RISK-BASED ANALYSIS
FOR EVALUATION OF ALTERNATIVES
GRAND FORKS, NORTH DAKOTA
AND
CROOKSTON, MINNESOTA

by

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Purpose and Overview

Risk-based studies for a proposed levee project for the Red River of the North at Grand Forks, North Dakota and for a proposed channel cutoff and levee project for the Red Lake River at Crookston, Minnesota used a Latin Hypercube analysis to sample the interaction among uncertain relationships associated with flood discharge and stage estimation. The write-up that follows discusses the sensitivity in the quantification of uncertainties, and the representation of risk for selected project levee heights. This work was done prior to: the development of the Flood Damage Analysis (HEC-FDA) computer program, the record flooding in 1997, and the 10 April 1997 Guidance on Levee Cetification for the National Flood Insurance Program memo from CECW-P/CECW-E.

Data and Uncertainty

Study Data. For the determination of simulation exceedence frequency, the project sizing option in the HEC spreadsheet was used since the reliability analysis does not provide simulation exceedence. This approach allows the determination of accurate simulation exceedence data not obtainable from the project reliability option in the risk spreadsheet developed by HEC. The uncertainty in the discharge-frequency, stage-discharge and stage-damage relationships and the impact on the project benefits is analyzed in the risk-based approach using the Latin Hypercube process. Latin Hypercube is a relatively new stratified sampling technique used in simulation modeling. Stratified sampling techniques, as opposed to Monte Carlo type techniques, tend to force convergence of a sampled distribution in fewer samples.

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Grand Forks

Discharge-Frequency Relationship. A USGS streamgage is currently located about 200 feet upstream from the DeMers Avenue bridge and 0.4 mile downstream from the Red Lake River in Grand Forks, North Dakota. Streamflow data with an equivalent record length of 112 years were used to derive the discharge-frequency curve at the gage. A Log-Pearson Type III distribution with a logarithmic mean of 4.1584, a logarithmic standard deviation of 0.3814, and a skew coefficient of -.20 was fit to annual peak streamflow data. This distribution is utilized directly in the Latin Hypercube analysis. The adopted computed and expected probability discharge-frequency curves are summarized in Table 1. The expected probability adjustment is not used for the Latin Hypercube simulations because the concept is explicitly incorporated when accounting for error in the discharge estimates. However, expected probability was utilized in the traditional analysis shown for comparison and the expected probability discharges were used to compute the water surface profiles on which the stage-discharge curve is based.

Uncertainty in discharge is associated with sampling errors in the mean and standard deviation for a stated exceedence. This method is often used to develop confidence limits for the discharge-frequency curve using the noncentral t-distribution, as defined by approximation equations (U.S. Department of Interior, 1982). With given values for parameters of the frequency curve (i.e.mean, standard deviation and skew), the sample size (i.e. years of record), and the exceedence frequency associated with a particular discharge, a distribution of errors about the given discharge is developed.

Table 1 - Grand Forks Feasibility Study Adopted Discharges - Annual Series June 1994		
Exceedence Frequency (percent)	Red River below Red Lake River Annual Peak Discharge (in cfs)	
	Computed Curve	Expected Probability
0.2	146,000	154,000
0.5	117,000	122,000
1.0	97,600	101,000
2.0	79,500	81,500
5.0	58,000	59,000
10.0	43,500	43,900
20.0	30,400	30,600
50.0	14,800	14,800
80.0	6.950	6,900
90.0	4,590	4,540
95.0	3,240	3,170
99.0	1,640	1,570

Stage-Discharge Relationship. The traditional Red River analysis defined the stage-discharge relationships utilizing the HEC-2 computer program. Resulting computed water surface elevations are shown in Table 2 for cross sections located at the previous and current U.S.G.S. gage locations. As noted earlier, these water surface elevations are based on the expected probability discharges. The water surface profile analysis was performed using cross-sectional data obtained from field surveys. Overbank data was also taken from field surveys as well as U.S.G.S. sheets. The model was calibrated to the U.S.G.S. streamgage data and to high water marks for the 1969, 1975, 1978, 1979 and 1989 flood events throughout the study area. Note that these elevations are based on a condition where the Grand Forks project is assumed to be in-place and encroachments on the East Grand Forks side are based on the adopted Flood Insurance Study floodway encroachments.

