Appendix A-1c
Hydrology

Fargo-Moorhead Metropolitan Area Flood Risk Management

Supplemental Draft Feasibility Report and Environmental Impact Statement

April 2011

US Army Corps of Engineers®

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Hydrologic Engineering Center

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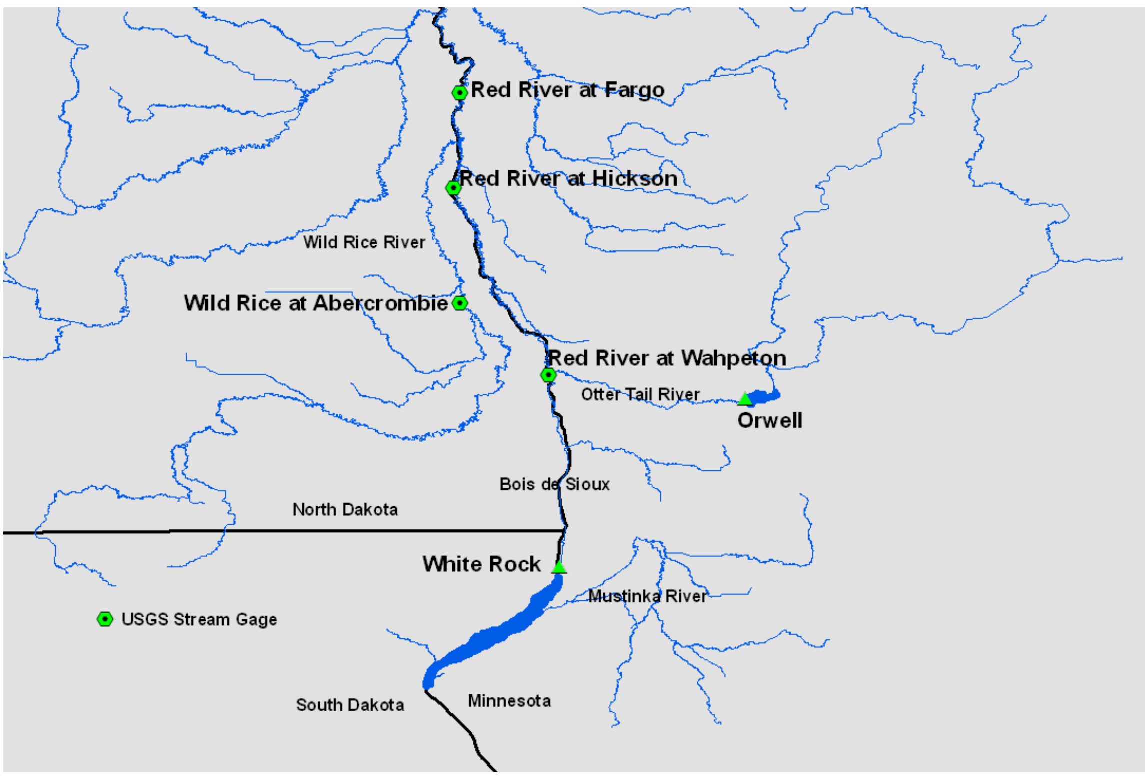
The use of Synthetic Floods for Defining the Regulated Flow Frequency Curve for the Red River at Fargo



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List of Figures

Figure 1. Red River above Fargo. 5
Figure 2. Unregulated annual peak flows at Fargo. 6
Figure 3. Results of Pettitt test to choose dry/wet break point. 7
Figure 4. Separate wet and dry period frequency curves, compared to full record. 8
Figure 5. Volume-Duration Frequency Curves for the Wet Period, Red River at Fargo. 13
Figure 6. Volume-Duration Frequency Curves for the Dry Period, Red River at Fargo. 14
Figure 7. Volume-Duration Frequency Curves for the Full Period of Record, Red River at Fargo 15
Figure 8. HEC-HMS Schematic of the Red River above Fargo. 18
Figure 9. Example of Manual Adjustments of a Local Runoff Hydrograph. 19
Figure 10. Upstream and Local Runoff Hydrographs that Produce the 1-Percent 1, 3, 7, 15, and 30-Day Flows at Fargo. 20
Figure 11. HEC-HMS Schematic of Upstream and Local Runoff Hydrographs that Produce the 1-Percent 1, 3, 7, 15, and 30-Day Flows at Fargo. 21
Figure 12. Local Runoff Hydrographs at Wahpeton for the 10, 2, 1, 0.5, and 0.2-Percent Events (Full Period Analysis). 22
Figure 13. White Rock Inflow and Outflow Hydrographs for the 0.2-Percent Event – Full Period Analysis. 24
Figure 14. Unregulated and Regulated Peak Flow Frequency Curves with Synthetic Events – Wet Period. 30
Figure 15. Unregulated and Regulated Peak Flow Frequency Curves with Synthetic Events – Dry Period. 31
Figure 16. Regulated Peak Flow Frequency Curves for Wet and Dry Periods with Combined Curve (0.8 wet and 0.2 dry weighting). 32
Figure 17. Regulated Peak Flow Frequency Curves for Wet and Dry Periods with Combined Curve (0.65 wet and 0.35 dry weighting). 33
Figure 18. Unregulated Peak Flow Frequency Curves for Wet and Dry Periods with Combined Curve (0.8 wet and 0.2 dry weighting). 35
Figure 19. Unregulated Peak Flow Frequency Curves for Wet and Dry Periods with Combined Curve (0.65 wet and 0.35 dry weighting). 36
Figure 20. Unregulated and Regulated Peak Flow Frequency Curves with Synthetic Events – Full Period. 38

List of Tables

Table 1. Straddle Stagger Parameters used for Hydrologic Routing Model...................... 9
Table 2. Annual Maximum Flows at Fargo - Natural Flows.. 10
Table 3. Volume-Duration Frequency Curves for Wet Period, Red River at Fargo. 16
Table 4. Volume-Duration Frequency Curves for Dry Period, Red River at Fargo........ 16
Table 5. Volume-Duration Frequency Curves for Full Period of Record, Red River at Fargo. 16
Table 6. Synthetic Events Volume-Duration Results from HMS-Model - Wet Period (compare to Table 3). 22
Table 7. Synthetic Events Volume-Duration Results from HMS-Model - Dry Period (compare to Table 4). 23
Table 8. Synthetic Events Volume-Duration Results from HMS-Model - Full Period (compare to Table 5). 23
Table 9. Peak Flows at Fargo from Synthetic Floods – Output from HEC-RAS Model. 25
Table 10. Unregulated and Regulated Peak Flows for the Red River at Fargo. 27
Table 11. Regulated Peak Flow Frequency Curves for Wet and Dry Periods and the Combined Frequency Curves.. 29
Table 12. Unregulated Peak Flow Frequency Curves for Wet and Dry Periods and the Combined Frequency Curves.. 34
Table 13. Unregulated and Regulated Peak Flow Frequency Curves for the Full Period of Record. 37

Introduction

The St. Paul District contacted HEC requesting help on updating the existing regulated peak flow frequency curve for the Red River at Fargo. This request was initiated as a response to an expert panel that concluded the Red River peak stream flows exhibited non-stationarity in the form of two flow regimes, a wet period and a dry period, and that this result should be incorporated in the development of the regulated peak flow frequency curve at Fargo. Separate flow frequency curves were developed for the wet period and the dry period, and then those frequency curves were combined to reflect estimates of the likelihood of experiencing either the wet or dry flow regime in future years. For comparison purposes, an additional analysis that incorporated the full period of record was included. Therefore, regulated peak flow frequency curves were developed for a wet period, dry period, combinations of wet and dry periods (possible future scenarios), and the full period of record.

To capture regulation from upstream reservoirs, the peak flow frequency curve was developed by graphically fitting a frequency curve to both the observed peak flow record and synthetic flood events, with the synthetic floods used to define the upper end of the frequency curve. The regulated peak flow frequency curve was developed for two scenarios. For scenario 1 the flow record was divided into two segments, a “dry” and a “wet” period, based on a test to determine the break point providing the strongest statistical evidence of separate homogeneous data sets. The resulting break point of 1941 defined the dry period with flows from water years 1902 through 1941 (40 years of record) and the wet period with flows from 1942 through 2009 (68 years of record). Separate peak flow frequency curves (and synthetic floods) were determined for both wet and dry periods and then combined for possible future conditions. For scenario 2, the entire flow record was analyzed to develop the peak flow frequency curve; water years 1902 through 2009 plus historical events from 1882 and 1897 (128 years of record).

A map of the study area is shown in Figure 1. The Red River begins at the confluence of the Otter Tail and Bois de Sioux rivers and flows north to Fargo. Two reservoirs regulate flows upstream of Fargo. Orwell dam went into operation in 1953 and White Rock dam went into operation in 1942. There are four USGS gages in the study area, three gages are located on the Red River and one is located on the Wild Rice River. The following steps provide a general overview of the process followed to develop the regulated peak flow frequency curve using observed data and synthetic floods to define the upper end of the curve. More detail is provided in the follow sections.

1) Determine break point between wet and dry periods
2) Develop the unregulated volume-duration frequency curves, 1, 3, 7, 15 and 30-days, for the Red River at Fargo. Volume-duration frequency curves were developed for the wet, dry, and full period of record.
3) Develop synthetic flood hydrographs that reproduce the 10, 50, 1, 0.5, and 0.2-percent flows on the unregulated volume-duration frequency curves.
4) Route the synthetic flood hydrographs through a reservoir model, HEC-5, to compute regulated flows downstream of the reservoirs at Hickson.

5) Route the synthetic flood hydrographs from Hickson to Fargo using an HEC-RAS model.
6) Use results from the synthetic flood events and observed data to develop the regulated peak flow frequency curve for the Red River at Fargo.
7) Combine wet period and dry period frequency curves with defined likelihoods

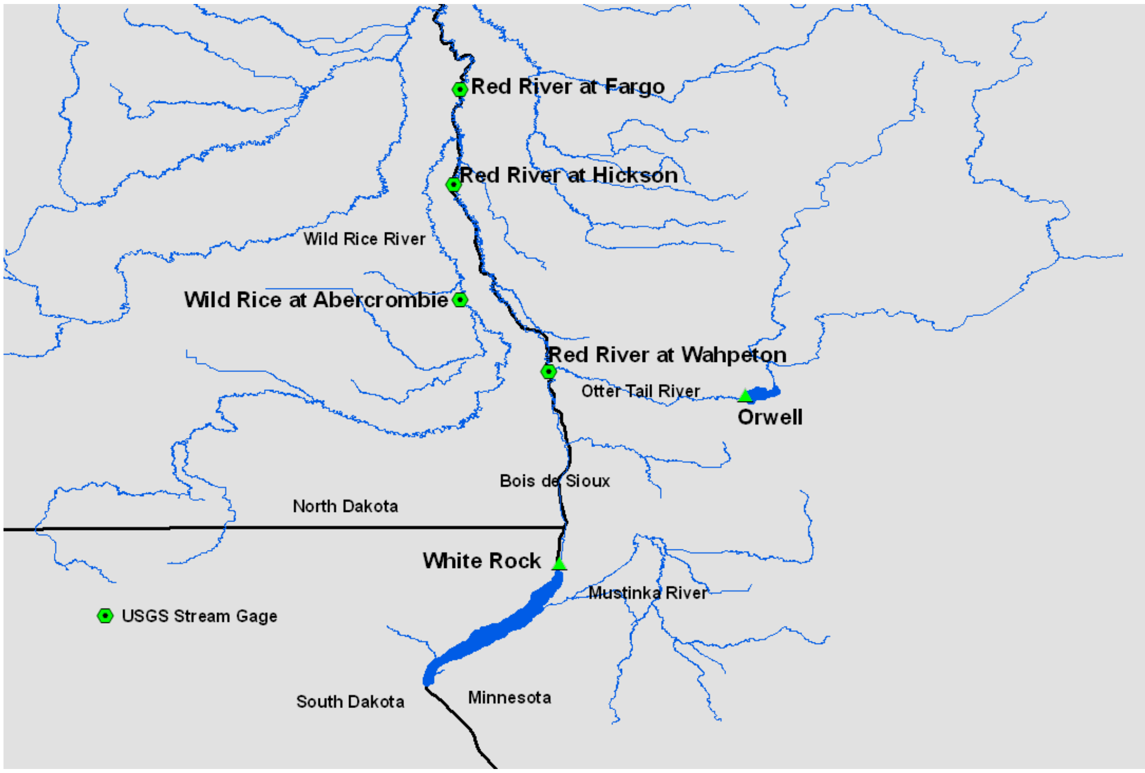


Figure 1. Red River above Fargo.

Determine break point between dry and wet periods

Figure 2 displays the record of unregulated annual peak flows on the Red River of the North at Fargo. There was a period of smaller annual peak flows in the early part of the 20th century. While the gaged record might suggest an upward trend, the large events that occurred in 1882 and 1897 (shown in the figure as estimates, but not used in the analysis) suggest instead that a cycle between wet and dry periods has been experienced in the basin. Tree-ring records of the Red River basin further support a cycle rather than a trend, showing even larger events in earlier centuries. The assumption in developing a frequency curve for a dry period and another for a wet period is that the period of each flow regime forms a homogeneous data set, and that the regime has switched at various times in the historical record. Since there is no hydrologic explanation to suggest a difference in flow regime, the EOE panel suggested seeking statistical evidence of a difference between wet and dry data sets using the Pettitt test.

