NOAA TECHNICAL MEMORANDUM NWS CR-117

A METHODOLOGY FOR DETERMINING RIVER FORECASTING SKILL USING MONTHLY CUMULATIVE DISTRIBUTION FUNCTIONS OF MEAN DAILY FLOW

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Under Secretary and Administrator

National Weather Service
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Assistant Administrator for Weather Services

A Methodology for Determining River Forecasting Skill using Monthly Cumulative Distribution Functions of Mean Daily Flow

Project Report for Master of Science in Water Resources Science

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1. Introduction

The National Weather Service (NWS) has provided river forecasts for navigation and flood warning since the mid 1800s (National Oceanic and Atmospheric Administration (NOAA), 1994). The NWS mission includes the protection of life and property and enhancement of the national economy. In so doing, the NWS strives to deliver quality forecasts with increasing accuracy. One method established to improve forecasts is completing a post-analysis or verification of the forecast data compared to observed data. The typical method used for determining the accuracy of a river forecast has been to pair observed and forecast values in order to calculate statistics such as root mean-squared error (RMSE) and mean absolute error. Such calculations are certainly useful in comparing magnitudes of error from one event to another at one forecast point, but they cannot easily be compared from one location to another. For example, one river may have variations in flow from thousands to tens of thousands while another varies from hundreds to thousands. An RMSE of 1000 cfs may be a "good" forecast for the former river, where an RMSE of 1000 cfs for the latter would not be. There is a need to have a measure that is normalized from one river to the next, so that the agency can make fair assessments and prioritize identified needs.

Statistics involving error magnitude also do not take the rarity of the event into account. River conditions vary greatly with the weather, and many other hydrologic and geologic variables, resulting in a wide range of flows. Those conditions that are common, or in line with climatology, might be considered "easier" to forecast compared to more rare events. The Linear Error in Probability Space (LEPS)-based skill score (Wilks, 1995) could take this difficulty into account and add valuable information to verification. Additionally, the LEPS-based skill score is not dependent on the scale of the variable and could be used as a normalized score.

2. Purpose

The purpose of this project is to develop the LEPS-based skill score (SS_{LEPS}) and test its usefulness with more traditional methods of verification. It will be determined using monthly cumulative distribution functions (CDF), or frequency curves, of mean daily flow for six separate river flow gaging points. The six points will have some similarities and differences in basin size, climate regime, and bed slope of the river. Results using the LEPS-based skill score will be used in conjunction with the RMSE to provide the forecaster or agency with additional information regarding the quality of the forecast.

3. Definition of Problem and Benefits of Solving Problem

Fulfilling the NWS mission to provide quality river forecasts has progressed with the implementation of vastly improved technology, higher resolution data sets, and the enhanced ability to apply scientific methods to hydrologic forecasting. Assessing forecasts after the fact can show trends in improvement and help to confirm resources are being used wisely. Post-analysis can also increase the experienced-based knowledge of the forecaster by indicating biases in forecast models or the input of inaccurate data into those models. Statistical calculations such as RMSE can show such trends. However, in serving the public, how can the NWS state whether or not the forecast was of good quality? During a flood, errors are typically higher than errors during normal flow. How can we relay the difference to the public?

A recent example of this occurred during the 1997 Red River of the North flood at Grand Forks, ND and East Grand Forks, MN. A near record forecast of 48.8 feet above the gage datum of 779 feet mean sea level was issued two months in advance. As the time to crest drew closer and additional precipitation added to the projected runoff, the NWS updated the forecast to 50 feet (LeFever, et. al., 1999). As meteorological conditions such as rapid warming exacerbated the snowmelt flooding, several upward revisions were made to the forecast to as high as 54.0 feet. The cities had built levees to provide protection to 52 feet. The crest occurred at 54.35 feet breaking the previous record of 50.2 feet set in 1897. The cities were inundated with flood waters. In this unprecedented event, the NWS provided the best forecast possible given the current technological applications. How good was it? The agency knows there is always room for improvement as an RMS error would show in this case. The addition of a skill score would allow a five foot error of a rare event to be compared to a smaller error in a more common event. This data could then be used together to gage the overall improvement of the quality of NWS river forecasts. The variation in error could also be used to define the limits of the hydrologic forecasting science for rare events.

4. Methodology

a. Data Stratification

The NWS provides river forecasts twice daily for major rivers, and twice daily during high flow for hundreds of smaller rivers and tributaries. Flows can vary greatly over a period of a few weeks and seasonal averages or extremes can mask this variation. For this reason, mean daily flows over monthly periods were chosen to represent a climatology of stream flows. A series of 12 monthly CDFs were created for six river forecast points using mean daily flow values from the U.S. Geological Survey (USGS) Hydro-Climatic Data Network (HCDN). The HCDN consists of streamflow records for 1,703 sites throughout the United States and its Territories, spanning the period 1874 through 1988. The records have been quality assured for accuracy and natural conditions (e.g. free of reservoir controls) (Slack and Landwehr, 1992).

The sites for this project were chosen through stratified random sampling (Maidment, 1992). The sampling area was made up of the Missouri and Upper Mississippi River basins, Region 10 and Region 7 of the HCDN, respectively, since forecast and observed flow data in this area would be readily available at the NWS Central Region Headquarters. To create the best possible CDF representing streamflow climatology, the sample set was limited to gaging stations with at least 50 years of data. Rivers forecasts by the NWS rarely fall to zero flow, therefore, the sample was further limited to those streams with perennial streamflow (i.e. non-zero flow). In an effort to use a variety of data sets, points were then separated according different groups of basin characteristics and U.S. standard climatic regions for temperature and precipitation (NOAA, 2000) as described below. Using these constraints, 70 gaging stations remained.

The 70 stations were divided into groups of various basin and climatological regimes. Rainfall, basin area, and basin bed slope, being important parameters affecting streamflow (Bedient and Huber, 1992), were chosen to use for grouping the data. Climatological regions were chosen within the Missouri and Mississippi River basins from the nine regions defined by the National Climatic Data Center and depicted in Figure 1. The East North Central and Central Regions were chosen due to availability of data. All 1703 sites in the HCDN were used to determine different classes of basin area. 1556 sites were available with slope information. Both basin area and slope histograms were created using Microsoft Excel (1995-96) and Jmp In software (Sall and Lehman, 1996) was used to test for normality. Both were not found to be normal. A variety of unequal class lengths were tried until normal distributions were found. Otherwise, most all the data would have been lumped into one class interval. The Histograms were plotted as relative frequencies divided by class interval with total area under the histogram equal to 1 (Johnson, 1994). Figure 2 shows the histogram and Table 1 the classes for basin area. Figure 3 and Table 2 show the histogram and classes for slope, respectively.

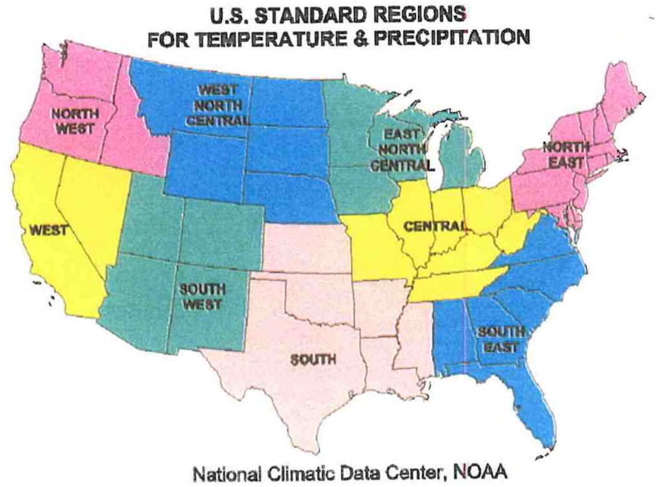

Figure 1

Classes	Frequency	Relative Frequency
0-10	87	0.05
10.01-200	622	0.37
200.01-2000	763	0.45
2000.01-10000	177	0.10
>10,000	54	0.03
Total	1703	1.00

Table 1. Basin Area Frequency

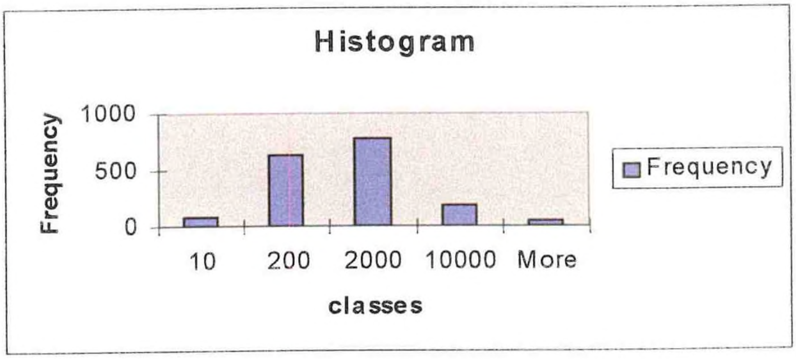

Figure 2. Basin Area Histogram

Classes	Frequency	Relative Frequency
0-3	186	0.12
3.01-8	397	0.26
8.01-40	502	0.32
40.01-150	328	0.21
> 50	143	0.09
Total	1556	1.00

Table 2. Slope Frequency

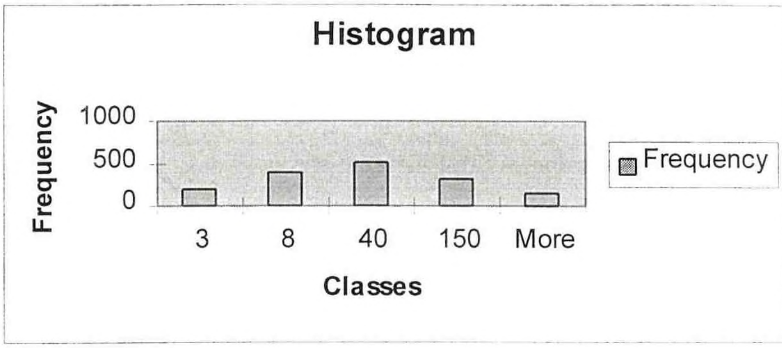

Figure 3. Slope Histogram

Two different basin areas and slopes were selected. Basin area classes ranging from 200.01 to 2000 mi^2 (A1) and 2000.01 to 10,000 mi^2 (A2) were chosen since forecasts are generally not made for smaller basins, and streamflow variability is less for larger basins. Variability is needed to show the use of the skill score at different streamflows. Slope classes were chosen from 3.01 to 8.00 $ft\text{-}mi^{-1}$ (S1) and 8.01 to 40.00 $ft\text{-}mi^{-1}$ (S2) as the two classes with the highest frequencies, thus more sites from which to choose.

b. Randomization of Data

The 70 sites were divided into the two climatic regimes, East North Central (ENC) and Central (CEN) Regions. Since the decision was made to create six CDFs, three combinations of the two slopes and two basin areas were needed within each climate regimes. Available combinations were ENC_S1A1, ENC_S1A2, ENC_S2A1, ENC_S2A2, CEN_S1A1, CEN_S1A2, CEN_S2A1, and CEN_S2A2, and are shown in Appendix A. To achieve an unbiased selection of six stations to study, the sites were selected randomly from the stratified groups using the random number generator in Excel. Selected groups were ENC_S1A1, ENC_S2A1, ENC_S1A2, CEN_S1A1, CEN_S2A1, and CEN_S1A2. The random number generator was then used to select one station from each group. These were Sugar River near Brodhead, WI (Station number (#) 5436500); Jump River at Sheldon, WI (#5362000); Nishnabotna River near Hamburg, IA (#6810000); Meramec River near Steeleville, MO (#7013000); Castor River at Zalma, MO (#7021000); and Gasconade River at Jerome, MO (#6933500), respectively.

c. Creation and Comparison of CDFs

The HCDN historical data files for the six selected sites were imported into Excel and ranked from largest to smallest. Since the distributions of mean daily flow by months were unknown, CDFs were created using the Cunnane plotting position equation (Bedient and Huber, 1992; Maidment, 1992),

$$F = 1 - (m-0.40)/(n+0.2) \quad (1)$$

where F is the empirical estimate of the frequency, m is the rank, and n is the sample size.

As suggested by Ritter (1999), the CDF computation was carried out to at least four decimal places (five places were significant). Graphical presentations of the CDFs can be found in Appendix B. JMP IN was used to create the graphical CDFs and to test them for normality. None were found to be normal. For each month, each CDF was compared to every other CDF to determine if a significant difference existed in the distributions using a Komolgorov-Smirnov (K-S) test of significance (Johnson, 1994; Kanji, 1993; Wilks, 1995) at the $\alpha = 0.05$ level. The K-S test was used since the data were not normal. The null hypotheses, H_0, and alternative hypothesis, H_A, were as follows:

$$H_0: F_{n1}(x_1) = F_{n2}(x_2) \quad (2)$$
$$H_A: F_{n1}(x_1) \neq F_{n2}(x_2) \quad (3)$$

where $F_{n1}(x_1)$ is an empirical distribution with n_1 observations of X_1 and $F_{n2}(x_2)$ is an empirical distribution with n_2 observations of X_2. From Wilks (1995), the K-S test statistic

$$D = \max | F_{n1}(x_1) - F_{n2}(x_2) | \quad (4)$$

looked for the largest (in absolute value) difference between the empirical CDFs. Since absolute values were used, the test was one-sided and the null hypothesis was rejected at the $a=(\alpha \cdot 100)\%$ level if

$$D > [\tfrac{1}{2}(1/n_1 + 1/n_2)\ln(a/2)]^{\frac{1}{2}} \quad (5)$$

Kanji expressed the limitations of the K-S test in that best results occur with a sufficiently large data set. Montgomery (1997) stated the probability of a Type II error, β (failure to reject H_0 when H_0 is false), is dependent on the sample size. As the sample size increases, β decreases and the power of the test ($1-\beta$) increases. With each CDF of 50 or more years of data containing 1723-2294 elements of mean daily flow values, it was concluded that the K-S test was sufficiently powerful.

The null hypothesis was rejected (i.e. the CDFs were significantly different) for most combinations except the following: Steeleville and Jerome for all months, and Brodhead and Sheldon for the month of June. One could conclude the same CDF could be used for Steeleville and Jerome from the CEN_S1A1 and CEN_S1A2 groups, respectively. With Brodhead and Sheldon having similar CDFs for only one month, it would be best to keep them separate. Since the ENC_S1A1 and ENC_S1A2 stations (Brodhead and Sheldon, WI) were significantly different, one cannot conclude the same CDF can be used for all S1A1 and S1A2 groups. One can conclude the divisions of selected climate, slope, and area are significantly different. The results of these comparisons generally support using individual CDFs for each site.

d. Verification of Forecast Flow Data

Of the six sites, four were noted as NWS forecast points: Brodhead, Hamburg, Steeleville, and Jerome. Once again, the random number generator was used to select Hamburg as the point to test the concept of verification using RMSE and SS_{LEPS}. RMSE incorporates both systematic and random errors (Maidment, 1992). A perfect RMSE is zero and increases as errors in forecast and observation pairs increase. The SS_{LEPS} calculates the difference in the probability of occurrence between forecasts and observations with respect to the scale of the climatological CDF, rather than comparing the magnitudes of the specific forecasts and observations. It is assumed that in the portion of the CDF where a forecast value is more likely, it should be easier to forecast than for those values that are climatologically less likely. The reference forecast in the skill score equation is the climatological median, 0.50000, or the point at which there is a 50% chance of a variable being less than the value at that point. According to Wilks (1995), "transforming forecasts and observations to the cumulative probability scale assesses larger penalties for forecast errors in regions where the probability is more strongly concentrated", such as around the 50th percentile of the CDF. This will need to be kept in mind when evaluating the usefulness of the skill score. A skill score of 1 is perfect, zero means no improvement over climatology, and negative values imply a worse forecast than climatology.

In a series of N forecasts where F_i represents the i-th forecast, O_i the i-th observation, and F(x) the climatological cumulative distribution function as defined by the frequency curves in Appendix B

$$RMSE = \left(\sum(F_i - O_i)^2 / N\right)^{1/2} \tag{6}$$

and

$$SS_{LEPS} = 1 - \sum|F(F_i) - F(O_i)| / \sum|0.50000 - F(O_i)| \tag{7}$$

The sample set was comprised of flood-only forecasts covering April 2, 1998 through July 26, 1998. The forecasts were in stage height and had to be converted to flow using a rating curve (Figure 4). To obtain the forecast and observed frequencies from the CDF curves, an interpolation algorithm was run using Corel Quattro Pro software (1997). The data can be found in Appendix C. In June and July, several of the forecast and observed flows were higher than the largest value in the CDF and the rating curve. In order to place a frequency value on those flows, the CDF and rating curve were extended using curve fitting routines in JMP IN.

Verification results are shown in Table 3. RMSEs for April and May were similar and lowest of the four months. July's RMSE was nearly twice that of April, but with a slightly higher skill score. The range in forecast flow frequency values in April was from 0.91785 to 0.99874 and from 0.94951 to 0.99995 in July, much above the median flow frequency of 0.50000. This is an indication of forecasting unlikely events, and therefore more difficult forecasts. The resulting April skill score of 0.98776 is quite high (1.0 is perfect). Comparing April to June one can see the verification indicates forecasts were not as good in June with a much higher RMSE (5399 compared to 1405 in April) and a skill score of 0.94805. Still, with 1.0 being perfect, this would appear to be a "good" skill score. Comparing the flow frequency ranges in Table 4, June has a wider range and could explain the lower skill score.

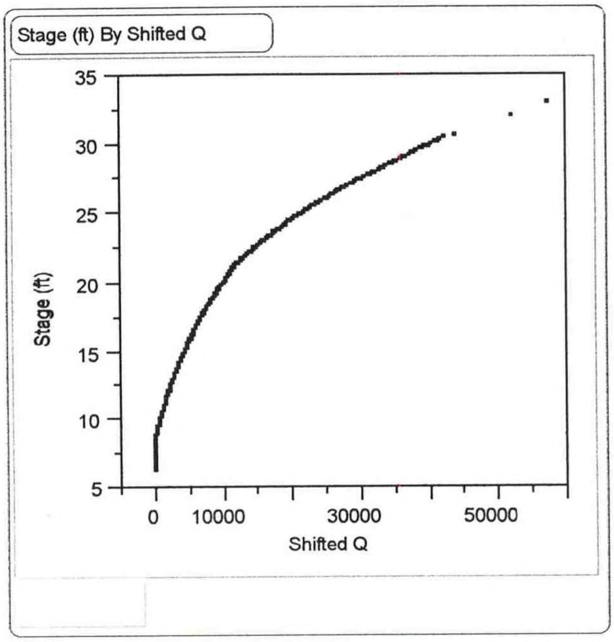

Figure 4. Hamburg Rating Curve

Month	RMSE (cfs)	SS_{LEPS}
April	1405	0.98776
May	1359	0.97544
June	5399	0.94805
July	2951	0.98836

Table 3. Verification scores for Hamburg, IA

Month	Min F(F)	Max F(F)
April	0.91785	0.99874
May	0.86749	0.99333
June	0.79560	0.99999
July	0.94951	0.99995

Table 4. Maximum and Minimum Forecast Flow Frequency Values for Hamburg, IA

It appeared that flood-only forecasts might not provide a wide range of skill scores to evaluate. It was then decided to investigate scores for a daily forecast point. As none of the four forecast points selected in the random sampling were daily forecast points, another selection option would need to be used. Of the four HCDN selected rivers, only the Meramec River had a daily forecast point, Eureka, MO. It was desirable to have a wide range of flows to hopefully show more variety in the skill score, and Eureka was found to have a variety of flows from June through August 1998. It was also stated Eureka was a good site for such an experiment as it "is a mid-basin point..., downstream of a couple modeled tributary rivers. This modeling situation gives enough forecast lead time for a dampening out of many of the spurious signals that may be coming from any given headwater point, allowing the "true" signal to be read." (Buan, 2000). Eureka was also part of the HCDN data, and already part of the stratified group, CEN_S1A2. It seemed a very appropriate choice.

