Appendix A-2
Hydrology

Fargo-Moorhead Metropolitan Area Flood Risk Management

Supplemental Draft Feasibility Report and Environmental Impact Statement

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Preface

This Appendix begins by providing an overview of the discussion and ensuing analysis that catalyzed the need to revise the hydrological analysis presented in Appendix A-1 in order to incorporate the effects of climate variability. This is followed by a summary of the Bois de Sioux/ Red River of the North watershed upstream of Fargo, ND. For this phase of the Fargo Moorhead Feasibility Study analysis was not updated for the portion of the watershed upstream of Hickson, ND. A schematic displaying the study area between Lake Traverse and Fargo, ND is displayed in ***Figure 1****.*

This Appendix encompasses revised analysis for the mainstem of the Red River between Hickson, ND and Grand Forks, ND. Schematics displaying the Red River reaches between Fargo, ND and Halstad, MN and Halstad, MN and Grand Forks, ND are displayed in ***Figure 2*** *and* ***Figure 3,*** *respectively. The revised analysis includes applying statistical analysis to identify a change point in the flow record at Grand Forks in order to confirm analysis carried out at Fargo in Appendix A-1c. After confirming the methodology applied at Fargo, ND the annual peak flow-frequency analysis on the mainstem of the Red River at Hickson, ND, Fargo, ND, Halstad, MN, and Grand Forks, ND were updated for the WET, 25-year Look Ahead Period, and 50-year Look Ahead Period for both the regulated- "With Dam" and unregulated- "Without Dam" conditions. At the end of this report is a discussion describing how to determine confidence limits for these scenarios. This report also includes an updated annual instantaneous peak flow-frequency analysis for the Wild Rice River-ND at Abercrombie, ND.*

In addition to carrying out flow frequency analysis for mainstem locations, this Appendix includes flow-frequency analysis representative of the coincident flows with the peak on the Red River at the mouths of significant tributaries. Coincident flow-frequency analysis was carried out for the WET (1942-2009), 25-year Look Ahead Period, and 50-year Look Ahead Period for the Wild Rice River-ND, Buffalo River, the Wild Rice River-MN, and the Sheyenne River. This Appendix also includes flow-frequency analysis for ungaged locations of interest along the Red River. For ungaged locations between Hickson and Fargo discharge frequencies were based primarily on interpolations between adopted discharge-frequencies at Fargo and Hickson. It also incorporated the coincidental flow-frequencies from the Wild Rice River-ND, Buffalo River and Wild Rice River-MN.

Flow-Frequency analysis is utilized to develop balanced hydrographs which can be used as boundary conditions for hydraulic modeling and to design hydraulic structures. This Appendix describes the methodology used to generate balanced hydrographs. The process requires the development of volume-duration relationships and the 2006 pattern event at points of interests within the study area between Hickson and Grand Forks. Volume duration analysis was carried out either directly by generating volume duration curves based on gaged mean daily flow record or indirectly by utilizing a gaged based volume duration curve located in a hydrologically similar location. The 2006 pattern hydrograph was adopted as a typical event for the Red River Basin and is used to define the timing and shape of balanced hydrographs. There are some limitations to utilizing this methodology to develop balanced hydrographs and this Appendix includes some discussion of these limitations. This Appendix also includes a summary of the initial analysis carried out to determine coincidental flow-frequency curves and balanced hydrographs at the Sheyenne River. The methodology adopted in this Appendix has been updated in Appendices A-3 to A4b.

1. Introduction

The first phase of the discharge-frequency estimates for this study included an analysis based only on the recorded events. Because of the recent record of flooding in the Red River Basin and the apparent dissimilarity between the earlier vs. latter portion of the period-of- record (POR), concerns from technical experts and local stakeholders have been expressed about the effect of climate change or variability on the homogeneity of the POR. To address these concerns the St. Paul District convened a panel of "hydro-climatic" experts to review and provide recommendations. This process follows the Corps guidelines outlined in; "Technical guide for Use of Expert Opinion Elicitation for U.S. Army Corps of Engineers Risk Assessments", **(*reference 1*)**. The results and recommendations from this panel (EOE) are presented as Appendix A-1B.

