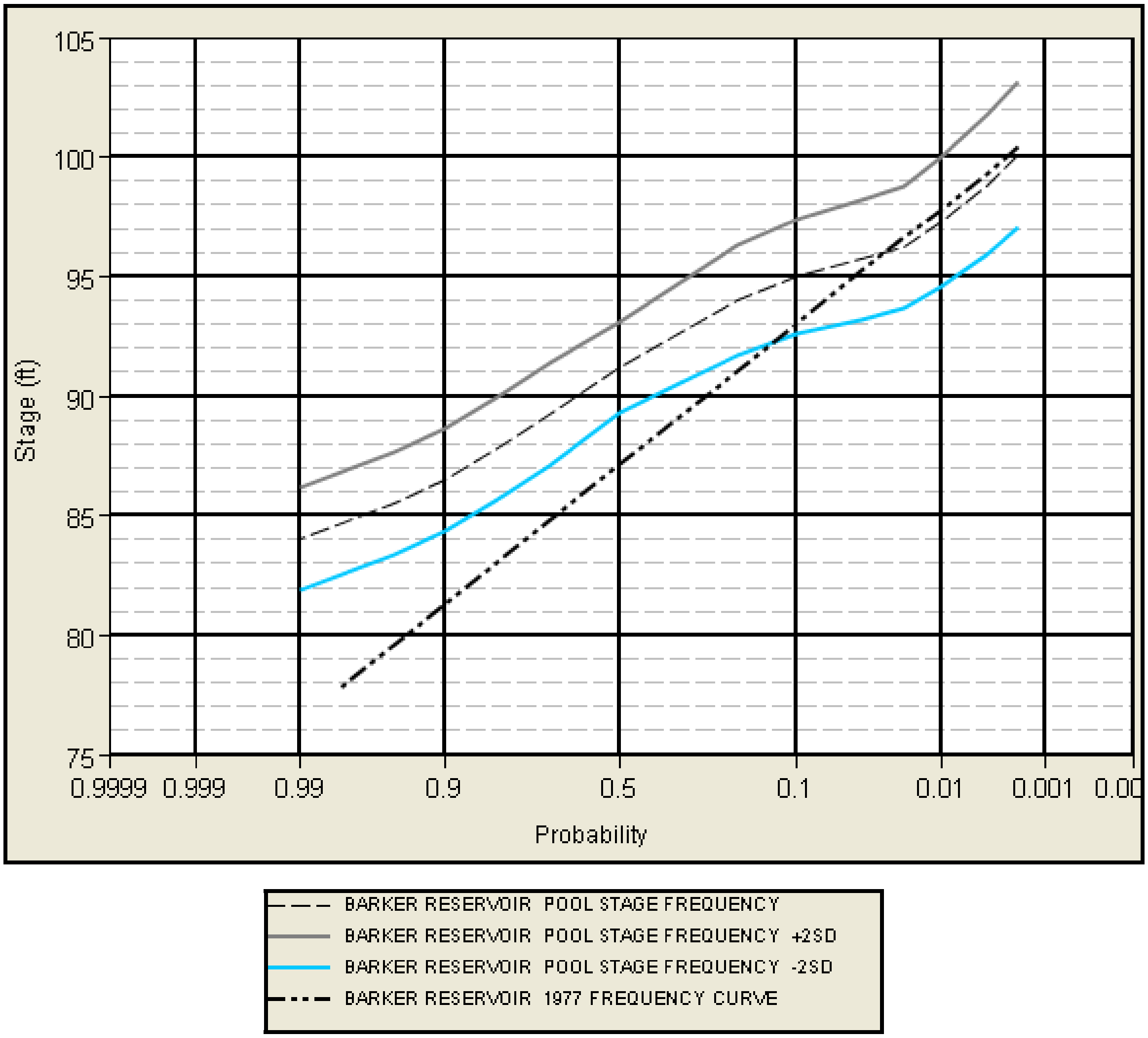

Figure 06: Barker Reservoir – Probability versus Stage (with 1977 Data)

The stage-frequency curves are based on a horizontal axis of *probability* and a vertical axis of *stage*. The similarities in curve shapes, which are roughly linear, indicate parallel behaviors between Addicks and Barker Reservoirs. Confidence limits correspond to plus and minus two standard deviations from the mean stage.

The current stage-frequency analysis curves and the past stage-frequency analysis curves (Report of 1977) approach similar probability versus stage ratios at the upper-end of rare events, e.g. greater than the 4-% annual chance event. The lower-end of the curves, i.e. less than the 4-% annual chance event, are significantly different in ratio due to increased development in the Addicks and Barker Watersheds. Further, the limiting operating procedure of 2000-CFS at the USGS Gage Station Number 08073700 (Piney Point) is a cause of differences in the lower-end of the curves.

3.3 RISK-RELIABILITY ANALYSIS

The results of risk-reliability analysis consist of engineering performance tables and stage-frequency curve comparisons.

HEC Flood Damage Analysis (FDA) results for three target stages are shown in **Table 04: Addicks Reservoir Performance** and **Table 05: Barker Reservoir Performance**. The three target stages for Addicks Reservoir include the following: extended watch stage at 90.00-feet, State Highway-6 edge-of-pavement (EOP) at 99.10-feet, and government owned real estate limit at 106.10-feet. The three target stages for Barker Reservoir include the following: extended watch stage at 87.00-feet, Westheimer Parkway EOP at 95.50-feet, and government owned real estate limit at 97.30-feet. The target stages correspond to the locations where damages are likely to occur in the lower overbank floodplain areas. The extended watch is defined as the minimum amount of impounded pool that would impact downstream properties if instantly released.

Table 04: Addicks Reservoir Performance

Description		Extended Watch	State Highway-6 (EOP)	Government Owned Real Estate Limit
Target Stage	Elevation	90.00 FT-MSL	99.10 FT-MSL	106.10 FT-MSL
Annual Exceedance Probability	Median	0.8670	0.1570	0.0040
Long-Term Risk	02-YR	0.9823	0.2894	0.0080
	04-YR	1.0000	0.4950	0.0160
	10-YR	1.0000	0.8188	0.0411
	25-YR	1.0000	0.9860	0.0997
	50-YR	1.0000	0.9999	0.1894
Conditional Annual Non-Exceedance Probability by Event	10-%	0.0000	0.3514	0.9975
	4-%	0.0000	0.1327	0.9975
	2-%	0.0000	0.0370	0.9975
	1-%	0.0000	0.0000	0.9972
	0.4-%	0.0000	0.0000	0.6155
	0.2-%	0.0000	0.0000	0.0628

Table 05: Barker Reservoir Performance

Description		Extended Watch	Westheimer Parkway (EOP)	Government Owned Real Estate Limit
Target Stage	Elevation	87.00 FT-MSL	95.50 FT-MSL	97.30 FT-MSL
Annual Exceedance Probability	Median	0.8720	0.0530	0.0100
Long-Term Risk	02-YR	0.9840	0.1030	0.0200
	04-YR	1.0000	0.1960	0.0390
	10-YR	1.0000	0.5000	0.0960
	25-YR	1.0000	0.7440	0.2220
	50-YR	1.0000	0.9340	0.3950
Conditional Annual Non-Exceedance Probability by Event	10-%	0.0000	0.6737	0.9835
	4-%	0.0000	0.4248	0.9256
	2-%	0.0000	0.2646	0.8354
	1-%	0.0000	0.0636	0.4998
	0.4-%	0.0000	0.0040	0.1144
	0.2-%	0.0000	0.0000	0.0154

Annual Exceedance Probability:
Annual exceedance probability is a measure of the likelihood or probability of exceeding a specified elevation (target stage) in any given year. For Addicks Reservoir, the annual exceedance probability for State Highway-6 stage is 0.1570, which theoretically indicates State Highway-6 EOP will be exceeded approximately 16-exceedances per 100-years. The extended watch will be exceeded approximately 87-exceedances per 100-years.

Similarly, for Barker Reservoir, the annual exceedance probability for Westheimer Parkway stage is 0.0530, which theoretically indicates Westheimer Parkway EOP will be exceeded approximately 5-exceedances per 100-years. The extended watch will be exceeded approximately 87-exceedances per 100-years.

Long-Term Risk:
Long-term risk is an index of the measure of the likelihood or probability of exceeding a target stage one or more times within a given duration. For Addicks Reservoir, the long-term risk for State Highway-6 indicates there is a 0.4950 probability (50% probability) that State Highway-6 EOP will be exceeded at least once in 4-years. In comparison, the extended watch has a 98% probability of being exceeded at least once in 2-years.

Similarly, for Barker Reservoir, the long-term risk for Westheimer Parkway indicates there is a 0.5000 probability (50% probability) that Westheimer Parkway EOP will be exceeded at least once in 10-years. In comparison, the extended watch has a 98% probability of being exceeded at least once in 2-years.

Conditional Annual Non-Exceedance Probability:
Conditional annual non-exceedance probability is a measure of the likelihood or probability that a specified target stage will not be exceeded within a particular event. For Addicks Reservoir the conditional annual non-exceedance probability indicates there is a 0.3514 probability (35% probability) that State Highway-6 EOP will not be exceeded in a 10-% annual chance event. Conversely, there is a 65-% chance that it will be exceeded by the 10-% chance event. The extended watch has a 0-% probability of not being exceeded in a 10, 4, 2, 1, 0.4, and 0.2-% annual chance event; that is, there is a 100-% probability of being exceeded in a 10, 4, 2, 1, 0.4, and 0.2-% annual chance event. The government owned real estate limits have a 62-% probability of not being exceeded in a 0.4-% (250-years) annual chance event.

Similarly, for Barker Reservoir the conditional annual non-exceedance probability indicates there is a 0.6737 probability (67% probability) that Westheimer Parkway EOP will not be exceeded in a 10-% annual chance event. The extended watch has a 0-% probability of not being exceeded in a 10, 4, 2, 1, 0.4, and 0.2-% annual chance event; that is, there is a 100-% probability of being exceeded in a 10, 4, 2, 1, 0.4, and 0.2-% annual chance event. The government owned real estate limits have a 50-% probability of not being exceeded in a 1-% (100-year) annual chance event.