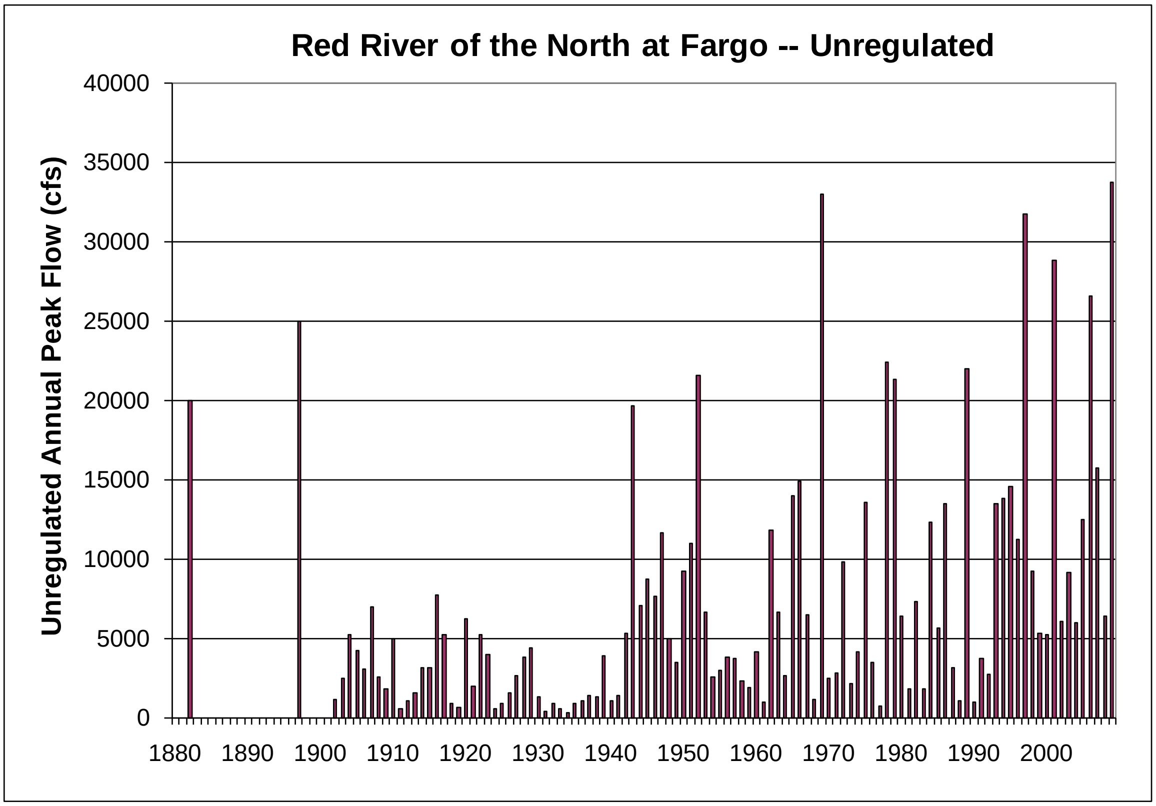


Figure 2. Unregulated annual peak flows at Fargo.

The Pettitt test is a determination of the best break point to divide a continuous data set into separate portions. The procedure involves performing a non-parametric hypothesis test on the difference between sample means for the dry period and the wet period. The test is repeated on the pair of samples created by every possible break point year between dry and wet periods. The year that provides the strongest evidence of a difference in sample means is chosen as the break point between dry and wet. Figure 3 displays the p-value or significance of the hypothesis test at each year. A p-value of 5% is often chosen as adequate evidence of an alternative hypothesis, meaning that there is a 5% chance of accepting the alternative hypothesis (sample means are not the same) when it is not true. For this data set, p-values are a lower than 5% by several orders of magnitude. This computation suggests that the year 1941 it the break point with the greatest evidence of the record containing two different flow regimes, and that year was chosen as dividing year between dry and wet periods.

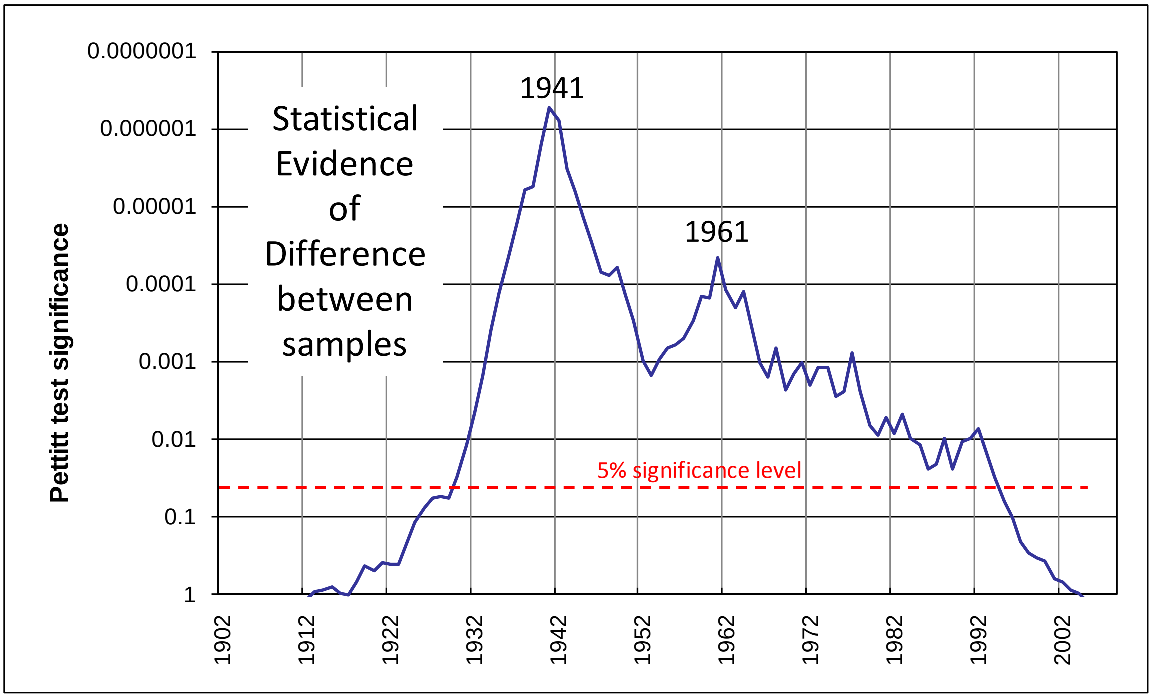


Figure 3. Results of Pettitt test to choose dry/wet break point.

Figure 4 contains a view of the unregulated annual peak flow frequency curve at Fargo based on the full period of record, and the separate frequency curves for the wet and the dry periods. Note that when the record split between wet and dry, the resulting variability within each portion is significantly less than the variability of the full record. The resulting smaller standard deviation of both the wet record and the dry record, compared to the full record, generates frequency curves with smaller slope, and therefore lower upper end. Therefore, counter-intuitively, the estimate of a less frequent event such as the 500-year flow is lower for the wet period frequency curve than the full record. However, this result is supported by the logic in dividing the record between wet and dry, and the understanding that for times within the wet period, the full variability of the record will not be experienced, but rather the limited variability of the wet assumption.

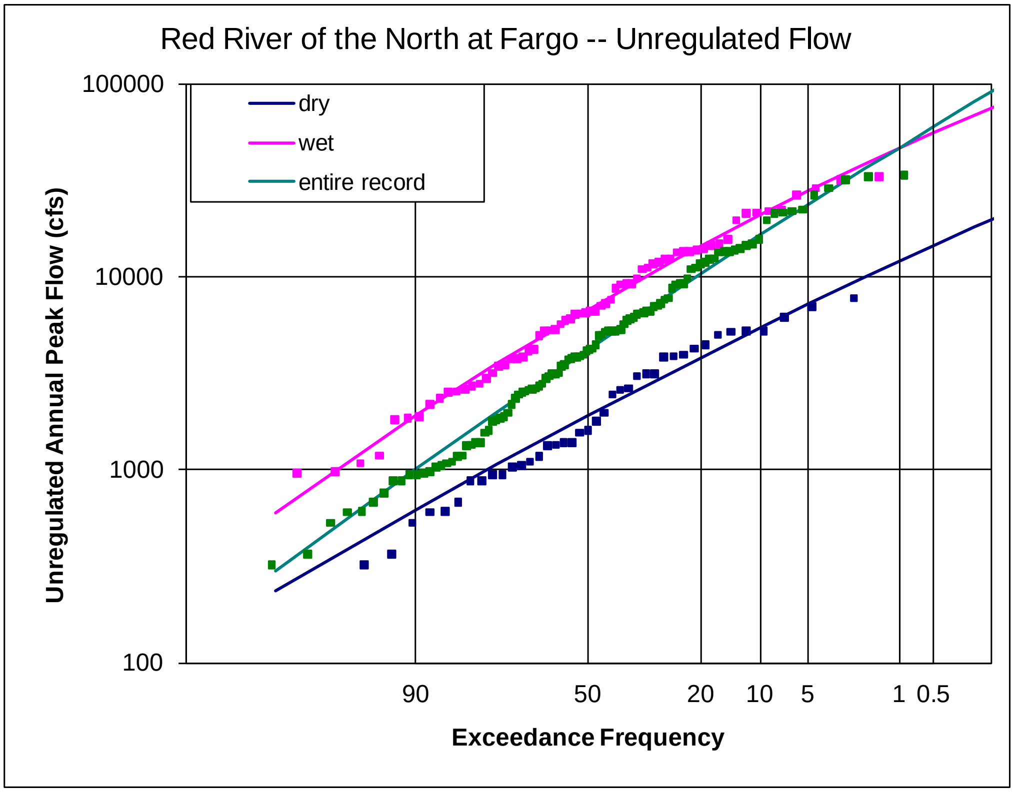


Figure 4. Separate wet and dry period frequency curves, compared to full record.

Develop Unregulated Volume-Duration Frequency Curves

Unregulated volume-duration frequency curves were needed to develop the synthetic flood. Due to reservoirs upstream of Fargo, the natural (unregulated) flows for the Red River were estimated using observed flow measurements and a hydrologic routing model. The St. Paul district provided estimates of natural flows for the entire period of record, including daily average flow time-series at multiple locations on the Red River.

The following description explains how the natural flow time-series were estimated at gaged locations along the Red River. Natural flows were first estimated at the upstream reservoirs and for incremental areas in-between gages. Reservoir inflows were computed using observed outflow and stage. Incremental local flows were estimated by routing observed flows from an upstream gage to a downstream gage and subtracting the routed flow from the measured flow at the downstream gage. For example, the incremental local runoff at the Hickson gage was computed by routing the observed flow at the Wahpeton gage downstream to the Hickson gage. Then, the routed flow was subtracted from the observed flow at the Hickson gage. This computed time-series is the estimated incremental local runoff from the drainage area between the Wahpeton and Hickson gages. Incremental local flows were computed at the Wahpeton, Hickson, and Fargo gages. The St. Paul District used an HEC-5 model and the Straddle Stagger method for routing the time-series to estimate the natural flow time-series. The routing parameters, contained in Table 1, were calibrated to historic flood events.

Once reservoir inflow and incremental local runoff hydrographs were estimated, then the natural flow time-series for the Red River could be computed from upstream to downstream. The natural flow time-series at Wahpeton was computed by routing computed inflows into Orwell and White Rock dams downstream to Wahpeton. Then the routed flow was combined with the incremental local runoff at Wahpeton. The natural flow time-series at Hickson was computed by routing the natural flow time-series from Wahpeton downstream to Hickson and adding the computed incremental local runoff. The natural flow time-series at Fargo was computed by routing the natural flow time-series from Hickson and the observed flow time-series from the Wild Rice at Abercrombie gage to Fargo and adding the incremental local runoff. This analysis resulted in natural flows, daily average flow time-series, from 1942 – 2009. Flows recorded before 1942, prior to White Rock and Orwell dams, were considered natural; therefore, the full period of natural flows at Fargo was 1902 – 2009.

Table 1. Straddle Stagger Parameters used for Hydrologic Routing Model.

Reach	Lag Time (min)	Duration (min)
Wild Rice at Abercrombie Gage to Fargo Gage	2880	7200
Orwell Dam to Wahpeton Gage	1440	4320
White Rock Dam to Wahpeton Gage	1440	4320
Wahpeton Gage to Hickson Gage	2880	7200
Hickson Gage to Fargo Gage	1440	4320

The Hydrologic Engineering Center's Statistical Software Package (HEC-SSP) was used to compute the volume-duration frequency curves at Fargo using the natural flows time-series. The Volume-Duration Frequency Analysis within HEC-SSP extracts the annual maximum flows for each duration specified; in this case the annual maximum 1, 3, 7, 15, and 30-day duration flows were extracted. Once the annual maximums flows were extracted, HEC-SSP fit a Log Person III distribution to each set of annual maximums. In some cases, the skew and standard deviation were manually modified so that frequency curves did not cross one another. For the wet and dry periods, regional skew values were not appropriate and so only station skew coefficients were used.

The peak, 1, 3, 7, 15, and 30-day annual maximum natural flows are contained in Table 2. Peak flows from 1942 – 2009 were estimated from the 1-day flow using a relationship developed by the St. Paul District, the maximum 1-day flow is multiplied by 1.012. Measured peak flows prior to 1942 were considered natural. The 1, 3, 7, 15, and 30-day flows for the two historical events, 1882 and 1897, were estimated using a regression analysis with data in Table 2. For example, the 3-day flows for the 1882 and 1897 events were estimated using a regression analysis of 1 and 3-day flows from 1902 – 2009.

Plots of the volume-duration frequency curves for the wet, dry, and full periods are shown in Figure 5 – Figure 7 (Red River at Fargo). These figures also show the LPIII statistics for each frequency curve. Table 3 - Table 5 contains the 10, 50, 1, 0.5, and 0.2 percents flows for the peak, 1, 3, 7, 15, and 30-day durations (Red River at Fargo). Values in these tables were used to develop the synthetic flood events.

Table 2. Annual Maximum Flows at Fargo - Natural Flows.