Following the conclusion of the EOE panel, the St. Paul District contracted with the U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC) to implement the EOE recommendations for the Fargo frequency curve. This analysis generates three frequency curves: one for the present climate condition labeled as WET, a second labeled as a combination of WET and DRY with 80% weight for WET and 20% weight for Dry, and a third frequency curve combination with a weight of 65% Wet and 35% DRY. The WET curve represents year one in the planning period transitioning to the second combination curve in 25 years and again a transition to the third combination curve at the end of the 50-yr planning period. A description of this methodology is presented in Appendix A-1C.

The hydraulic analysis affirmed the importance of defining the upper end of the discharge-frequency curve, especially since the project design is focused on a 500-yr event. HEC was tasked with supplementing the discharge-frequency analysis, which was based on recorded events, with synthetic events for the upper end of the curve. These events were for the 2-, 1-, 0.5-, and 0.2- exceedance frequency events. This was done not only for the set of WET and DRY curves based on their respective period of record, but also for the entire POR. Therefore, the curves presented in the first part of this appendix were updated and graphically redrawn with these additional plotting positions. HEC did this for Fargo for the POR and combination curves. The St. Paul District did this for Hickson POR curve. The plotting positions for the stations downstream of Fargo were not supplemented in this way.

2. Description of the Watershed

2.1 HEADWATERS

The Bois de Sioux River forms the eastern boundary of both Center Township and Wahpeton, which is also the state boundary between Minnesota and North Dakota. The river follows a winding course northward from White Rock Dam at Lake Traverse until it reaches a confluence with the Ottertail River at Wahpeton, where together they form the Red River of the North.

The Ottertail River rises west of Fergus Falls, Minnesota. The river flows south through a series of lakes until it reaches Ottertail Lake where it turns and flows west to its confluence with the

Bois de Sioux River at Wahpeton. This basin contains more than 1,100 lakes covering more than 15 percent of the total basin area. An additional six percent of the basin is covered by swamps and marshes. The average slope of the Ottertail River from Orwell Dam near Fergus Falls to Wahpeton is three feet per mile.

The watersheds drained by the Bois de Sioux and Ottertail Rivers lie within the former bed of Glacial Lake Agassiz. As a result, most of the Bois de Sioux watershed is a flat lowland glacial plain. The western portion of the watershed is a gently rolling upland glacial plain. The transition zone between the upland and lowland plains is composed of former beach ridges with moderate slopes. The Bois de Sioux River has an average channel slope of approximately 0.3 foot per mile between Lake Traverse and Wahpeton.

Soils in the Bois de Sioux – Ottertail River basin are lacustrine sediments, which are underlain by cretaceous shales with a thin layer of sand in the western half of the basin, and by Precambrian crystalline rocks in the eastern portion. The major land use is agricultural – approximately 91 percent of the basin is used for agricultural purposes. These include grain crops, primarily wheat and corn, and livestock. Less than one percent of the basin is forested.

2.2 WILD RICE RIVER- ND

The Wild Rice River of North Dakota flows easterly from its headwaters in western Sargent County to Lake Tewaukon. At the lake, it turns to follow a northerly course, finally reaching a confluence with the Red River of the North approximately 18 miles south of Fargo. The upper reaches of the Wild Rice River lie within a glacial upland plain. East of Lake Tewaukon, physical features of the watershed include morainic hills, large swamps, low swales and potholes. The average slope of the river is about 1.7 feet per mile; the steepest channel slopes are in the reaches above Lake Tewaukon, where it averages 4.2 feet per mile.