Government owned real estate limits for Addicks Reservoir (106.10-feet) and Barker Reservoir (97.30-feet) are the boundary of federally owned land versus privately owned land. For the purposes of this report, FEMA 100-year floodplains are not utilized for comparison or analyses purposes.

3.4 GENERAL DISCUSSION

Appendix A – Dam Data shows the highest pool elevations recorded for Addicks and Barker Reservoirs. The maximum impoundments in Addicks and Barker Reservoirs occurred in 1992 when pool elevation reached 100.58-feet mean-sea-level (MSL) and 95.89-feet MSL, respectively. These maximum pools are below the 100-year frequency pool elevation determined for Report of 1977. In addition, the corresponding volumes for these maximum observed volumes were contained on government-owned land.

Appendix A – Dam Data highlights the highest reservoir pool elevations that have occurred within the past fifteen-years. Increased pool elevations result from the combination of increased inflows into the reservoirs and reduced discharges to the downstream channel. Increased inflows are most likely caused by increased urbanization in the Addicks and Barker Watersheds. A study by USGS supports the linkage of increased urbanization and runoff. Based on rainfall and runoff data from drainage basins in the Houston, Texas, metropolitan area, this study concludesd that *complete urbanization increases the magnitude of a 2-year flood nine times and increases the magnitude of a 50-year flood five times.*

There are two likely causes of reduced discharges from the reservoirs: increased rainfall runoff directly into the discharge channel due to downstream urbanization and conservative reservoir release decisions due to encroachment along the discharge channel. Increased direct runoff, primarily storm water drainage discharges, are routed to the discharge channel via drainage ditches and storm water outfalls; these non-point direct inflows are uncontrolled and un-gaged. The inflows are quantified as the difference between flow at the downstream control (Piney Point) and the estimated combined releases from the reservoirs. Throughout a 12-month period, these direct inflows will exceed the normal operating limit of 2,000-CFS at Piney Point. The exceedance duration is typically less than 24-hours.

Conservative reservoir release decisions can further restrict releases to the discharge channel. The normal channel discharge is limited to 2,000-CFS, as measured at the Piney Point stream gage. The limit includes the combined discharges from both reservoirs and inflows below the reservoirs. While the reservoir releases are controlled, the downstream inflows are uncontrolled and depend primarily on storm water volumes discharged directly to the downstream channel. Currently, the operating manual requires the reservoir gates to be closed when 0.5-inch of rainfall occurs in the Buffalo Bayou watershed over 24-hours or when flooding is predicted downstream. The basis is that this rainfall provides inflow values equal to or greater than that of the normal discharge limit of 2,000-CFS.

Complications in the release decision result from the required length of the forecasting period and uncertainties in rainfall predictions. There is an 8-hour travel time for waters discharged from the reservoirs to reach the Piney Point stream gage. To protect stream bank integrity near the reservoir outlet structures, the closing of the conduit gates is staggered, which requires additional time. Thus, release decisions are required at a minimum of 8-hours before any predicted rainfall occurs. As the reliability of a quantitative forecast on a small watershed such as Buffalo Bayou is suspect, conservative operations encourage gate closings given lower probabilities of rainfall. These decisions may lead to increased durations of reservoir pool impoundments.

4.0 Conclusions

This section provides conclusions to the reanalysis of stage-duration curves and stage-frequency curves. Methodology, discussion, and results consist of three phases: stage-duration analysis, stage-frequency analysis, and risk-reliability analysis.

Period of record analysis consists of collecting data, determining peaks, and graphing stage-duration. Graphing stage-duration curves is the end result for the period of record analysis. The similarities in curve shapes indicate parallel behaviors between Addicks and Barker Reservoirs. The general trend illustrates an empty stage, a noise stage, and a level-out stage. The resulting stage-duration curves are indicative of the operation of the reservoirs for different seasons under current developed watershed conditions. In general, the curves reflect that the Summer season (July-September) has lower pool stages for both reservoirs than the other seasons.

Probability analysis consists of gathering stage data, modeling infrequent events, and graphing stage-frequency. Graphing stage-frequency curves is the end result for the period of analysis. The similarities in curve shapes indicate parallel behaviors between Addicks and Barker Reservoirs. All Weibull plotting positions and Hydrologic Engineering Center (HEC) Hydrologic Modeling System (HMS) hypothetical storm events fall within the plus and minus two standard deviations boundary. As a result, the data sets are within confidence and match closely with the frequency curves; the stage-frequency curves are an accurate forecast of probability versus stage with associated uncertainty represented by the confidence bands.

Risk-reliability analysis consists of determining an equivalent period of record and engineering performance. Quantifying the reservoir pool elevation frequencies is a fundamental step in understanding and communicating water inundation risks to stakeholders located in and around the reservoirs. While the reservoirs are designated as flood control structures, major thoroughfares crossing through the reservoirs are subject to inundation, which is probable for more frequent than 1-% annual chance events. These thoroughfare inundations may lead to significant adverse economic consequences in addition to transportation inconveniences. Similarly, for both Addicks and Barker Reservoirs, there are significant residential encroachments within the footprints of the maximum reservoir flood pools.

The potential benefits of this study are improved communication with local stakeholders and improved reservoir operation during impoundment periods.

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Note: Website references dated per visit, data download.

Appendix A:

Dam Data

Top Ten Pools: Addicks Reservoir
Top Ten Pools: Barker Reservoir

TOP TEN POOLS
ADDICKS DAMS & RESERVOIRS

ADDICKS DAM & RESERVOIR					11-Jul-07
DATE	ELEV. (1)	SURFACE AREA IN ACRES	CAPACITY IN ACRE-FEET (2)	% CAPACITY MAX. POOL (3)	% CAPACITY OF GOL (4)
9 MAR '92	100.58	8,446	57,956	28.9	49.8
7 NOV '02	99.57	7,730	49,797	24.8	42.8
St Hwy 6 (edge)	99.10	7,424	46,236	23.0	40.0
17 NOV '98	98.82	7,242	44,183	22.0	38.0
23 OCT '94	98.75	7,196	43,678	21.7	37.6
15 MAY '68	98.28 (5)	* * *	* * *	* * *	* * *
25 NOV '04	98.00	6,718	38,461	19.2	33.1
8 JUL '07	97.94	6,682	38,059	19.0	32.7
4 SEP '81	97.37	6,337	34,349	17.1	29.5
17 SEP '98	97.07	6,159	32,474	16.2	27.9
20 APR '91	96.78	5,971	30,715	15.3	26.4
100 YR FEQ (9)	104.10	11,213	92,572	46.1	79.6
GOL (7)	106.10	12,460	116,263	57.9	100.0
MAX POOL (8)	112.00	16,423	200,840	100.0	172.7

NOTES:
(1) Elevations of water surface are in feet-NGVD (1973 Adjustment).
(2) One acre-foot of water is one acre of water, one foot deep.
(3) Percent of capacity of maximum possible pool before water spills around the ends of the dams.
(4) Percent of capacity of maximum possible pool contained within the government owned land.
(5) Original elevation of 100.03 MSL adjusted to reflect the1973 adjustment.
(6) Original elevation of 94.60 MSL adjusted to reflect the 1973 adjustment.
(7) Maximum possible pool contained within the government owned land.
(8) Maximum possible pool before water spills around the ends of the dams.
(9) Pool that would result from a 100 year storm event over the entire watershed.

TOP TEN POOLS
BARKER DAMS & RESERVOIRS

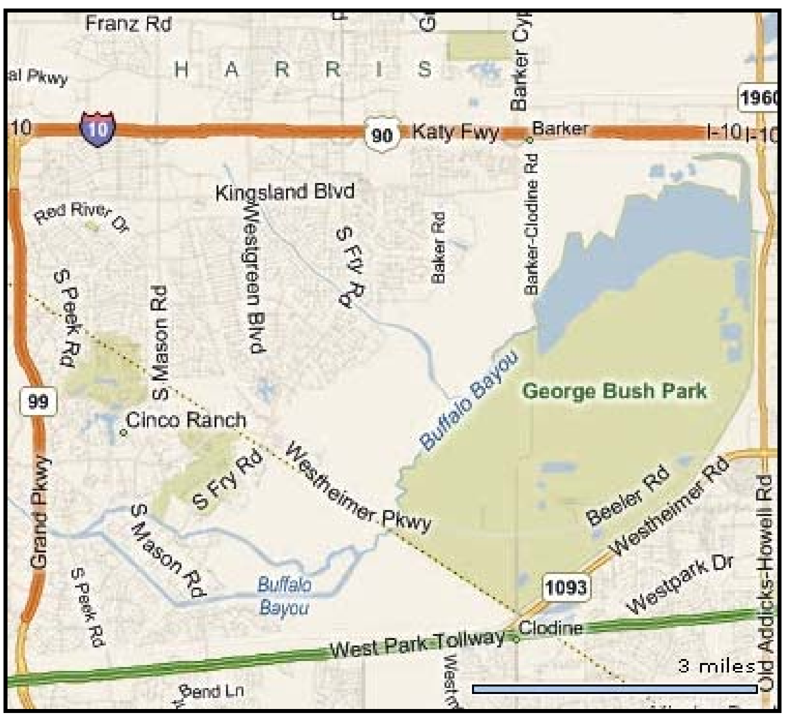
BARKER DAM & RESERVOIR					11-Jul-07
DATE	ELEV. (1)	SURFACE AREA IN ACRES	CAPACITY IN ACRE-FEET (2)	% CAPACITY MAX. POOL (3)	% CAPACITY OF GOL (4)
6 MAR '92	95.89	11,338	66,910	32.0	80.2
7 NOV '02	95.53	11,184	62,856	30.1	75.4
W. Pkwy (edge)	95.50	11,171	62,521	30.0	75.0
18 NOV '98	94.60	10,753	52,646	25.2	63.1
9 JUL '07	94.14	10,519	47,754	22.8	57.3
28 NOV '04	93.98	10,434	46,077	22.0	55.2
20 APR '91	93.63	10,179	42,470	20.3	50.9
15 MAY '68	92.89 (6)	* * *	* * *	* * *	* * *
31 MAY '97	92.87	9,502	34,950	16.7	41.9
22 OCT '94	92.83	9,432	34,571	16.5	41.4
17 SEP '98	92.65	9,123	32,901	15.7	39.4
GOL (7)	97.30	12,060	83,410	39.9	100.0
100 YR FEQ (9)	97.80	12,293	89,498	42.8	107.3
MAX POOL (8)	106.00	16,739	209,013	100.0	250.6
NOTES:					
(1) Elevations of water surface are in feet-NGVD (1973 Adjustment).					
(2) One acre-foot of water is one acre of water, one foot deep.					
(3) Percent of capacity of maximum possible pool before water spills around the ends of the dams.					
(4) Percent of capacity of maximum possible pool contained within the government owned land.					
(5) Original elevation of 100.03 MSL adjusted to reflect the1973 adjustment.					
(6) Original elevation of 94.60 MSL adjusted to reflect the 1973 adjustment.					
(7) Maximum possible pool contained within the government owned land.					
(8) Maximum possible pool before water spills around the ends of the dams.					
(9) Pool that would result from a 100 year storm event over the entire watershed.					