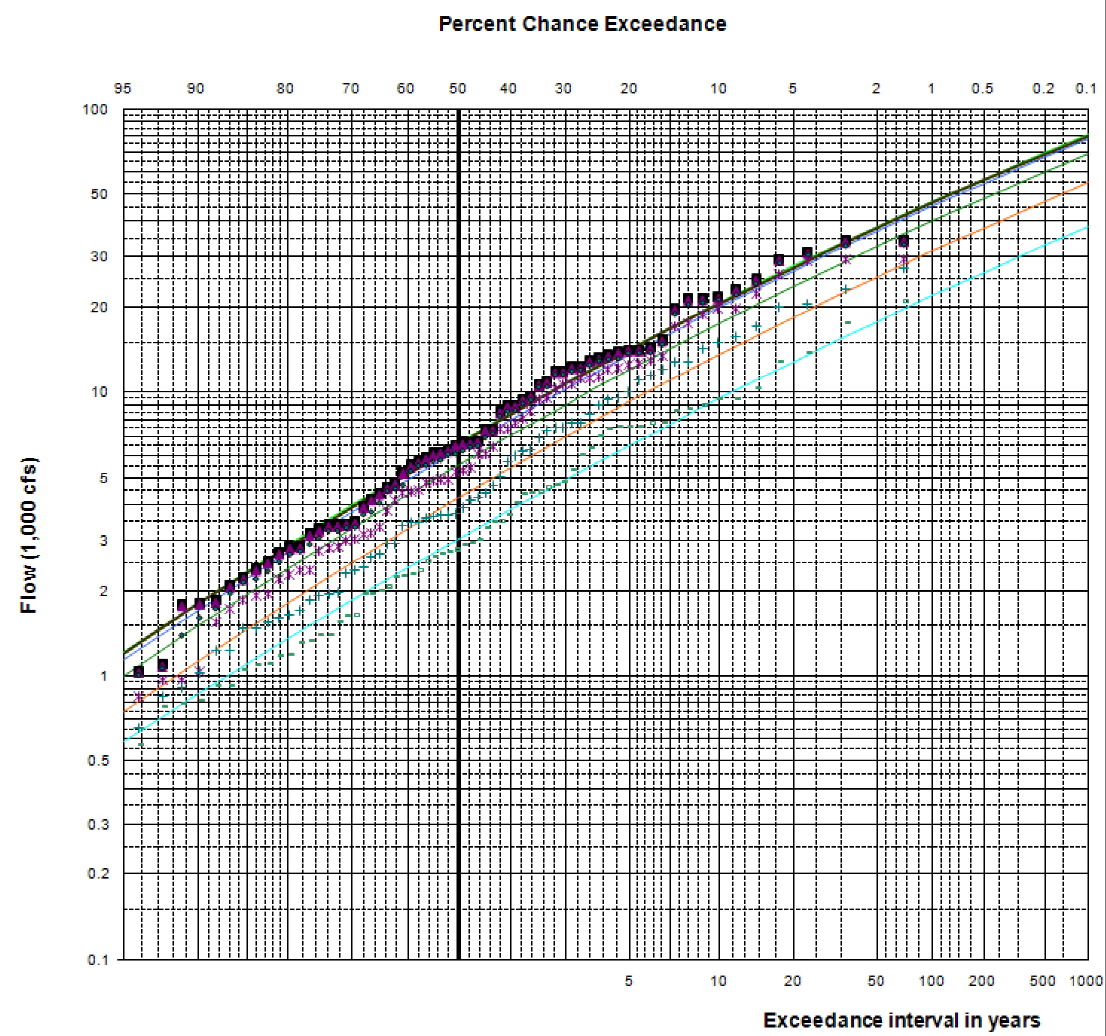
Year	Peak	1-Day	3-Day	7-Day	15-Day	30-Day
1882	20000	19760	19272	17472	13649	9541
1897	25000	24700	24090	21840	17061	11926
1902	1180	1180	1140	1094	966	947
1903	2450	2450	2410	2256	1858	1260
1904	5220	2830	2787	2590	2590	2590
1905	4250	4250	4117	3644	2611	1809
1906	3050	3050	2883	2566	2472	2053
1907	7000	4420	4353	4026	3076	2920
1908	2600	2600	2520	2421	2150	1933
1909	1780	1780	1610	1601	1451	1209
1910	5000	4700	4600	4371	3450	2448
1911	608	608	529	471	415	408
1912	1100	1100	1070	1049	922	753
1913	1560	1460	1430	1283	953	649
1914	3140	3060	2907	2499	1873	1819
1915	3130	3110	3110	2866	2437	2260
1916	7740	7720	7667	7491	6800	6075
1917	5240	5200	5133	4869	3915	3175
1918	874	750	733	692	617	524
1919	680	630	630	596	570	532
1920	6200	6120	5987	5366	3466	2153
1921	1970	1970	1603	1238	937	802
1922	5200	5200	5067	4617	3947	3806
1923	3960	3960	3853	3053	1916	1257
1924	530	530	503	457	381	330
1925	940	885	885	806	751	614
1926	1600	1600	1447	1282	917	652
1927	2650	2650	2463	2023	1325	1194
1928	3840	3840	3787	3359	2088	1227
1929	4440	4440	4387	4017	2692	1629
1930	1340	1340	1320	1244	1027	805
1931	365	365	325	268	229	194
1932	875	868	763	556	360	243
1933	605	605	588	458	347	252
1934	323	323	298	240	163	106
1935	942	930	930	871	656	448
1936	1050	1050	990	904	641	530
1937	1390	1300	1300	1117	724	578
1938	1350	1160	814	575	496	428
1939	3870	3600	3540	3203	2201	1297
1940	1030	970	970	876	697	471
1941	1390	1390	1323	1185	979	709
1942	4639	4584	4479	4174	3394	2897
1943	19709	19475	18828	17114	12719	7561
1944	5691	5624	5506	4941	3672	2708
1945	8556	8455	8229	7381	5666	3720
1946	7423	7335	6917	6031	4169	2787

Table 2. Continued.

Year	Peak	1-Day	3-Day	7-Day	15-Day	30-Day
1947	11840	11700	11510	10336	7318	4733
1948	4795	4738	4688	4421	3670	2634
1949	3412	3372	3231	2759	1932	1177
1950	8973	8867	8538	7828	6249	4634
1951	10700	10573	10407	9556	6919	4433
1952	21643	21386	21207	19770	15604	9541
1953	6529	6452	6020	4904	4247	3489
1954	2084	2059	1951	1840	1693	1390
1955	3171	3133	2905	2348	1592	1110
1956	3968	3921	3694	3177	2288	1622
1957	3489	3448	3319	2855	1927	1194
1958	2379	2351	2186	1724	1231	797
1959	1815	1793	1722	1552	1222	925
1960	4410	4358	4056	3344	2614	2007
1961	883	873	851	763	578	494
1962	11851	11710	11511	10688	8337	7588
1963	6651	6572	6205	5207	3906	2534
1964	2718	2686	2513	2178	1844	1549
1965	13889	13724	13038	11206	7546	4462
1966	14366	14196	13704	12034	9050	6031
1967	6722	6642	6443	5447	3616	2744
1968	1096	1083	1061	968	841	777
1969	34202	33796	32817	28945	20506	12832
1970	2527	2497	2328	1944	1470	1317
1971	2847	2813	2676	2257	1634	1328
1972	9721	9606	9368	8535	6167	4076
1973	2215	2189	2131	1927	1472	1056
1974	4210	4160	3769	2822	1965	1387
1975	14147	13979	13736	12891	9998	7010
1976	3406	3366	3236	3039	2346	1637
1977	636	628	536	499	400	360
1978	23063	22790	22064	19702	15021	9479
1979	21375	21122	20683	18873	14254	8747
1980	6148	6075	5692	4825	3479	2233
1981	1840	1818	1382	848	521	476
1982	7406	7318	7167	6430	4431	2942
1983	1788	1767	1598	1041	1029	922
1984	12266	12121	11827	10642	7749	4825
1985	5874	5804	5521	4460	3585	2263
1986	13522	13362	13132	12151	9554	7847
1987	3284	3245	3062	3827	2939	2064
1988	1041	1029	1005	969	903	820
1989	21338	21085	20358	17414	12793	7525
1990	917	906	842	797	651	572
1991	3441	3400	3334	3012	2413	1951
1992	2864	2830	2744	2347	1534	1092
1993	12929	12776	12437	11124	7762	6401
1994	13175	13019	12887	12691	11410	7476

Table 2. Continued.

Year	Peak	1-Day	3-Day	7-Day	15-Day	30-Day
1995	14145	13977	13808	12509	11964	9007
1996	10920	10791	10441	9403	7538	5343
1997	31080	30711	30480	29519	27462	20935
1998	9452	9340	9102	8114	5941	4407
1999	5525	5459	5261	4512	3720	3320
2000	5248	5186	4573	3152	2678	2287
2001	29432	29083	28483	26012	20049	13857
2002	6084	6012	5755	4838	2910	1955
2003	8995	8888	8616	7458	5051	3505
2004	6273	6199	6053	5267	3480	2354
2005	12309	12163	11974	11358	9494	7786
2006	25019	24722	24102	22143	16991	10293
2007	15292	15111	14728	13417	11080	8591
2008	6642	6563	6396	6056	4703	3008
2009	34357	33950	33157	29542	23024	17615



STATISTICS:

	Mean	Std.Dev.	Skew
Peak	3.802	0.415	-0.3
1-day	3.797	0.415	-0.3
3-day	3.778	0.418	-0.3
7-day	3.723	0.418	-0.3
15-day	3.606	0.424	-0.3
30-day	3.467	0.408	-0.3

RED RIVER

VOLUME-FREQUENCY CURVES
FARGO
UNREGULATED CONDITIONS WET

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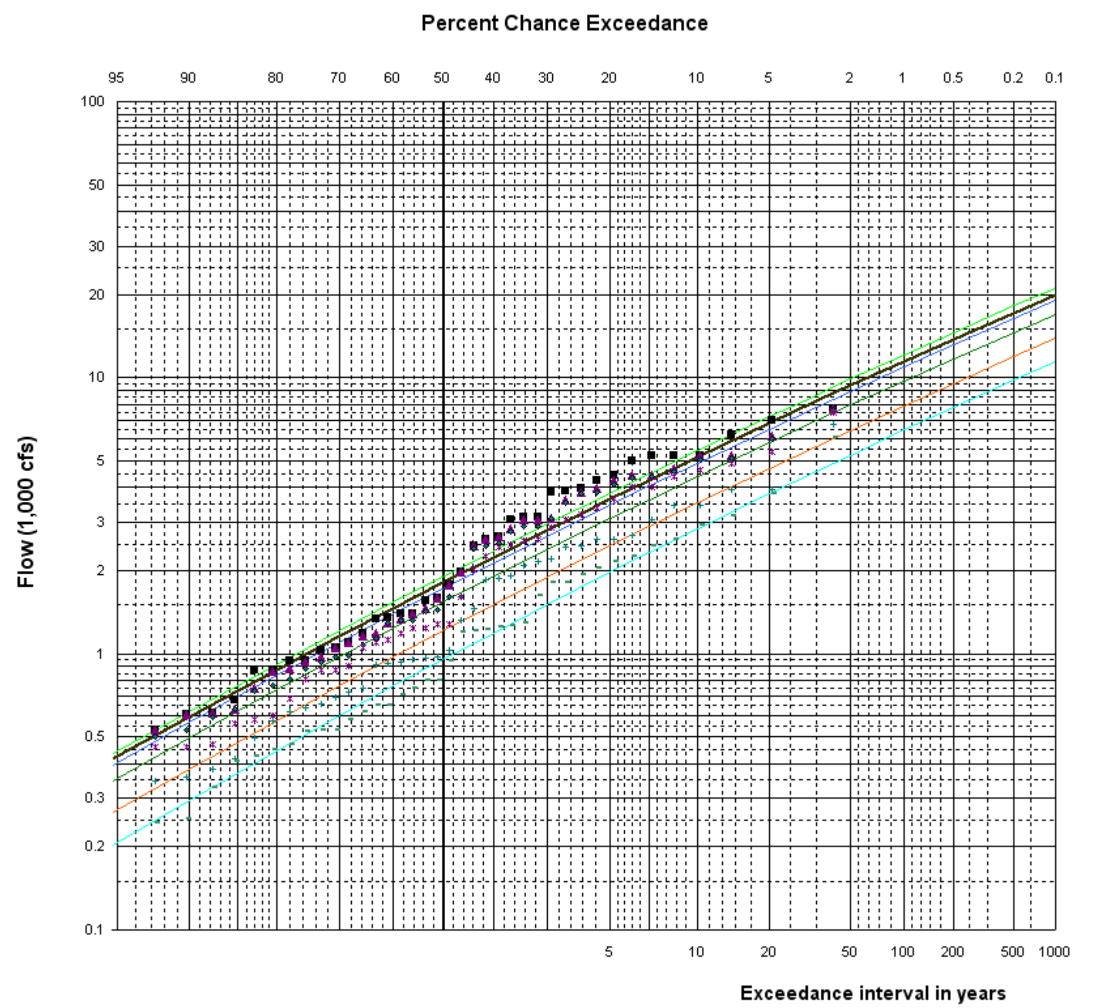
Figure 5. Volume-Duration Frequency Curves for the Wet Period, Red River at Fargo.