Table 2- Red River of the North at Grand Forks, North Dakota Computed Water Surface Elevations for Existing Conditions

Cross Section Number	River Mile	Minimum Channel Bottom in Feet	Grand Forks Project Assumed to be In-Place and East Grand Forks Encroachments based on Adopted Flood Insurance Study Floodway Encroachments							
			38-Percent (2.6-Year) CWSEL	27-Percent (3.7-Year) CWSEL	20-Percent (5-year) CWSEL	10-Percent (10-year) CWSEL	4-Percent (25-year) CWSEL	2-Percent (50-year) CWSEL	1-Percent (100-year) CWSEL	0.2-Percent (500-year) CWSEL
7790	295.70	773.15	811.10	814.30	817.20	821.70	825.00	827.30	829.60	834.80
7800	296.00	774.2	811.32	814.51	817.39	821.87	825.19	827.52	829.83	835.01
7922	297.55	774.60	812.26	815.41	818.26	822.74	826.27	828.83	831.58	837.25
44 (1)	297.65	772.40	812.38	815.53	818.39	822.91	826.67	829.18	831.84	837.59

(1) Current Location of U.S.G.S. gage.

Ratings at streamgage locations provide an opportunity to directly analyze stage-discharge uncertainty. The measured data are used to derive the "best fit" stage-discharge rating at the streamgage location, which generally represents the most reliable information available. In this study, the adopted rating curve corresponds to the computed water surface elevations using the calibrated HEC-2 model. The adopted elevations shown in Table 4 were obtained from this adopted stage-discharge rating curve.

If a single index location is appropriate for the flood damage reduction study, and a streamgage exists at that location, measurements at the gaged location may be used directly in assessing the uncertainty of the stage-discharge relationship. For this study, the U.S.G.S. gage has been located at four different sites in the study reach represented by the four cross sections presented in Table 2. The observed gage data was transferred to the current gage site at river mile 297.65 based on the adjustments presented in Table 3 which were computed from the water surface elevations in Table 2. These adjustments were plotted versus the corresponding discharge below the Red Lake River and curves were developed to obtain adjustments for other discharges. The adjustments in column 8 of Table 4 were obtained from these curves based on the discharge for the event in column 3.

Table 3 - Adjustments to Transfer Observed Elevations from Previous U.S.G.S. Gage Sites to Current Gage Site at RM 297.65 (XS 44)

Probability	Expected Probability Discharge in cfs		XS 7790 RM 295.70	XS 7800 RM 296.00	XS 7922 RM 297.55
	Below Red Lake River	Above Red Lake River			
38-Percent	20,000	12,500	1.28	1.06	0.12
27-Percent	25,000	16,100	1.23	1.02	0.12
20-Percent	30,600	20,300	1.19	1.00	0.13
10-Percent	43,900	30,300	1.21	1.04	0.17
4-Percent	63,500	45,800	1.67	1.48	0.40
2-Percent	81,500	58,800	1.88	1.66	0.35
1-Percent	101,000	73,500	2.24	2.02	0.26

The deviations of the observed elevations from the curve were used to estimate the uncertainty of the stage-discharge rating curve shown on Plate 1. The deviations reflect the uncertainty in data values as a result of changes in flow regime, bed form, roughness/resistance to flow, and other factors inherent to flow in natural streams. Errors also result from field measurements or malfunctioning equipment. A minimum of 8 to 10 measurements is normally required for meaningful results.

The standard deviation for a data set may be computed as follows:

$$StandardDeviation(SD) = \sqrt{\frac{\Sigma (X-M)^2}{N-1}}$$

Where:

X = Observed Elevation Adjusted to Current Gage Location (if necessary)
M = Computed Elevation from Adopted Rating Curve
N = Number of measured discharge values (events)

The stage uncertainty was computed for two different discharge ranges for this analysis. Based on a plot of the observed elevations on the adopted rating curve, it was evident that there was greater uncertainty for discharges less than about the 10-percent event due to ice, downstream agricultural levees and other factors. Therefore, the standard deviation was computed for discharges greater than about 22,000 cfs, which approximately corresponds to the zero damage elevation based on the adopted rating curve, and less than 44,000 cfs, which is slightly greater than the 10-percent event computed probability discharge. The standard deviation was also computed for discharges greater than 50,000 cfs. During the 112 year period of record, there were 23 events with a discharge between 22,00 and 44,000 cfs and 9 events with a discharge greater than 50,000 cfs. The standard deviation computations are summarized in the Table 4 below. As can be seen, the standard deviation for discharges between 22,000 and 44,000 cfs is 1.66 feet and for discharges greater than 50,000 cfs it is 0.50 feet. In the risk and uncertainty simulations, the standard deviation was linearly interpolated between 1.66 and 0.50 feet for discharges between 44,000 and 50,000 cfs. A vertical lookup table was added to the Hydrologic Engineering Center spreadsheet template to accomplish this.