Eureka CDFs for June, July, and August were created as above and are contained in Appendix D. These CDFs were also compared to the other CEN_S1A2 basin, the Gasconade River at Jerome, MO to see if significant differences existed. Again using the K-S test of significance as before, the hypothesis that the Jerome and Eureka distributions were the same was rejected for all three months, further supporting the need for individual CDFs. The forecasts and observations for Eureka were converted from stage height to flow using the Eureka rating table (Figure D4 in Appendix D), and frequency values were obtained through interpolation of the CDFs. The August CDF had to be extended due to a higher flow than in the HCDN data set.

Since the flow data for Eureka varied more from low to high flow, it was decided to separate the data into two groups, the more extreme and the more common, so as not to attenuate differences between the two groups. The 25^{TH} and 75^{th} quartiles (Johnson, 1994) of the CDFs were determined using JMP IN. CDF values in the upper 25% and lower 25% were grouped together as the more extreme flows, and values in the inner quartiles were grouped as the more common occurrences. The forecast flow data with accompanying observations were then placed in one of the two groups, depending on the frequency value of the forecast data. Eureka RMSE and SS_{LEPS} were derived for these two groups as well as for the month as a whole (all quartiles). Results are shown in Table 5.

The forecast data for Hamburg were also divided up according to its CDF inner and outer quartiles, and found that all observed-forecast pairs fell in the outer quartiles, specifically the 75^{th} Quartile (Q_{75}). Using the Q_{75} data for Eureka provided the additional advantage of being able to compare the Hamburg flood-only scores with the scores for Eureka as both data sets were based on a specific range in probabilities. It no longer mattered that one was a daily forecast point, and the other flood-only. Skill scores for Hamburg and Eureka in June were 0.94805 and 0.89884, respectively. For July, Hamburg had a score of 0.98836 and Eureka had 0.73059. Are these differences significant? To answer that, individual skill scores were calculated for each pair of forecast and observed flow values in June and July. Since the skill scores were not normally distributed and the data set was small, a test of significance was computed using the Wilcoxon Rank Sum test in Jmp In. Skill scores for both months were shown to be significantly different. Looking only at these scores one might look further into the Eureka forecasts to identify any particular problems in July, 1998 such as model deficiencies, sparsity of data, etc.

With data split into the inner and outer quartiles, Table 5 shows a wide variety of skill scores. The values in the more common group, the inner quartiles, are much lower (worse) than scores in the outer quartiles. As stated earlier, skill scores in regions of the higher probability of occurrence assess a higher penalty. These results show usefulness in the skill scores, especially in the outer quartiles. For example, it is obvious that June showed "better" forecasting than July in the outer quartiles where the RMSE was 3602 cfs for June compared to 5424 cfs in July, and respective skill scores were 0.89884 and 0.76189. The calculations over the individual months (all quartiles)

Month	Inner Quartiles			Outer Quartiles			Q_{75}		
	n	RMSE (cfs)	SS_{LEPS}	n	RMSE (cfs)	SS_{LEPS}	n	RMSE (cfs)	SS_{LEPS}
June	7	362	0.53366	22	3602	0.89884	22	3602	0.89884
July	4	1131	0.38125	27	5424	0.76189	25	5652	0.73059
August	1	387	-0.33333	30	2581	0.80103	24	2861	0.93684

	All Quartiles					
	n	RMSE (cfs)	SS_{LEPS}		Min F(F)	Max F(F)
June	29	3142	0.87352		0.43276	0.97870
July	31	5092	0.70572		0.00020	0.99773
August	31	2540	0.77024		0.00038	0.99997

Table 5. Verification results for Eureka, MO, June-August, 1998

showed a similar trend to the outer quartile calculations but with slightly lower values. However, these monthly values failed to reflect the lower RMSEs in the inner quartiles, important information regarding error in the actual forecast. This further supports the idea of using the inner and outer quartiles as a verification method rather than combining all the data for a month.

Since RMSEs involve squaring errors, they will be increasingly higher where differences in forecasts and observations increase. Large differences strongly influence RMSEs. If it is true that forecasting in the inner quartiles is easier, RMSEs should be noticeably lower. The results shown in Table 5 support this. Using only RMSE values, one would conclude forecasts in the inner quartile were better than the outer quartile. Comparing only the skill scores, one would conclude the forecasts for the more extreme events were much better than for the common events. How can the two scores be used together? Is there a relation between RMSE and SS_{LEPS} that would provide a more complete test of quality? These questions may be answered by creating a climatology of RMSE values and skill scores such that the forecaster could evaluate how his/her forecast scores compare to typical scores. An RMSE for a single forecast is the same as an absolute error (AE), |F-O|. Providing a normal absolute error with each forecast might give the public a better understanding of the typical range in the forecast. (DeWeese, 2000) and could add significant value. Additionally, the NWS could track improvement in forecasts.

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An advantage with the skill scores, because they are based on probabilities, is that a flood on one river can be compared to a flood on another river. As shown above, a group of flood-only forecasts should not be compared to a group of daily forecasts. But if forecast or observed data for any point are split into similar probability ranges such as with the inner and outer quartiles, or flood only with the 75th Quartile, the results can be compared.

e. Grand Forks case study

In April 1997 an unprecedented flood occurred in the Red River of the North basin in North Dakota and Minnesota. The only verification score to use at the time was one comparing the magnitudes of the forecast and observed stages. However, the flood was literally "way off the charts" and went beyond the scientific and technical capabilities of the NWS river forecast models. It came down to forecaster subjectivity, knowledge of the river, and experience. Citing differences between crest forecasts during the week before the observed crest, and the actual observed crests, some forecasts were as much as four feet too low. Given the rarity of the event, how "good" were these forecasts?

An April CDF, Figure 5, was calculated for Grand Forks using USGS historical data from the National Water Information System as it was not available in the HCDN. Estimated data was deleted. The rating curve shown in Appendix D, Figure D5, was used to convert gage height to flow as before. This rating curve provided by the North Central River Forecast Center was for

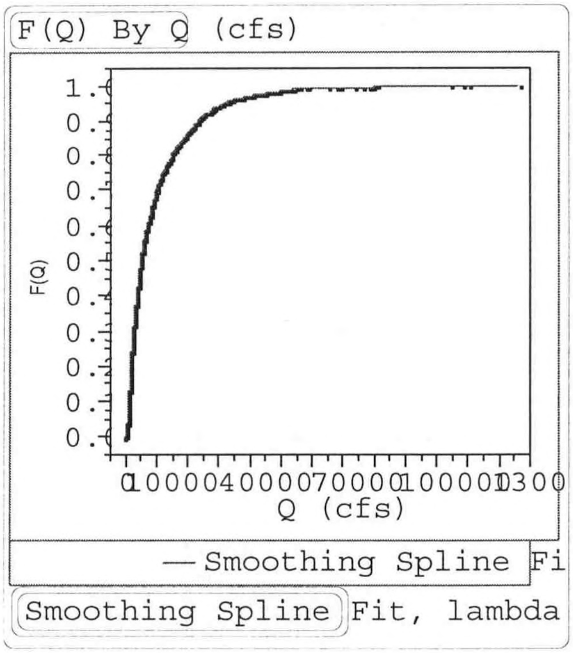

Figure 5. April CDF of mean daily flows for Grand Forks, North Dakota

the observed flow during the flood, and is quite complicated in that some rising stages had decreasing flows due to damming effects. Since forecasters during the week prior to the crest were working with the increasing flow portion of this rating, that was the portion used for the flow values in these calculations (Figure D6). Extending this rating for higher stages resulted in higher flows, contrary to what actually happened due to damming.

Table 6 shows the forecast and observed crest flows, estimated using the rating curve in Figure D6, as well as individual and overall verification scores. Forecasts were for crests only, therefore each forecast was paired with the observed crest flow estimated to be 115,000 cfs from Figure D5. (Note: Individual RMSEs are the same as absolute error, $|F_i - O_i|$.)

Date forecast issued	Forecast Crest (ft)	Observed Crest (ft) 4/22/97	Forecast Crest (cfs)	Observed Crest (cfs)	RMSE (cfs)	SS_{LEPS}
02/27/97	48.8	54.35	68667	115000	46333	0.99137
04/03/97	49	54.35	70000	115000	45000	0.99186
04/14/97	50	54.35	82500	115000	32500	0.99768
04/15/97	50	54.35	82500	115000	32500	0.99768
04/16/97	50.5	54.35	93125	115000	21875	0.99800
04/17/97	52	54.35	125000	115000	10000	0.99955
04/18/97	53	54.35	139711	115000	24711	0.99938
04/18/97	54	54.35	160412	115000	45412	0.99926
			All forecasts		34525	0.99685

Table 6. Grand Forks crest forecasts, observation, and verification

A trend of increasing skill scores and lowering RMSEs is shown in the individual forecasts from February 27 - April 17, 1997. April 18 marked the beginning of decreasing flow with continued rising stage at which point RMSEs increased rapidly and skill scores decreased. The near perfect skill scores reflect the rarity of the event. Very small changes must be considered as the rate of change in the CDF in this region is very small. The range in frequency values for the forecast flows was from 0.99520 to 0.99988. The range for the Hamburg data in April was from 0.91785 to 0.99874. The April skill score for Hamburg was 0.98776 and for Grand Forks for the combined forecasts, 0.99685. Again using the Wilcoxon Rank Sum test of significance for the individual skill scores of Hamburg April data and for all crest forecast data for Grand Forks, the scores were not found to be significantly different. One could conclude the forecasts were equally good for the two extreme events.

5. Conclusions

The LEPS-based skill score adds more information to more traditional verification methods and appears to be quite useful as it is not dependent on the scale of the variable being verified. By taking into account the rarity of the event, it bears information as to the quality of the forecast. The LEPS-based skill score by itself can be used to compare a forecast from one river to an entirely different river. This would be of great benefit to the NWS in making fair assessments and prioritizing identified needs. For individual rivers forecast points, SS_{LEPS} should be used the actual magnitude of the forecast. Additional benefit would be attained by developing a climatology of RMSE or AE values and skill scores such that the forecaster could evaluate his/her forecast compared to typical errors and skill scores. The agency could also track improvement in forecasts over time.

This study did not show that one common CDF for different sites or sites with similar basin characteristics could be used in calculating the LEPS-based skill score. Individual CDFs using years of mean daily flow data would need to be created. Current NWS river forecasting software will create CDFs on an annual basis, not monthly. If a change could be made such that the software could create monthly CDFs of mean daily flow, use of the SS_{LEPS} could be further evaluated.

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Appendix A

Stratified list of Hydro-Climatic Data Network Stations

Stn# = USGS station number
HUC = Hydrolocic Unit Code
DA = Drainage Area (mi^2)
ENC = East North Central
CEN = Central

Slope 1 = S1 = 3.01 - 8.00 $ft\text{-}mi^{-1}$
Slope 2 = S2 = 8.01 - 40.00 $ft\text{-}mi^{-1}$
Area 1 = A1 = 200.01 - 2000.00 mi^2
Area 2 = A2 = 2000.01 - 10,000.00 mi^2

ENC_S1A1				
Years of dat	Stn#	HUC	Slope	DA
50	5384000	7040008	7.5	615
52	5316500	7020006	7	629
52	6898000	10280102	3.51	701
53	5317000	7020008	6	1280
53	6600500	10230002	4.38	886
55	5286000	7010207	3.7	1360
55	5421000	7080102	3.58	1048
55	6809500	10240003	4.68	894
56	5383000	7040006	6.98	398
58	5107500	9020314	3.7	1220
59	5379500	7040005	3.64	643
60	5385000	7040008	6.5	1270
61	5062500	9020108	7.2	888
63	5470000	7080105	7.34	315
71	5333500	7030001	5.71	1580
74	5436500	7090004	3.18	523
75	5418500	7060006	4.1	1553
78	5381000	7040007	5.81	749

Table A1. East North Central Stations, Slope 1-Area 1

ENC_S2A1				
Years	Stn#	HUC	Slope	DA
50	5313500	7020004	12.4	653
50	5408000	7070006	9.13	266
54	5413500	7060003	9.73	269
55	5300000	7020003	12.7	983
57	5062000	9020106	9.7	1040
61	5397500	7070002	8.28	375
62	5399500	7070002	10.1	224
73	5362000	7050004	8.3	576

Table A2. East North Central Stations, Slope 2-Area 1

ENC_S1A2				
Years	Stn#	HUC	Slope	DA
60	5280000	7010204	3.3	2520
61	6810000	10240004	4.44	2806
78	5340500	7030005	3.64	6240

Table A3. East North Central Stations, Slope 1-Area 2

CEN_S1A1				
Years	Stn#	HUC	Slope	DA
53	5500000	7110003	3.4	620
58	5514500	7110008	4.6	903
60	6899500	10280102	3.67	1670
61	6817500	10240010	4.21	1240
66	5497000	7110002	4.8	452
66	6813000	10240005	4.9	508
66	7013000	7140102	6.29	781
66	7018500	7140104	3.36	917

Table A4. Central Stations, Slope 1-Area 1

CEN_S2A1				
Years	Stn#	HUC	Slope	DA
68	7021000	7140107	8.92	423

Table A5. Central Stations, Slope 2-Area 1

CEN_S1A2				
Years	Stn#	HUC	Slope	DA
66	6933500	10290203	3.01	2840
69	7019000	7140102	3.44	3788