STATISTICS:

	Mean	Std.Dev.	Skew
Peak	3.270	0.368	-0.2
1-day	3.249	0.367	-0.2
3-day	3.227	0.367	-0.2
7-day	3.177	0.370	-0.2
15-day	3.073	0.377	-0.2
30-day	2.969	0.384	-0.2

RED RIVER

VOLUME-FREQUENCY CURVES
FARGO
UNREGULATED CONDITIONS DRY

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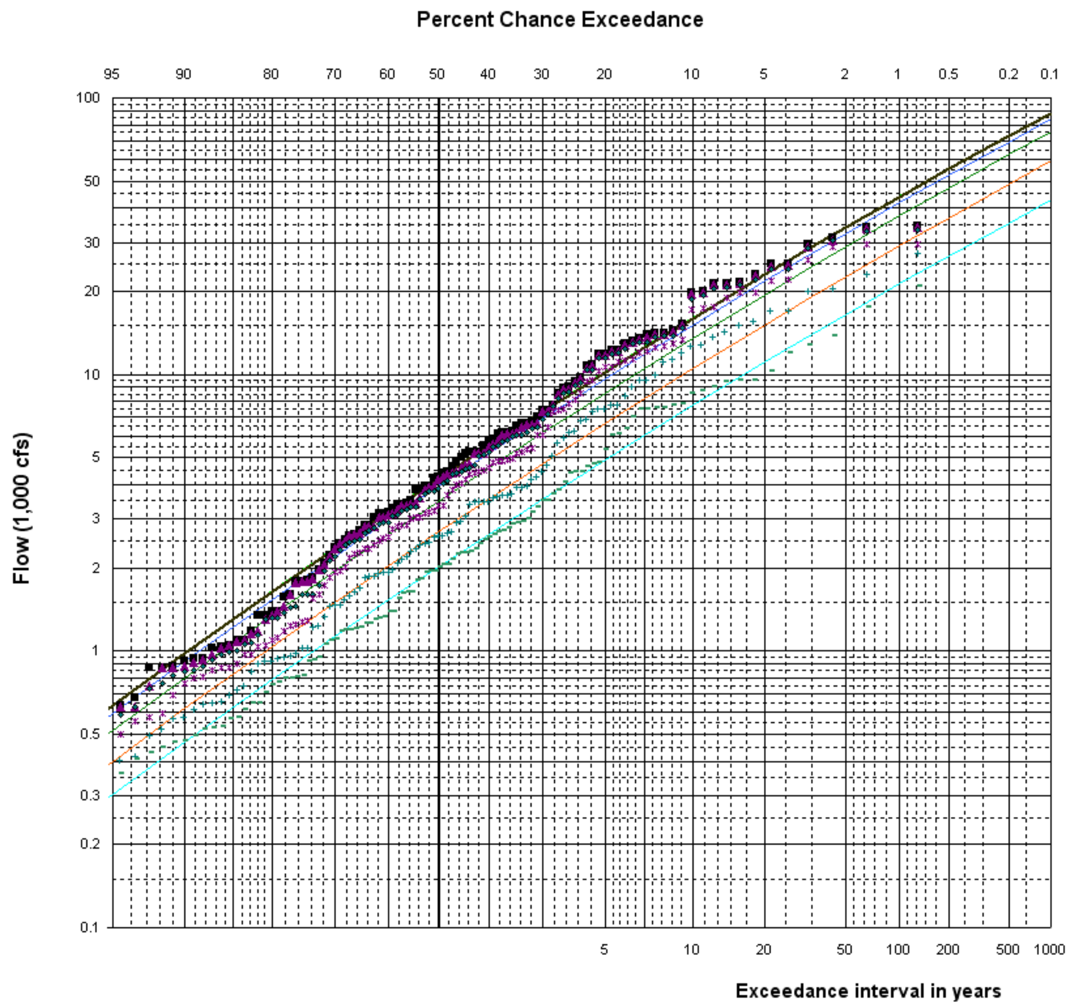
Figure 6. Volume-Duration Frequency Curves for the Dry Period, Red River at Fargo.



STATISTICS:

	Mean	Std.Dev.	Skew
Peak	3.611	0.475	-0.2
1-day	3.608	0.474	-0.2
3-day	3.581	0.476	-0.2
7-day	3.527	0.479	-0.2
15-day	3.416	0.480	-0.2
30-day	3.290	0.475	-0.2

RED RIVER

VOLUME-FREQUENCY CURVES
FARGO
UNREGULATED CONDITIONS FULL PERIOD OF RECORD

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Figure 7. Volume-Duration Frequency Curves for the Full Period of Record, Red River at Fargo

Table 3. Volume-Duration Frequency Curves for Wet Period, Red River at Fargo.

Percent Chance Exceedance	Peak (cfs)	1-Day (cfs)	3-Day (cfs)	7-Day (cfs)	15-Day (cfs)	30-Day (cfs)
10	20811	20572	19862	17515	13611	9500
2	38458	38017	36867	32603	25562	17767
1	47168	46628	45284	40097	31531	21933
0.5	56540	55893	54353	48187	37993	26475
0.2	69931	69130	67330	59789	47287	33063

Table 4. Volume-Duration Frequency Curves for Dry Period, Red River at Fargo.

Percent Chance Exceedance	Peak (cfs)	1-Day (cfs)	3-Day (cfs)	7-Day (cfs)	15-Day (cfs)	30-Day (cfs)
10	5433	5158	4908	4396	3528	2837
2	9877	9356	8903	7954	6453	5248
1	12122	11474	10918	9739	7929	6474
0.5	14581	13792	13124	11684	9545	7821
0.2	18176	17177	16346	14513	11903	9793

Table 5. Volume-Duration Frequency Curves for Full Period of Record, Red River at Fargo.

Percent Chance Exceedance	Peak (cfs)	1-Day (cfs)	3-Day (cfs)	7-Day (cfs)	15-Day (cfs)	30-Day (cfs)
10	16155	15989	15138	13504	10491	7729
2	34198	33970	32290	28941	22520	16460
1	44122	43909	41794	37521	29212	21293
0.5	55463	55301	52702	47382	36908	26837
0.2	72769	72748	69429	62530	48735	35334

Develop Synthetic Flood Hydrographs

The synthetic flood hydrographs were developed to reproduce the 10, 2, 1, 0.5, and 0.2 percent flows on the natural flow volume-duration frequency curves contained in Table 3 - Table 5. Upstream hydrographs (inflows into White Rock and Orwell Dams and flow at the Wild Rice at Abercrombie gage) and local runoff hydrographs (local at Wahpeton, Hickson, and Fargo) were adjusted so that when routed and combined downstream they produce a balanced hydrograph at Fargo. The balanced hydrograph contains the 1 – 30-day volumes for a specific frequency. For example, the balanced 1-percent hydrograph at Fargo for the full period of record analysis contains a maximum 1-day flow of 43909 cfs, 3-day flow of 41794 cfs, 7-day flow of 37521 cfs, 15-day flow of 29212 cfs, and 30-day flow of 21293 cfs.

An HEC-HMS model was used to develop the balanced synthetic hydrographs by routing and combining the upstream and local runoff hydrographs. Figure 8 shows the HEC-HMS model schematic for the Red River above Fargo. Routing parameters in the HEC-HMS model were the same as those in the HEC-5 model developed by the St. Paul District.

The 2006 flood event was selected to shape synthetic flood hydrographs for both the wet period and full period of record analyses, and the 1945 event was used to shape the synthetic flood hydrographs for the dry period analysis. The use of these historic events provides information about the timing of the flood hydrograph. For example, an historic event provides information about how timing of the peak flow on the Wild Rice coincides with the peak flow on the Red River. These flood events were chosen because they are among the largest for their respective analysis periods, the 2006 is among the largest floods on record and the 1945 event is a large flood typical of what occurred during the dry period (1902 – 1941).

HEC-HMS was used because it has an option to ratio the ordinates of all inflow hydrographs. The ratio option was used to adjust the upstream hydrographs (inflows into White Rock and Orwell Dams and flow at the Wild Rice at Abercrombie gage) and local runoff hydrographs (local at Wahpeton, Hickson, and Fargo). Because the ratio option applies a uniform adjustment for all ordinates of the hydrographs, some manual adjustment of the upstream and local runoff hydrographs was needed. For example, the 1-day flow from the 2006 event has a lower annual exceedance probability than the 30-day flow. Uniform adjustment using the ratio option in HEC-HMS would not be able to reproduce a balanced hydrograph at Fargo (the 30-day flow would be too low); therefore, hydrograph shapes were modified. More flow was added to the receding limb of the hydrograph for the 2006 event. Figure 9 shows the estimated incremental local runoff hydrograph at Wahpeton and the hydrograph after manual edits. Notice that flows affecting the 7-day average were reduced and those affecting the 15 and 30-day average were increased. Similar edits were made for all inflow and local runoff hydrographs. In addition, separate edits were made to hydrographs used for the wet, dry, and full period analyses. These manual adjustments were made in conjunction with adjustments to the ratio option in HEC-HMS with the goal to create balanced hydrographs at Fargo.

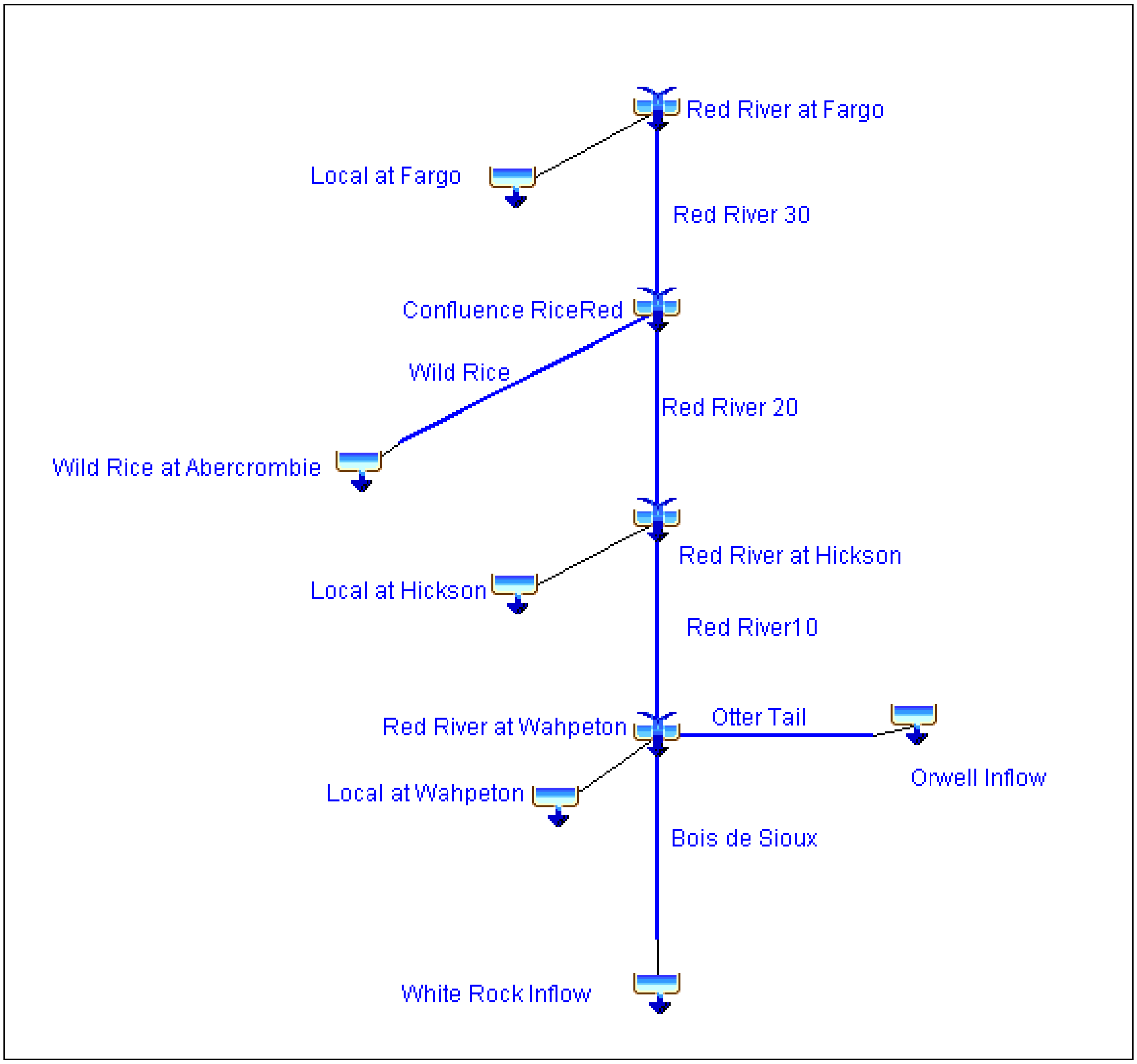

Figure 8. HEC-HMS Schematic of the Red River above Fargo.

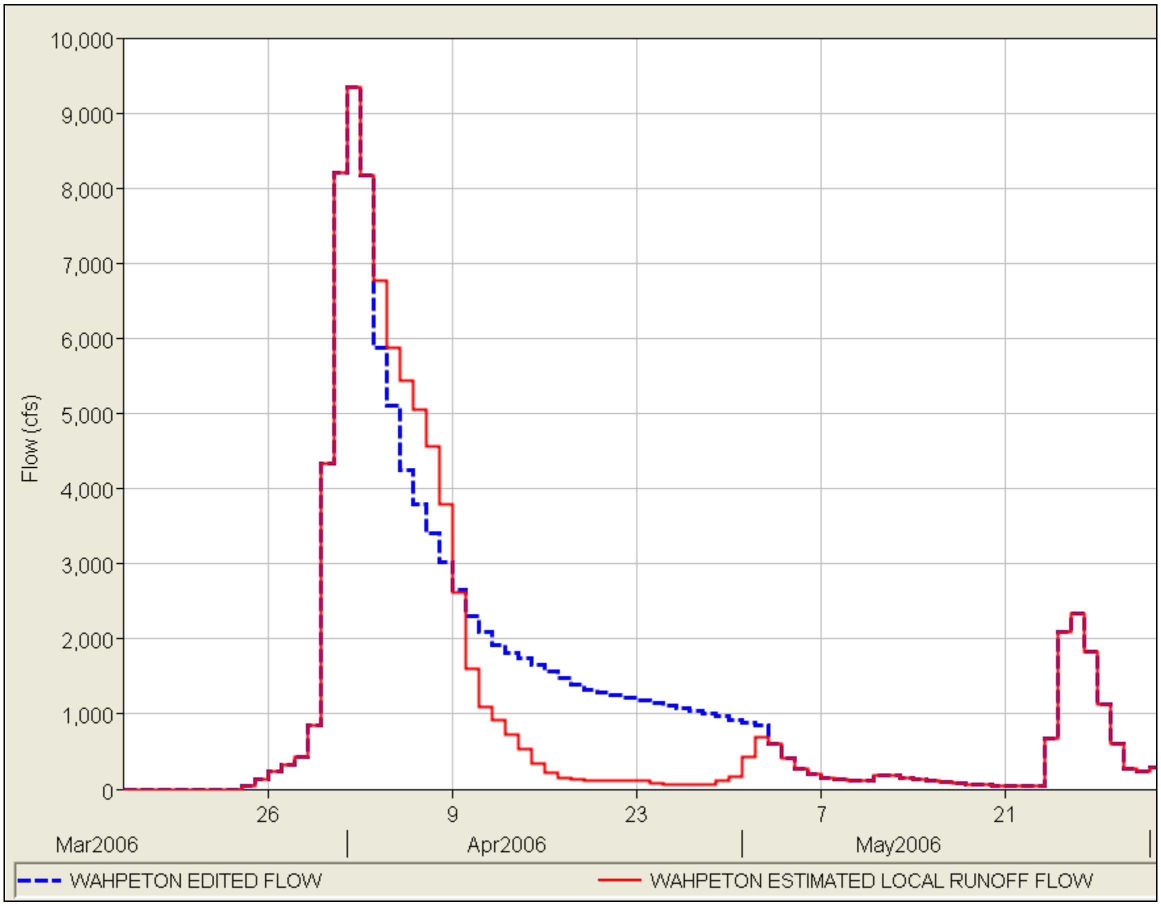

Figure 9. Example of Manual Adjustments of a Local Runoff Hydrograph.