Table 4 - Determination of Standard Deviation for flows between 22,000 & 44,000 cfs and for flows greater than 50,000 cfs

Station RED RIVER OF THE NORTH AT GRAND FORKS, ND Id - 05082500
State ND Drainage Area 30100.0 Hydrologic Unit 9020301
County 035 Contributing 26300.0 Years 1882-1991
Latitude 47:56:34 Gage Datum 778.35 Continuous Yes /No
Longitude 097:03:10 Base Flow 4500.0 Ann/Par Cnt 110 /118

YEAR	DATE	DISCHARGE in cfs	Stage in Feet	Observed Elevation in Feet	River Mile	Gage Zero in Feet	Gage Location Adjust-ment in Feet	X Observed Elevation in Feet at RM 297.65	M Adopted Elevation- in Feet at RM297.65	(X-M) Observed minus Adopted RM297.65	$(X-M)^2$
1892	04/17/92	23,000	33.40	813.30	297.55	779.90	0.12	813.42	814.40	-0.98	0.9604
1951	04/12/51	23,600	33.52	811.94	296.00	778.42	1.03	812.97	814.75	-1.78	3.1684
1976	04/03/76	23,600	34.58	812.93	295.70	778.35	1.24	814.17	814.75	-0.58	0.3364
1952	04/21/52	23,800	33.60	812.02	296.00	778.42	1.03	813.05	814.80	-1.75	3.0625
1982	04/12/82	23,900	37.18	815.53	285.70	778.35	1.24	816.77	814.85	1.92	3.6864
1916	04/17/16	26,100	41.00	819.40	297.55	778.40	0.13	819.53	816.15	3.38	11.4244
1993	08/03/93	26,200	36.39	815.39	297.65	779.00	0.00	815.39	816.20	-0.81	0.6561
1962	06/16/62	26,600	34.45	812.80	296.00	778.35	1.01	813.81	816.40	-2.59	6 7801
1994	07/12/94	26,800	34.30	813.30	297.65	779.00	0.00	813.30	816.50	-3.20	10.2400
1906	04/18/06	27,600	36.00	814.40	297.55	778.40	0.13	814.53	816.95	-2.42	5.8564
1943	04/12/43	28,200	38.16	816.58	296.00	778.42	1.00	817.58	817.25	0.33	0.1089
1967	04/04/67	28,200	37.50	815.85	295.70	778.35	1.19	817.04	817.25	-0.21	0.0441
1920	03/29/20	30,200	41.00	819.40	297.55	778.40	0.13	819.53	818.20	1.33	1.7689
1907	04/07/07	30,400	39.95	818.35	297.55	778.40	0.13	818.48	818.40	0.08	0.0064
1972	04/18/72	30,800	38.73	817.08	295.70	778.35	1.18	818.26	818.50	-0.24	0.0576
1986	04/02/86	31,900	37.00	817.00	297.65	780.00	0.00	817.00	818.95	-1.95	3.8025
1984	04/02/84	32,300	37.06	817.06	297.65	780.00	0.00	817.06	819.15	-2.09	4.3681
1904	04/27/04	33,000	40.65	819.05	297.55	778.40	0.13	819.18	819.45	-0.27	0.0729
1947	04/22/47	34,200	40.71	819.13	296.00	778.42	1.00	820.13	819.90	0.23	0.0529
1948	04/16/48	34,200	41.68	820.10	296.00	778.42	1.00	821.10	819.90	1.20	1.4400
1974	04/19/74	34,300	40.25	818.60	295.70	778.35	1.18	819.78	819.95	-0.17	0.0289
1989	04/12/89	37,900	44.37	823.37	297.65	779.00	0.00	823.37	821.20	2.17	4.7089
1883	04/26/83	38,600	42.20	822.10	297.55	779.90	0.14	822.24	821.45	0.79	0.6241
1975	04/23/75	42,200	43.30	821.65	295.70	778.35	1.20	822.85	822.45	0.40	0.1600
										$\Sigma(X-M)^2$	= 63.34
									Variance	$= SD^2$	= 2.75
								Standard	Deviation	= SD	= 1.66
1965	04/17/65	52,000	44.92	823.27	296.00	778.35	1.24	824.51	824.65	-0.14	0.0196
1893	04/24/93	53,300	45.50	825.40	297.55	779.90	0.34	825.74	824.95	0.79	0.6241
1969	04/16/69	53,500	45.69	824.04	295.70	778.35	1.45	825.49	825.00	0.49	0.2401
1950	05/12/50	54,000	45.61	824.03	296.00	778.42	1.28	825.31	825.05	0.26	0.0676
1978	04/11/78	54,200	45.73	824.08	295.70	778.35	1.47	825.55	825.10	0.45	0.2025
1966	04/04/66	55,000	45.55	823.90	295.70	778.35	1.50	825.40	825.25	0.15	0.0225
1882	04/18/82	75,000	48.00	827.90	297.55	779.90	0.40	828.30	828.35	-0.05	0.0025
1979	04/26/79	78,400	48.81	827.16	295.70	778.35	1.85	829.01	828.80	0.21	0.0441
1897	04/10/97	85,000	50.20	830.10	297.55	779.90	0.36	830.46	829.60	0.86	0.7396
										$\Sigma(X-M)^2$	= 1.96
									Variance	$= SD^2$	= 0.25
								Standard	Deviation	= SD	= 0.50