Table A6. Central Stations, Slope 1-Area 2

Appendix B - Cumulative Distribution Function (CDF) graphs

October CDFs

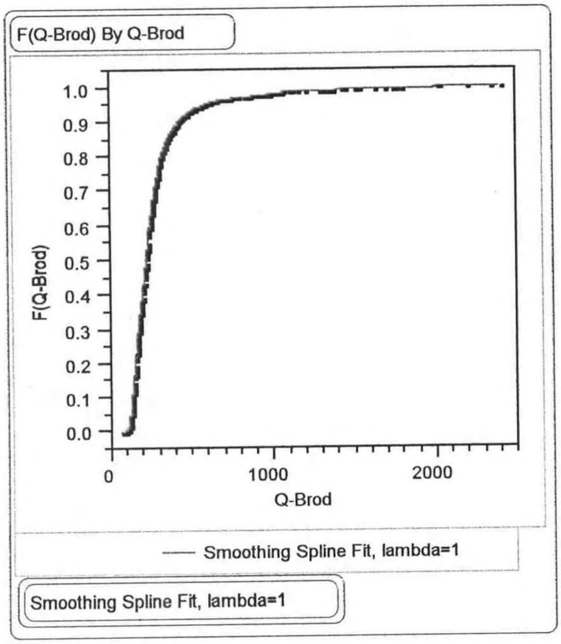

Figure B1. Sugar River near Brodhead, WI

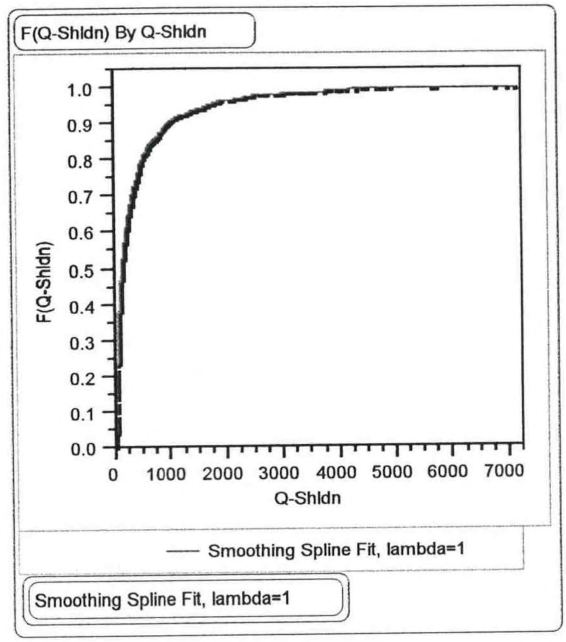

Figure B2. Jump River at Sheldon, WI

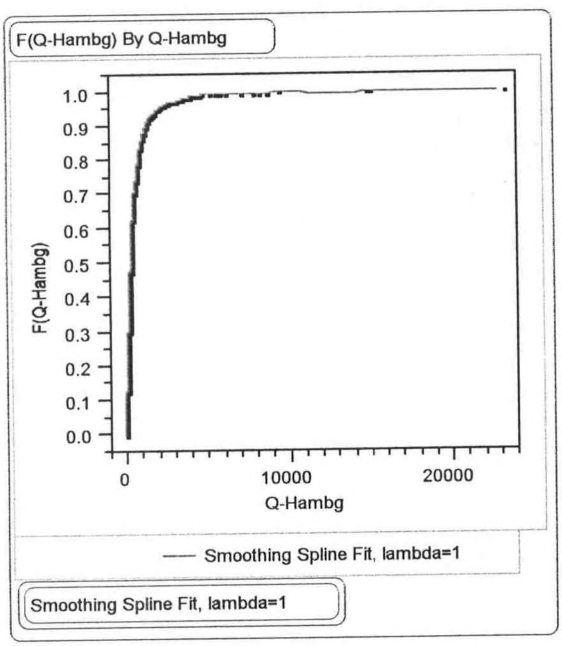

Figure B3. Nishnabotna River near Hamburg, IA

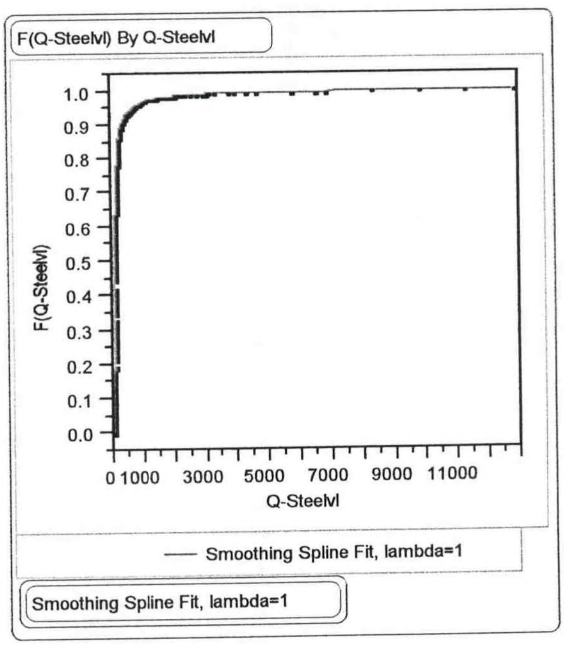

Figure B4. Meramec River near Steeleville, MO

October CDFs

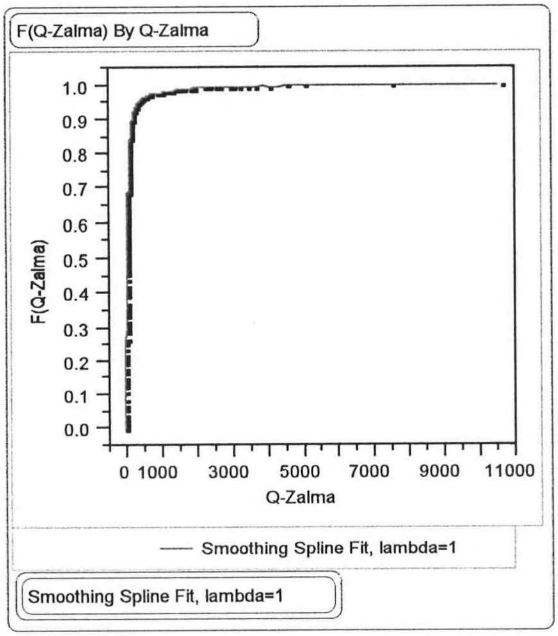

Figure B5. Castor River at Zalma MO

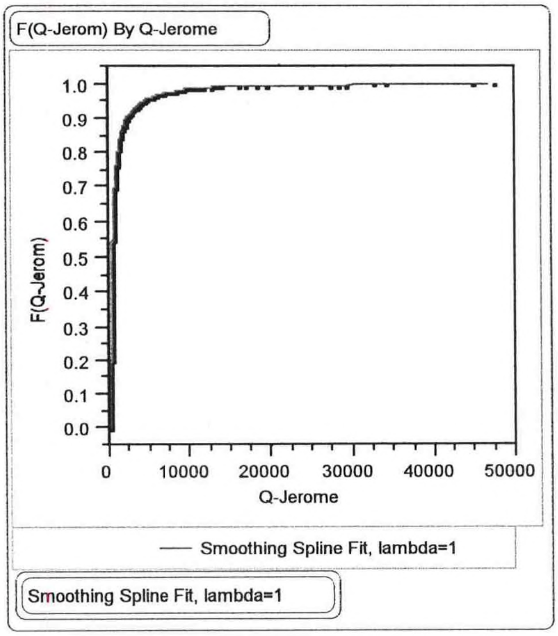

Figure B6. Gasconade River at Jerome, MO

November CDFs

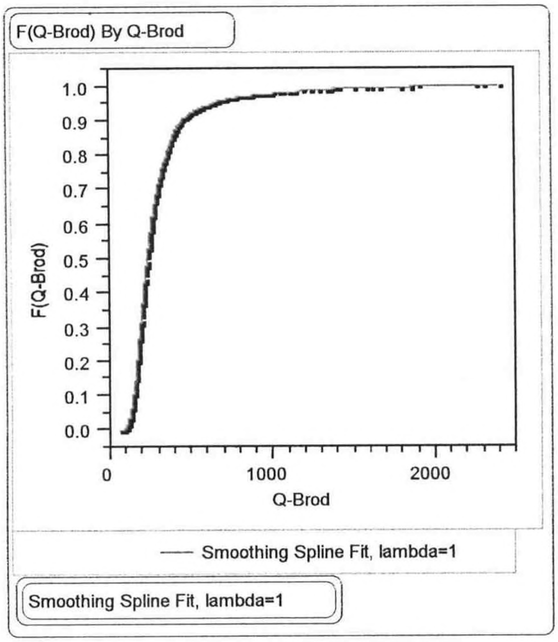

Figure B7. Sugar River near Brodhead, WI

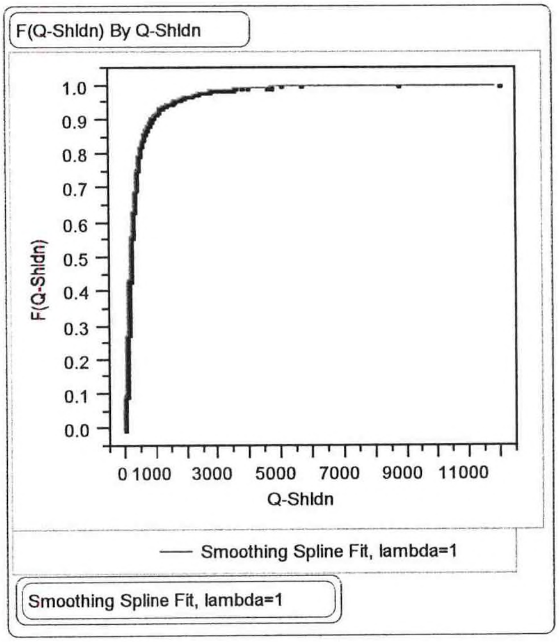

Figure B8. Jump River at Sheldon, WI

November CDFs

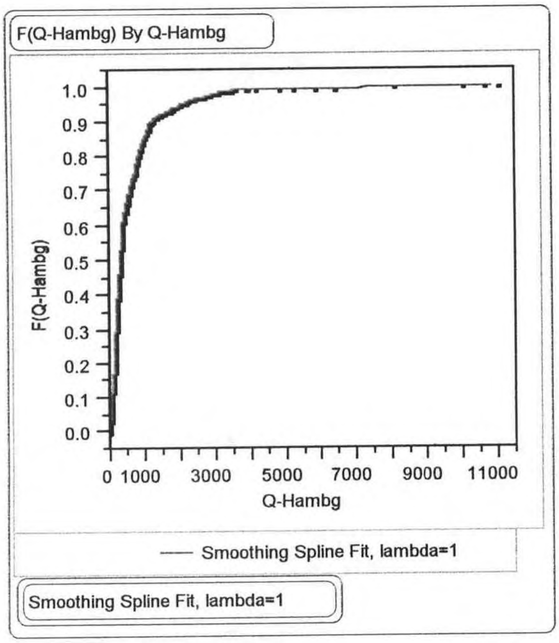

Figure B9. Nishnabotna River near Hamburg, IA

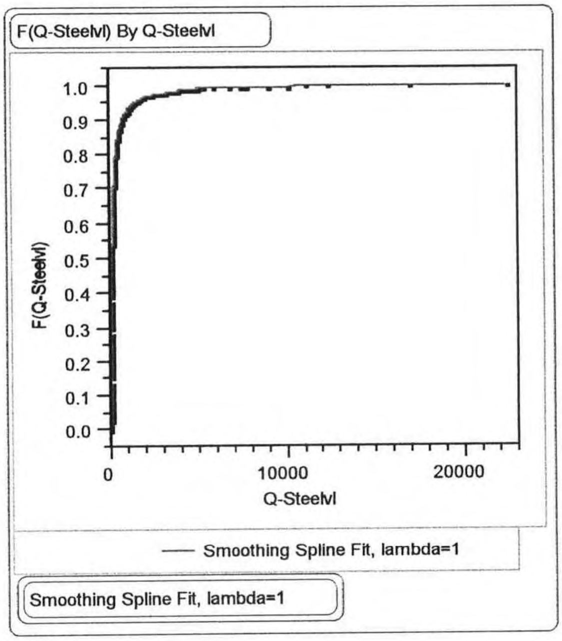

Figure B10. Meramec River near Steeleville, MO

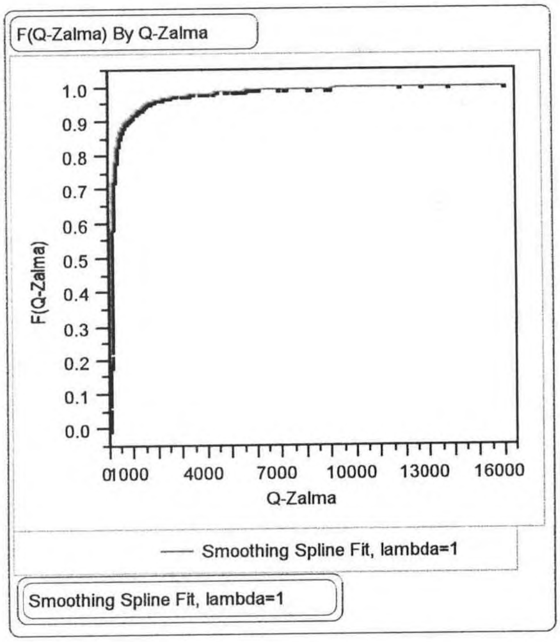

Figure B11. Castor River at Zalma MO

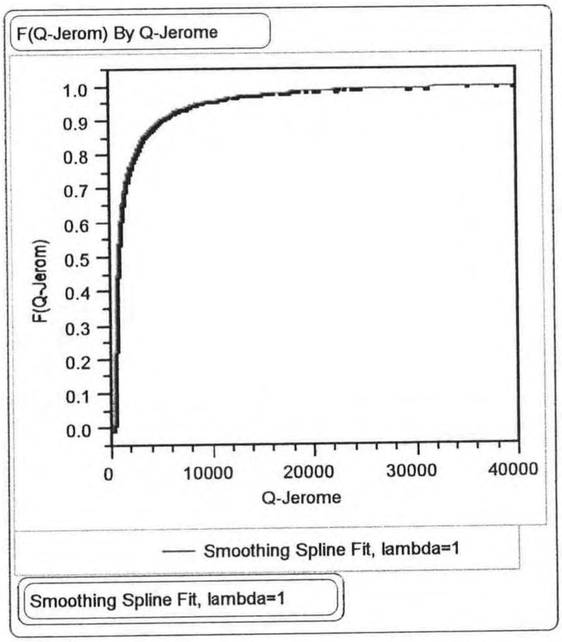

Figure B12. Gasconade River at Jerome, MO

December CDFs

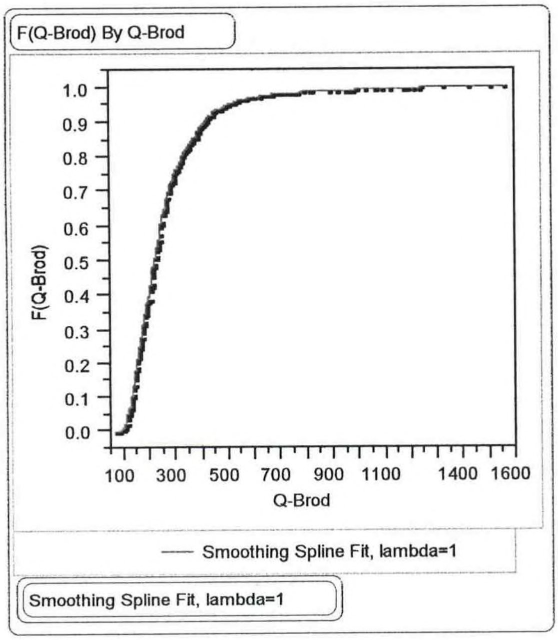

Figure B13. Sugar River near Brodhead, WI

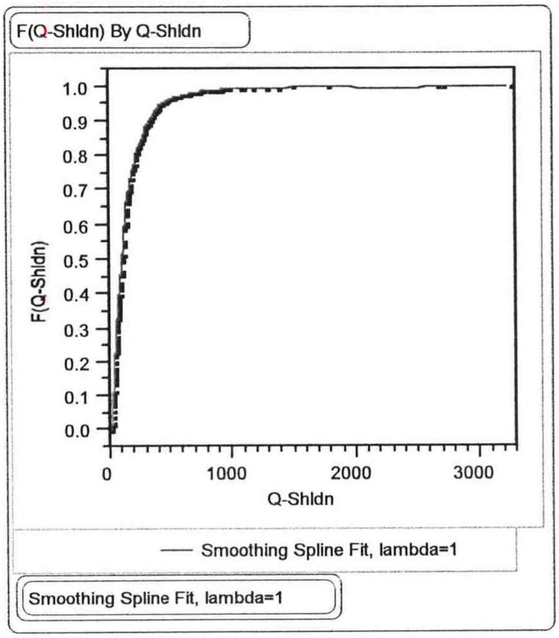

Figure B14. Jump River at Sheldon, WI

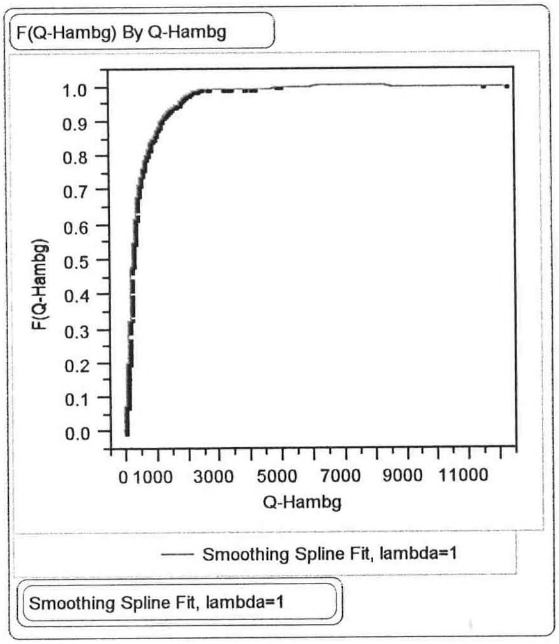

Figure B15. Nishnabotna River near Hamburg, IA

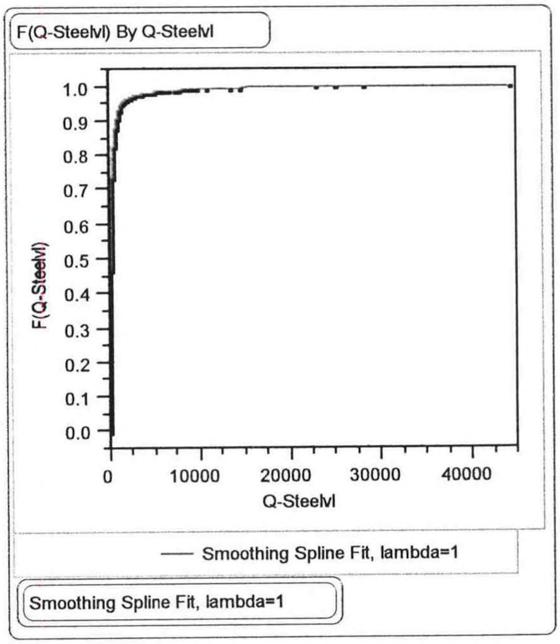

Figure B16. Meramec River near Steeleville, MO

December CDFs

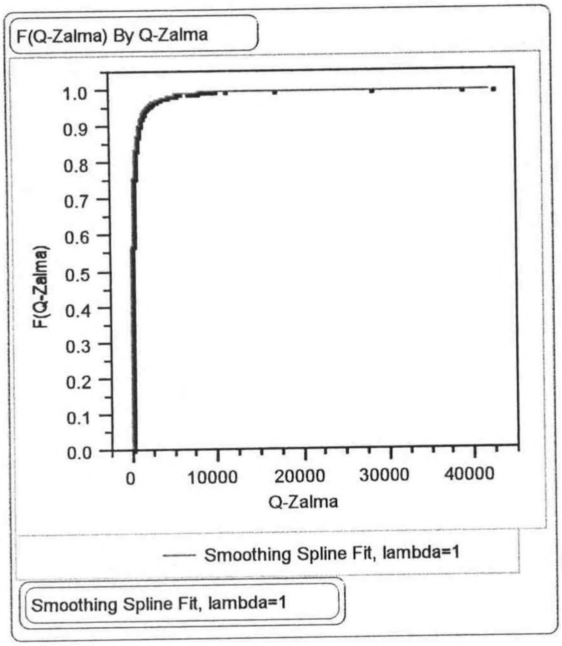

Figure B17. Castor River at Zalma MO

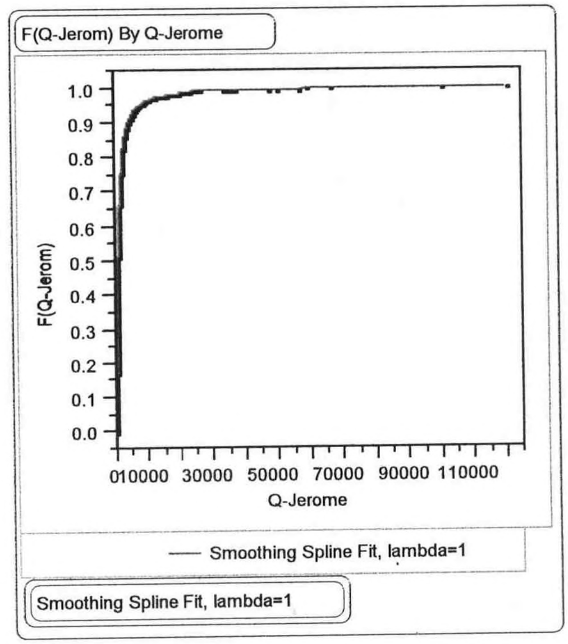

Figure B18. Gasconade River at Jerome, MO

January CDFs

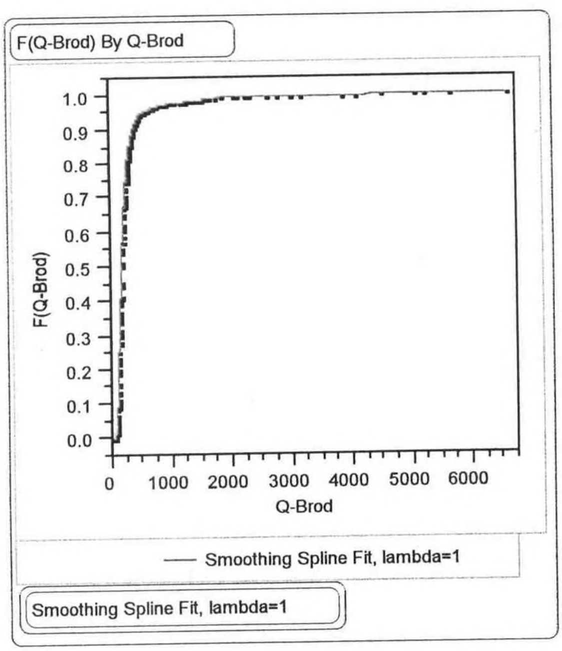

Figure B19. Sugar River near Brodhead, WI

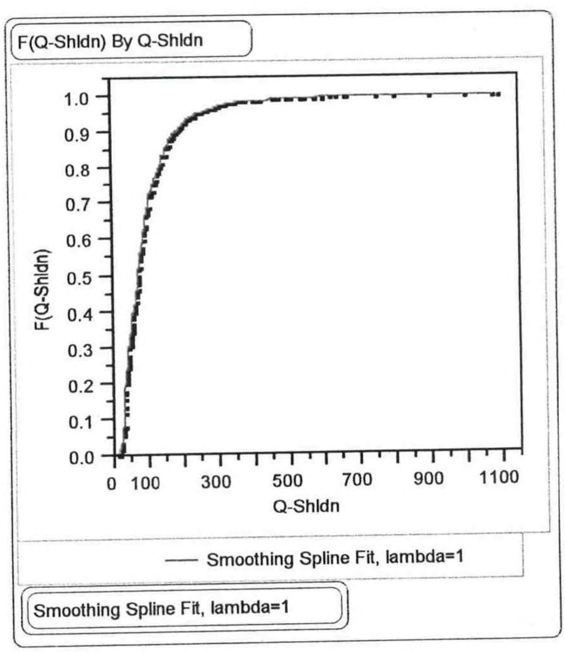

Figure B20. Jump River at Sheldon, WI

January CDFs

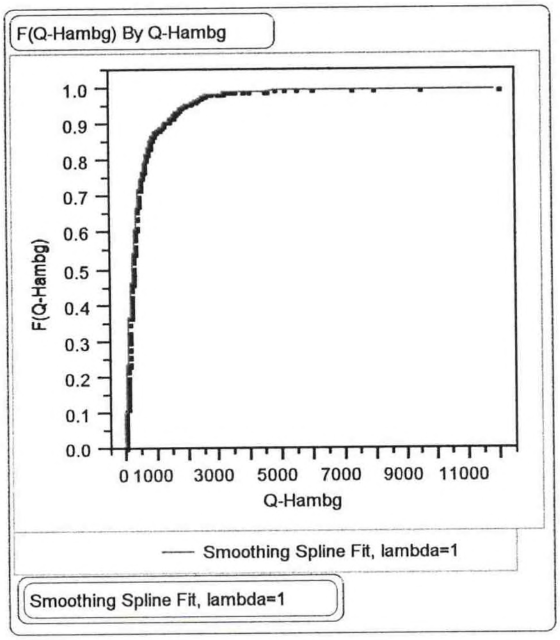

Figure B21. Nishnabotna River near Hamburg, IA

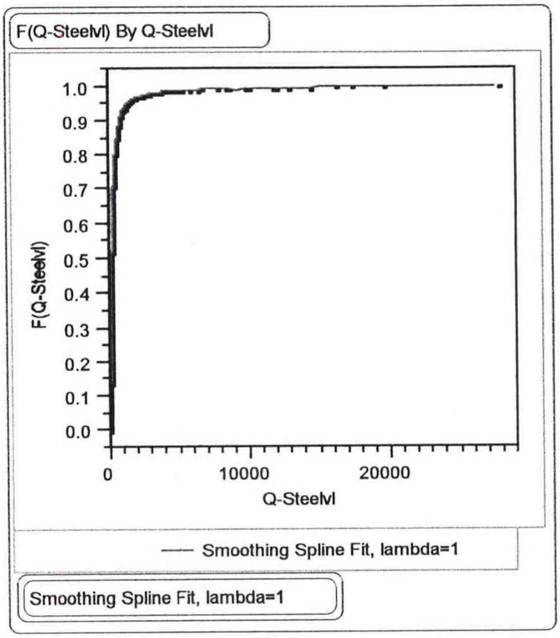

Figure B22. Meramec River near Steeleville, MO

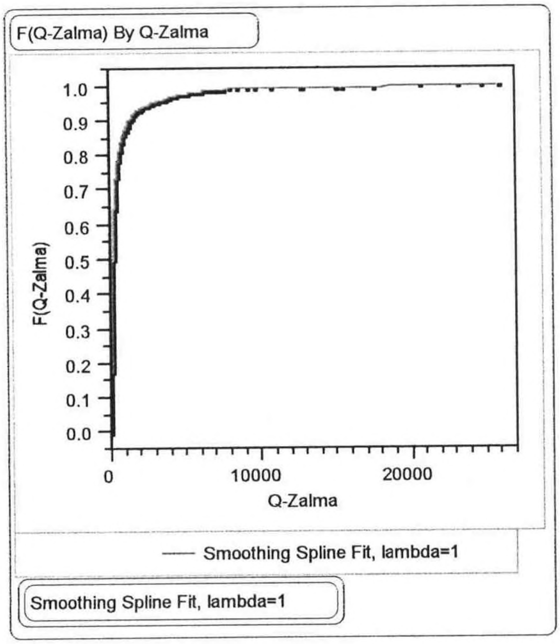

Figure B23. Castor River at Zalma MO

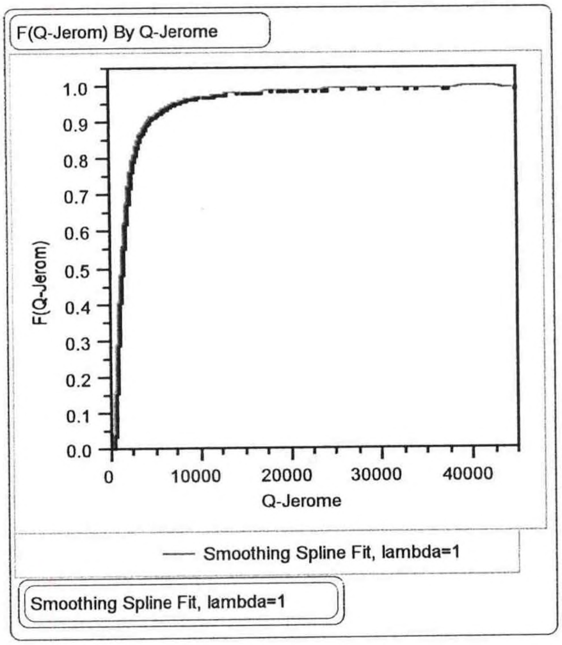

Figure B24. Gasconade River at Jerome, MO

February CDFs

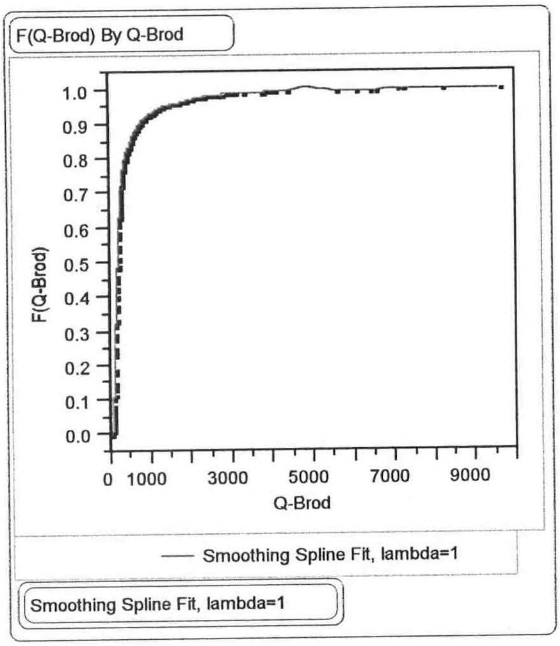

Figure B25. Sugar River near Brodhead, WI

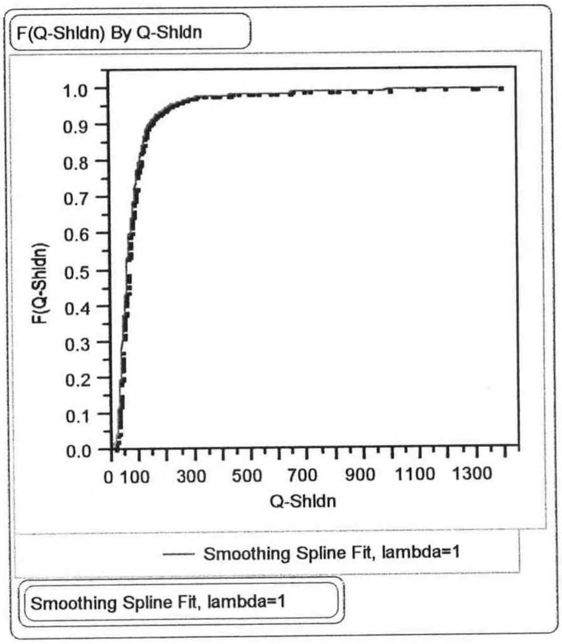

Figure B26. Jump River at Sheldon, WI

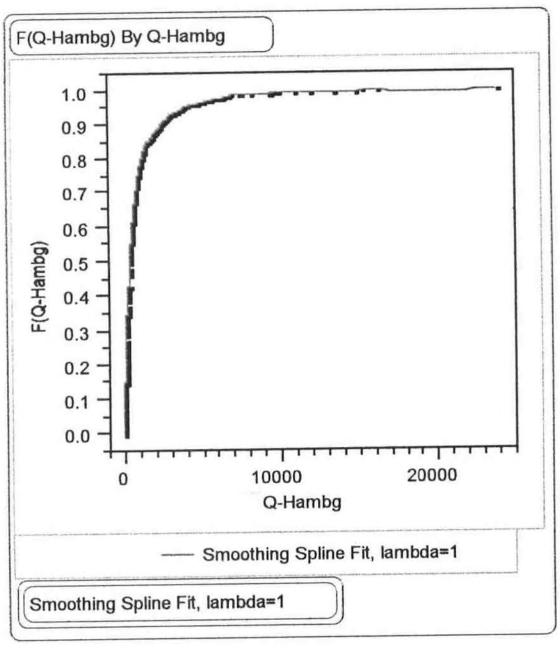

Figure B27. Nishnabotna River near Hamburg, IA

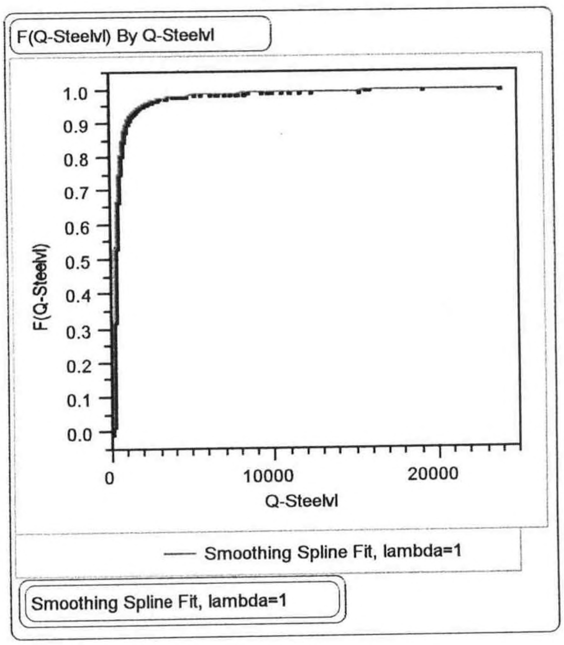

Figure B28. Meramec River near Steeleville, MO

February CDFs

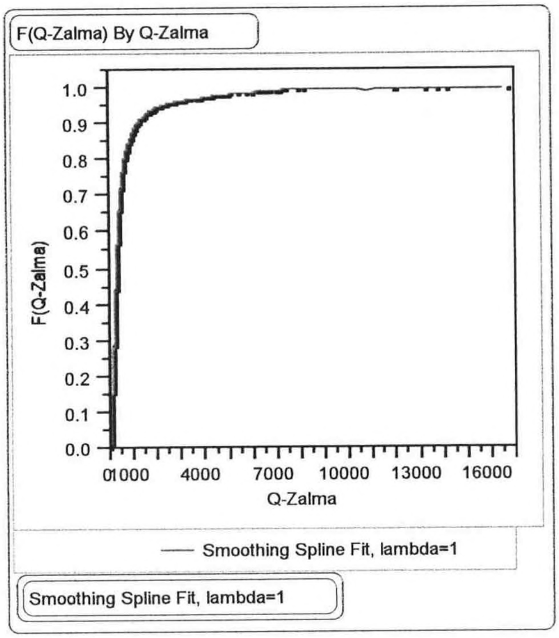

Figure B29. Castor River at Zalma MO

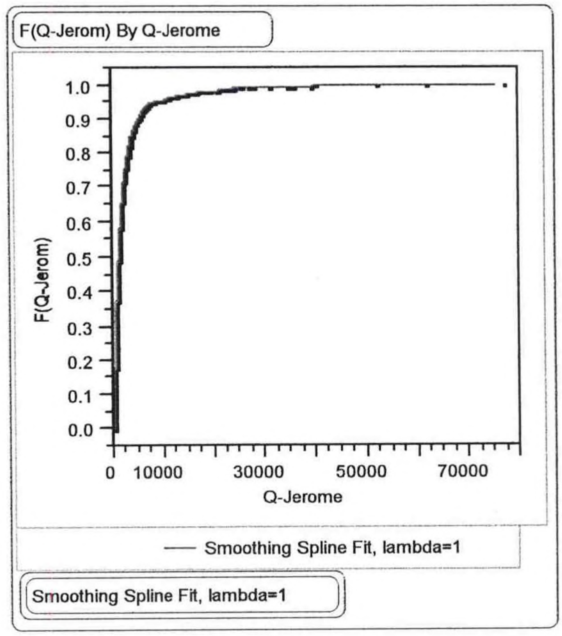

Figure B30. Gasconade River at Jerome, MO

March CDFs

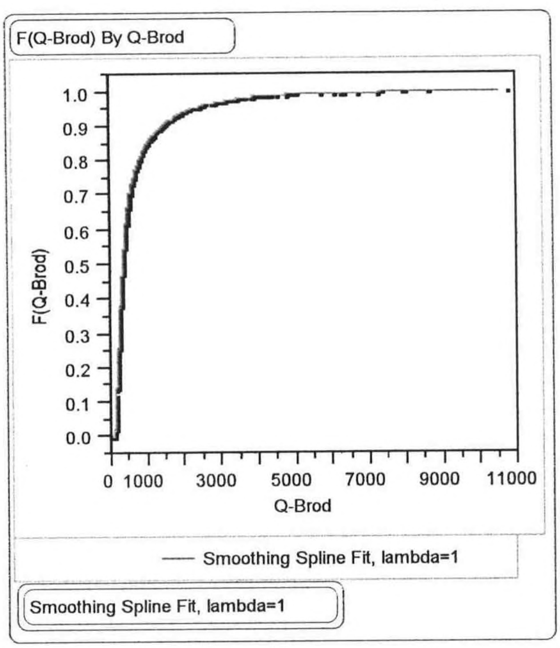

Figure B31. Sugar River near Brodhead, WI

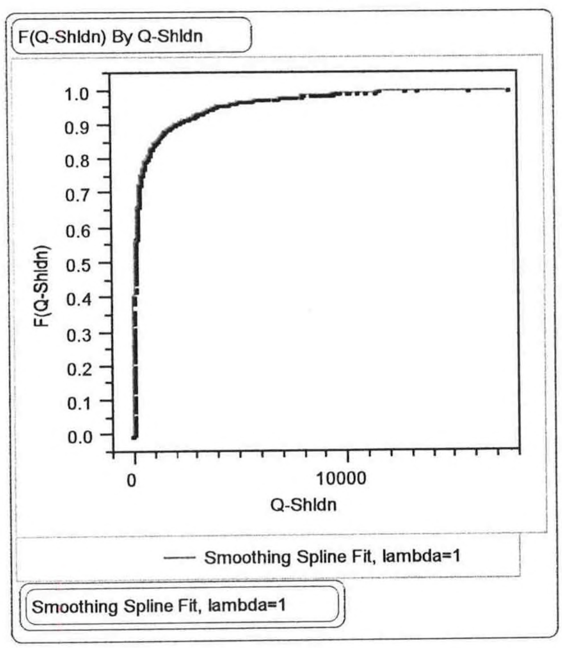

Figure B32. Jump River at Sheldon, WI

March CDFs

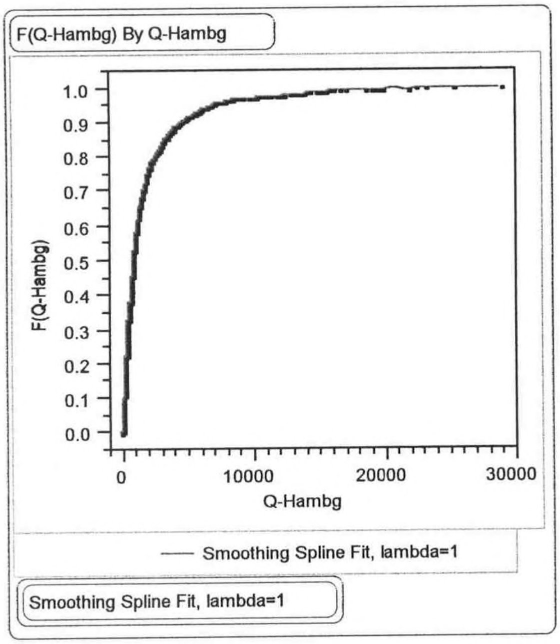

Figure B33. Nishnabotna River near Hamburg, IA