Using HEC-HMS to develop the synthetic hydrographs was an iterative procedure. After a flow ratio was applied to the inflow and local runoff hydrographs, the computed flow time-series at Fargo was exported from HEC-HMS to a spreadsheet and the 1, 3, 7, 15, and 30-day average flows were computed. The maximum flow from each duration was then compared with the appropriate values from the natural conditions volume-duration frequency curves, Table 3 - Table 5. The ratio was then increased or decreased to improve the results. An effort was made to match the 1-day flows for each frequency event, 10, 2, 1, 0.5, and 0.2. For the maximum 3, 7, 15, and 30-day flows an effort was made to ensure that HMS results were within 5-percent of the natural conditions volume-duration frequency curves.

Figure 10 and Figure 11 show the inflow and local runoff hydrograph that reproduce the 1-percent 1, 3, 7, 15, and 30-day flows at Fargo (full period of record analysis). Figure 11 illustrates how the inflow and local runoff hydrographs are referenced in the HEC-HMS model. As shown, six hydrographs are routed and combined to create the final hydrograph at Fargo. A separate set of hydrographs were developed for each frequency event, 10, 2, 1, 0.5, and 0.2-percent events. Figure 12 shows how the local runoff hydrograph at Wahpeton varies for the different frequency events. In addition, synthetic hydrographs were developed for the wet, dry, and full period analyses. This results in 15 different simulations with 6 hydrographs for each. Table 6 – Table 8 contain the maximum 1, 3, 7, 15, and 30-day flows at Fargo from the synthetic hydrographs generated by the HEC-HMS model. Values in these tables compare favorably to the natural volume-duration frequency curves in Table 3 - Table 5.

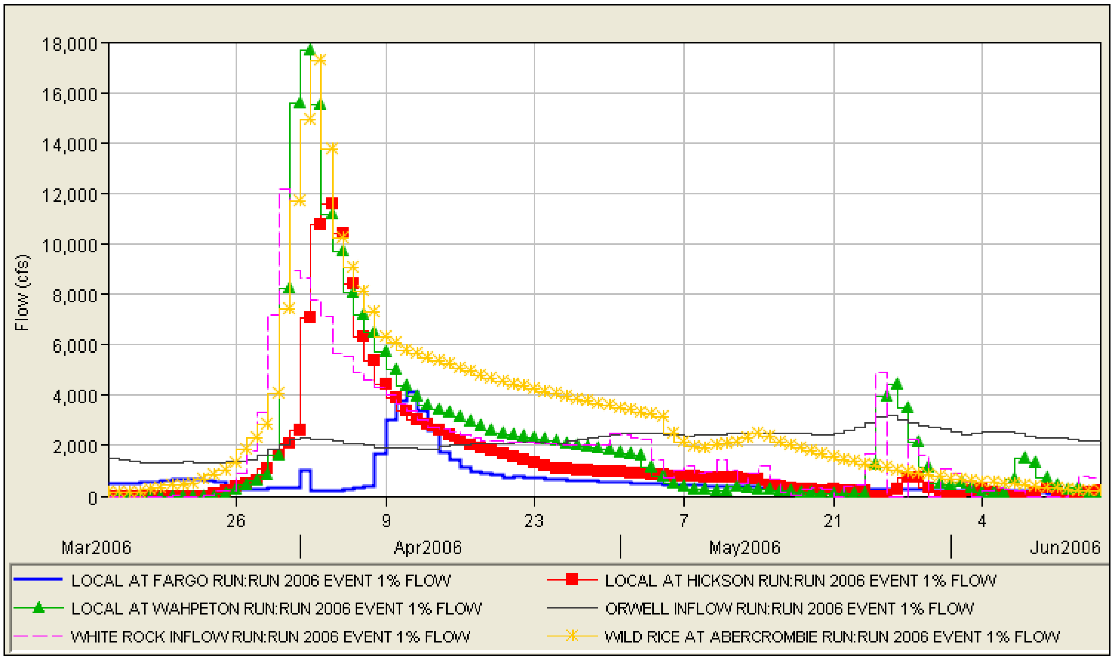

Figure 10. Upstream and Local Runoff Hydrographs that Produce the 1-Percent 1, 3, 7, 15, and 30-Day Flows at Fargo.

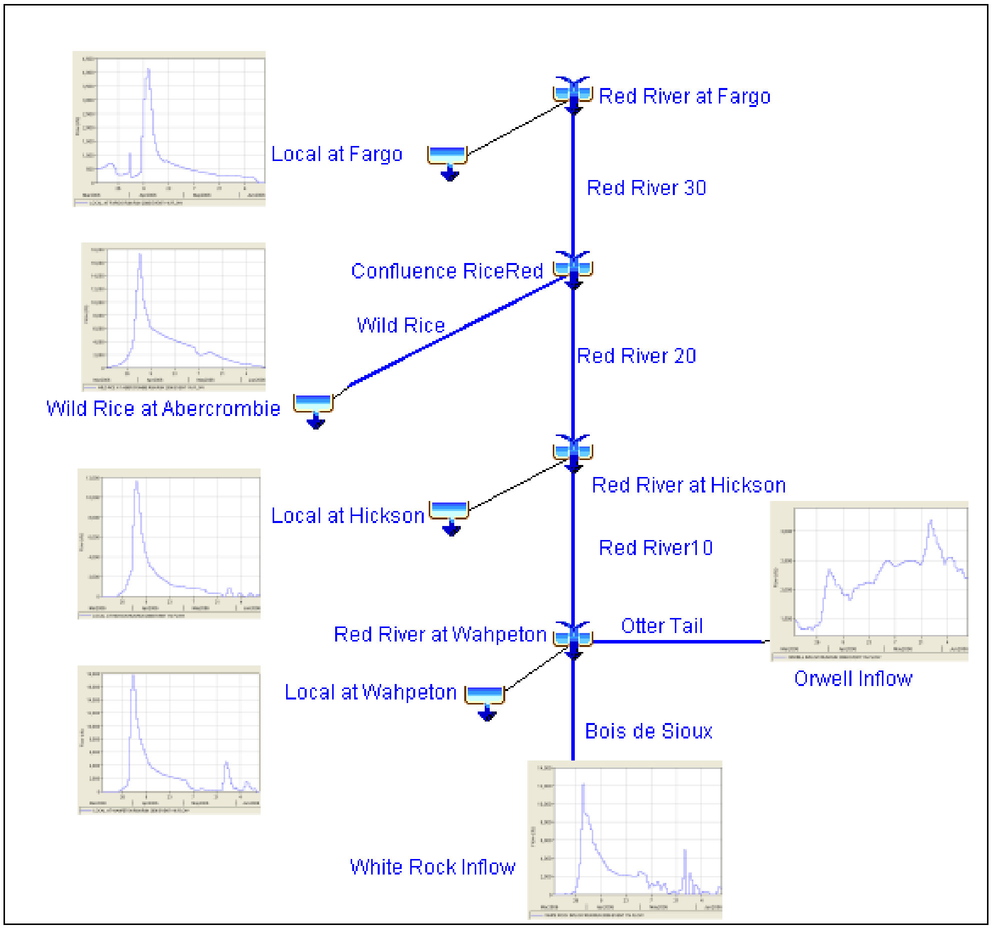

Figure 11. HEC-HMS Schematic of Upstream and Local Runoff Hydrographs that Produce the 1-Percent 1, 3, 7, 15, and 30-Day Flows at Fargo.

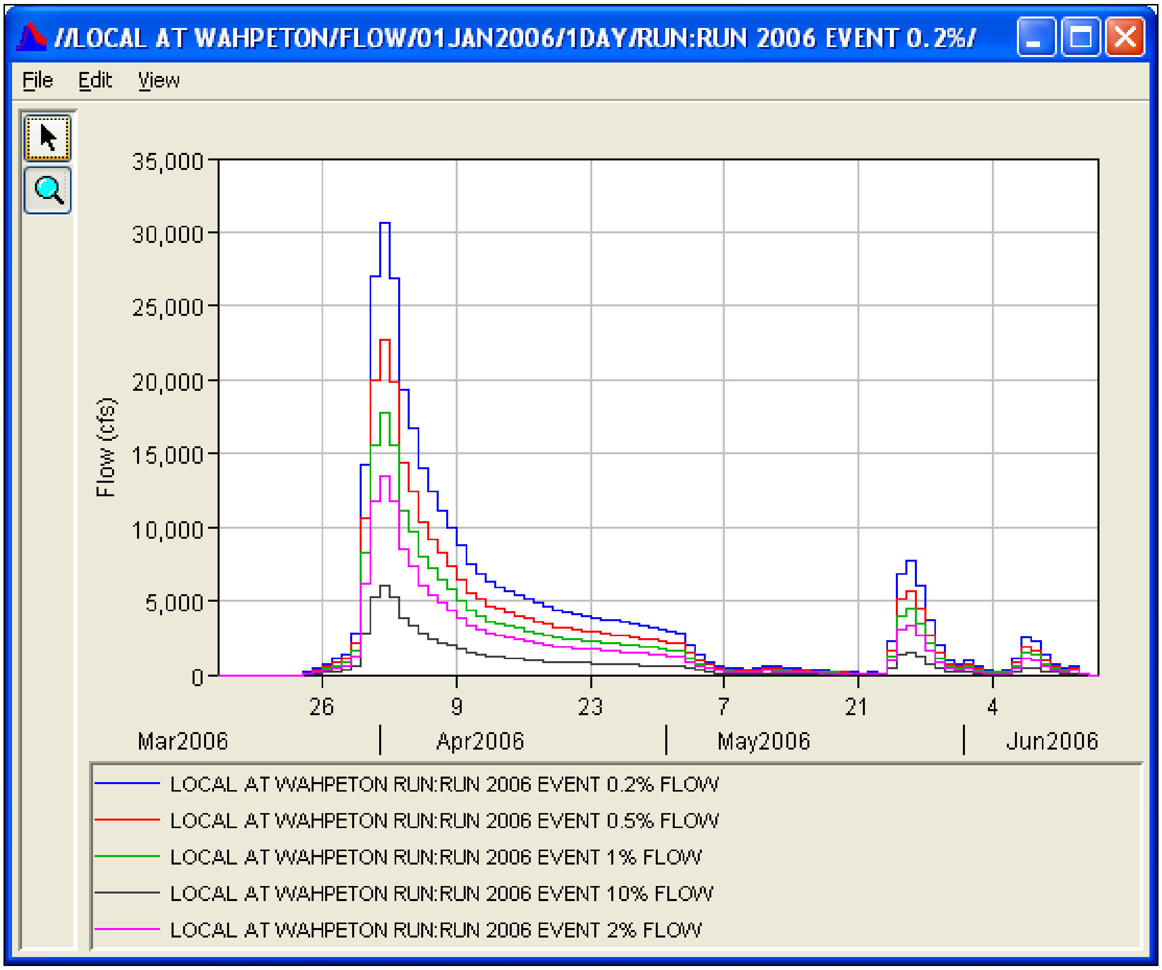

Figure 12. Local Runoff Hydrographs at Wahpeton for the 10, 2, 1, 0.5, and 0.2-Percent Events (Full Period Analysis).

Table 6. Synthetic Events Volume-Duration Results from HMS-Model - Wet Period (compare to Table 3).

Percent Chance Exceedance	1-Day (cfs)	3-Day (cfs)	7-Day (cfs)	15-Day (cfs)	30-Day (cfs)
10	20572	20129	18096	14319	9660
2	38035	37216	33458	26473	17859
1	46609	45604	40999	32440	21885
0.5	55905	54700	49177	38910	26250
0.2	69126	67636	60807	48112	32458

Table 7. Synthetic Events Volume-Duration Results from HMS-Model - Dry Period (compare to Table 4).

Percent Chance Exceedance	1-Day (cfs)	3-Day (cfs)	7-Day (cfs)	15-Day (cfs)	30-Day (cfs)
10	5158	4908	4499	3698	2841
2	9356	8902	8159	6707	5153
1	11474	10918	10007	8226	6320
0.5	13792	13124	12029	9888	7597
0.2	17177	16344	14981	12315	9462

Table 8. Synthetic Events Volume-Duration Results from HMS-Model - Full Period (compare to Table 5).

Percent Chance Exceedance	1-Day (cfs)	3-Day (cfs)	7-Day (cfs)	15-Day (cfs)	30-Day (cfs)
10	15994	15449	13684	10759	7725
2	33983	32825	29074	22860	16413
1	43911	42415	37568	29538	21208
0.5	55300	53416	47313	37200	26709
0.2	72748	70270	62240	48937	35136

Route the Unregulated Synthetic Flood Hydrographs through the HEC-5 Model

The St. Paul District provided an HEC-5 model that was used to route the natural conditions hydrographs through Orwell and White Rock Dams. Output from the HEC-HMS model was referenced by the HEC-5 input file as boundary conditions (inflows) for the reservoirs. 15 simulations were run using the HEC-5 model; 5 frequency events for the wet, dry, and full period analyses. Figure 10 shows the inflow and regulated outflow hydrographs for White Rock Dam from the 0.2-percent event (full period analysis). The HEC-5 model provided output, regulated flows, at the Hickson gage. These regulated flows were used as an upstream boundary condition for an unsteady HEC-RAS model.