Project Sizing Simulation Results. The simulation (true) exceedence frequencies for alternative top of levee heights are summarized in Table 5. These frequencies were plotted versus the levee top heights and the curve, shown on Plate 2, was developed to estimate the levee top height that would have a simulation exceedence frequency of 1 percent in any given year. A levee top height with a simulation exceedence frequency of 1 percent is the tentatively proposed FEMA requirement for a project developed using risk and uncertainty. As can be seen in Plate 2, a levee top height of 831.5 has an exceedence frequency of 1 percent.

Table 5 - Levee Top Height Exceedence Frequencies

Alternative Levee Top Height	Simulation (True) Exceedence Frequency in Percent
829.0	2.10
830.0	1.64
831.0	1.18
832.0	0.90
833.0	0.82
834.0	0.66
835.0	0.34
831.5	1.00

Project Reliability Simulation Results. The project reliability results for the 1 percent (100-year) event are summarized to a limited degree in the last row of Table 6 and are extensively summarized in Tables 7 and 8. The far right column of Tables 7 and 8 contains the reliability results based on the adopted values for the Grand Forks project. The remaining columns present results for a sensitivity analysis that is described later.

<u>Levee Requirements.</u> A summary of simulation (true) exceedence and reliability for levees with top heights based on old and new criteria requirements is shown in Table 6.

Table 6 - SUMMARY OF NEW CRITERIA FOR LEVEES - GRAND FORKS

	ITEM	ELEVATION /PROBABILITY
CONDITION	1. 100-yr flood, w/ GF project, w/ EGF floodway, w/ expected probability	831.8 FEET
	2. 100-yr flood, w/ GF project, w/ EGF floodway, w/o expected probability	831.4 FEET
	3. 1.0% chance of being exceeded in any given year - Previously proposed FEMA requirement	831.5 FEET
LEVEE HEIGHT	4. Freeboard criteria, w/ GF project, w/ EGF floodway, w/ expected probability + 3.0 ft	834.8 FEET
	5. Freeboard criteria, w/ GF project, w/ EGF floodway, w/o expected probability + 3.0 ft	834.4 FEET
	6. Optimized using risk and uncertainty	NA
	7. Previously proposed FEMA Criteria	831.5 FEET
RISKS-DURING ANY GIVEN YEAR	8. True probability of overtopping old Corps criteria design during any given year using levee height shown on line 4.	0.0042
	9. True probability of overtopping during any given year using the levee height shown on line 5.	0.0056
	10. True probability of overtopping optimized design during any given year using levee height shown on line 6.	NA
RELIABILITY DURING .01 EVENT (100YR-FLOOD)	11. Percent chance of exceedence for 0.01 event for old Corps criteria design using levee height shown on line 4.	7.0 PERCENT
	12. Percent chance of exceedence for 0.01 event for levee height shown on line 5.	9.2 PERCENT
	13. Percent chance of exceedence for 0.01 event for optimized design using levee height shown on line 6.	NA
	14. Percent chance of exceedence for 0.01 event for levee at previously proposed FEMA Criteria.	47.2 PERCENT

References:
1. Proceedings of a Hydrology and Hydraulics Workshop on Riverine Levee.Freeboard, 27-29 August 1991, Monticello, Minnesota.
2. Draft EC, 1 August 1992. Risk Analysis Framework for Evaluation of Hydrology/Hydraulics and Economics in Flood Damage Reduction Studies.
3. Draft EC, November 1993. Risk-Based Analysis for Sizing and Performance Evaluation of Flood Damage Reduction Projects.