Appendix B:

Facility Data

Location Map
Layout and Feature Data

Addicks Reservoir – North View
(maps.live.com)



Barker Reservoir – North View
(maps.live.com)

US Army Corps of Engineers

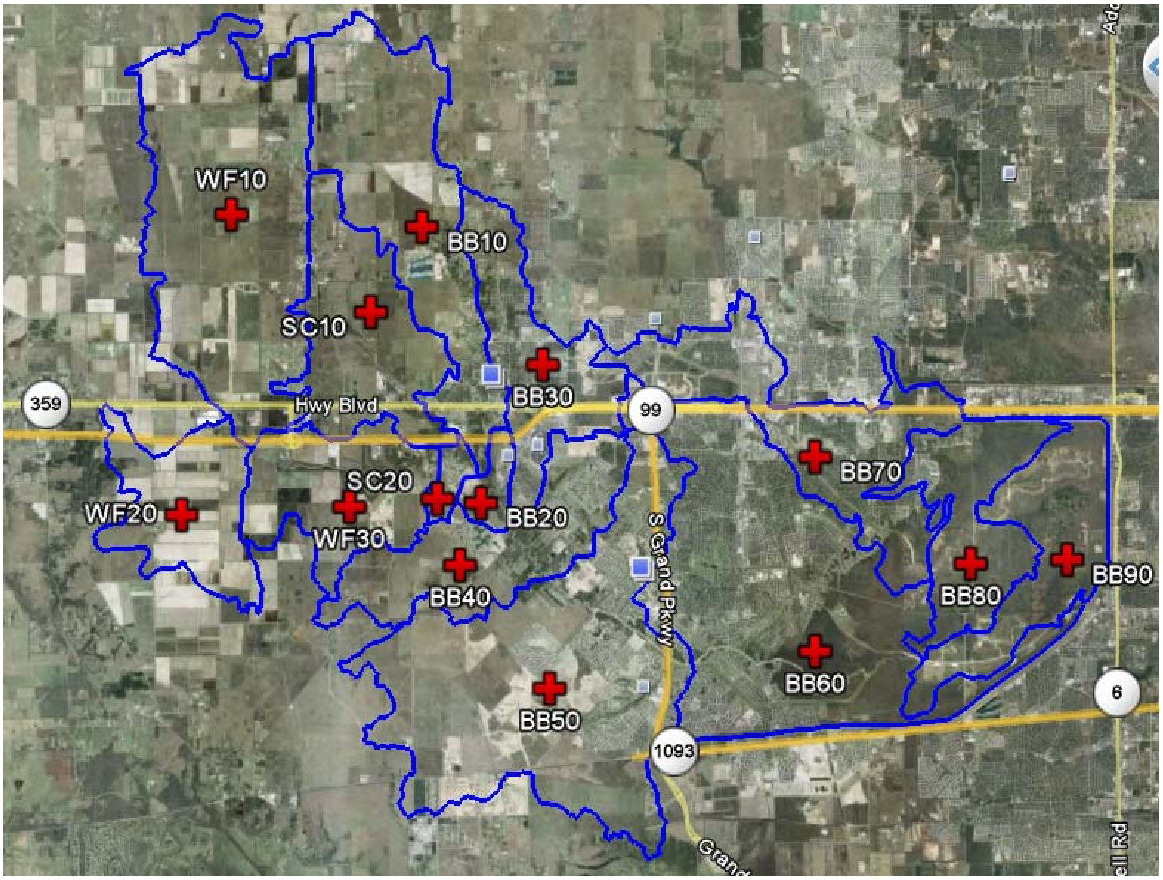
ADDICKS AND BARKER DAMS AND RESERVOIRS
LAYOUT AND FEATURE DATA

Item	Addicks Reservoir		Barker Reservoir	
DRAINAGE AREA	136 square miles		130 square miles	
DAM				
Type	Rolled earth embankment		Rolled earth embankment	
Length	61,166 feet		71,900 feet	
Height (above stream bed)	48.5 feet		36.5 feet	
RESERVOIR	Elevation, feet (MSL) (1)	Storage Capacity acre-feet	Elevation, feet (MSL) (1)	Storage Capacity acre-feet
Top of dam	122.7	---	114.7	---
Natural ground at ends of dam	112.0	200,800	106.0	209,000
Maximum design water surface (2)	114.0	235,200	105.4	192,500
Government owned real estate limit	106.1	116,300	97.3	83,400
Standard project flood max. water surface	110.6	178,600	100.4	123,700
Conduit invert	71.1	0	73.2	0
OUTLET WORKS				
Conduits	5 conduits, 8' wide x 6' high x 252' long each		5 conduits, 9' wide x 7' high x 190.5' long each	
Number of conduits gated	5 conduits		5 conduits	
Discharge-maximum design water surface-through 5 conduits	7852 c.f.s.		8734 c.f.s.	
Stilling basin	43.5' convex spillway, 40' long, 60' wide longitudinal stilling basin; and 150' of rip-rap lined outlet channel		55.5' convex spillway, 50' long 60' wide longitudinal stilling basin; and 160' of rip-rap lined outlet channel	

Appendix C:

Workmaps

Workmap 01 – Addicks Reservoir Watershed by TSARP
Workmap 02 – Barker Reservoir Watershed by TSARP
Workmap 03 – FIS Watershed by FEMA
Workmap 04 – Barker Reservoir Watershed based on Google Earth



Barker Reservoir – North View
(Google Earth)

Appendix D:
Additional Data

Predicted vs. Recorded Rainfall:

Predicative rainfall data examines the 10, 2, and 1-% annual chance events. Rainfall data were determined via four sources:

- National Weather Service (NWS) Technical Paper 40 *(TP-40)*.
- Southern Regional Climate Center (SRCC) Technical Report 97-1 *(TR-97-1)*.
- Determination of Updated Precipitation Depth Duration Frequency – Values After Tropical Storm Allison for Houston County Flood Control District *(PBSJ)*.
- United States Geological Survey (USGS), Houston County Flood Control District, Region 1: Spring Creek, Cypress Creek, Little Cypress Creek, Willow Creek, Barker Reservoir, and Addicks Reservoir (*HCFCD-1*).

Hydrology calculations utilize HCFCD-1 data, which are generally accepted rainfall data. Comparing TP-40, TR-97-1, PBSJ, and HCFCD-1 rainfall data (predicative rainfall data) to recorded data (extractions from morning reports) allows one to relate the frequency-magnitude relationships of *expected* heavy rainfall storm events to actual rainfall storm events.

Rainfall data for the 10, 2, and 1-% annual chance vents, 24-hour are shown in **Table A: Rainfall Data, 24-Hour**.

Table A: Rainfall Data, 24-Hour

Storm Event (year)	10	50	100
Probability (%)[A]	10.0	2.0	1.0
TP-40 (inches)	8.1	10.9	12.4
TR-97-1 (inches)	7.5	10.8	12.2
PBSJ (inches)	7.4	11.5	13.9
HCFCD-1 (inches)	7.1	10.6	12.4

A: Probability of being equaled or exceeded in any one year.

Comparison hydrology calculations utilize HCFCD-1 data, which are generally accepted rainfall data. As **Table A: Rainfall Data, 24-Hour** indicates, predicated rainfall data per source are similar in magnitude. The standard deviation of rainfall depth is 0.42, 0.39, and 0.79-inches for the 10, 2, and 1-% annual chance events, respectively. As a result, the rainfall data sources are within reason.

While **Table A: Rainfall Data, 24-Hour** shows predicted rainfall data based on 24-hours, predicted rainfall data is also based on duration: 1, 2, 3, 6, 12, and 24-hour.

The graphical summaries that follow are representative of the limited predicative precipitation depth-duration data for the 10, 25, 50, and 100-year storm events determined from TP-40, TR-97-1, PBSJ, and HCFCD-1.