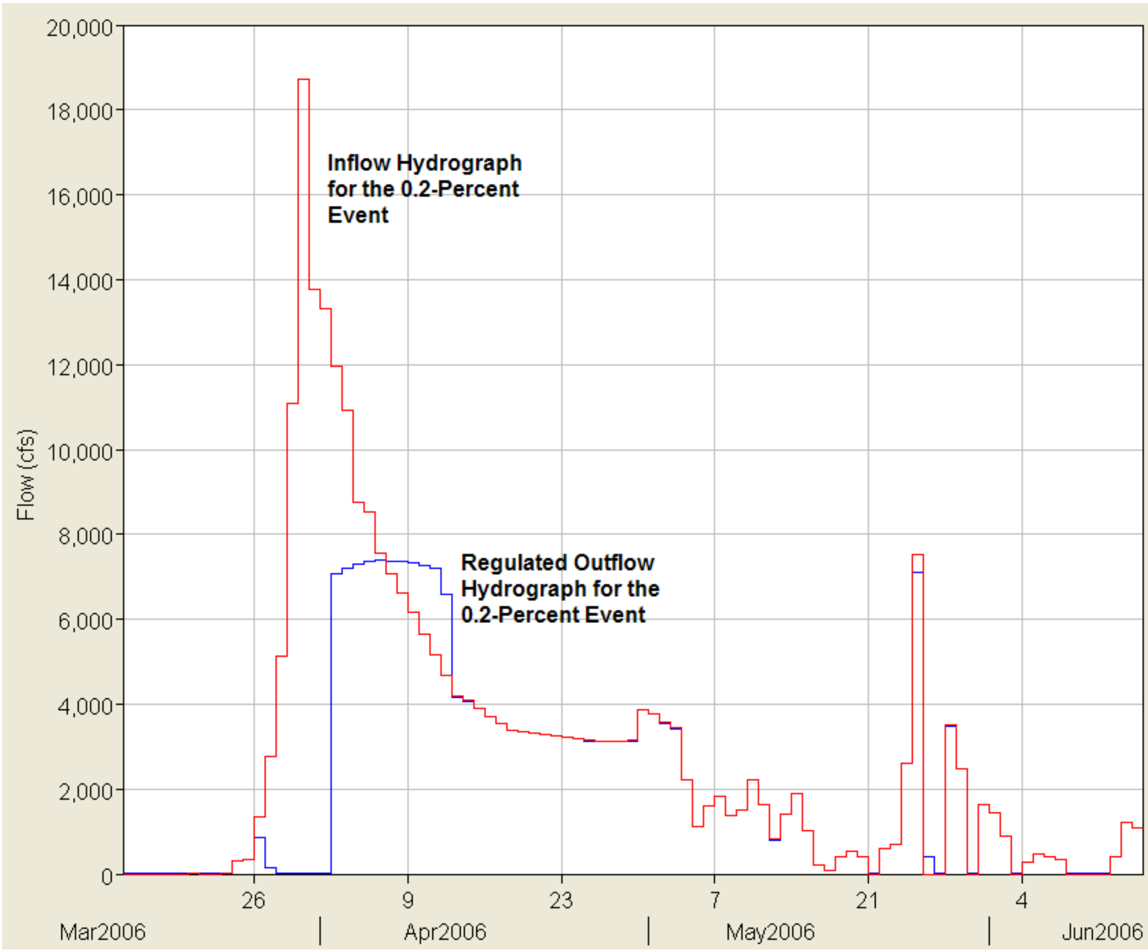

Figure 13. White Rock Inflow and Outflow Hydrographs for the 0.2-Percent Event – Full Period Analysis.

Route Synthetic Hydrographs to Fargo using HEC-RAS

The St. Paul District provided an HEC-RAS model of the Red River. This model was used to route regulated flow at Hickson, computed by the HEC-5 model, downstream to Fargo as well as the synthetic hydrographs from the Wild Rice at Abercrombie gage, developed by the HEC-HMS model, downstream to Fargo. The local runoff hydrographs for Fargo (includes runoff from areas downstream of the Hickson and Abercrombie gages and upstream of Fargo and were also developed by HEC-HMS model) were treated as uniform lateral inflows by the HEC-RAS model.

The HEC-RAS model, as received from the St. Paul District, was modified before it was used to run the synthetic flood events. All geometry below the “RoseC to Shey” reach was removed in order to shorten the compute time. The removal of the downstream geometry had little effect on results at the Fargo cross section.

A total of 15 simulations were run using the HEC-RAS model. These include simulations of the 10, 2, 1, 0.5, and 0.2-percent events for the wet, dry, and full period analyses. Output from the HEC-RAS model was the summation of flows from cross section 2383053 and storage area connections 139, 149, and 156. Table 9 contains the peak flows at Fargo from the synthetic flood events.

Table 9. Peak Flows at Fargo from Synthetic Floods – Output from HEC-RAS Model.

Percent Chance Exceedance	Wet Period (cfs)	Dry Period (cfs)	Full Period (cfs)
10	16676	4654	13089
2	29314	7803	26028
1	34662	9259	32927
0.5	46117	10874	43422
0.2	61693	13318	66199

Add Results from Synthetic Flood Events to the Regulated Flow Frequency Curve

The regulated peak flow frequency curve for the Red River at Fargo was developed using both observed stream flow data and synthetic floods (output from the HEC-RAS model). Table 10 contains regulated annual maximum peak flows for the Red River at Fargo. Gaged peak flows measured after 1942 were treated as regulated. Peak flows prior to 1942 (before upstream dams were constructed) were converted to regulated flow using a regression analysis of measured and estimated unregulated flows from 1942 - 2009.

The regulated peak flow frequency curves were developed graphically by fitting a curve to the observed/estimated annual maximum peaks plotted against empirical frequency estimates, and the synthetic floods plotted against their specified frequencies. Separate frequency curves were developed for the wet, dry, and full periods of record. Table 11 contains both the wet and dry period regulated peak flow frequency curves. Figure 14 and Figure 15 show plots of the regulated curves for the wet and dry periods, respectively. Notice the synthetic floods are used to define the upper end of the regulated flow frequency curves. Table 13 contains the unregulated and regulated peak flow frequency curve for the full period of record analysis and Figure 20 shows both the full period of record analysis unregulated and regulated peak flow frequency curves as well as results from the synthetic floods.

Combine Dry and Wet frequency curves based on assumed future likelihoods

Good statistical evidence of a difference between dry and wet portions of the gaged flood record led to development of a separate peak flow frequency curve for each period. To determine which frequency curve is applicable in any future year, it would be preferable to predict the transition of the apparent cycle from the wet period back to the dry. However, the period of the cycle in unknown and irregular, and there is no way to determine when the current wet regime might shift back to dry. Given this uncertainty in which flow regime will be experienced in the future, the appropriate flood frequency description for any future year is a combination of the dry and wet frequency curves that respects the likelihood of each condition.

Combination of the wet and dry regulated flow frequency curves for a given future year used the total probability theorem, stated as

$$P(Q>q)_t = P(Q>q|wet) * P(wet)_t + P(Q>q|dry) * P(dry)_t$$

with $P(Q>q)_t$ = exceedance probability for a flow q in year t,
$P(Q>q|wet)$ = exceedance probability for flow q given the wet condition
$P(wet)_t$ = probability of the wet condition in year t
$P(Q>q|dry)$ = exceedance probability for flow q given the wet condition
$P(dry)_t$ = probability of the wet condition in year t

This method requires estimating the likelihood of experiencing the wet or the dry condition in any year. For Year 0 of the economic analysis, as we seem to be currently within the wet period, probability of the wet period is set at 100%, and probability of the dry period at 0%. Year 50 is far enough into the future that we cannot make a strong assumption about which hydrologic regime the basin will experience, and so we defer to long-term or steady-state probabilities of the wet versus dry period. Long-term is estimated simply by percentage of the gaged record in each data set, providing 65% chance any future year is in a wet period, and 35% chance it is in a dry period. The assumed probabilities for Year 25 were placed at 80% chance wet and 20% chance dry to be a reasonable estimate between Years 0 and 50.

Using these probabilities, multiple regulated peak flow frequency curves for the Red River at Fargo were developed. That used for Year 0 is simply the wet period curve.

Table 11 also contains the possible future scenario regulated frequency curves that are combinations of both wet and dry curves. These future scenario frequency curves are shown in Figure 16 and Figure 17. For comparison purposes, the unregulated peak flow frequency curve for both wet and dry conditions and possible future scenarios are contained in Table 12 and shown in Figure 18 and Figure 19.

Table 10. Unregulated and Regulated Peak Flows for the Red River at Fargo.

Year	Unregulated Flow (cfs)	Regulated Flow (cfs)
1897	25000	20050
1882	20000	16040
1902	1180	999
1903	2450	2075
1904	5220	4421
1905	4250	3600
1906	3050	2583
1907	7000	5929
1908	2600	2202
1909	1780	1508
1910	5000	4235
1911	608	515
1912	1100	932
1913	1560	1321
1914	3140	2660
1915	3130	2651
1916	7740	6556
1917	5240	4438
1918	874	740
1919	680	576
1920	6200	5251
1921	1970	1669
1922	5200	4404
1923	3960	3354
1924	530	449
1925	940	796
1926	1600	1355
1927	2650	2245
1928	3840	3252
1929	4440	3761
1930	1340	1135
1931	365	309
1932	875	741
1933	605	512
1934	323	274
1935	942	798
1936	1050	889
1937	1390	1177
1938	1350	1143
1939	3870	3278
1940	1030	872
1941	1390	1177
1942	4639	3380
1943	19709	16000
1944	5691	4150
1945	8556	7700
1946	7423	5970

Table 10. Continued.

Year	Unregulated Flow (cfs)	Regulated Flow (cfs)
1947	11840	9300
1948	4795	3390
1949	3412	2660
1950	8973	7800
1951	10700	8010
1952	21643	16300
1953	6529	6720
1954	2084	1920
1955	3171	2760
1956	3968	3870
1957	3489	2540
1958	2379	2280
1959	1815	1250
1960	4410	3900
1961	883	1020
1962	11851	9580
1963	6651	4930
1964	2718	2400
1965	13889	11400
1966	14366	10700
1967	6722	5900
1968	1096	788
1969	34202	25300
1970	2527	2480
1971	2847	1910
1972	9721	7250
1973	2215	1950
1974	4210	4150
1975	14147	13200
1976	3406	3200
1977	636	878
1978	23063	17500
1979	21375	17300
1980	6148	5470
1981	1840	1710
1982	7406	5920
1983	1788	1750
1984	12266	9550
1985	5874	4690
1986	13522	8640
1987	3284	3300
1988	1041	981
1989	21338	18900
1990	917	1220
1991	3441	2630
1992	2864	2590
1993	12929	10100

Table 10. Continued.

Year	Unregulated Flow (cfs)	Regulated Flow (cfs)
1994	13175	11200
1995	14145	11000
1996	10920	9940
1997	31080	28000
1998	9452	8610
1999	5525	4900
2000	5248	5630
2001	29432	20300
2002	6084	4250
2003	8995	6710
2004	6273	5430
2005	12309	9810
2006	25019	19900
2007	15292	13500
2008	6642	4840
2009	34357	29449

Table 11. Regulated Peak Flow Frequency Curves for Wet and Dry Periods and the Combined Frequency Curves.

	Regulated Instantaneous Peak Flow Frequency Curves at Fargo			
Exceedance Frequency	Wet Flow (cfs)	Dry Flow (cfs)	Combine(0.8wet, 0.2dry) Flow (cfs)	Combine(0.65wet, 0.35dry) Flow (cfs)
0.9999	60	50	62	59
0.999	175	95	126	116
0.99	440	200	301	265
0.9	1450	525	989	817
0.75	2800	902	1991	1601
0.5	5600	1610	4352	3506
0.25	10600	2825	8968	7630
0.1	17000	4600	15394	13965
0.05	22000	6100	20345	18855
0.02	29300	8000	27441	25764
0.01	34700	9500	32921	31304
0.005	46200	11000	42242	38787
0.002	61700	13500	57641	54034

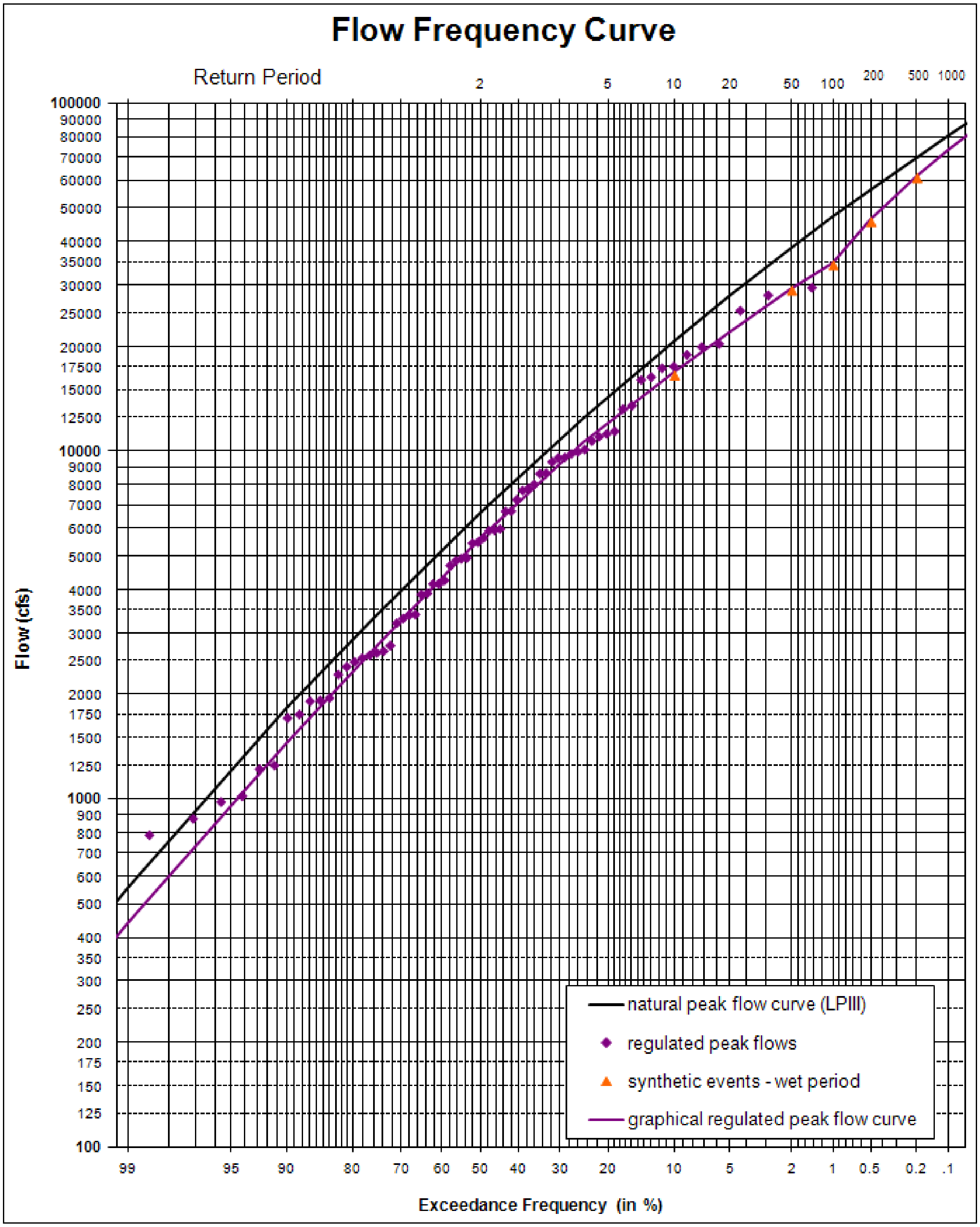

Figure 14. Unregulated and Regulated Peak Flow Frequency Curves with Synthetic Events – Wet Period.