Sensitivity. Tables 7 and 8 below summarize the results of the reliability analysis for the 1-percent event. These tables also contain columns which illustrate the sensitivity of the results to the number of iterations, the rating curve standard deviation of error and the number of years of record used in the analysis. Columns 6 and 7 of the tables contain reliability information for the adopted values for the Grand Forks project for 8000 and 5000 iterations respectively. This information illustrates that 5000 iterations are adequate because the elevations and frequencies change only an insignificant amount with 8000 iterations. Columns 2, 3, and 7 illustrate the sensitivity of the results to the number of years of record. Columns 2 uses a period of record (N value) of 100,000 years which simulates a discharge frequency curve with an extremely long period of record and; therefore, confidence limits that approach the computed discharge frequency. This essentially eliminates the uncertainty in the risk analysis due to discharge and allows the determination of the top elevation of levee resulting from the uncertainty in stage. Column 3 uses a period of record of 10,000 years. Column 7 uses the actual period of record of 112 years for the U.S.G.S. gage which is considered a long period of record. As can be seen, the elevations and probabilities change a significant amount when the period of record is reduced to the actual period of record. For instance, the 95 percent reliability elevation in Table 7 changes from 832.3 to 835.2, an increase of 2.9 feet. Conversely, the reliability for an elevation of 831.5 in Table 8 decreases from 57 or 58 percent to 52 percent. Columns 4, 5 and 7 illustrate the sensitivity of the results to the uncertainty in the stage-discharge rating curve as measured by the standard deviation of the curve. The 95 percent reliability elevation in Table 7 with the adopted standard deviation of 0.50 feet is 835.18. This decreases only 0.16 feet to 835.02 with a standard deviation of 0.01 feet and increases only 0.41 feet with a standard deviation of 1.00 feet. Conversely, the reliability for an elevation of 831.5 in Table 8 increases only 0.1 percent for a standard deviation of 0.01 feet and decreases only 1.2 percent for a standard deviation of 1.00 feet. In summary, the reliability results in Tables 7 and 8 show that reliability is much more dependent on the period of record than on the uncertainty in the stage-discharge rating curve.

Table 7 - Sensitivity of Hydrologic and Hydraulics Project Reliability for Grand Forks, North Dakota						
Percent	P event=.01 N=100,000 SDrc=0.50 I=5000	P event=.01 N=10,000 SDrc=0.50 I=5000	P event=.01 N=112 SDrc=1.00 I=5000	P event=.01 N=112 SDrc=.01 I=5000	P event=.01 N=112 SDrc= 0.50 I=8000	Adopted Values Pevent=.01 N=112 SDrc=0.50 I=5000
80 Percent	831.82	831.87	833.46	833.32	833.31	833.31
85 Percent	831.92	831.97	833.92	833.72	833.75	833.73
90 Percent	832.04	832.11	834.53	834.13	834.25	834.28
91 Percent	832.07	832.14	834.70	834.31	834.39	834.43
92 Percent	832.11	832.18	834.87	834.48	834.55	834.62
93 Percent	832.14	832.23	835.09	834.66	834.72	834.81
94 Percent	832.19	832.26	835.33	834.84	834.94	834.97
95 Percent	832.23	832.31	835.59	835.02	835.21	835.18
96 Percent	832.29	832.37	835.87	835.49	835.56	835.54
97 Percent	832.35	832.44	836.25	835.97	835.97	835.94
98 Percent	832.44	832.53	836.70	836.44	836.55	836.52
99 Percent	832.56	832.65	837.38	836.90	837.10	837.14
100 Percent	833.27	833.65	839.94	837.61	838.58	838.42

P event = probability of flood event (decimal).
N = number of years of record. Values greater than 112-years used for sensitivity analysis only.
SDrc = standard deviation of elevation discharge rating curve data points above 50,000 cfs.
I = number of iterations for Latin Hypercube simulation.