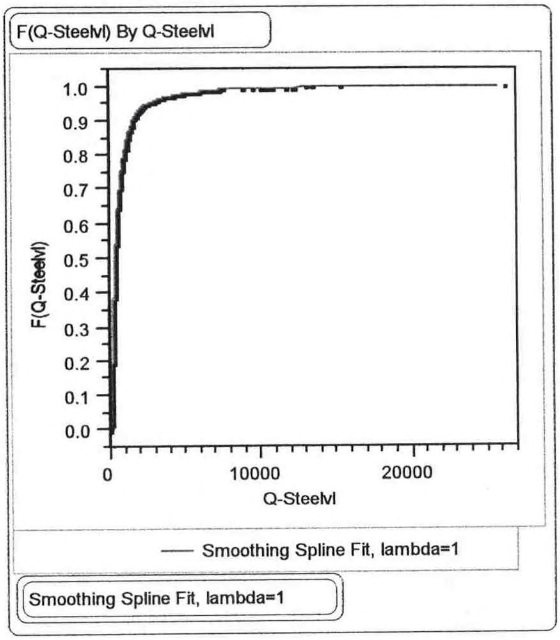

Figure B34. Meramec River near Steeleville, MO

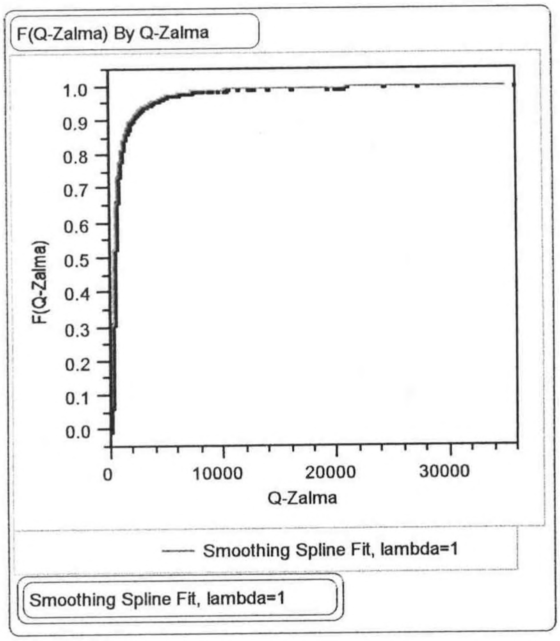

Figure B35. Castor River at Zalma MO

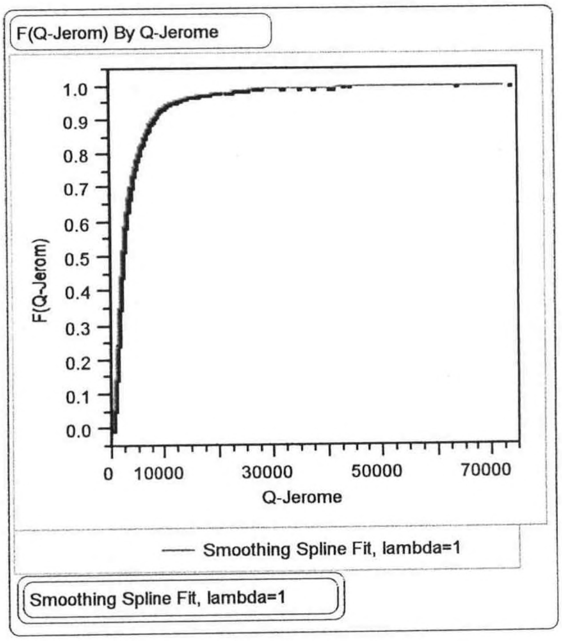

Figure B36. Gasconade River at Jerome, MO

April CDFs

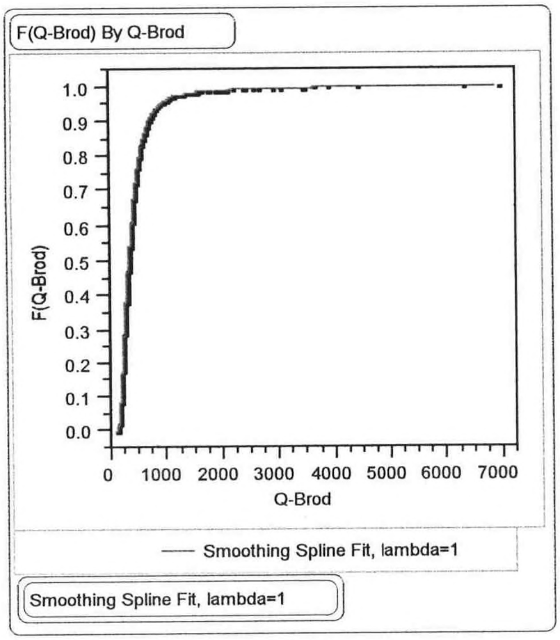

Figure B37. Sugar River near Brodhead, WI

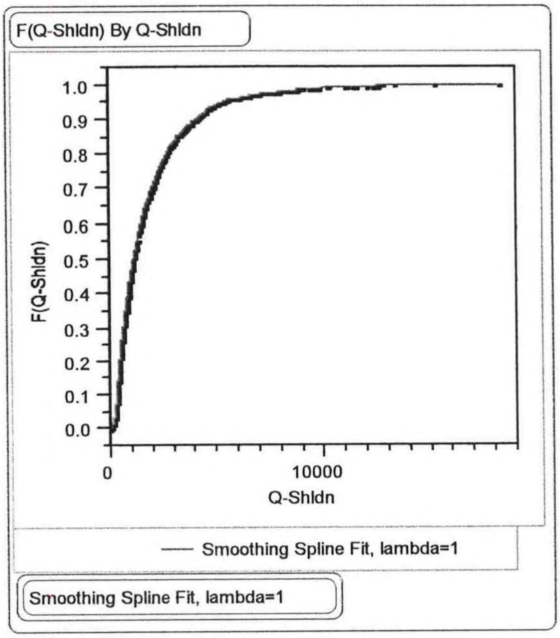

Figure B38. Jump River at Sheldon, WI

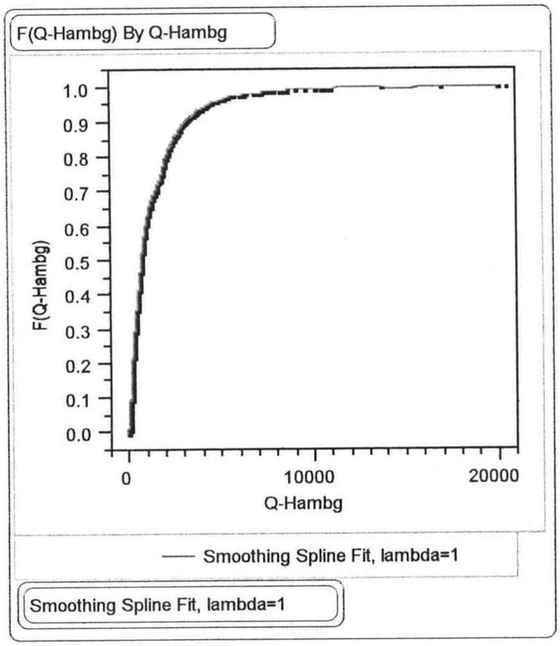

Figure B39. Nishnabotna River near Hamburg, IA

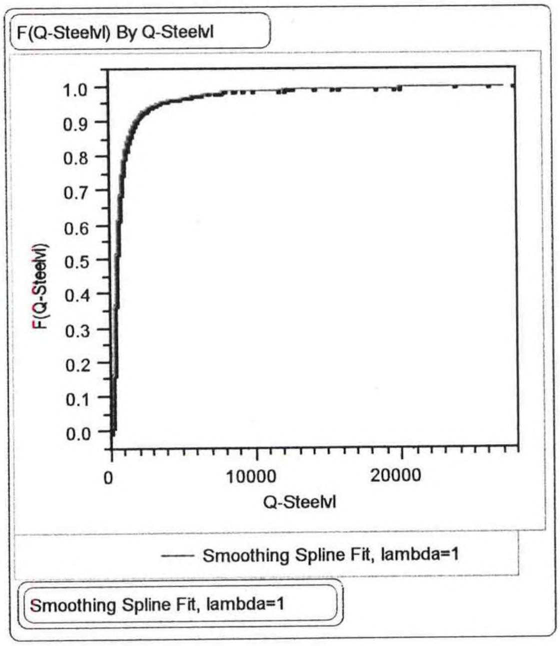

Figure B40. Meramec River near Steeleville, MO

April CDFs

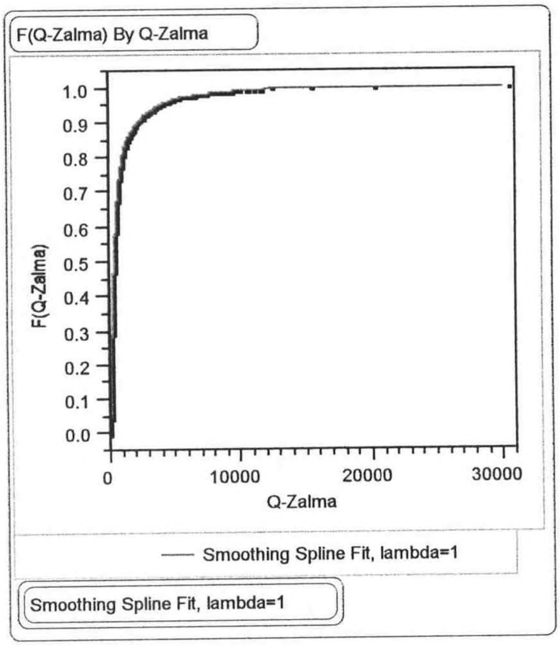

Figure B41. Castor River at Zalma MO

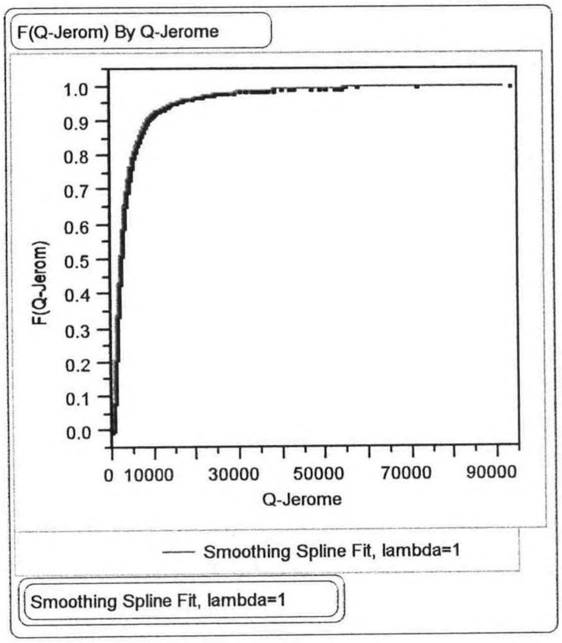

Figure B42. Gasconade River at Jerome, MO

May CDFs

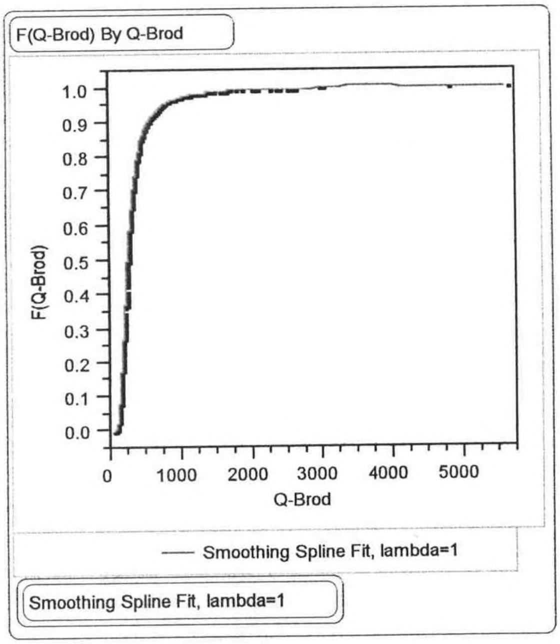

Figure B43. Sugar River near Brodhead, WI

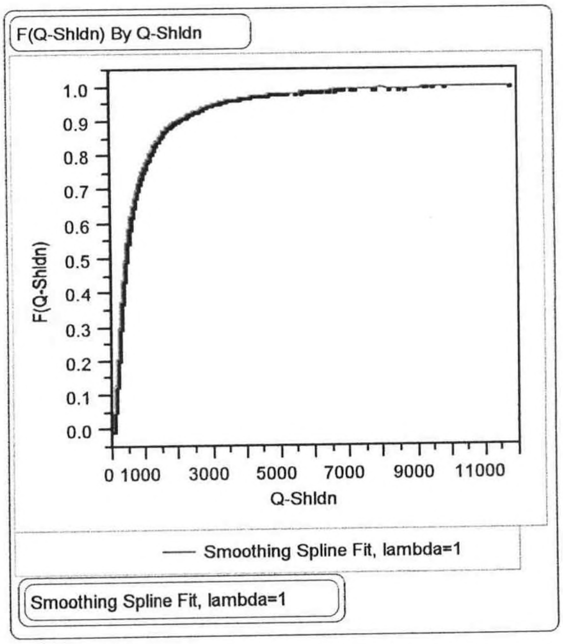

Figure B44. Jump River at Sheldon, WI

May CDFs

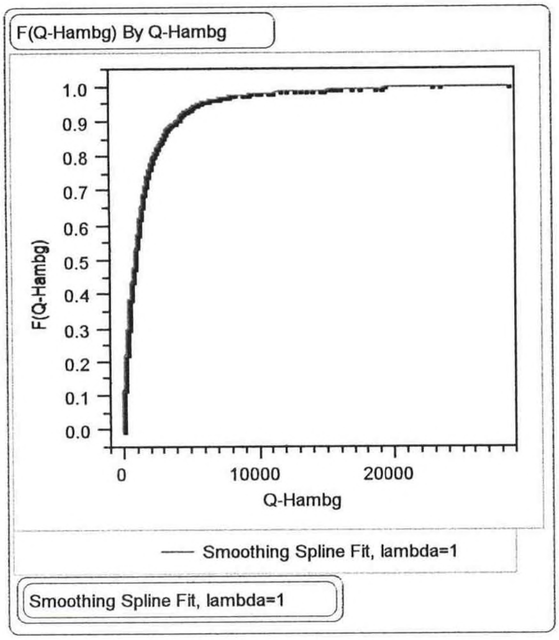

Figure B45. Nishnabotna River near Hamburg, IA

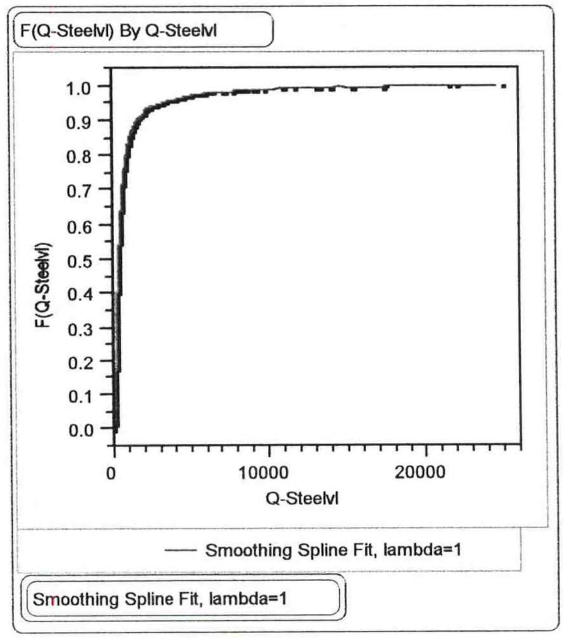

Figure B46. Meramec River near Steeleville, MO

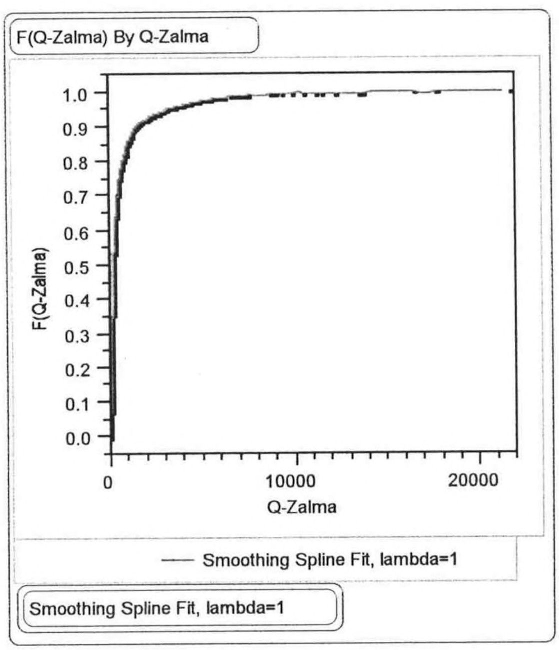

Figure B47. Castor River at Zalma MO

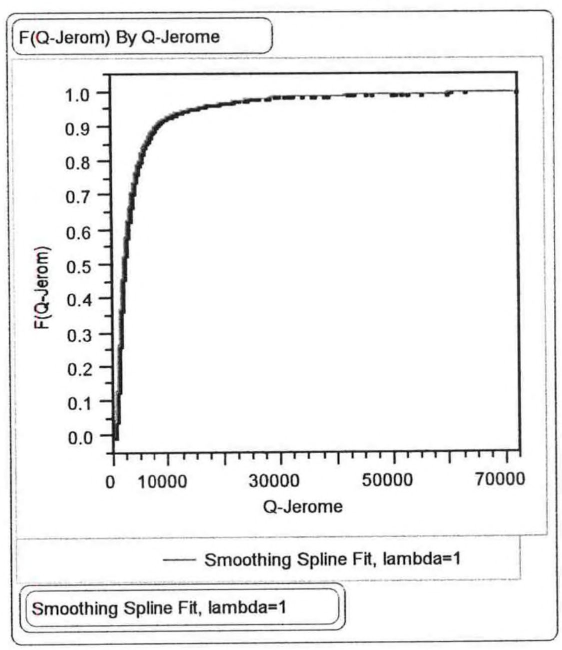

Figure B48. Gasconade River at Jerome, MO

June CDFs

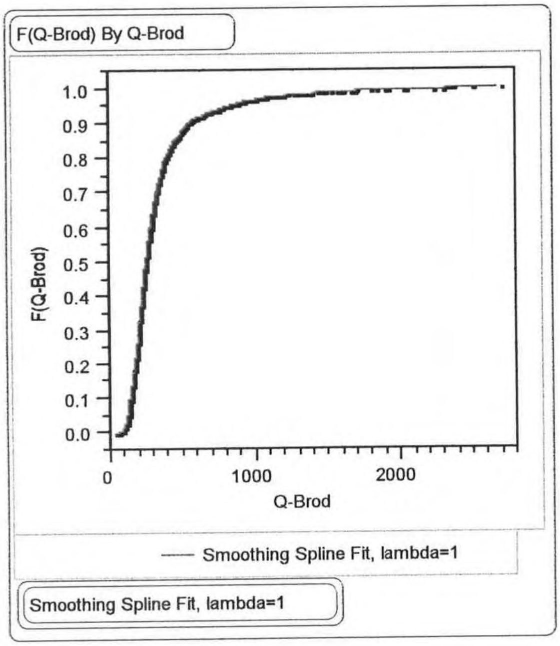

Figure B49. Sugar River near Brodhead, WI

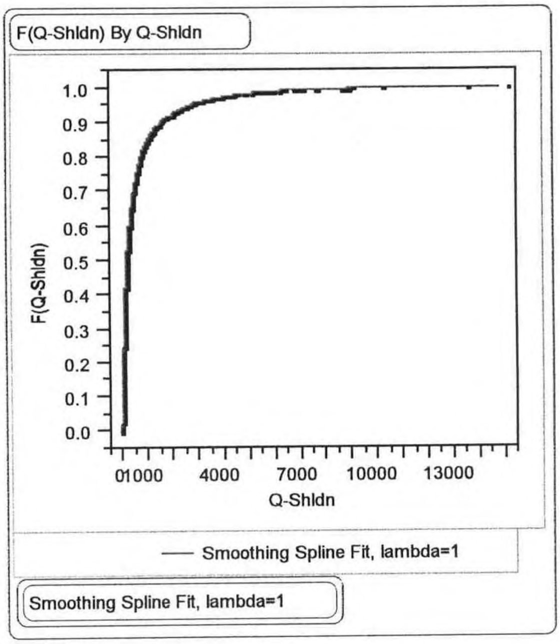

Figure B50. Jump River at Sheldon, WI

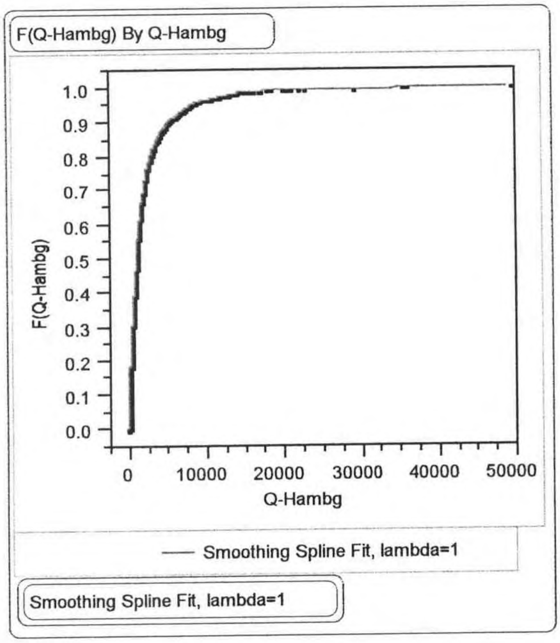

Figure B51. Nishnabotna River near Hamburg, IA

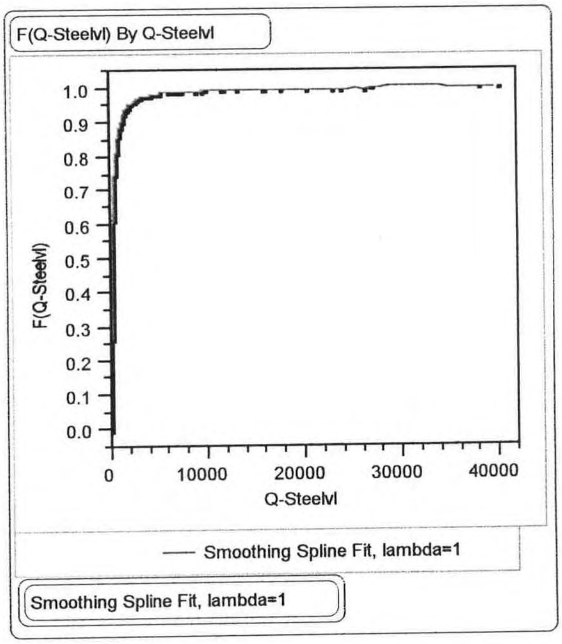

Figure B52. Meramec River near Steeleville, MO

June CDFs

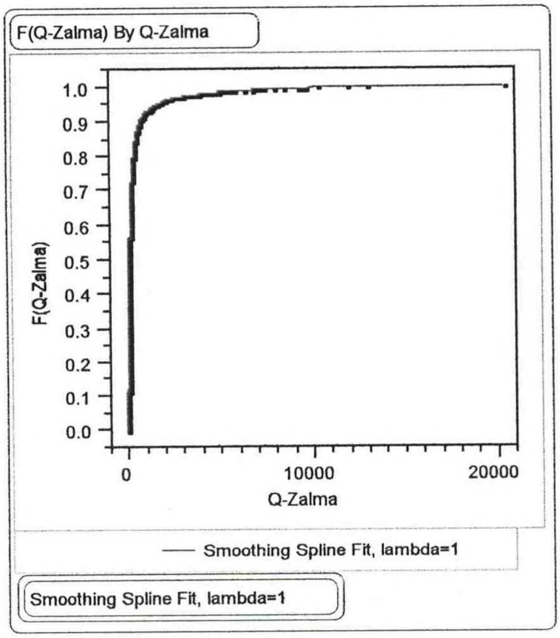

Figure B53. Castor River at Zalma MO

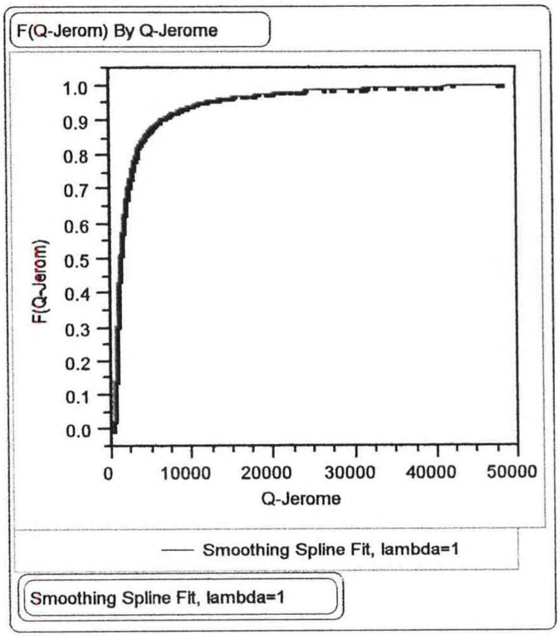

Figure B54. Gasconade River at Jerome, MO

July CDFs

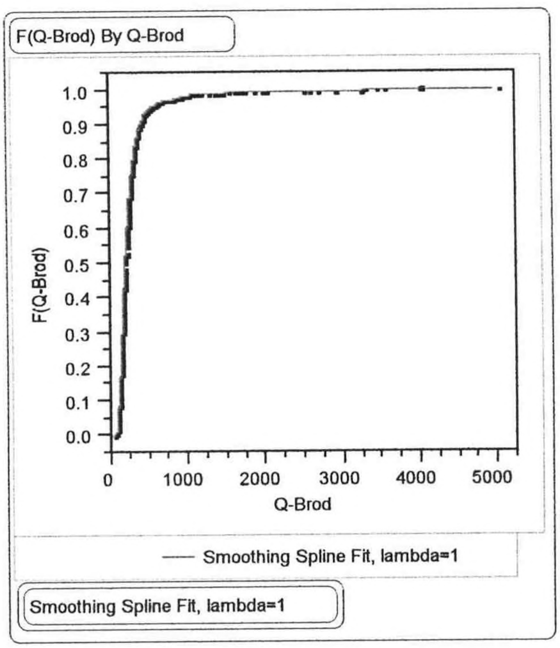

Figure B55. Sugar River near Brodhead, WI

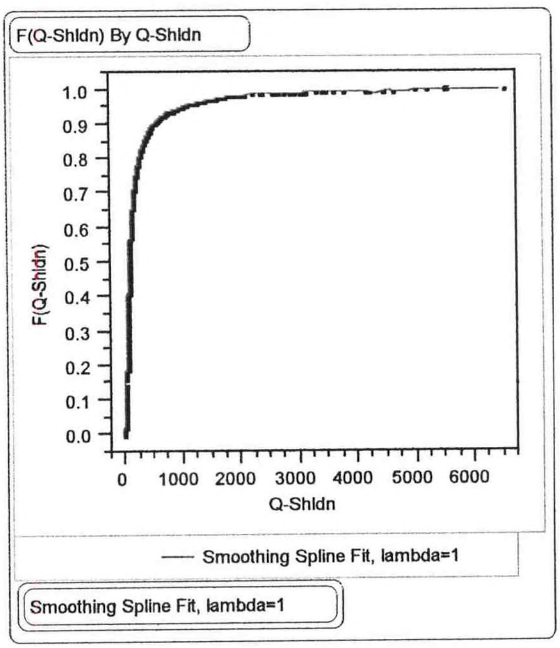

Figure B56. Jump River at Sheldon, WI

July CDFs

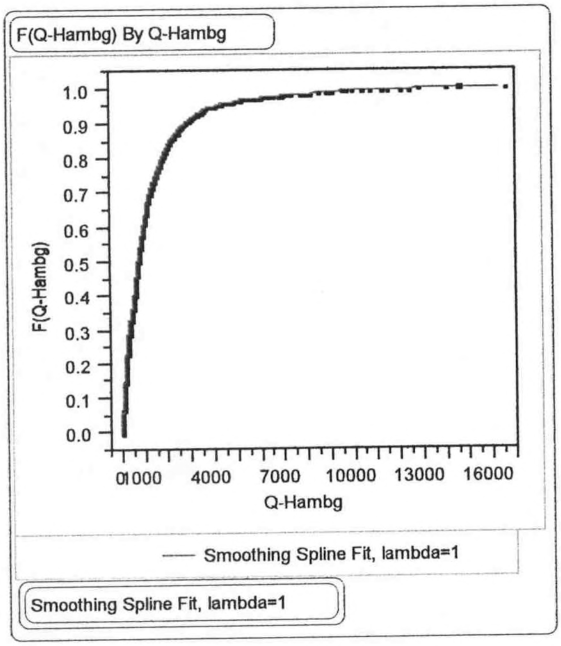

Figure B57. Nishnabotna River near Hamburg, IA

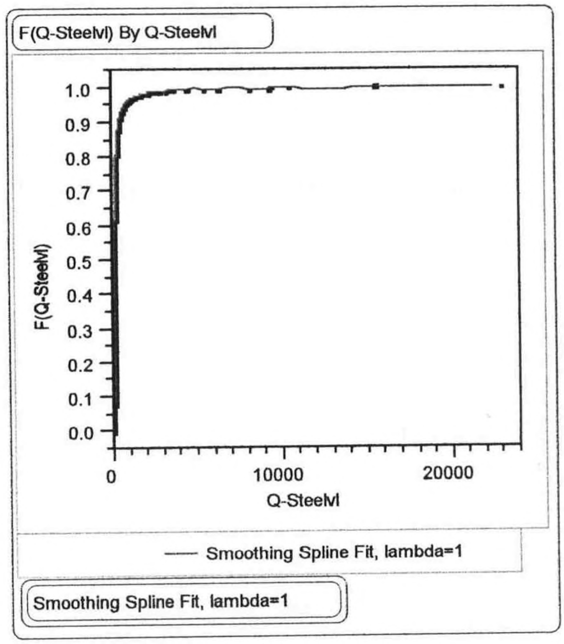

Figure B58. Meramec River near Steeleville, MO

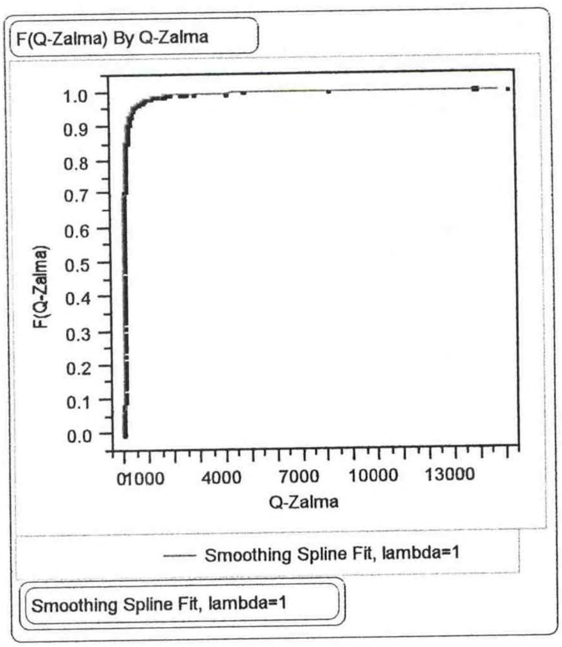

Figure B59. Castor River at Zalma MO

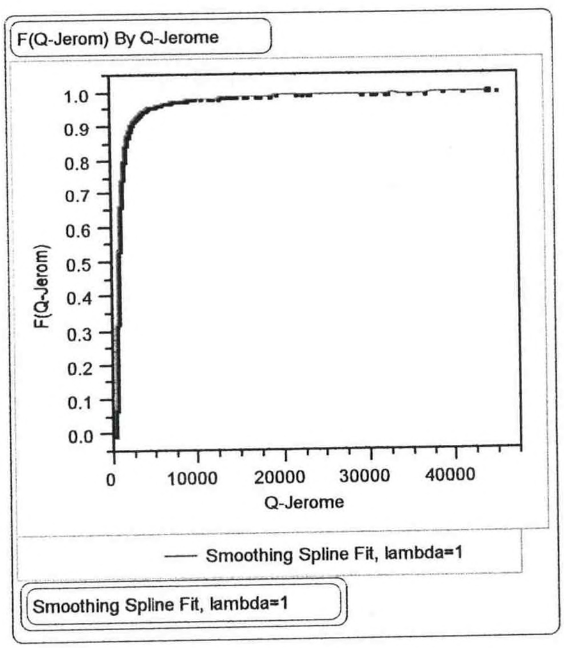

Figure B60. Gasconade River at Jerome, MO

August CDFs

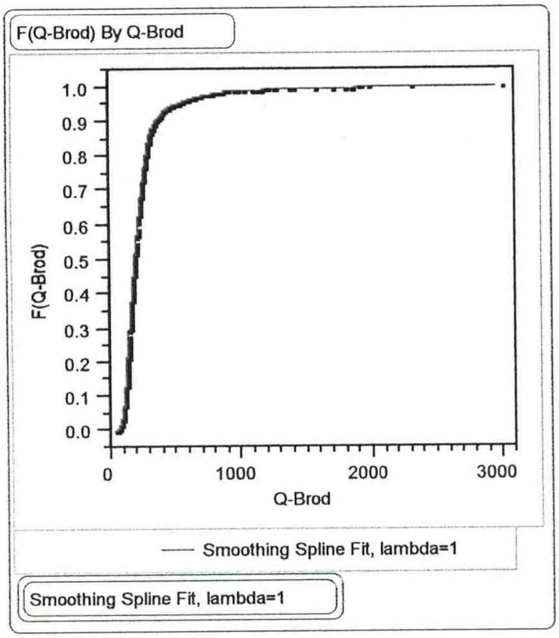

Figure B61. Sugar River near Brodhead, WI

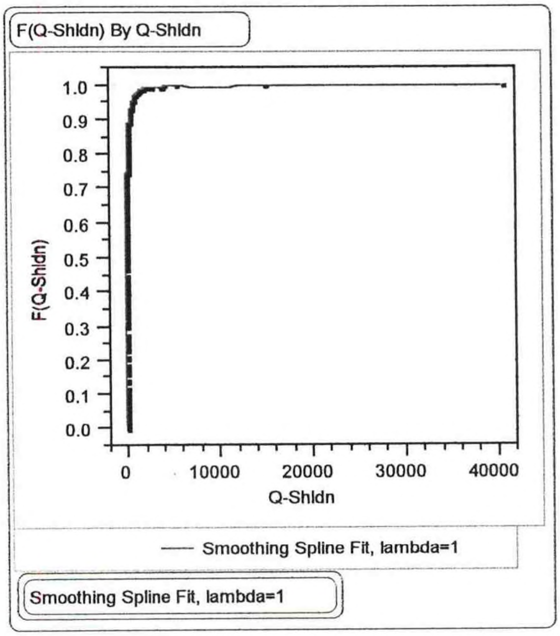

Figure B62. Jump River at Sheldon, WI

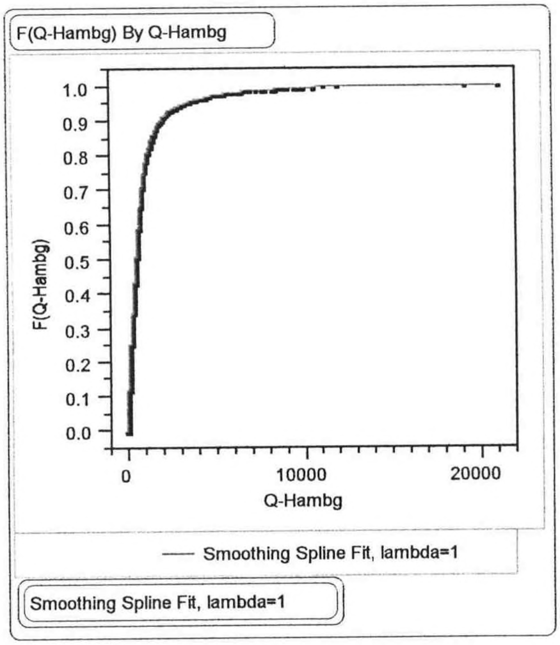

Figure B63. Nishnabotna River near Hamburg, IA

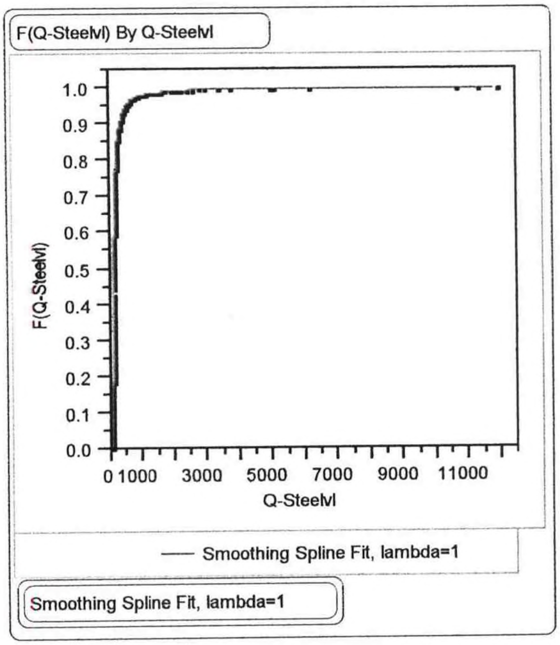

Figure B64. Meramec River near Steeleville, MO

August CDFs

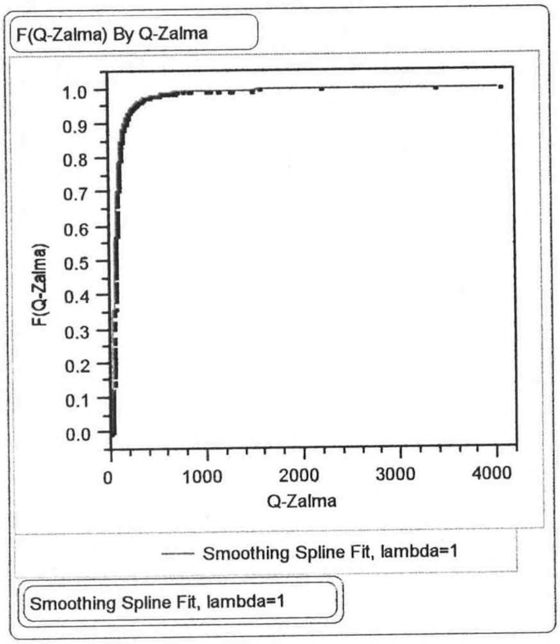

Figure B65. Castor River at Zalma MO

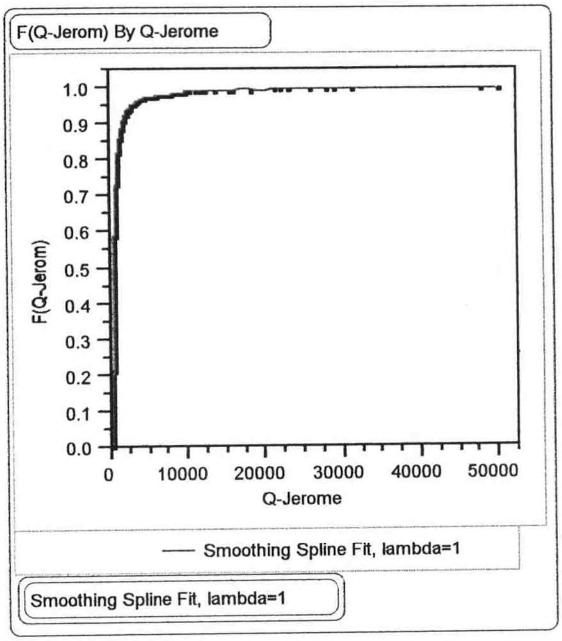

Figure B66. Gasconade River at Jerome, MO

September CDFs

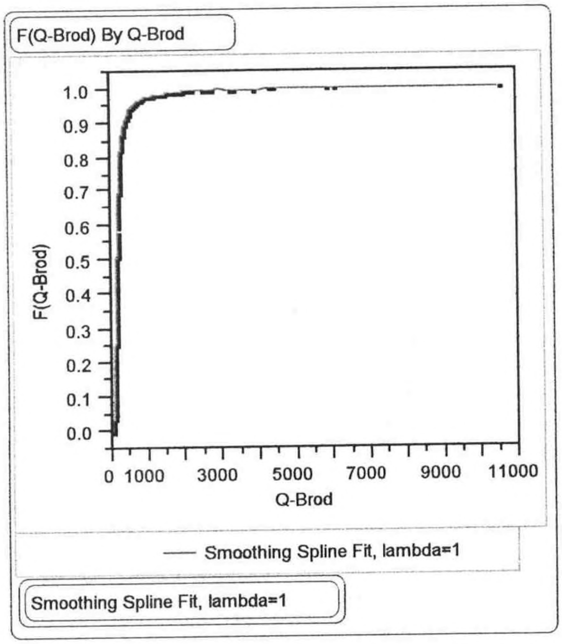

Figure B67. Sugar River near Brodhead, WI

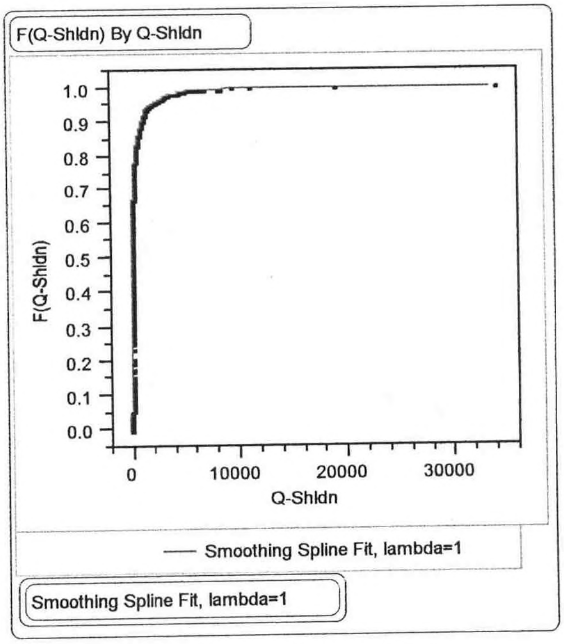