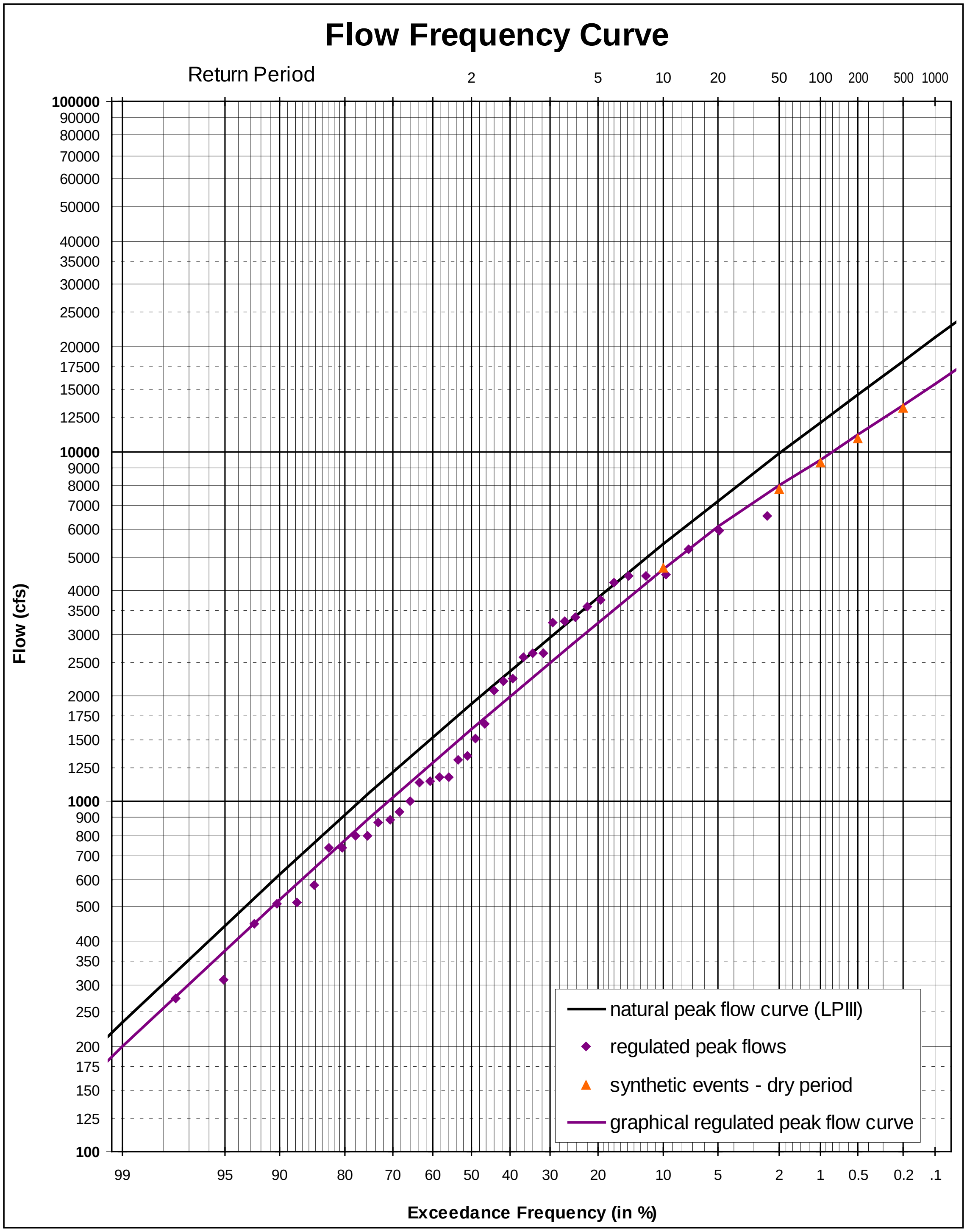

Figure 15. Unregulated and Regulated Peak Flow Frequency Curves with Synthetic Events – Dry Period.

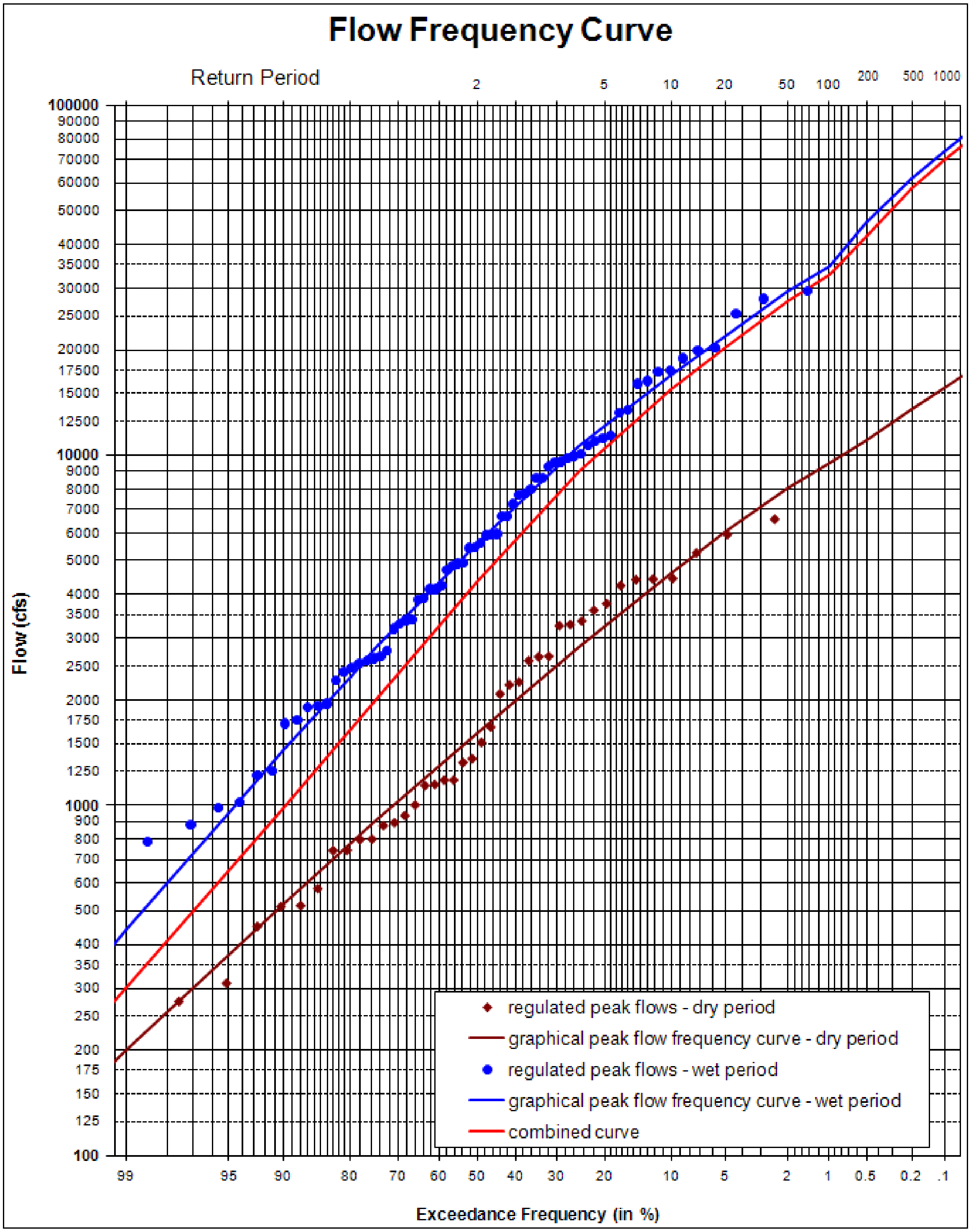

Figure 16. Regulated Peak Flow Frequency Curves for Wet and Dry Periods with Combined Curve (0.8 wet and 0.2 dry weighting).

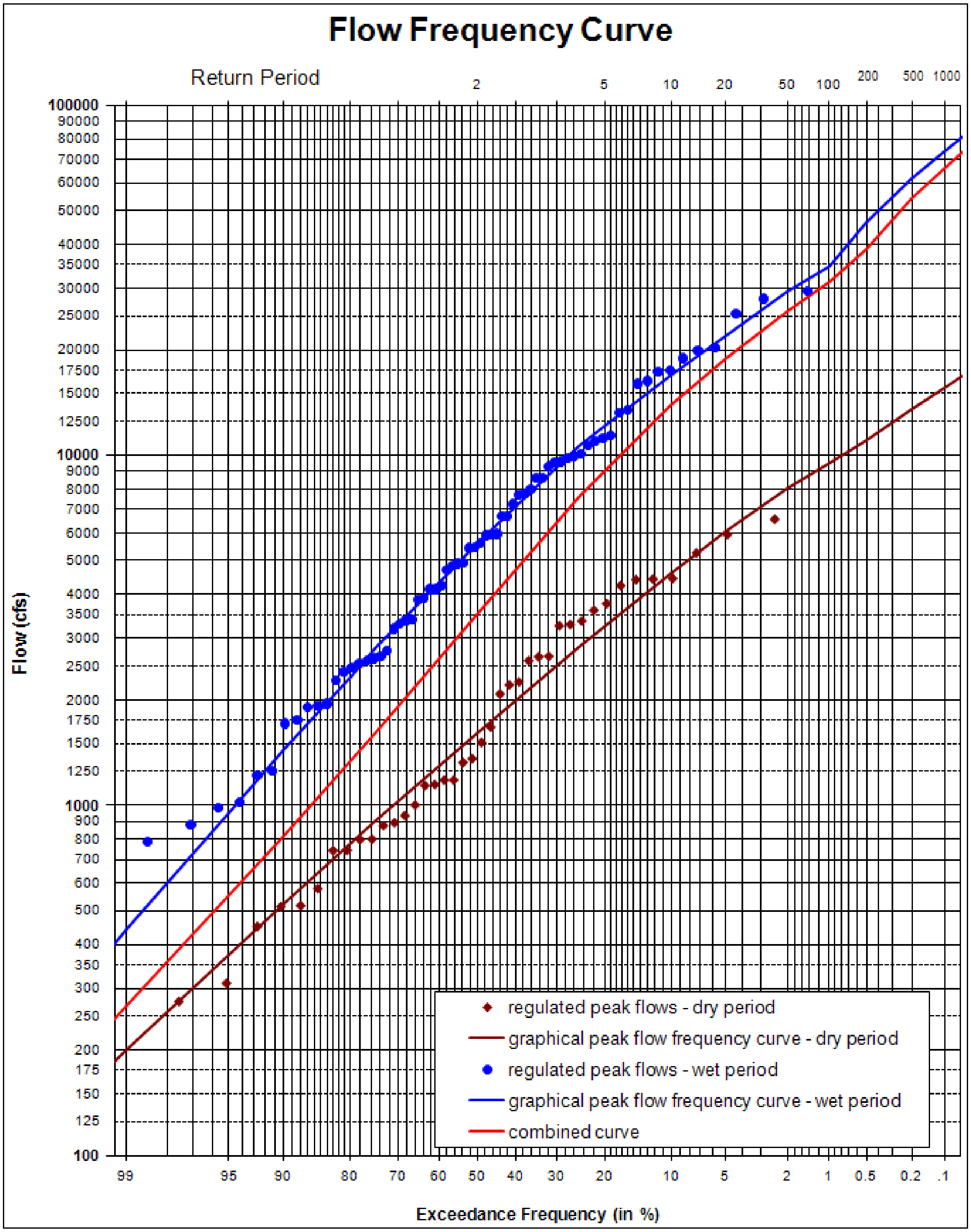

Figure 17. Regulated Peak Flow Frequency Curves for Wet and Dry Periods with Combined Curve (0.65 wet and 0.35 dry weighting).

Table 12. Unregulated Peak Flow Frequency Curves for Wet and Dry Periods and the Combined Frequency Curves.