Table 8 - Sensitivity of Hydrologic and Hydraulics Project Reliability for Grand Forks, North Dakota						
FEMA Requirement						
Elevation in Feet with one percent chance of being exceeded in any given year - Simulation Exceedence	P event=.01 N=100,000 SDrc=0.50 I=5000	P event=.01 N=10,000 SDrc=0.50 I=5000	P event=.01 N=112 SDrc=1.00 I=5000	P event=.01 N=112 SDrc=.01 I=5000	P event=.01 N = 112 SDrc=0.50 I=8000	Adopted Values Pevent=.01 N=112 SDrc=0.50 I=5000
EL 831.5	57.9 Percent	57.3 Percent	50.6 Percent	51.9 Percent	51.4 Percent	51.8Percent

P event = probability of flood event (decimal).
N = number of years of record. Values greater than 112-years used for sensitivity analysis only.
SDrc = standard deviation of elevation discharge rating curve data points above 50,000 cfs.
I = number of iterations for Latin Hypercube simulation.

Crookston

General. The risk analysis for the Red Lake River at Crookston, Minnesota, was very similar to that for Grand Forks. The main difference was the uncertainty in the stage-discharge relationship and only that will be discussed here. The Red Lake River at Crookston has a significant history of ice-jam flooding. The following discusses how this was addressed in the risk-based analysis.

As shown on Plate 3, which is the adopted stage-discharge rating curve at the gage in Crookston, the stages are only impacted by ice for lower discharges. The stage uncertainty had to be analyzed for both unobstructed open flow conditions and for ice impacted conditions. Therefore, it was decided that a normal distribution would be used for the open flow conditions stage uncertainty and a lognormal distribution would be used for the ice impacted stage uncertainty.

Existing conditions computed water surface elevations are based on the HEC-2 model calibrated to unobstructed open flow conditions. The adopted stage-discharge rating curve at the gage shown on Plate 3 is based on these computed water surface elevations. The standard deviation for open flow conditions is computed in Table 2. The adopted stages shown in this table were obtained from this adopted stage-discharge rating curve. As shown in the table, the standard deviation for open flow conditions is 0.83 feet. The 2- and 98-percent confidence limits shown on Plate 3 for discharges greater than about 23,000 cfs are based on plus or minus two standard deviations of 0.83 feet. For discharges less than 23,000 cfs, the 2-percent lower confidence limit was continued at open flow two standard deviations below the adopted rating curve. This curve encompassed all events lower than the adopted rating curve. Then another curve was drawn above the adopted rating curve that encompassed all the ice impacted stages higher than the curve. This curve was assumed to be the 98-percent confidence limit. The resulting stages at six discharges are shown in Table 9. Lognormal parameters that fit these distributions were determined and are shown in Table 10. In order to get the distributions to match it was necessary to determine a 0% stage - the stage that has a 100% chance of being exceeded, also called the shift. This stage and the other parameters were determined by trial and error until the resulting distribution had the correct chance of being exceeded at the 2% and 98% stages in Table 9. In determining the lognormal parameters the HEC-2 computed rating curve values were considered the most likely (mode) values rather than the means.

Distributions for the ice impacted portion of the rating curve tried were normal, beta, triangular and lognormal. The lognormal gave the best fit. The normal distribution didn't work since the distribution is skewed by the impact of ice. The triangular distribution didn't fit as well since it seems to underestimate the clustering of points near the rating curve and doesn't have the long tails that represent extreme possibilities. The beta distribution is not commonly used and is harder to fit to the historic data since it's more trial and error than the lognormal. The log normal distribution was fit at 1000, 3000, 5000, 10000, 15000 and 20000 cfs.

After the stage-discharge rating curve uncertainty analysis had been completed, EM 1110-2-1619 was received. On page 5-3 it recommends using a gamma distribution for rating curve uncertainty. As a check the gamma distribution of one discharge, 15,000 cfs, was determined and compared to the lognormal distribution. For the gamma distribution there are 3 unknowns: the shift, alpha (or k) and beta (or b). A lotus 1-2-3 spreadsheet was used to find the 3 unknowns. The Lotus spreadsheet did not have a @gamma function so a @chidist function was used. The conversion from a chi-square to a gamma distribution is shown on page 294 of Probability, Statistics and Decision for Civil Engineers by Benjamin and Cornell. The 3 unknowns were varied until the resulting distribution matched the 2%, 98% and mode of the data. Again the computed HEC-2 rating curve elevation was considered the most likely (mode) value rather than the mean value. For the gamma distribution the mode is equal to beta(alpha-1). Plate 4 is the spreadsheet used to find the gamma parameters. Plates 5 compares the gamma and the log normal distributions for 15,000 cfs. The graphs plot on top of each other - the log normal and gamma results are basically the same.