Figure B68. Jump River at Sheldon, WI

September CDFs

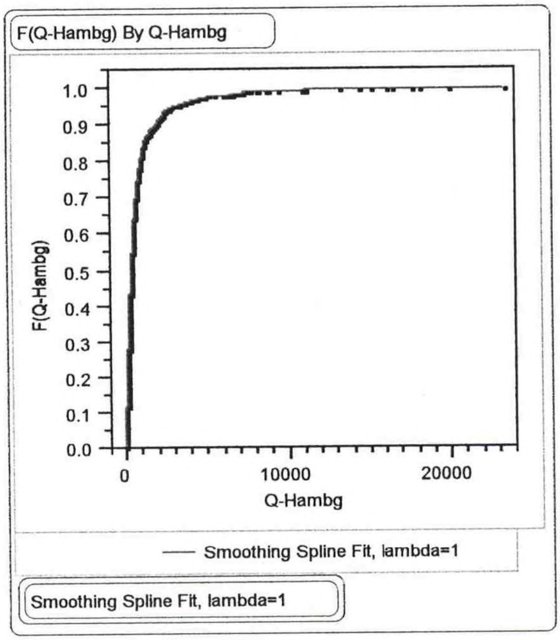

Figure B69. Nishnabotna River near Hamburg, IA

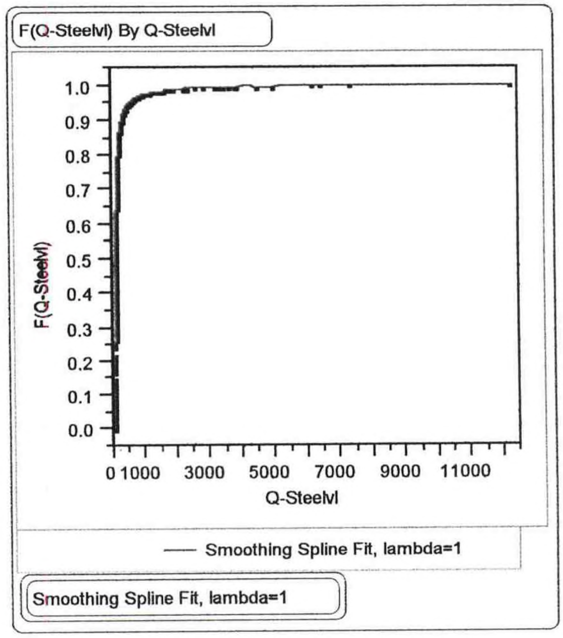

Figure B70. Meramec River near Steeleville, MO

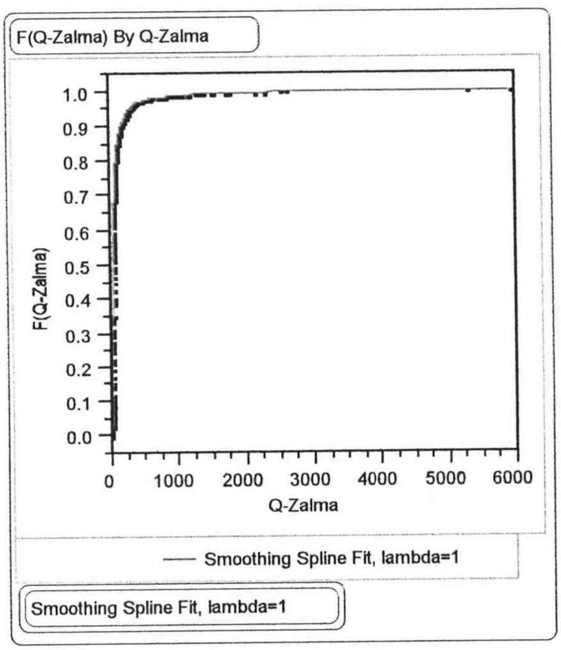

Figure B71. Castor River at Zalma MO

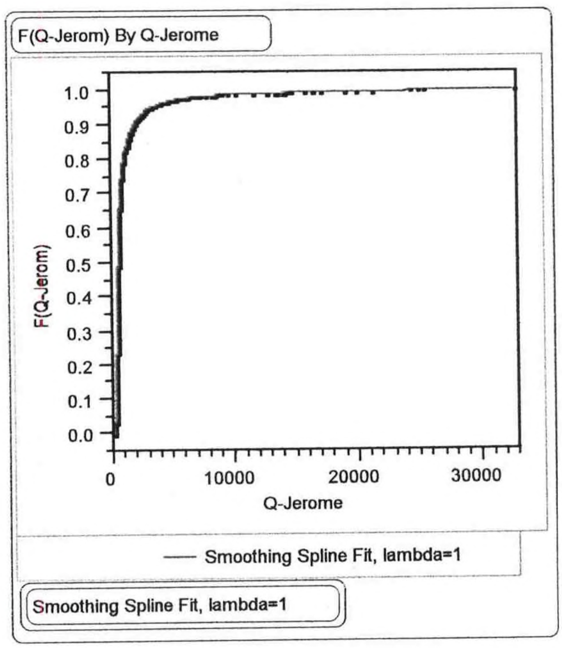

Figure B72. Gasconade River at Jerome, MO

Appendix C

Forecast and Observed Flow data for Hamburg, IA

Day	Time (UTC)	F_i	O_i	$F(F_i)$	$F(O_i)$
1	18	7608	7401.2	0.98895	0.98712
1	24	7350	6921.8	0.98665	0.98387
2	6	7221	6574.6	0.98585	0.98296
2	12	6963	6258.1	0.98402	0.98044
2	18	5839	6023.3	0.97851	0.97884
2	24	5431	5778.2	0.97375	0.97840
3	6	4921	5553.6	0.96282	0.97515
3	12	4567	5329.0	0.95533	0.97097
6	18	3948	3974.2	0.93591	0.93615
6	24	3771	3938.8	0.92820	0.93582
7	6	3594	3921.1	0.92205	0.93526
7	12	3505	5165.6	0.91785	0.96717
7	18	8253	7749.5	0.99032	0.98929
7	24	12898	8639.6	0.99786	0.99256
8	6	15698	10381.6	0.99836	0.99509
8	12	17898	14064.0	0.99874	0.99808
8	18	15998	16145.4	0.99841	0.99843
8	24	16598	14852.8	0.99851	0.99821
9	6	14898	13112.8	0.99822	0.99790
9	12	12898	11599.6	0.99786	0.99760
9	18	11298	10577.6	0.99754	0.99551
9	24	10598	9737.6	0.99557	0.99430
10	6	9898	9135.6	0.99445	0.99373
10	12	9178	8639.6	0.99377	0.99256
11	18	6963	6901.3	0.98402	0.98373
11	24	6758	6707.4	0.98316	0.98311
12	6	6452	6523.6	0.98282	0.98290
12	12	6146	6370.4	0.97927	0.98238
14	18	5125	5196.3	0.96607	0.96766
14	24	4921	5114.6	0.96282	0.96588
15	6	4744	5104.4	0.95958	0.96573
15	12	5023	5135.0	0.96403	0.96625
15	18	5329	5099.5	0.97097	0.96568
15	24	5431	5024.8	0.97375	0.96406
16	6	5431	4933.5	0.97375	0.96288
16	12	5329	4896.5	0.97097	0.96270
16	18	4655	4939.9	0.95837	0.96291
16	24	4478	5091.4	0.95257	0.96559
17	6	4390	5082.7	0.94995	0.96550
17	12	4301	5023.9	0.94525	0.96405

Table C1. April, 1998 data for Hamburg, IA

Day	Time (UTC)	F_i	O_i	$F(F_i)$	$F(O_i)$
16	18	6963	8110.7	0.96726	0.97624
16	24	7350	8967.6	0.96954	0.97906
17	6	8253	8355.8	0.97674	0.97761
17	12	7479	7452.8	0.97146	0.97108
17	18	6963	6370.4	0.96726	0.96114
17	24	5942	5471.9	0.95823	0.94860
18	6	5023	4655.3	0.93640	0.93150
18	12	4478	4053.8	0.92243	0.90416
20	18	3240	4115.7	0.86749	0.90571
20	24	3417	4655.3	0.88037	0.93150
21	6	3505	4566.8	0.88468	0.92572
21	12	3682	4195.3	0.89092	0.90888
21	18	4478	3965.3	0.92243	0.89950
21	24	5125	6002.9	0.93949	0.95891
22	6	6044	6299	0.95913	0.96087
22	12	6656	5523	0.96501	0.95074
22	18	7866	10409.6	0.97367	0.98392
22	24	9498	12532.8	0.98145	0.98787
23	6	11898	11389.6	0.98712	0.98592
23	12	15498	10283.6	0.99333	0.98376
23	18	9178	9093.6	0.97954	0.97935
23	24	7866	8188.1	0.97367	0.97652
24	6	6656	7169	0.96501	0.96832
24	12	5431	6258.1	0.94758	0.96072
24	18	5635	5563.8	0.95311	0.95146
24	24	6554	5267.7	0.96380	0.94412
25	6	8253	8330	0.97674	0.97723
25	12	9038	10241.6	0.97922	0.98361
25	18	10698	10185.6	0.98417	0.98342
25	24	8640	8471.9	0.97874	0.97858
26	6	6554	6595	0.96380	0.96465
26	12	4921	5676.1	0.93436	0.95403

Table C2. May, 1998 data for Hamburg, IA

Day	Time (UTC)	F_i	O_i	$F(F_i)$	$F(O_i)$