Soils in the Wild Rice basin are lacustrine sediments from Glacial lake Agassiz. Due to the flat topography, natural drainage is very poor. Approximately 78 percent of the watershed is cultivated, and about an additional 14 percent is used for pasture.

2.3 DRAINAGE AREAS- SOUTH OF FARGO

The drainage basin areas for the Wild Rice, Bois de Sioux, Ottertail and Red River of the North are listed in **Table 1**. **Figure 3 of Appendix A-1** shows a schematic with these areas. These drainage areas are divided into primary, secondary and non-contributing drainage areas defined as follows:

A. Primary contributing drainage area is that area which has a direct watercourse to the main stem of the river.
B. Secondary contributing drainage area is the area which begins to contribute during floods greater than the 50-year flood. Secondary contribution area is assumed to be enclosed by a 5-foot contour line on a 7.5 minute USGS topographical map.

C. Non-contributing drainage area is that area which does not contribute to flow. Non-contributing areas are assumed to be enclosed by a 10-foot or more contour line on the 7.5 minute topographical maps.

Table 1. Drainage Areas above Fargo

River	Location	Drainage Area , sq. mi.			
		Primary	Secondary	Non-contributing	Total
Bois de Sioux					
	White Rock Dam	1,160			1,160
	Local areas between White Rock and Wahpeton	807			807
	Above confluence with Ottertail River	1,967			1,967
Ottertail					
	Above Orwell	245		1,585	1,830
	Local area between Orwell & Wahpeton	213		1,585	2,043
	Mouth (Wahpeton)	458			213
Red River of the North					
	USGS Gage @ Wahpeton	2,425		1,585	4,010
	Hickson	2,715		1,585	4,300
Wild Rice- ND					
	Near Mantador	687	120	550	1,357
	CSAH 13 near Wahpeton	895	120	590	1,605
	Abercrombie	1,370	120	590	2,080
Red River					
	Local area between Hickson, Abercrombie, & Fargo	420			420
	Fargo	4,505	120	2,175	6,800

2.4 FLOODING IN THE RED RIVER BASIN

Several different factors cause flooding in the Red River basin. Geomorphologic factors combined with meteorological factors determine the severity of flooding.

The Red River is located in a flat plain, has a shallow, meandering river channel and flows northward. As a result of these landform factors, the timing of spring snowmelt can greatly aggravate flooding in the Red River Basin. Snow in the upstream (southern) portion of the basin melts first, while the downstream (northern) portion of the river remains frozen. This melt pattern increases the likelihood of backwater effects caused by ice jams and frozen river-channel ice. Additionally, the Red River's gentle channel slope of only 0.5 to 1.5 feet per mile (on average) inhibits channel flow and encourages overland flooding.

Spring floods are primarily snowmelt driven. Spring flooding is caused when the basin experiences above-normal fall precipitation followed by the freezing of the saturated ground in either late fall or early winter, before significant snowfall has occurred. These conditions produce a dense layer of frost that limits infiltration of runoff during spring snowmelt. Above normal winter snowfall, precipitation during snowmelt, and high temperatures during snowmelt cause increased flood risk. Summer Floods are caused by intense precipitation, saturated ground and limited vegetative cover. These factors lead to less absorption of water and more runoff (USGS).

3. Nomenclature

Evaluation of the flow characteristics for the Red River of the North at Fargo, ND can be categorized in terms of two conditions. One is with Lake Traverse (White Rock) Dam and Orwell Dam in place. The other condition is without these dams in place. The first section designates these conditions as "regulated" and "natural" conditions, respectively. Phase II of the hydrologic analysis changed the "natural" designation to "unregulated" condition. The without dams condition is interchangeably referred to as the "without dam," "natural" and "unregulated" condition. The with dams condition is interchangeably referred to as the "with dam" or "regulated" condition.