The lognormal distributions developed for the various discharges less than 23,000 cfs and incorporated into the Hydrologic Engineering Center @RISK spreadsheet template. The equations in the spreadsheet used the lognormal distributions for discharges less than 23,000 cfs and normal distributions with a standard deviation of 0.83 feet above this discharge. A vertical lookup table was added to the spreadsheet so that the appropriate variables were used in the lognormal distributions.

Table 9 - Crookston Stages			
Discharge	2% Stage	Rating Curve Stage	98% Stage
1,000 cfs	3.4	5.0	9.5
3,000 cfs	6.6	8.2	19.1
5,000 cfs	9.6	11.2	21.0
10,000 cfs	16.0	17.6	23.5
15,000 cfs	20.0	21.6	25.3
20,000 cfs	22.6	24.2	26.7

Table 10 - Crookston Log Normal Parameters			
Discharge	0% Stage	LN (Mean Stage)	LN Std Deviation
1,000 cfs	1.349	1.4082	0.3365
3,000 cfs	5.453	1.3753	0.6040
5,000 cfs	8.398	1.3589	0.5731
10,000 cfs	14.376	1.3479	0.4210
15,000 cfs	17.450	1.4983	0.2742
20,000 cfs	17.646	1.9017	0.1471

Table 11- Determination of Standard Deviation for Open Flow Conditions

Station RED LAKE RIVER AT CROOKSTON, MN Id - 05079000
State MN Drainage Area 5280 Hydrologic Unit 9020303
County 119 Years 1901 - PRESENT
Latitude 47:46:32 Gage Datum 832.72
Longitude 096:36:33

Year	Date	Discharge in cfs	X Observed Stage in Feet	M Adopted Stage in Feet	(X-M) Observed minus Adopted	$(X-M)^2$
1902	05/21/02	5,170	10.00	11.44	-1.44	2.0736
1904	04/24/04	13,700	20.42	20.64	-0.22	0.0484
1905	05/13/05	8,730	14.50	16.15	-1.65	2.7225
1906	04/15/06	14,600	21.00	21.28	-0.28	0.0784
1907	04/04/07	6,330	12.04	13.24	-1.20	1.4400
1908	04/10/08	10,700	17.00	18.50	-1.50	2.2500
1909	07/21/09	3,680	8.77	9.13	-0.36	0.1296
1911	06/10/11	3,620	8.45	9.04	-0.59	0.3481
1914	06/12/14	2,630	7.40	7.51	-0.11	0.0121
1915	06/29/15	7,860	14.25	15.12	-0.87	0.7569
1916	04/17/16	15,900	21.80	22.14	-0.34	0.1156
1918	04/02/18	1,950	6.50	6.45	+0.05	0.0025
1919	07/05/19	14,900	21.10	21.50	-0.40	0.1600
1922	05/13/22	6,910	13.00	13.99	-0.99	0.9801
1924	04/23/24	1,140	5.20	5.20	0.00	0.0000
1925	06/09/25	7,300	13.50	14.45	-0.95	0.9025
1926	03/24/26	6,500	12.30	13.50	-1.20	1.4400
1927	04/13/27	7,700	14.00	14.93	-0.93	0.8649
1930	05/13/30	4,770	10.30	10.82	-0.52	0.2704
1932	04/09/32	4,390	9.78	10.23	-0.45	0.2025
1934	04/08/34	1,490	6.89	5.74	+1.15	1.3225
1938	05/10/38	5,910	12.62	12.59	+0.03	0.0009
1939	04/24/39	3,050	8.92	8.16	+0.76	0.5776
1943	04/08/43	9,420	16.88	16.98	-0.10	0.0100
1944	08/11/44	5,770	12.20	12.37	-0.17	0.0289
1945	03/28/45	9,130	15.96	16.63	-0.67	0.4489
1947	06/12/47	12,400	18.08	19.71	-1.63	2.6569
1949	06/02/49	10,700	17.43	18.50	-1.07	1.1449
1950	05/07/50	27,400	25.70	26.87	-1.17	1.3689
1951	04/07/51	12,600	19.00	19.86	-0.86	0.7396
1952	04/11/52	6,320	12.65	13.22	-0.57	0.3249
1954	04/12/54	5,330	11.37	11.69	-0.32	0.1024
1955	04/08/55	12,400	18.30	19.71	-1.41	1.9881
1956	04/20/56	14,000	19.78	20.86	-1.08	1.1664
1957	06/29/57	11,800	18.10	19.28	-1.18	1.3924
1958	07/07/58	3,370	8.62	8.65	-0.03	0.0009
1959	04/05/59	5,630	11.72	12.15	-0.43	0.1849
1961	03/27/61	1,450	5.67	5.68	-0.01	0.0001
1962	06/11/62	16,700	21.90	22.53	-0.63	0.3969
1963	04/09/63	6,820	13.25	13.88	-0.63	0.3969
1966	04/03/66	21,500	24.41	24.87	-0.46	0.2116
1967	04/01/67	19,300	23.49	23.80	-0.31	0.0961
1968	07/19/68	11,100	17.17	18.78	-1.61	2.5921
1969	04/12/69	28,400	27.33	27.15	+0.18	0.0324
1971	04/10/71	15,300	20.74	21.78	-1.04	1.0816
1973	09/26/73	4,960	10.86	11.12	-0.26	0.0676
1975	04/18/75	15,600	21.97	22.00	-0.03	0.0009
1976	04/03/76	12,500	19.45	19.78	-0.33	0.1089
1977	05/20/77	3,440	8.66	8.76	-0.10	0.0100
1978	04/07/78	18,100	23.11	23.22	-0.11	0.0121
1979	04/26/79	21,900	24.99	25.06	-0.07	0.0049
1981	06/29/81	7,120	13.56	14.24	-0.68	0.4624
1984	06/10/84	14,400	20.71	21.14	-0.43	0.1849
1985	08/19/85	9,580	16.38	17.17	-0.79	0.6241
1991	06/13/91	1,300	6.99	5.45	+1.54	2.3716