7	18	3240	3302	0.81918	0.82235
7	24	3152	3257.7	0.81242	0.81957
8	6	3077	3222.4	0.80718	0.81886
8	12	2929	3310.8	0.79560	0.82277
8	18	3328	3646.9	0.82516	0.84223
8	24	3328	4257.2	0.82516	0.86819
9	6	3240	4814.5	0.81918	0.88123
9	12	3505	6237.7	0.83398	0.91747
9	18	10198	12745.1	0.96634	0.97931
9	24	13798	16049.4	0.98381	0.99011
10	6	14898	16200.3	0.98792	0.99039
10	12	15698	14612	0.98947	0.98731
10	18	15498	13808.8	0.98911	0.98384
10	24	12898	10633.6	0.97972	0.96789
11	6	10698	9051.6	0.96798	0.95991
11	12	8511	8110.7	0.95333	0.94627
11	18	7737	8020.4	0.94204	0.94511
11	24	8253	9443.6	0.95000	0.96319
12	6	9598	16891.9	0.96344	0.99133
12	12	11698	23450.8	0.97398	0.99700
12	18	24698	26557.5	0.99710	0.99726
12	24	22998	26970.6	0.99696	0.99730
13	6	20698	22756.7	0.99497	0.99691
13	12	18498	15924.2	0.99311	0.98988
13	18	12598	11906.4	0.97888	0.97510
13	24	10998	10507.6	0.97016	0.96772
14	6	9178	10059.6	0.96066	0.96596
14	12	7479	18302	0.93682	0.99294
14	18	25298	27119.3	0.99715	0.99731
14	24	36998	33256.4	0.99916	0.99818
15	6	39398	33983.6	0.99926	0.99830
15	12	35398	35599.6	0.99854	0.99858
16	18	34998	37902.4	0.99848	0.99920
16	24	32198	34630	0.99800	0.99841
17	6	30998	42749.6	0.99779	0.99939
17	12	29298	53973.6	0.99750	0.99985
17	18	57307	51673.6	0.99999	0.99976
17	24	51896	47901.6	0.99977	0.99960
18	6	43716	44451.6	0.99943	0.99946
18	12	36198	37585.8	0.99912	0.99918
18	18	34998	32716.1	0.99848	0.99809
18	24	29298	31172.8	0.99750	0.99782
19	6	25998	29629.6	0.99721	0.99756
19	12	22698	27932.1	0.99687	0.99738
19	18	33398	26697.5	0.99820	0.99727
19	24	31398	25514.4	0.99786	0.99717
20	6	29298	24331.3	0.99750	0.99707
20	12	28498	23148.2	0.99743	0.99697
20	18	28898	15786.3	0.99746	0.98963
20	24	27698	15809.5	0.99736	0.98967
21	6	26298	16312.4	0.99724	0.99094
21	12	24998	16619.7	0.99713	0.99115
21	18	25298	16563.9	0.99715	0.99111
21	24	23998	16290	0.99704	0.99088

22	6	22398	15892.3	0.99667	0.98982
22	12	20698	15438.4	0.99497	0.98900
22	18	20698	14858.4	0.99497	0.98781
22	24	19298	14082.9	0.99341	0.98434
23	6	17898	13167.3	0.99257	0.98073
23	12	17698	12222.6	0.99239	0.97588
23	18	11598	11333.3	0.97343	0.97199
23	24	11098	10458	0.97043	0.96765
24	6	10398	9583.7	0.96757	0.96342
24	12	9898	8825.6	0.96529	0.95699
24	18	9998	8200.2	0.96579	0.94886
24	24	9598	7660.7	0.96344	0.94015
25	6	9038	7199.2	0.95986	0.93185
25	12	8769	6841.8	0.95628	0.92830
25	18	10998	6588	0.97016	0.92301
25	24	10598	6337.2	0.96784	0.92037
26	6	9998	6020.5	0.96579	0.91384
26	12	9598	5643.6	0.96344	0.90716
26	18	9898	5336.7	0.96529	0.90038
26	24	9498	5109.3	0.96328	0.89309
27	6	9178	4922.9	0.96066	0.88444
27	12	8898	4768.7	0.95823	0.87978
27	18	8769	4645.2	0.95628	0.87704
27	24	8511	4550.6	0.95333	0.87539
28	6	8382	4606.6	0.95047	0.87678
28	12	8124	5732.7	0.94645	0.90905
28	18	10598	6426.5	0.96784	0.92220
28	24	10698	5639.8	0.96798	0.90705
29	6	10198	4952.5	0.96634	0.88507
29	12	9498	4638.3	0.96328	0.87700
29	18	8382	4555.5	0.95047	0.87552
29	24	8253	4514	0.95000	0.87426
30	6	8124	4394.6	0.94645	0.87152
30	12	7995	4258.3	0.94446	0.86822