4. Reach Routing Parameters

The Hec-5 model ***(reference 2***) used the Straddle-Stagger method of routing for "with and without dams" flows. The model routed historic events and the synthetic events down to Fargo. The parameters were based on previous studies done on the Red, most notably the "Volume I, Timing Analysis" **(*reference 3*)**. **Table 2** lists the parameter values for each reach.

Table 2. Hec-5 Reach Routing Parameters

REACH	STRADDLE	STAGGER
Lake Traverse to Wahpeton	3	1
Orwell to Wahpeton	3	1
Wahpeton to Hickson	5	2
Hickson to Fargo	3	1
Abercrombie to Fargo	5	2

5. Flow-Frequency Analysis

5.1 ANNUAL PEAK FLOW-FREQUENCY ANALYSIS- MAIN STEM RED RIVER

Station statistics and flow frequencies were determined for the following USGS gage stations on the main stem of the Red River of the North: Hickson, Fargo, Halstad, and Grand Forks.

5.1.1 Period of Record Based Analysis

The methodology described in Bulletin 17b **(*reference 4*)** was used to develop the POR curves for the unregulated flow-frequency curves at Fargo, Halstad and Grand Forks. The regulated flow-frequency curve for the POR at Fargo was supplemented with synthetic events. Appendix A-1C describes the methodology.

As described in **Section 4.3** of **Appendix A-1** the USGS gage for the Red River at Hickson, has a relatively short period of record (from 1976 to present). The record at Hickson was back-extended using reconstituted flows from HEC-5 for the regulated condition for the period from 1942 to 1975. The HEC-5 model also generated flows for the unregulated condition from 1942 to present.

To develop the full period of record curve at Hickson as displayed in **Figure 6**, the Hickson event flows were correlated to the long term station at Fargo by assigning plotting positions equivalent to Fargo event plotting positions for the concurrent period and corresponding rank (this methodology is described in greater detail in **Appendix A-1**). To define the upper end of the regulated flow-frequency curve at Hickson, synthetic flood events were determined using the HEC-HMS **(*reference 5*)** model for the 2-, 1-, 0.5-, and 0.2- percent exceedance frequency events. The methodology used to develop these synthetic events is the same as the method used to develop synthetic events at Fargo as described in Appendix A-1C**.** Table 3 lists the peak flows at Hickson for the synthetic flood events. The regulated peak flow-frequency curve at Hickson was developed graphically by fitting a curve to the equivalent annual maximum peaks plotted using the Fargo array and the synthetic floods plotted against their specified frequencies.

Table 3. Regulated Peak Flows at Hickson for Synthetic Floods- POR

Red River of the North @ Hickson	
Annual Instantaneous Peaks	
Synthetic Results- Full Period of Record	
Event	**Flow (cfs)**
500-yr	35,000
200-yr	28,300
100-yr	23,100
50-yr	19,000

Table 4 and **Table 5** lists annual discharge frequency flows and statistics for the unregulated condition based on the period of record (POR) at each gage. The unregulated POR tables represent the annual instantaneous and annual mean daily peak flows, respectively. **Table 6** was developed for the regulated condition. The Flow-Frequency curves for the unregulated and regulated POR at Fargo can be found in **Figure 20** of **Appendix A-1C**.

Figure 4- Figure 6 displays the flow-frequency curves for the POR at Grand Forks, Halstad and Hickson, respectively.

Table 4. Summary Table Statistics- POR Without Dams, Instantaneous Peak Discharge Frequency

Location	Mean Log	Standard Deviation	Adopted Skew	Discharge-Frequency (cfs) % Chance Exceedance				
				10	2	1	0.5	0.2
Hickson[1,2]	3.5272	0.4456	-0.3380	12,000	22,900	28,300	34,200	42,600
Fargo[2]	3.6113	0.4746	-0.2027	16,152	34,183	44,104	55,442	72,746
Halstad[1]	3.9756	0.3994	-0.2674	29,800	54,600	66,900	80,200	99,200
Grand Forks	4.2124	0.3931	-0.2678	50,500	91,700	112,000	134,000	165,000