Sum = 36.9123
Standard Deviation Squared (Variance) = 0.6836
Standard Deviation = 0.8268

Potential Impacts of New Guidance

General. As mentioned at the start of this paper, the work presented was done prior to the development of the Flood Damage Analysis (HEC-FDA) program, the record flood of 1997, and the 10 April 1997 Guidance on Levee Certification for the National Flood Insurance Program memo from CECW-P/CECW-E. Some of these changes could impact the results.

HEC-FDA. It is expected that this program could be used for the Grand Forks analysis with no impact on the results but could not be used for Crookston. The program allows variation in the standard deviation of the uncertainty in the stage-discharge relationship. This was needed for the Grand Forks study and required the modification of the original HEC spreadsheet. The HEC-FDA program would make this analysis more straight forward. The Crookston analysis used different uncertainty distributions for portions of the stage-discharge rating curve. The lower portion used a lognormal distribution due to ice impacts and a normal distribution for the upper portion, which is not ice impacted. The HEC @risk spreadsheet was modified to handle this but the HEC-FDA program is not designed for this and would likely be too difficult to modify by the field. Therefore, we would not use the HEC-FDA program for any future Crookston-like analysis.

Flood of 1997. The 1997 flood was a new record for both Grand Forks and Crookston. The impact of the flood on the risk analysis at Grand Forks will be determined but no results are available now. The Feasibility Study for Crookston has been approved and the impact of the 1997 flood will not be quantified. Analysis to date indicates the discharge-frequency curve at Grand Forks will be significantly impacted by the 1997 flood. While the measured peak stage and discharge at Grand Forks was fairly close to the previous stage-discharge rating curve, it appears the uncertainty we had used, a standard deviation of 0.50 ft, may be increased. The damages sustained could have an impact on the previous stage-damage curve. It appears the damages were higher than anticipated, however, many buildings were destroyed and won't be replaced and therefore won't contribute to the possible future damages. The net result of this on the stage-damage curve is not known.

New Levee Certification Guidance. The guidance presented in the 10 April 1997 memo from CECW-P/CEWC-E concerns how to certify a levee for FEMA when risk and uncertainty analysis is used. The method proposed is a significant improvement over the method previously proposed by FEMA. FEMA's past proposal was that the levee elevation had to have a true probability of overtopping of 1%. Line 3 of Table 6 showed that for Grand Forks this resulted in a top of levee of 831.5. Line 14 of that table shows this elevation has a 47.2% chance of being overtopped during a 1% flood event. This was far too high a probability to allow our district to certify the levee as providing flood protection from the regulatory flood. This had the potential of confusing the locals when two federal agencies couldn't agree on what levee height was required for certification. The 10 April 1997 policy is summarized in Plate 6. Applying this to the Table 6 data shows that either the 100-yr flood with or without expected probability levee heights, lines 1 and 2, could be certified since they each have less than a 10% chance of being exceeded during a 1% event, lines 11 and 12.