30	18	7221	4163.7	0.93212	0.86382

Table C3. June, 1998 data for Hamburg, IA

Day	Time (UTC)	F_i	O_i	$F(F_i)$	$F(O_i)$
30	24	7092	4088.9	0.98178	0.95021
1	6	6963	4027.2	0.98030	0.94944
1	12	6860	4036.1	0.97934	0.94951
1	18	6656	4105.4	0.97862	0.95060
1	24	6554	4098.1	0.97831	0.95046
2	6	6452	3982.4	0.97796	0.94920
2	12	6350	3847.7	0.97740	0.94721
3	18	5533	5574.0	0.97142	0.97169
3	24	5431	5492.4	0.97087	0.97110
4	6	5227	5410.7	0.96909	0.97079
4	12	5125	5614.9	0.96687	0.97179
4	18	4213	6074.3	0.95308	0.97413
4	24	4478	6431.7	0.95846	0.97785
5	6	4832	6503.1	0.96154	0.97815
5	12	5227	6125.4	0.96909	0.97451
5	18	7221	5859.9	0.98238	0.97324
5	24	15698	9471.6	0.99943	0.99216
6	6	21998	9499.6	0.99979	0.99219
6	12	23698	11207.6	0.99995	0.99579
6	18	12198	12370.4	0.99717	0.99740
6	24	12598	14412.0	0.99770	0.99890
7	6	13098	16947.2	0.99818	0.99968
7	12	13598	18550.9	0.99840	0.99969
7	18	15998	19767.5	0.99952	0.99969
7	24	14298	20154.6	0.99880	0.99969
8	6	12598	20569.4	0.99770	0.99969
8	12	11398	20016.3	0.99624	0.99969
8	18	18798	19822.8	0.99969	0.99969
8	24	17098	19380.4	0.99968	0.99969
9	6	15498	18468.0	0.99938	0.99969
9	12	12598	17334.3	0.99770	0.99968
9	18	15498	16007.1	0.99938	0.99952
9	24	13798	14713.6	0.99849	0.99916
10	6	11898	13553.6	0.99686	0.99838
10	12	9998	12486.4	0.99333	0.99755
10	18	11398	11571.6	0.99624	0.99657
10	24	10398	11039.6	0.99439	0.99543
11	6	9298	10661.6	0.99195	0.99474
11	12	8511	10185.6	0.98645	0.99383
11	18	9598	9639.6	0.99235	0.99246
11	24	9178	9093.6	0.99180	0.99134
12	6	8640	8562.2	0.98710	0.98684
12	12	8124	8110.7	0.98463	0.98456
12	18	7866	7749.5	0.98349	0.98321
12	24	7608	7439.9	0.98305	0.98286
13	6	7350	7169.0	0.98276	0.98223
13	12	7092	6911.6	0.98178	0.97982
13	18	6758	6717.6	0.97888	0.97878
13	24	6554	6533.8	0.97831	0.97825
14	6	6350	6350.0	0.97740	0.97740
14	12	6146	6156.0	0.97478	0.97496
14	18	5942	6002.9	0.97355	0.97379
14	24	5839	5829.3	0.97302	0.97292
15	6	5635	5686.4	0.97184	0.97196

15	12	5431	5563.8	0.97087	0.97167
15	18	5431	5523.0	0.97087	0.97133
15	24	5329	5941.6	0.97006	0.97355
16	6	5329	6625.7	0.97006	0.97855
16	12	5227	6350.0	0.96909	0.97740
16	18	6350	5829.3	0.97740	0.97292
16	24	6146	5625.1	0.97478	0.97181
17	6	5839	6191.1	0.97302	0.97570
17	12	5431	6419.8	0.97087	0.97779
17	18	5839	5665.9	0.97302	0.97191
17	24	5431	5329.0	0.97087	0.97006
18	6	5227	5124.8	0.96909	0.96687
18	12	5023	4971.6	0.96589	0.96381
22	18	7995	5461.7	0.98404	0.97098
22	24	10298	8717.0	0.99413	0.98724
23	6	11598	10129.6	0.99660	0.99368
23	12	16298	10227.6	0.99960	0.99394
23	18	10298	10339.6	0.99413	0.99424
23	24	10298	10143.6	0.99413	0.99372
24	6	10298	9779.6	0.99413	0.99283
24	12	10198	9177.6	0.99386	0.99180
24	18	9038	8304.2	0.99050	0.98606
24	24	8511	7543.1	0.98645	0.98298
25	6	8124	6942.2	0.98463	0.98011
25	12	7737	6523.6	0.98320	0.97821
25	18	5839	6176.4	0.97302	0.97539
25	24	5329	5859.9	0.97006	0.97324
26	6	4832	5584.2	0.96154	0.97172
26	12	4478	5359.6	0.95846	0.97059
26	18	5125	5206.5	0.96687	0.96866
26	24	4744	5043.1	0.96049	0.96625
27	6	4390	4885.2	0.95725	0.96261
27	12	4036	4717.2	0.94951	0.96021