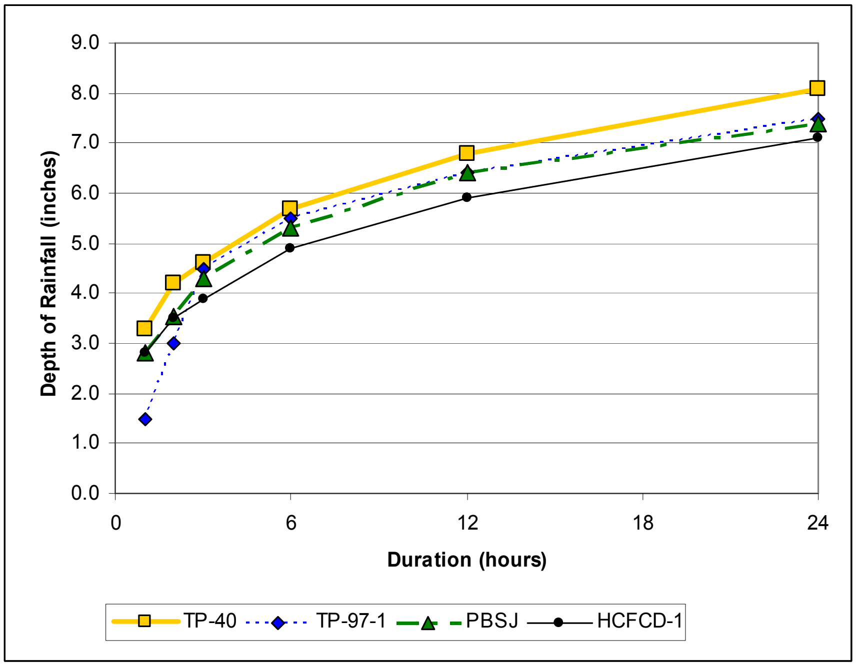


Figure A: 10-% Annual Chance Event

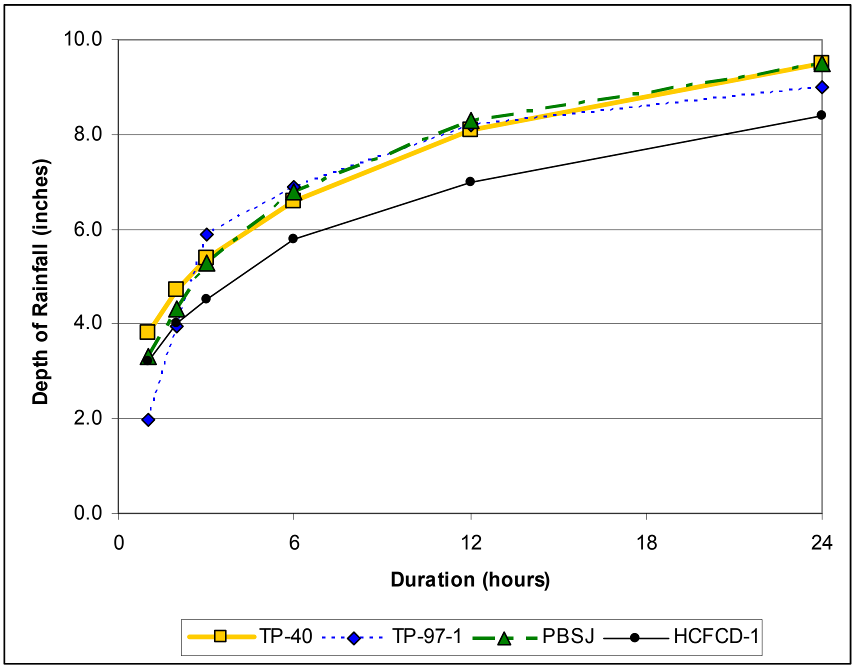


Figure B: 4-% Annual Chance Event
Note: HCFCD-1 is 100% Interpolated Data.

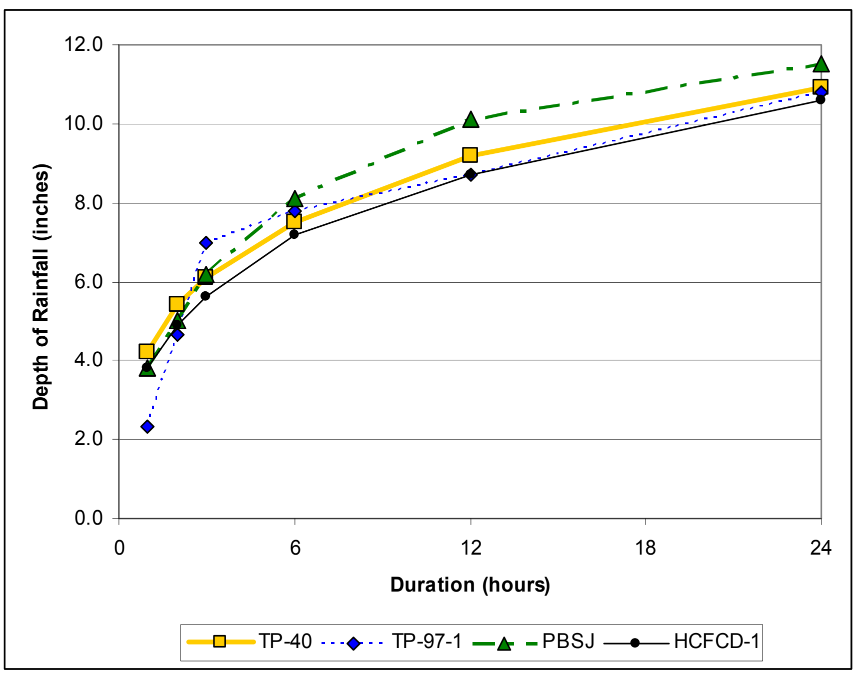


Figure C: 2-% Annual Chance Event

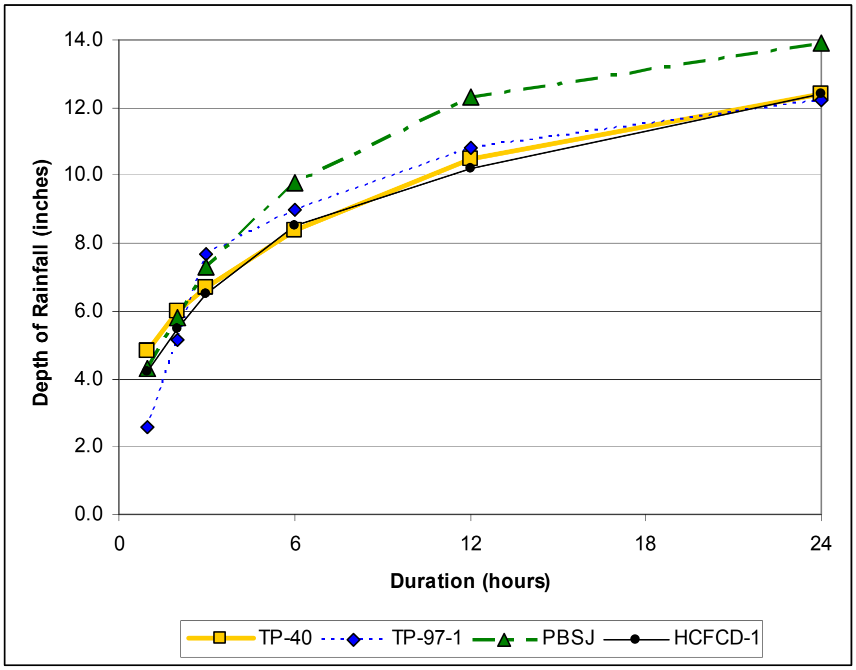


Figure D: 1-% Annual Chance Event

Figures A to D indicate predicative precipitation depth-duration data are similar in magnitude and slope, parabolic function. For example, the slopes for the 10-year storm are 0.19, 0.22, 0.18, and 0.17 for TP-40, TP-97-1, PBSJ, and HCFCD-1, respectively. The slopes have a standard deviation of 0.02. As a result, the depth-duration data sources are within reason.

Graphical summaries depicting annual and seasonal data versus peak stage results are shown in Figures E to N. Data are derived from the daily morning reports.