	Unregulated Instantaneous Peak Flow Frequency Curves at Fargo			
	Wet	Dry	Combine(0.8wet, 0.2dry)	Combine(0.65wet, 0.35dry)
Exceedance Frequency	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)
0.9999	95	59	78	72
0.999	216	112	159	142
0.99	554	235	373	321
0.9	1814	620	1210	983
0.75	3428	1065	2438	1935
0.5	6655	1904	5216	4212
0.25	12362	3336	10534	9017
0.1	20808	5431	18627	16720
0.05	27960	7215	25568	23444
0.02	38445	9865	35744	33326
0.01	47153	12106	44250	41640
0.005	56524	14559	53407	50596
0.002	69914	18145	66504	63420
		Years of Record	62	58
		Mean	3.6879	3.5874
		STDev	0.4680	0.5146
LPIII statistics		Skew	-0.3791	-0.4349

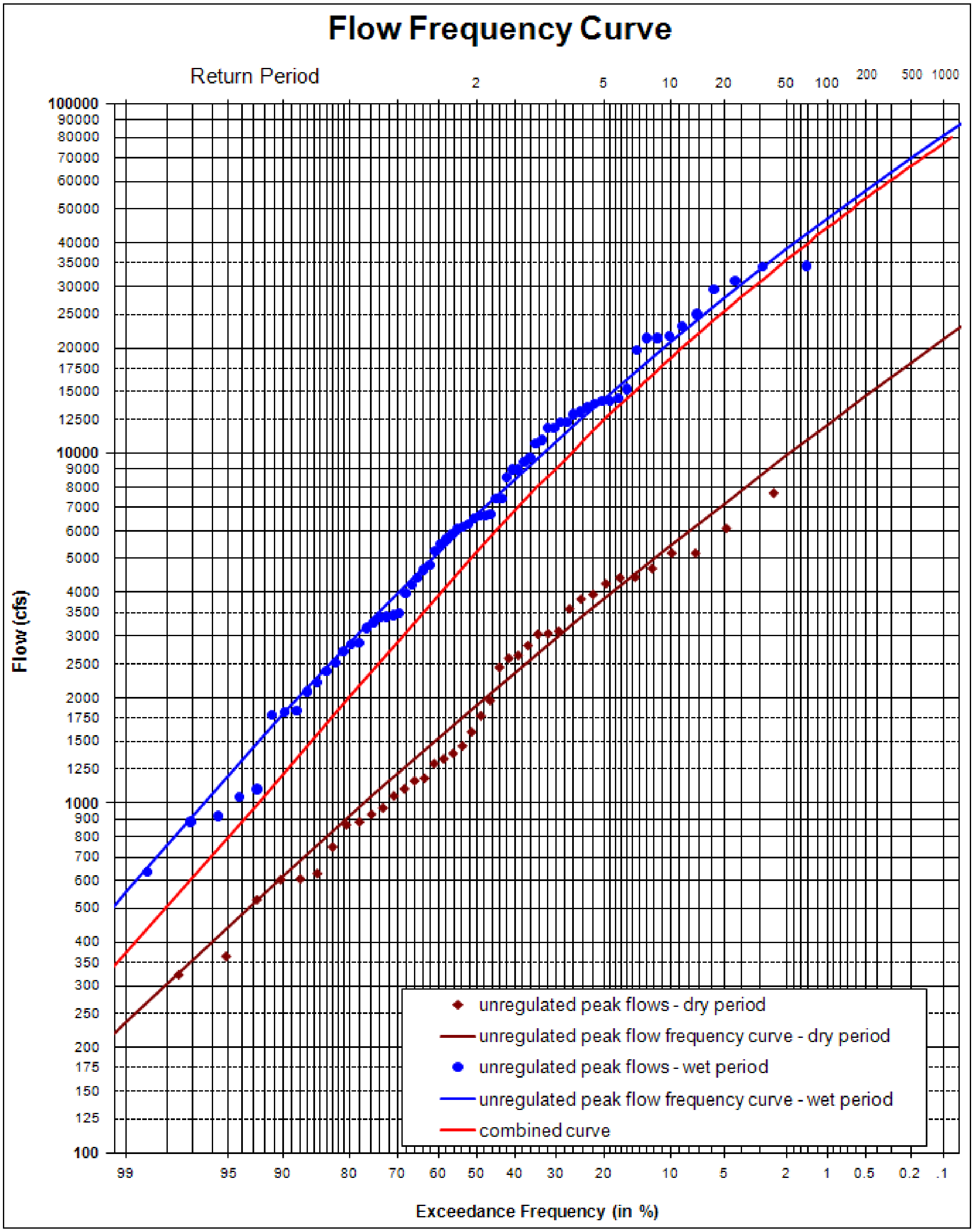

Figure 18. Unregulated Peak Flow Frequency Curves for Wet and Dry Periods with Combined Curve (0.8 wet and 0.2 dry weighting).

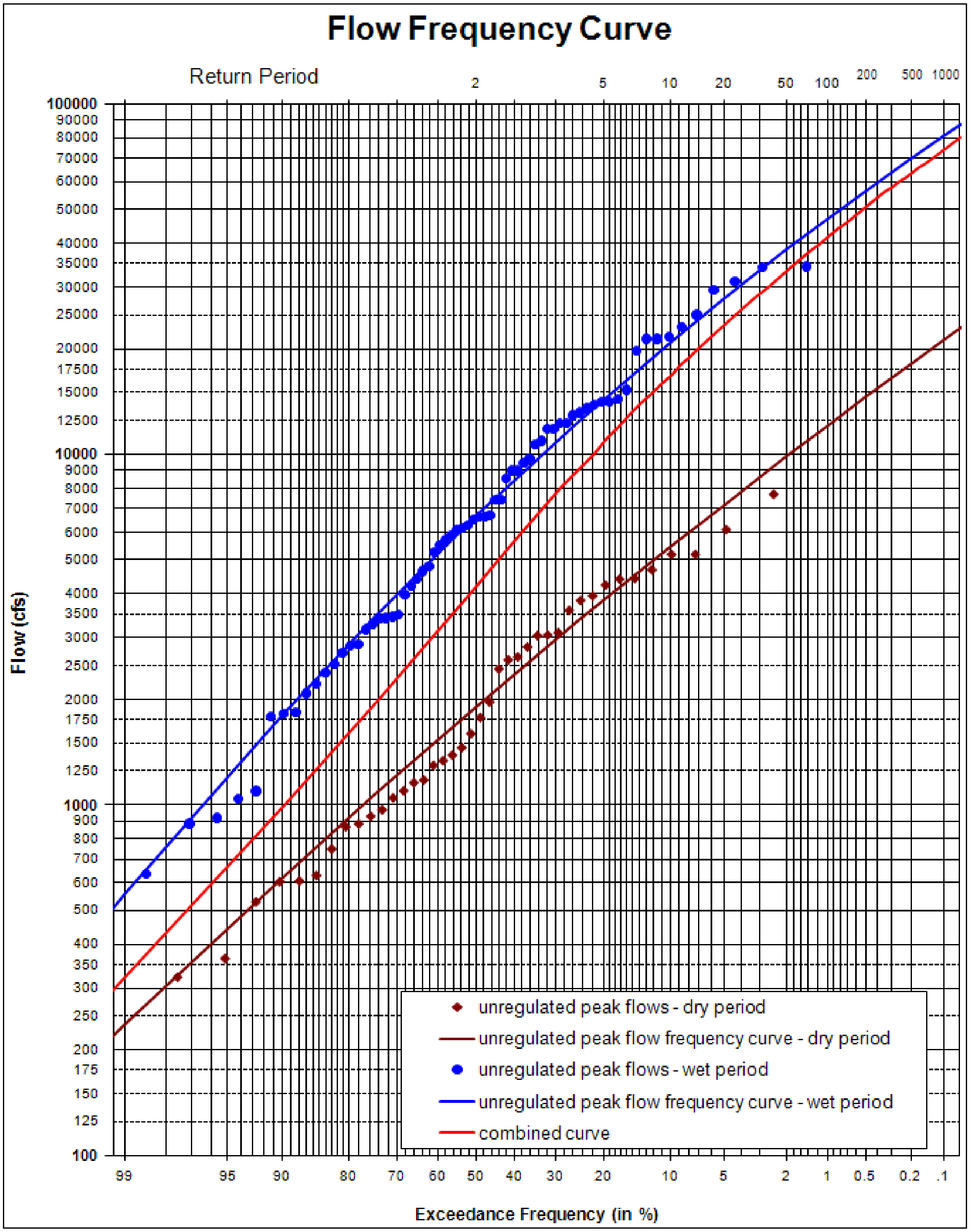

Figure 19. Unregulated Peak Flow Frequency Curves for Wet and Dry Periods with Combined Curve (0.65 wet and 0.35 dry weighting).

Table 13. Unregulated and Regulated Peak Flow Frequency Curves for the Full Period of Record.

Instantaneous Peak Flow Frequency Curves at Fargo - Full Period			
		Unregulated Freq Curve	Regulated Freq Curve
Exceedance Frequency		Flow (cfs)	Flow (cfs)
0.9999		43	37
0.999		101	87
0.99		273	235
0.9		986	846
0.75		1998	1715
0.5		4240	3639
0.25		8699	7467
0.1		16152	13865
0.05		23102	19831
0.02		34183	26000
0.01		44104	33000
0.005		55442	43500
0.002		72746	66000
	Years of Record	128	
	Mean	3.6113	
	STDev	0.4746	
LPIII statistics	Skew	-0.2027	

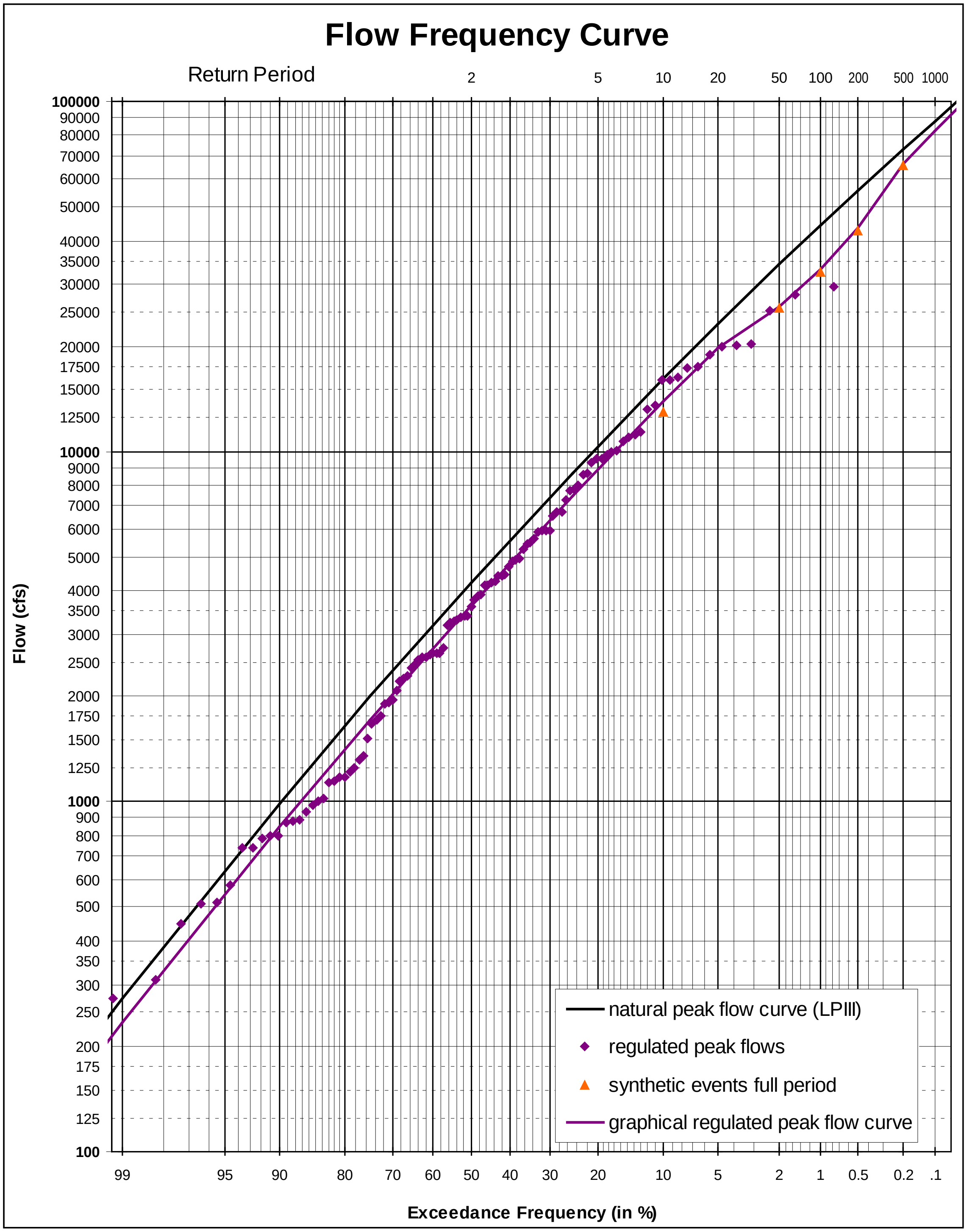

Figure 20. Unregulated and Regulated Peak Flow Frequency Curves with Synthetic Events – Full Period.

Conclusion

The purpose of this study was to develop a regulated peak flow frequency curve for the Red River at Fargo. Due to non-stationarity and an apparent cycle in the observed stream flow record, the stream flow record was divided into a wet period and a dry period, and regulated peak flow frequency curves were developed for both data sets. Then the wet and dry period frequency curves were combined for possible future conditions to estimate the likelihood of the flow regime being wet or dry. For comparison purposes, an additional analysis that incorporated the full period of record was included. The regulated peak flow frequency curves were developed graphically by fitting a curve to the observed/estimated annual maximum peak flows versus empirical frequency estimates and synthetic floods versus their defined frequencies. The synthetic floods were developed using natural conditions volume duration frequency curves, historic hydrograph shapes patterned after floods in 2006 and 1945, an HEC-5 model to regulate flows, and an HEC-RAS model to route the regulated flows from the HEC-5 model to Fargo. Table 11 contains the regulated peak flow frequency curves at Fargo for the wet and dry periods and the possible future conditions. Table 13 contains the regulated peak flow frequency curve at Fargo for the full period of record analysis.