Table C4. August, 1998 data for Hamburg, IA

Appendix D

Case Study data

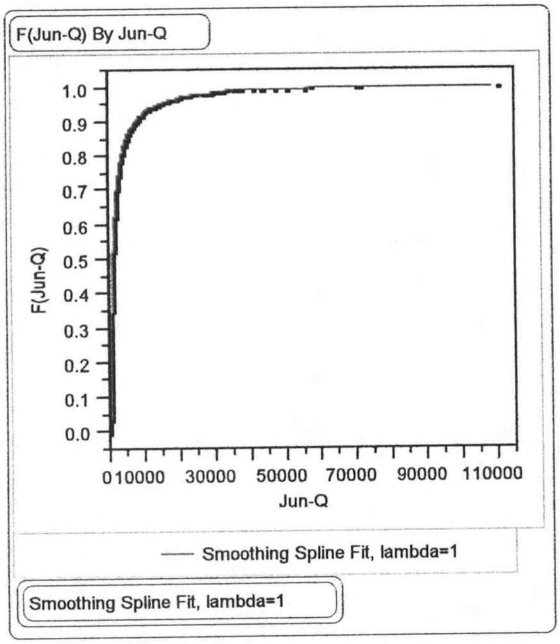

Figure D1. Eureka, MO June Flow CDF

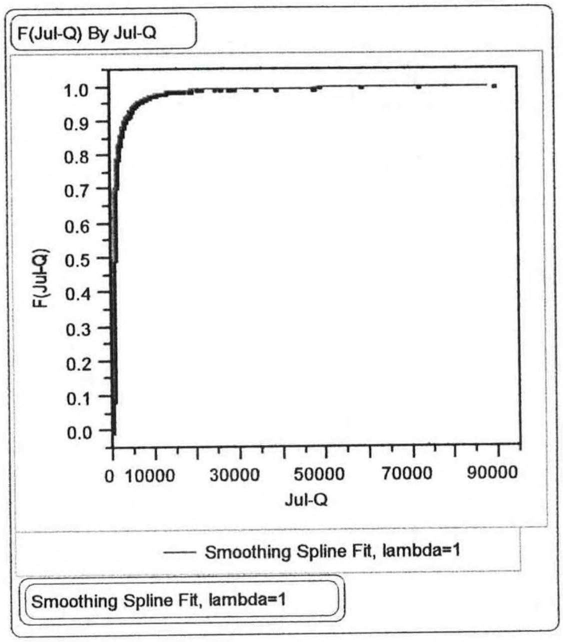

Figure D2. Eureka, MO July Flow CDF

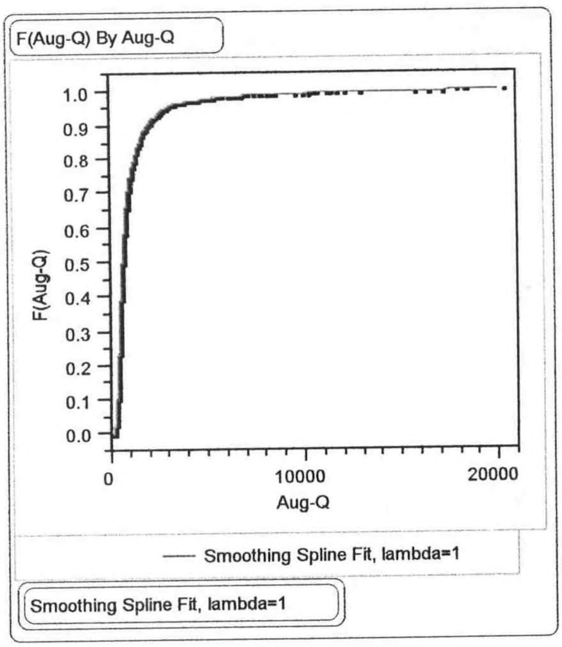

Figure D3. Eureka, MO Aug Flow CDF

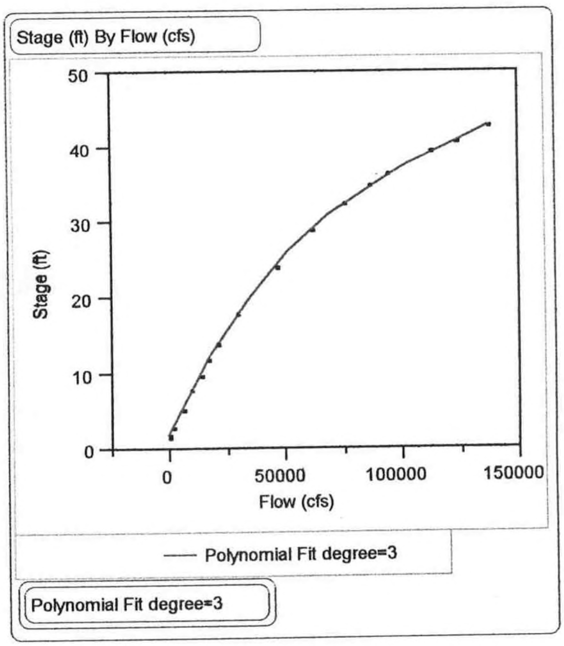

Figure D4. Eureka, MO rating curve

Forecast and Observed Flow data for Eureka, MO

	1200 UTC data			
Date	Fi	Oi	F(Fi)	F(Oi)
06/02/98	1904	1711.3	0.57405	0.53559
06/03/98	1621	1414.6	0.51019	0.44948
06/04/98	1363	1453.3	0.43276	0.46111
06/05/98	3444	11585.25	0.75307	0.93512
06/06/98	16445	24318	0.95812	0.98089
06/07/98	22890	21609	0.97796	0.97640
06/08/98	20800	20440	0.97459	0.97140
06/09/98	23100	13263.9	0.97870	0.94538
06/10/98	3598	5665.44	0.76514	0.85069
06/11/98	4830	5878.12	0.82533	0.85805
06/12/98	9690	8250.32	0.91813	0.90040
06/13/98	8708.4	8135.8	0.90671	0.89979
06/14/98	8381.2	8495.72	0.90226	0.90335
06/15/98	8872	8086.72	0.90838	0.89915
06/16/98	7236	6156.24	0.88735	0.86683
06/17/98	5138	4106.2	0.83688	0.79182
06/18/98	3598	3613.4	0.76514	0.76640
06/19/98	3444	3105.2	0.75307	0.72897
06/20/98	3136	3336.2	0.73114	0.74584
06/21/98	4214	5538.4	0.79534	0.84800
06/22/98	8054	6777.92	0.89892	0.87962
06/23/98	8381.2	12054.55	0.90226	0.93911
06/24/98	12939	7546.84	0.94454	0.89219
06/25/98	4830	4660.6	0.82533	0.81740
06/26/98	4368	3536.4	0.80398	0.76058
06/27/98	3290	2489.2	0.74273	0.66432
06/28/98	2058	2027.2	0.59907	0.59340
06/29/98	2058	1672.6	0.59907	0.52200
06/30/98	3598	2489.2	0.76514	0.66432

Table D1. June 1998 data for Eureka, MO

	1200 UTC data			
Date	F_i	O_i	$F(F_i)$	$F(O_i)$
07/01/98	3290	1234	0.88987	0.65978
07/02/98	1234	718	0.65978	0.33545
07/03/98	589	427.75	0.20363	0.06336
07/04/98	3598	237.75	0.89959	0.00028
07/05/98	3598	212.375	0.89959	0.00025
07/06/98	172.5	241.375	0.00020	0.00050
07/07/98	1105	3274.6	0.60144	0.88787
07/08/98	3290	3105.2	0.88987	0.88251
07/09/98	2212	2689.4	0.82461	0.85755
07/10/98	2366	2412.2	0.83718	0.83948
07/11/98	2366	2042.6	0.83718	0.81204
07/12/98	4060	3136	0.91061	0.88323
07/13/98	3444	3151.4	0.89652	0.88392
07/14/98	2366	2905	0.83718	0.87222
07/15/98	2828	2781.8	0.86808	0.86386
07/16/98	2674	2381.4	0.85639	0.83761
07/17/98	2058	1796.2	0.81339	0.78731
07/18/98	1621	1873.2	0.75884	0.79388
07/19/98	1904	1711.3	0.79703	0.77389
07/20/98	1621	1646.8	0.75884	0.76414
07/21/98	1621	1750	0.75884	0.78025
07/22/98	1621	1646.8	0.75884	0.76414
07/23/98	1621	1621	0.75884	0.75884
07/24/98	1621	1582.3	0.75884	0.75304
07/25/98	1621	1530.7	0.75884	0.74458
07/26/98	1492	1517.8	0.73654	0.74153
07/27/98	1492	1873.2	0.73654	0.79388
07/28/98	6418	9346.44	0.95361	0.97267
07/29/98	27300	19440	0.99535	0.99231
07/30/98	39667	16315.5	0.99742	0.98991
07/31/98	45533	57950	0.99773	0.99874

Table D2. July 1998 data for Eureka, MO

1200 UTC data				
Date	F_i	O_i	$F(F_i)$	$F(O_i)$
08/01/98	44067	38933.33	0.99997	0.99991
08/02/98	21420	9101.04	0.99973	0.99107
08/03/98	3598	6483.44	0.96572	0.98431
08/04/98	5600	4522	0.98100	0.97376
08/05/98	3752	4460.4	0.96692	0.97320
08/06/98	4060	4075.4	0.96966	0.96973
08/07/98	4214	3875.2	0.97108	0.96860
08/08/98	3752	3397.8	0.96692	0.96227
08/09/98	3136	3459.4	0.95713	0.96340
08/10/98	3290	4229.4	0.95999	0.97115
08/11/98	4060	3074.4	0.96966	0.95641
08/12/98	2828	4814.6	0.94732	0.97500
08/13/98	4522	5122.6	0.97376	0.97754
08/14/98	4830	4167.8	0.97518	0.97087
08/15/98	3906	3228.4	0.96870	0.95821
08/16/98	2828	2535.4	0.94732	0.93172
08/17/98	2212	1621	0.91445	0.84934
08/18/98	1492	1363	0.83265	0.80133
08/19/98	1363	1092.1	0.80133	0.73533
08/20/98	1363	782.5	0.80133	0.55335
08/21/98	847	460	0.61172	0.16483
08/22/98	460	288	0.16483	0.02050
08/23/98	208.75	187	0.00175	0.00071
08/24/98	172.5	132.625	0.00066	0.00051
08/25/98	136.25	1440.4	0.00052	0.82122
08/26/98	100	1401.7	0.00038	0.81063
08/27/98	1363	1337.2	0.80133	0.79484
08/28/98	1363	1285.6	0.80133	0.78334
08/29/98	1234	1311.4	0.77534	0.79069
08/30/98	1363	1298.5	0.80133	0.78455
08/31/98	1234	1272.7	0.77534	0.78111

Table D3. August 1998 data for Eureka, MO

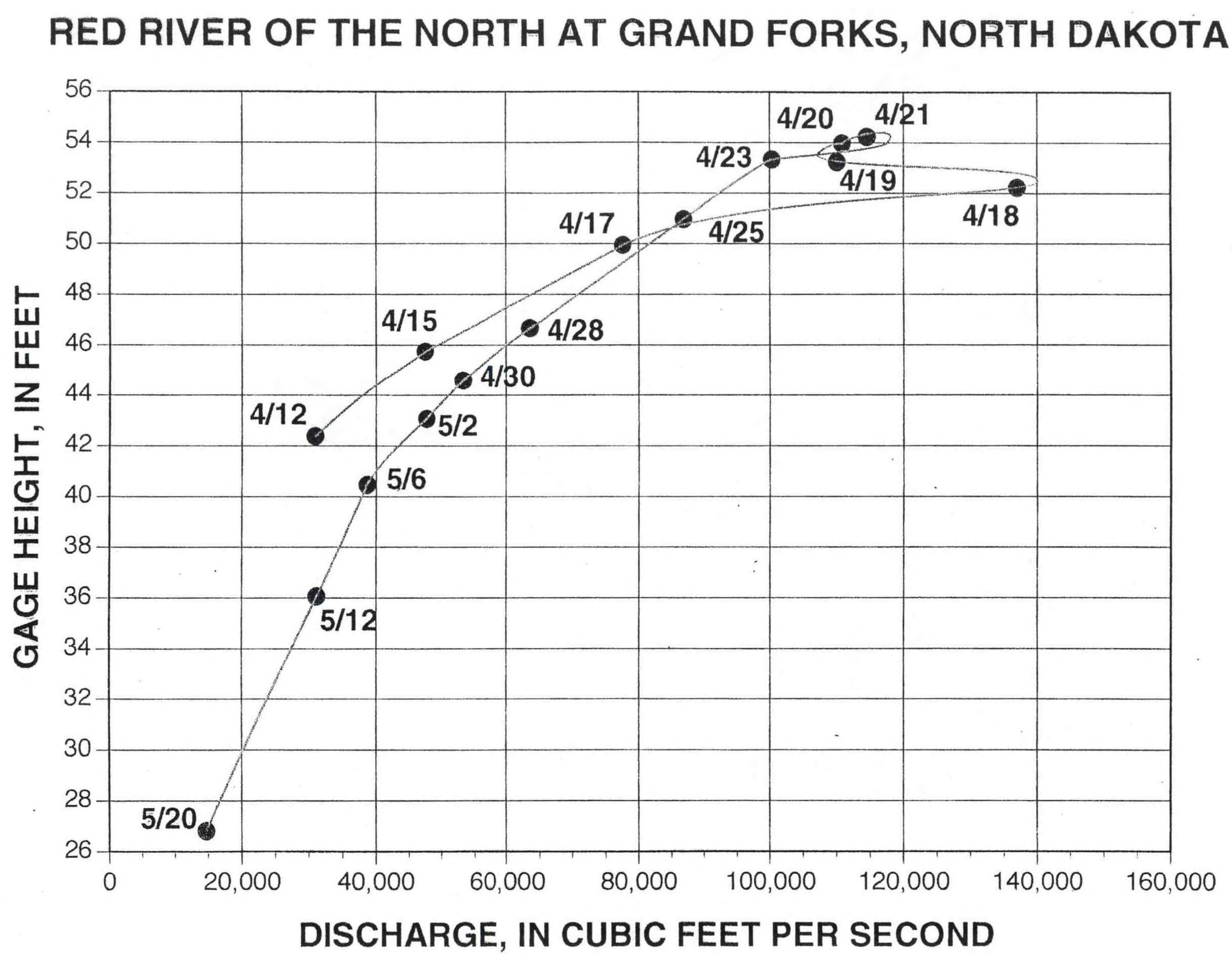

Figure D5. Observed discharge and stage rating curve for Grand Forks, ND.

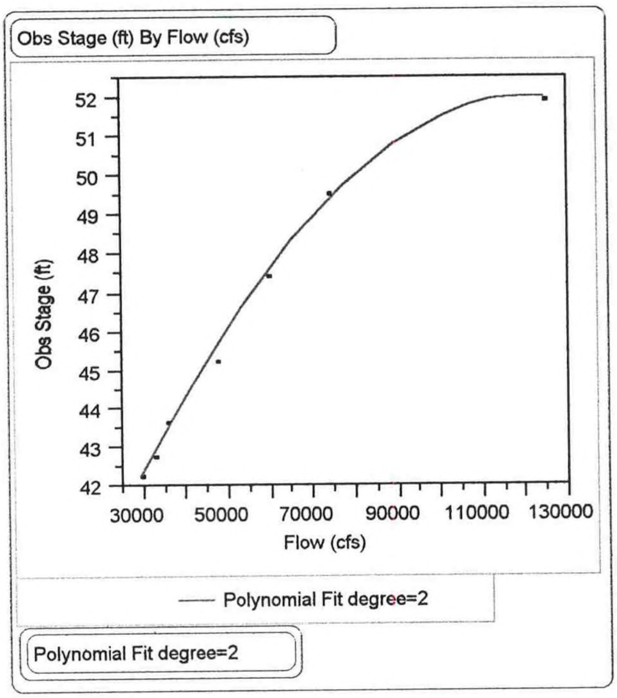

Figure D6. Grand Forks Rating curve from observed data, 4/12-4/18, 1997

NWS CR 74 On the Observation and Modeling of the Slope Winds of the Upper Current River Valley of Southeast Missouri and Their Relationship to Air-Mass Thunderstorm Formation. Bartlett C. Hagemeyer, June 1985 (PB85-226926/AS).

NWS CR 75 Complete Guide to Canadian Products in AFOS. Craig Sanders, July 1985 (PB85-228153/AS).

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NWS CR 77 Observation of Bow Echoes with the Marseilles Radar System. John E. Wright, Jr., September 1985 (PB86-102340).

NWS CR 78 Statistical Analysis of SHEF Coding Errors. Robert S. Cox, Jr., January 1986 (PB86-145141).

NWS CR 79 On the Midwestern Diurnal Convergence Zone on the West Side of the Warm Season Bermuda High. Bartlett C. Hagemeyer, March 1986 (PB86-171378).

NWS CR 80 Some Characteristics of Northeast Kansas Severe Weather 1963-1984. Larry W. Schultz, March 1986 (PB86-173952/AS).

NWS CR 81 The Severe Thunderstorm Outbreak of July 6, 1983 in Southeast Idaho, Western Wyoming and Southwest Montana. Gary L. Cox, April 1986 (PB86-184322/AS).

NWS CR 82 Some Proposals for Modifying the Probability of Precipitation Program of the National Weather Service. Wayne E. Sangster and Michael D. Manker, July 1986 (PB86-226636/AS).

NWS CR 83 Deformation Zones and Heavy Precipitation. Henry Steigerwaldt, August 1986 (PB86-229085/AS).

NWS CR 84 An Overview of the June 7, 1984 Iowa Tornado Outbreak. Charles H. Myers, August 1987.

NWS CR 85 Operational Detection of Hail by Radar Using Heights of VIP-5 Reflectivity Echoes. Richard B. Wagenmaker, September 1987.

NWS CR 86 Fire Weather Verification: The Forecaster Does Make a Difference. Therese Z. Pierce and Scott A. Mentzer, December 1987 (PB88-140744).

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NWS CR 91 Heavy Snowfall in Northwest Wyoming. Michael S. Weiland, September 1988 (PB89-109524).

NWS CR 91 Heavy Snowfall in Northwest Wyoming. Michael S. Weiland, September 1988 (PB89-109524).

NWS CR 92 On the Utility of a Geographic Information System in Modelling Climatic Suitability. Bartlett C. Hagemeyer, September 1988 (PB89-109516).

NWS CR 93 The Synoptic and Meso-Alpha Scale Meteorology of Wyoming Flash Floods. Joseph A. Rogash, October 1988 (PB89-117709).

NWS CR 94 The Removal of Stagnant Winter Air Masses From Wyoming's Wind River Basin. Gary L. Cox and Jeffrey M. Graham, November 1988 (PB89-128664).

NWS CR 95 Floods Along Des Plaines and Fox Rivers: September-October 1986. Thomas L. Dietrich, February 1989 (PB89-152797/AS).

NWS CR 96 A Case Study Evaluation of Satellite-Derived Rainfall Estimates and Their Application to Numerical Model Precipitation Forecast Verification. Glenn A. Field, May 1989 (PB89-194591).

NWS CR 97 Central Region Applied Research Papers 97-1 through 97-6. NWS Central Region, Scientific Services Division, July 1989 (PB89-213375/AS).

NWS CR 98 The Record Rainfall of August 13-14, 1987 at Chicago, Illinois. Paul Merzlock, November 1989.

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NWS CR 101 Numerical Solutions to the Shallow Water Equations as Applied to a Local Meteorological Forecast Problem. Eric R. Thaler, March 1990 (PB90-191230).

NWS CR 102 Postprint Volume National Weather Service Aviation Workshop Kansas City, Missouri, December 10-13, 1991. NWS Central Region, Scientific Services Division, March 1992 (PB92-176148).

NWS CR 103 An Investigation of Two Microburst Producing Storms Using A Microburst Recognition Algorithm. David Eversole, January 1994 (PB94-156577).

NWS CR 104 Lincoln ASOS Temperature Test January 13-15, 1993, Gregory Grosshans and Phil Clark, March 1994 (PB94-159993).

NWS CR 105 Forecasting Snowfall Using Mixing Ratios on an Isentropic Surface "An Empirical Study", Crispin Garcia, Jr, May 1994 (PB94-188760).

NWS CR 106 The Use of Profiler Data for Analysis and Nowcasting of a Winter Season Extratropical Cyclone, Bradley S. Small, June 1994 (PB94-187804).

NWS CR 107 Flood Forecasting for the Lower Missouri River Basin: June - September, 1993, John F. Pescatore, September 1994 (PB95-123568).

NWS CR 108 Heterogeneous Nucleation and its Relationship to Precipitation Type, Gregory Smith, April 1995 (PB95-217170).

NWS CR 109 Synoptic, Mesoscale and Radar Aspects of the Northeast Kansas Supercell of September 21, 1993, Kenneth Labas and Brian Walawender, October 1995 (PB96-125075).

NWS CR-110 The Effect of Quantitative Precipitation Forecasts on River Forecasts, Noreen O. Schwein, January 1996 (PB96-154893)

NWS CR-111 Global Model Errors Associated with Rapid Low to High Zonal Wave Number Transitions, Edward K. Berry, March 1996 (PB96-166509).

NWS CR-112 Postprint: Fourth NWS Winter Weather Workshop, September 19-22, 1995, NWS CR, Scientific Services Division, Kansas City, MO, July 1996 (PB96-210190).

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