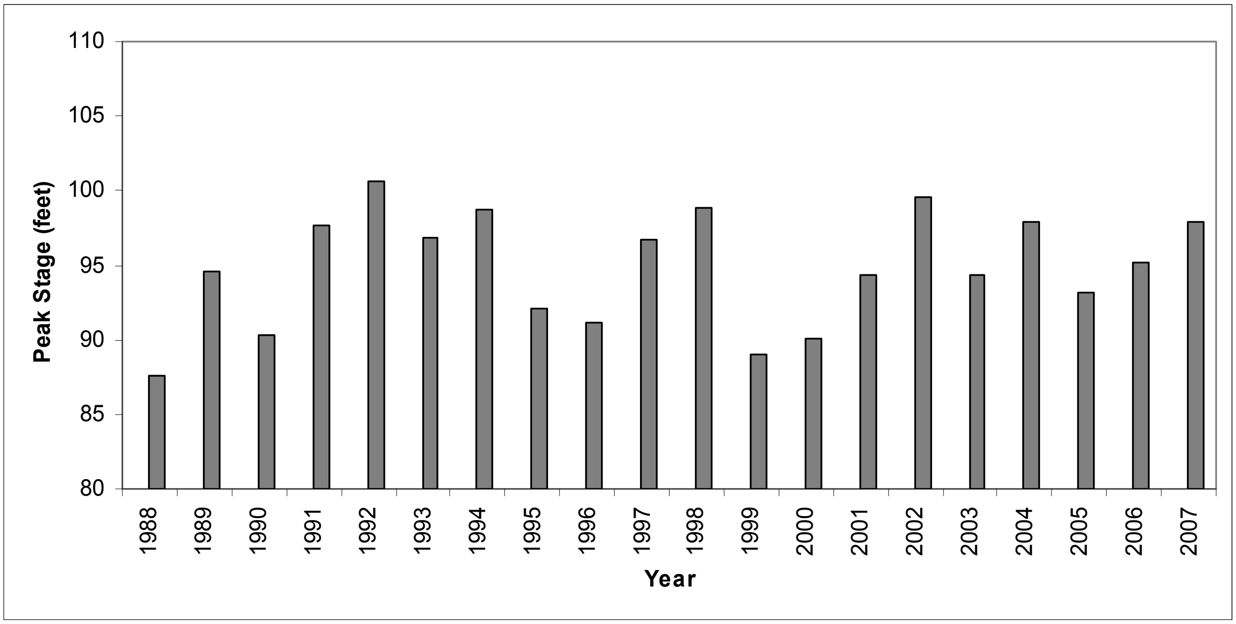


Figure E: Addicks Annual – Year versus Peak Stage

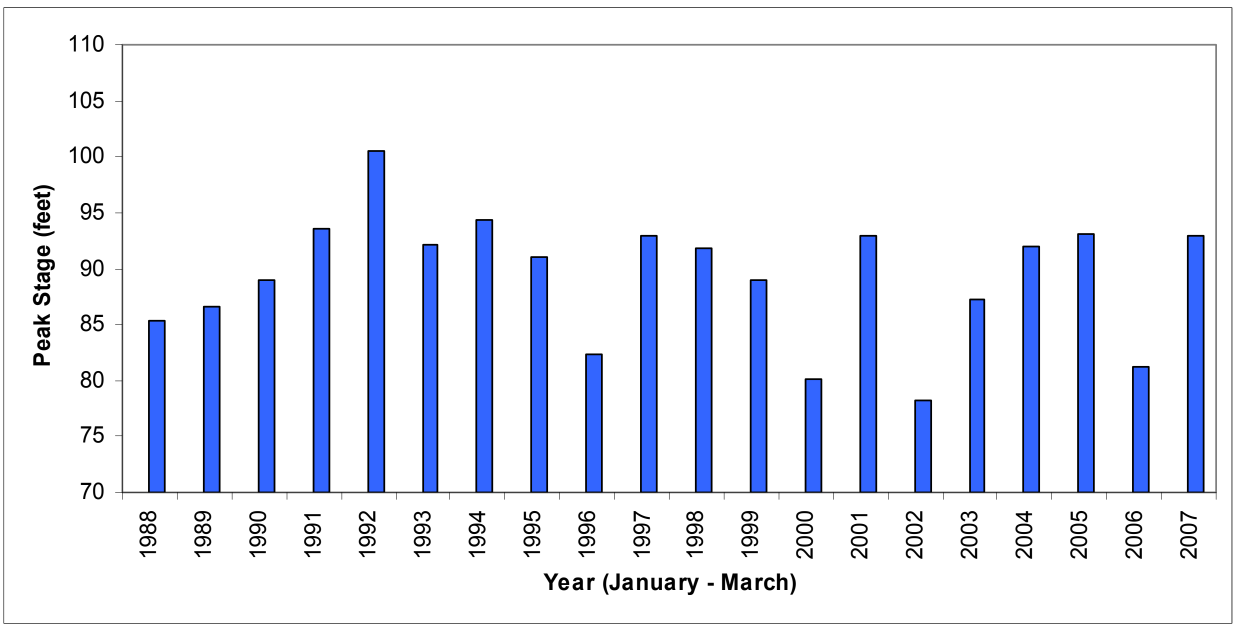


Figure F: Addicks Seasonal – Year (January-March) versus Peak Stage

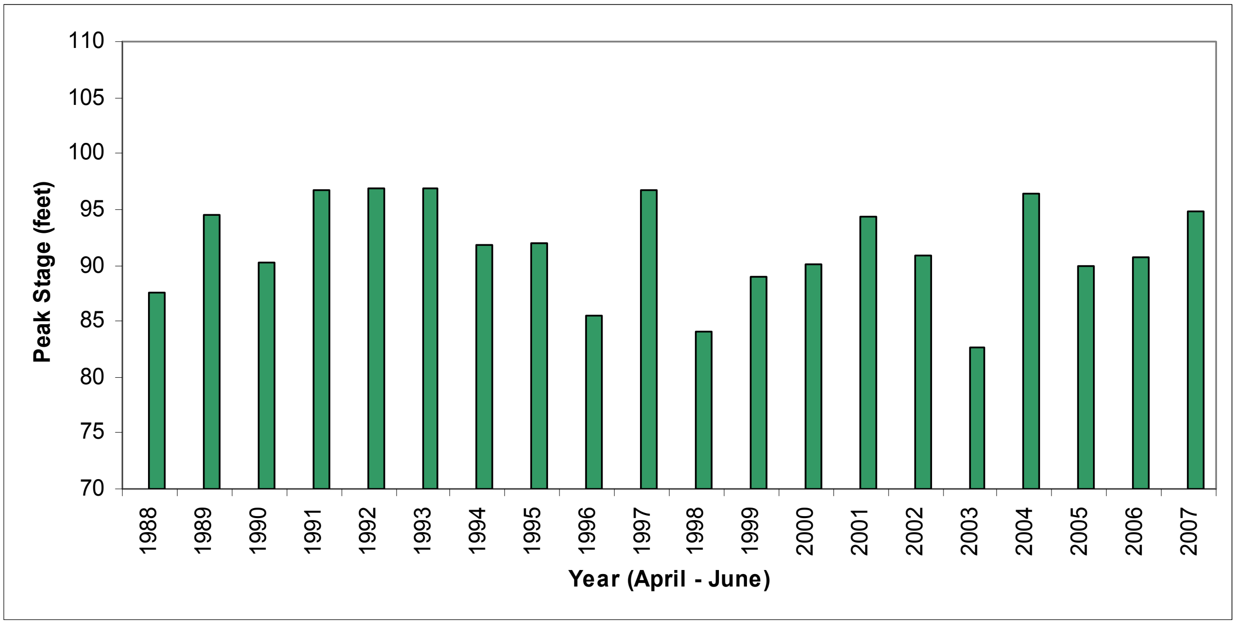


Figure G: Addicks Seasonal – Year (April-June) versus Peak Stage

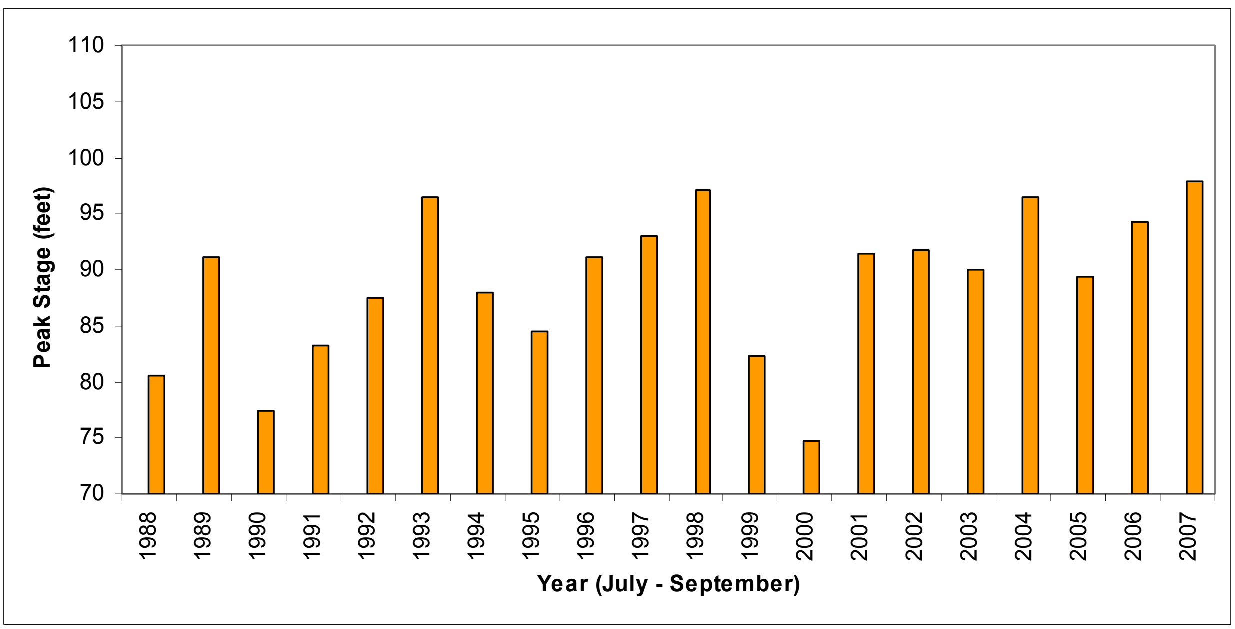


Figure H: Addicks Seasonal – Year (July-September) versus Peak Stage

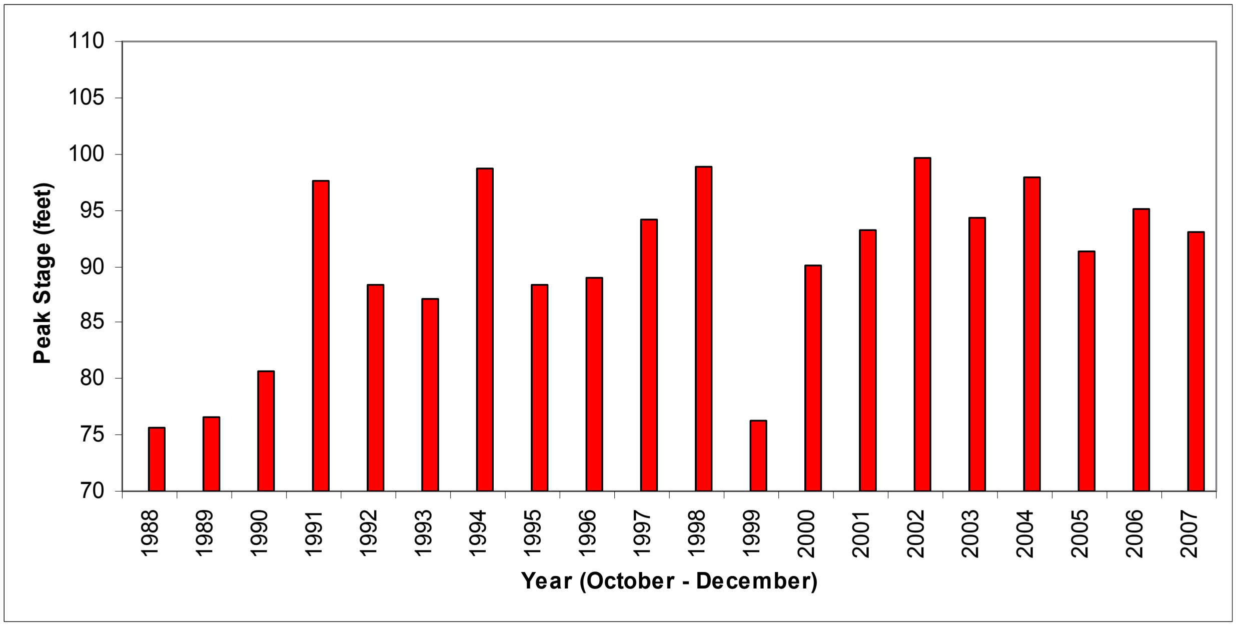


Figure I: Addicks Seasonal – Year (October-December) versus Peak Stage

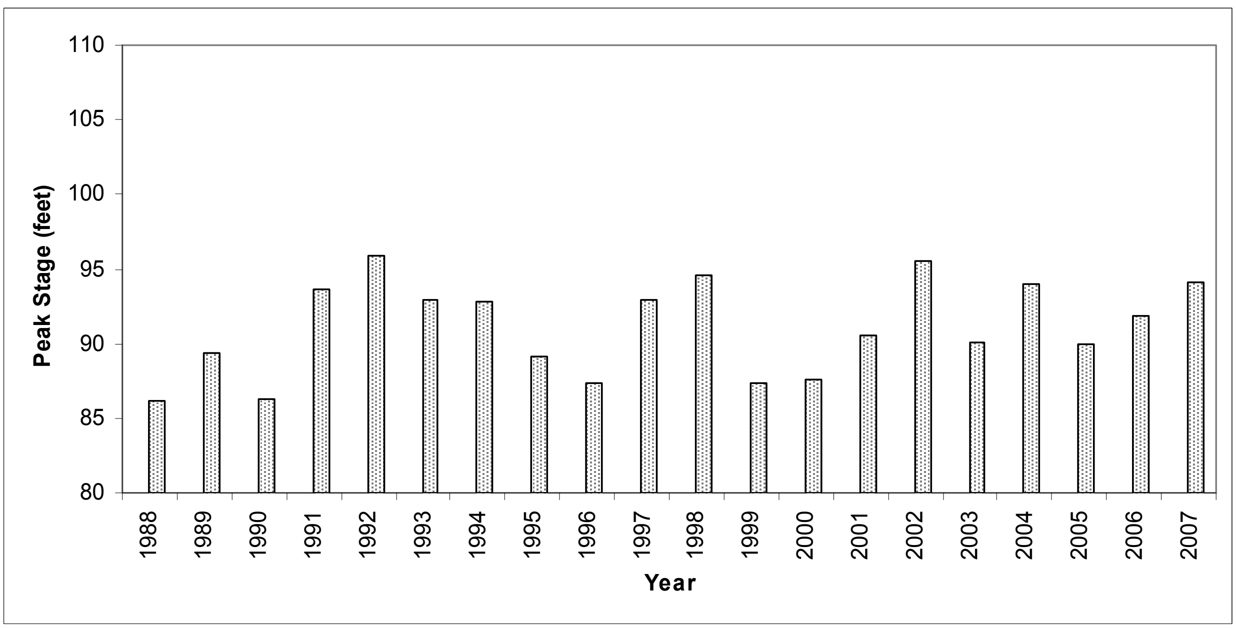


Figure J: Barker Annual – Year versus Peak Stage

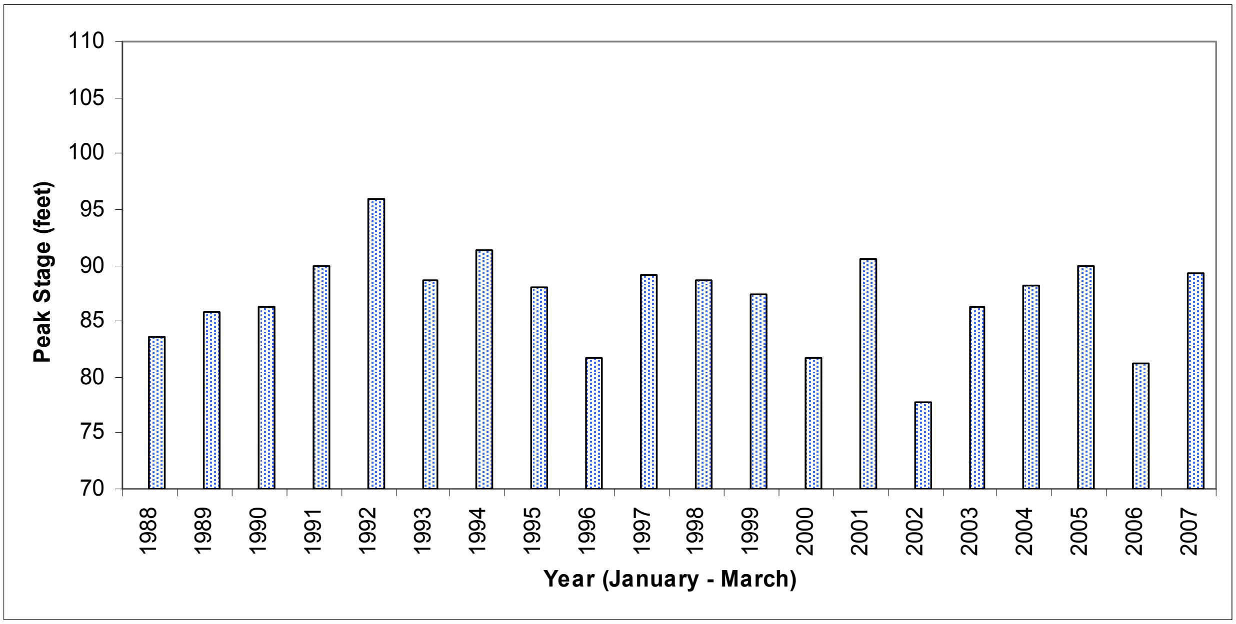


Figure K: Barker Seasonal – Year (January-March) versus Peak Stage

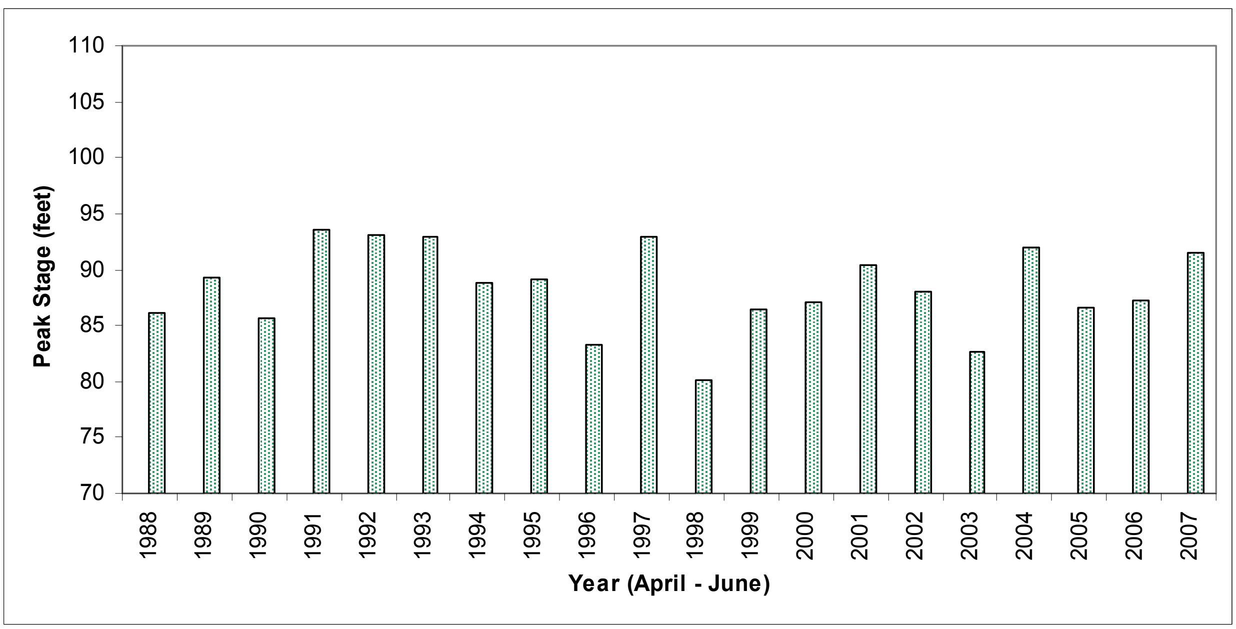


Figure L: Barker Seasonal – Year (April-June) versus Peak Stage

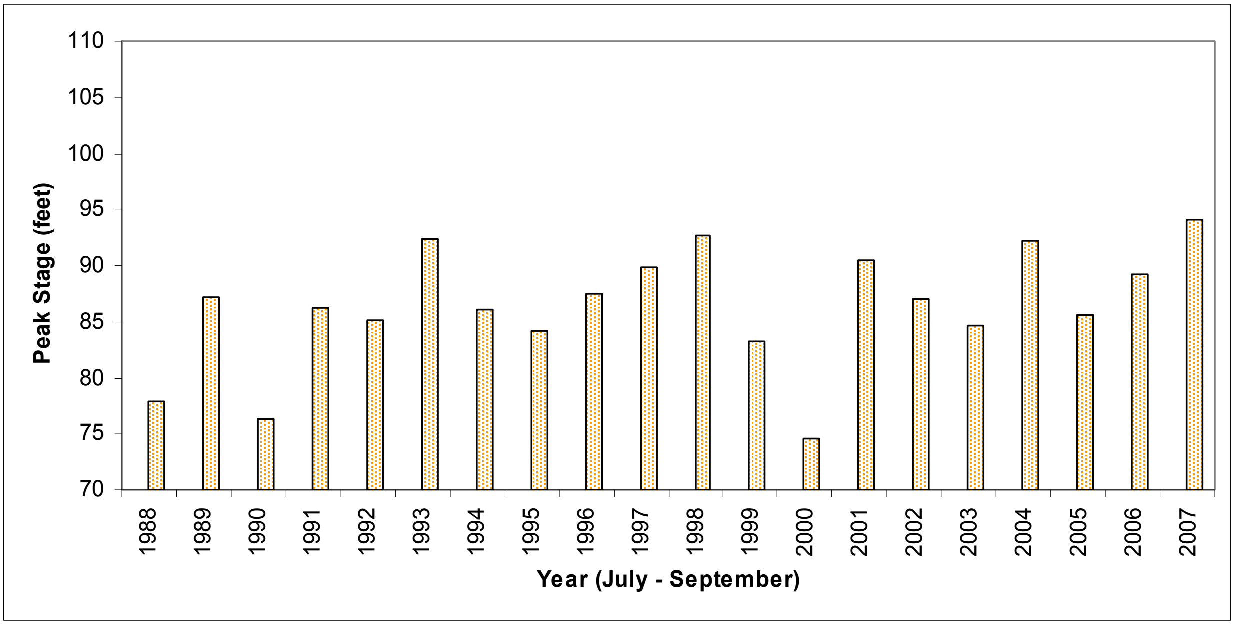


Figure M: Barker Seasonal – Year (July-September) versus Peak Stage

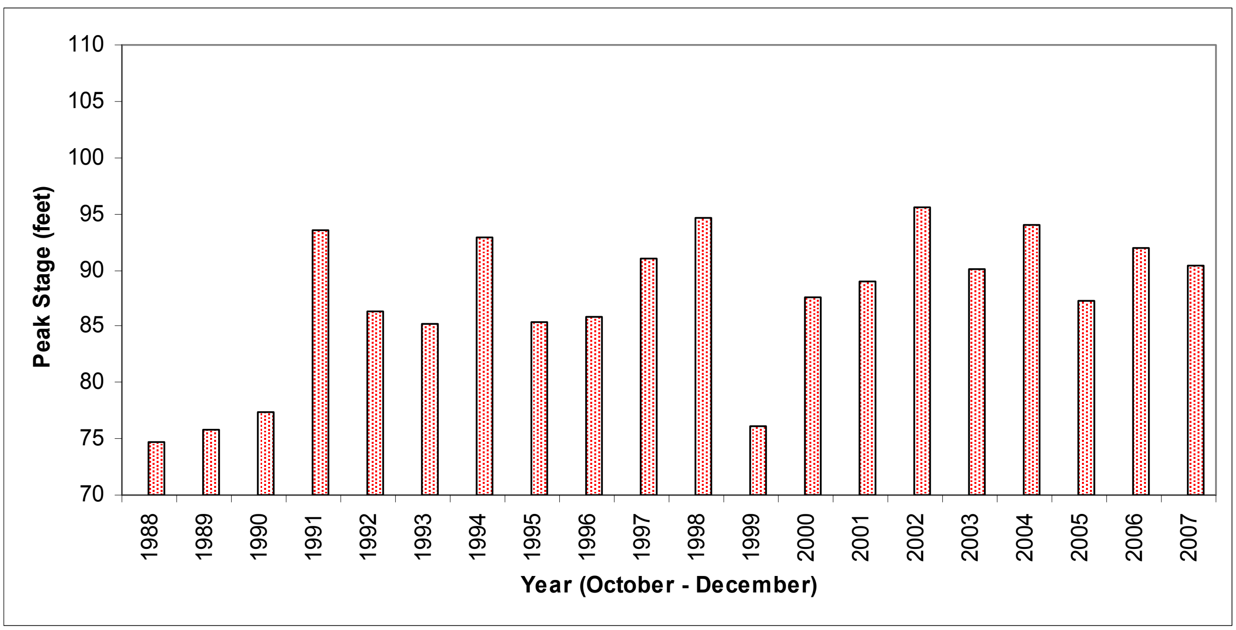


Figure N: Barker Seasonal – Year (October-December) versus Peak Stage

Note: One negative to a 6-hour stage recording is a peak stage may occur within the 6-hour stage interval; the stage recording data are measured on the 6-hour mark. As a result, the peak stages illustrated in Figures F to O may not represent the maximum peak stages. However, for the purposes of this report, the potential for differences in peak stages are considered negligible.

The annual peak stage for Addicks Reservoir is 94.83-feet. The peak stage is above the conduit invert at 71.10-feet and between the extended watch at 90.00-feet and State Highway-6 edge-of-pavement (EOP) at 99.10-feet. The data indicates the extended watch has been breached within the 20-years of data (13.47-% exceedance recorded); however, State Highway-6 EOP has not been breached. Further, the annual peak stage is shown as the average peak stage in **Figure E: Addicks Annual – Year versus Peak Stage**, and the annual peak stage falls within the confidence limits of the 2-year event (50% exceedance probability).

The annual peak stage for Barker Reservoir is 91.11-feet. The peak stage is above the conduit invert at 73.1-feet and between the extended watch at 87.00-feet and Westheimer Parkway EOP at 95.5-feet. The data indicates the extended watch has been breached within the 20-years of data (13.49-% exceedance recorded); however, Westheimer Parkways EOP has not been breached. Further, the annual peak stage is shown as the average peak stage in **Figure J: Barker Annual – Year versus Peak Stage**, and the annual peak stage falls within the confidence limits of the 2-year event (50% exceedance probability).

When comparing peak seasonal averages, Addicks and Barker Reservoirs experience their peak seasonal stages at 91.59 and 88.34-feet in April thru June, respectively.

Model Calibration:

Figure O: Addicks Reservoir – Probability versus Overflow (to Barker Reservoir) illustrates a rating curve relationship of overflow from Addicks Reservoir to Barker Reservoir. The approximate straight line is used to estimate total overflow volume for events such as the 4 and 0.4-% annual chance events. The volumes are added to the total volume into the reservoir and the corresponding pool elevations are derived as discussed in *Sub-Section 2.2: Probability Analysis*.

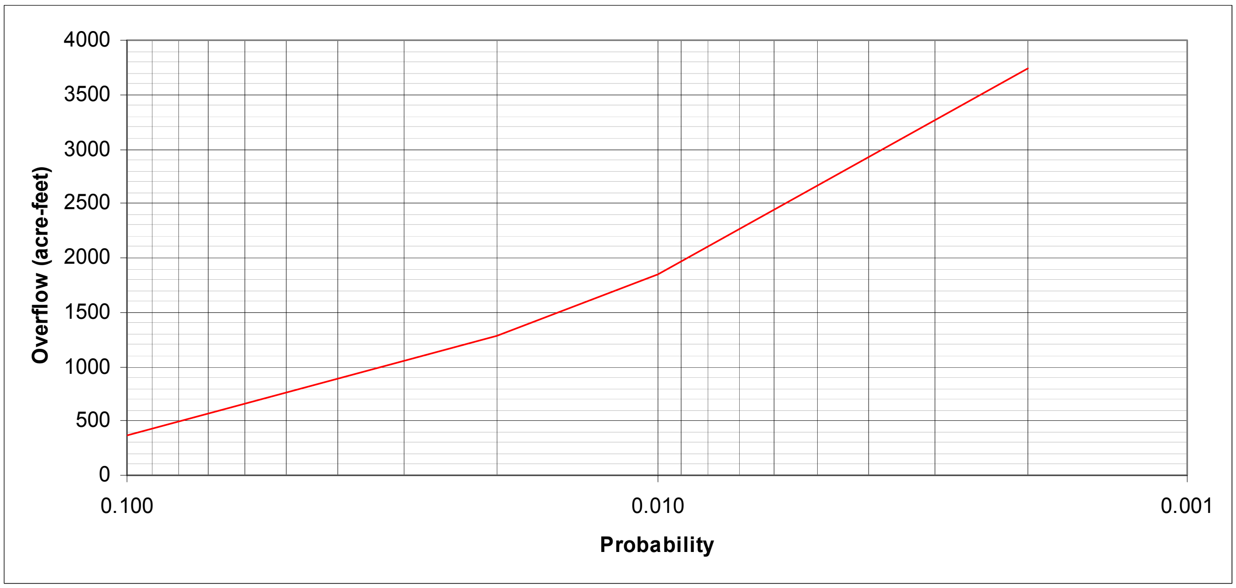


Figure O: Addicks Reservoir – Probability versus Overflow (to Barker Reservoir)

Table B: Peak Flow and Volume Comparison (Computed versus Observed) summarizes the results from Figures P to R, which illustrate computed versus observed inflow hydrographs for Barker Reservoir.

Table B: Peak Flow and Volume Comparison (Computed versus Observed)

Historical Storm	Computed Peak Flow	Computed Volume
October 2002	(-7%)	(-2%)
November 1998	+16%	(-7%)
November 1994	+8%	+21%

The greatest different in computed versus observed peak flow and volume is +21-% for the October 1994 storm. All other peak flows and volumes are within reasonable limits.

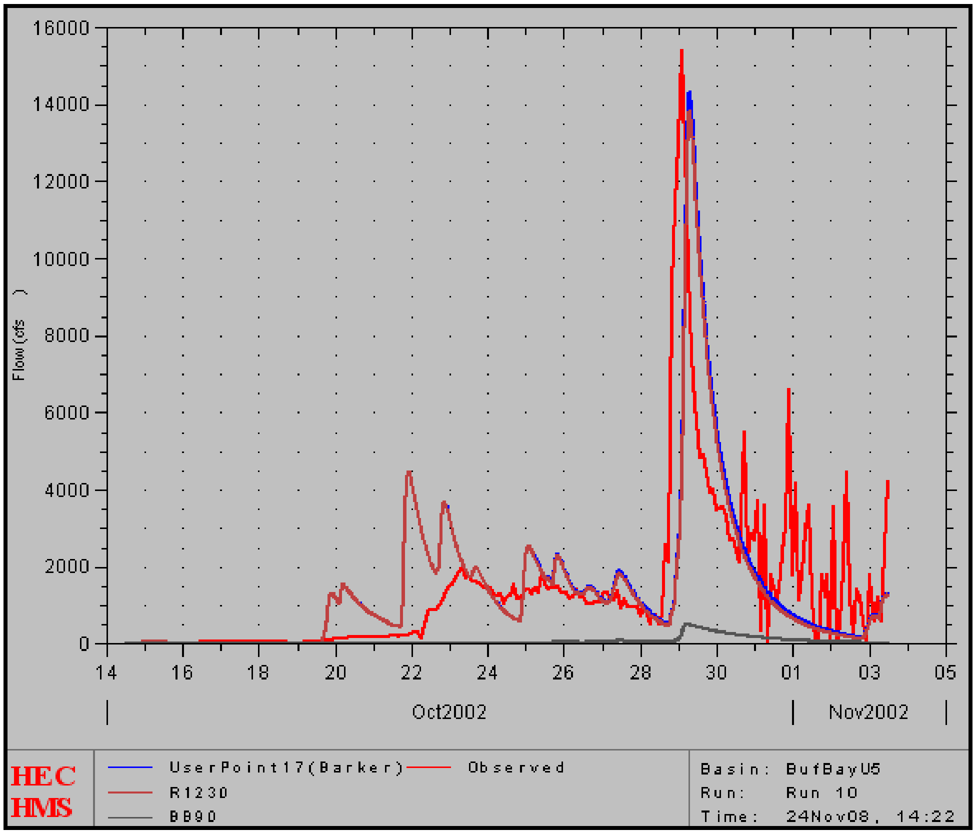


Figure P: Barker Hydrograph (October 2002)

Figure P: Barker Hydrograph (October 2002):
The following figure illustrates the hydrograph for the October 2002 storm event. The data collection starts on October 14, 2002 at 12:00 PM and ends on November 03, 2002 at 12:00 PM. The computed peak outflow is approximately 14,311-cubic-feet-per-second (CFS) and occurred on October 29, 2002 at 07:00 AM; the total outflow is approximately 58,598-acre-feet. The observed peak discharge is approximately 15,385-CFS and occurred on October 29, 2002 at 02:00 AM; the total observed discharge is approximately 59,947-acre-feet. The difference in peak flow is approximately -7-% (or 1,074-CFS). The difference in volume is approximately -2-% (or 1,349-acre-feet).

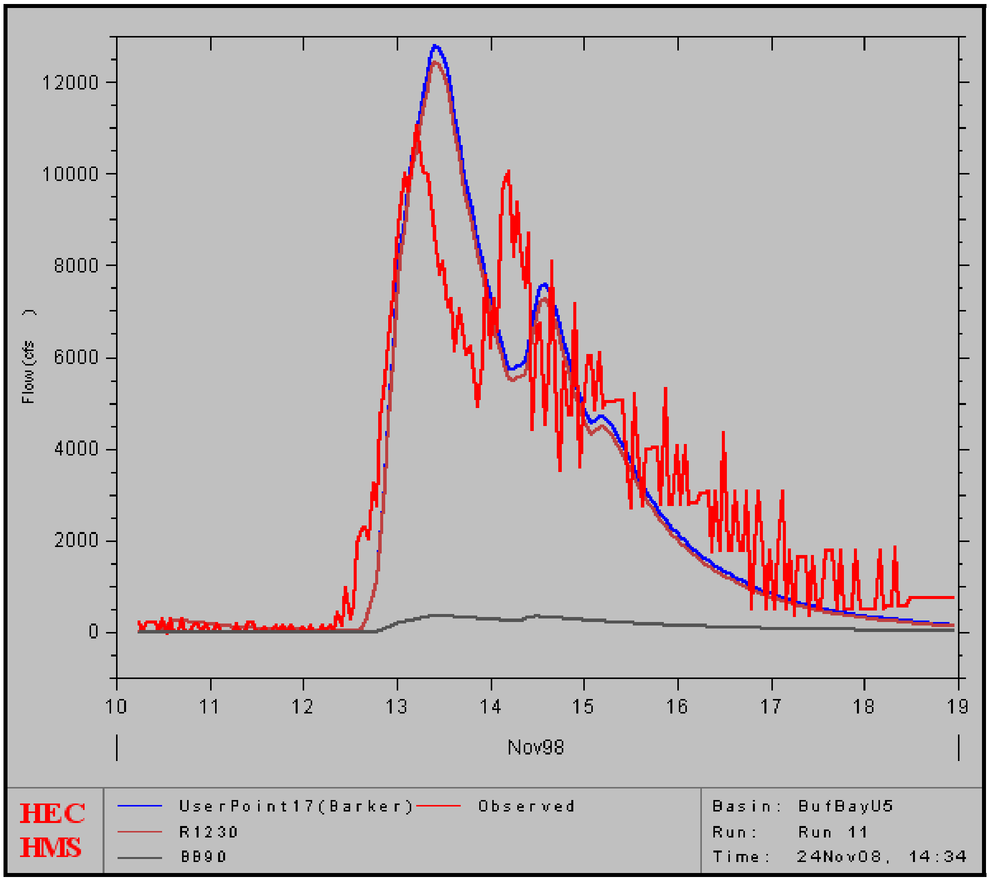


Figure Q: Barker Hydrograph (November 1998)

Figure Q: Barker Hydrograph (November 1998):
The following figure illustrates the hydrograph for the November 1998 storm event. The data collection starts on November 10, 1998 at 06:00 AM and ends on November 18, 1998 at 23:00 PM. The computed peak outflow is approximately 12,778-CFS and occurred on November 13, 1998 at 10:00 AM; the total outflow is approximately 47,097-acre-feet. The observed peak discharge is approximately 11,035-CFS and occurred on November 13, 1998 at 05:00 AM; the total observed discharge is approximately 50,377-acre-feet. The difference in peak flow is approximately +16-% (or 1,743-CFS). The difference in volume is approximately -7-% (or 3,280-acre-feet).

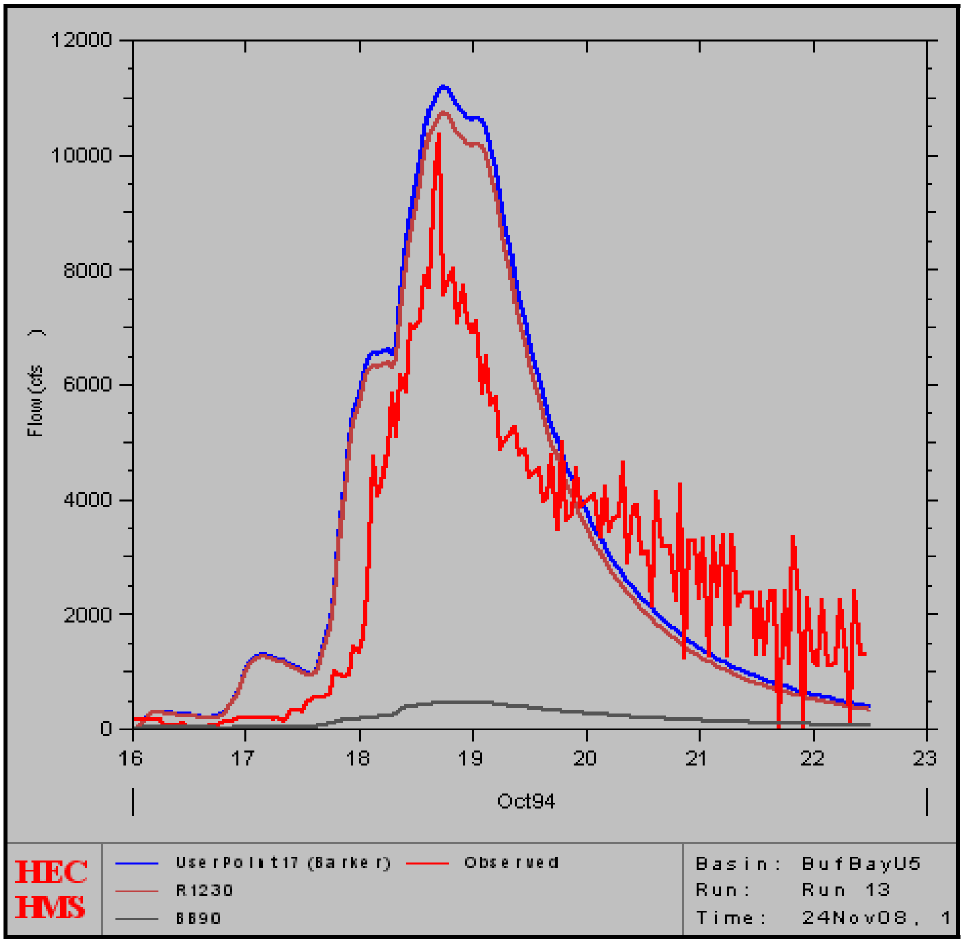


Figure R: Barker Hydrograph (October 1994)

Figure R: Barker Hydrograph (October 1994):
The following figure illustrates the hydrograph for the October 1994 storm event. The data collection starts on October 16, 1994 at 00:00 AM and ends on October 22, 1994 at 12:00 PM. The computed peak outflow is approximately 11,192-CFS and occurred on October 18, 1994 at 18:00 PM; the total outflow is approximately 43,128-acre-feet. The observed peak discharge is approximately 10,357-CFS and occurred on October 18, 1994 at 17:00 PM; the total observed discharge is approximately 35,653-acre-feet. The difference in peak flow is approximately +8-% (or 835-CFS). The difference in volume is approximately +21-% (or 7,475-acre-feet).