[1] Two-station comparison
[2] Without-dams condition

Table 5. Summary Table Statistics - POR Without Dams, Mean Daily Peak Discharge Frequency

Location	Mean Log	Standard Deviation	Adopted Skew	Discharge-Frequency (cfs) % Chance Exceedance				
				10	2	1	0.5	0.2
Hickson[1,2]	3.5014	0.4469	-0.338	11,400	21,700	26,900	32,400	40,400
Fargo[2]	3.6004	0.4761	-0.1910	15,848	33,788	43,725	55,124	72,597
Halstad[1]	3.9571	0.4107	-0.2935	29,400	54,300	66,600	79,800	98,700
Grand Forks	4.2035	0.3943	-0.2600	49,719	90,631	110,864	132,695	164,015

[1] Two-station comparison
[2] Without-dams condition

Table 6. Summary Table Statistics – POR *With Dams*, Instantaneous Peak Discharge Frequency

Location	Mean Log	Standard Deviation	Adopted Skew	Discharge-Frequency (cfs) % Chance Exceedance				
				10	2	1	0.5	0.2
Hickson[1,2]		Graphical		8,400	19,014	23,093	28,302	34,974
Fargo[2]		Graphical		13,865	26,000	33,000	43,500	66,000
Halstad[1]	3.9756	0.3994	-0.2674	29,800	54,600	66,900	80,200	99,200
Grand Forks	4.2124	0.3931	-0.2678	50,500	91,700	112,000	134,000	165,000

[1] Two-station comparison
[2] With-dams condition

For the POR curves, a main stem study of skew was performed so that the curves are consistent in their values from upstream to downstream. The station skews were plotted vs. mean. Three different smoothing schemes were looked at including a regression least squares fit and estimates based on 50 percent station skew and 50 percent regression based skew. The Grand Forks station skew was adopted as a regional skew value to weight with the station skews at Fargo and Halstad. The Grand Forks skew was chosen because it is the long-term station on the Red River. Station skew at Hickson was weighted with regional skew values published in the Minnesota USGS publication, "Generalized Skew Coefficients for Flood-Frequency Analysis in Minnesota" **(reference 6**).

5.1.2 Combined Curves - EOE Based Analysis

Table 7, **Table 8, and Table 9** present summaries for the WET, 25-yr, and 50-year look-ahead conditions at Fargo, Grand Forks, Halstad and Hickson. These curves represent the regulated condition. The WET, 25-yr, and 50-year look-ahead flow-frequency curves were derived based on the EOE recommendations and the guidance given by HEC. For these conditions, only the instantaneous peak flow summaries are provided in the tables.

Table 10, Table 11, and **Table 12** present summaries for the WET, 25-yr, and 50-year look-ahead conditions at Fargo, Grand Forks, and Halstad. These curves are representative of the unregulated condition. The effects of the reservoirs diminish considerably downstream of Fargo, ND due to increasing incremental drainage area. Therefore, Grand Forks and Halstad are not affected by regulatory effects and are thus the same for both the regulated and unregulated condition. Unregulated curves at Hickson were not generated in this phase of the project instead simplifying assumptions were used to generate the required flow-frequency data at that location. This will be further explained in **Section 5.1.4**. The WET, 25-yr, and 50-year look-ahead flow-frequency curves were derived based on the EOE recommendations and the guidance given by HEC. For these conditions, only the instantaneous peak flow summaries are provided in the tables.

Appendix A-1C developed by HEC, which precedes this section of the report describes the methodology used to develop the flow-frequency curves for the WET, 25-Year combined and 50-Year combined curves at Fargo, ND. The plotted flow-frequency curves at Fargo, ND for both the regulated and unregulated condition can be found in the Appendix A-1C in **Figure 14 - Figure 20**. The following sections describe how the corresponding flow frequency curves were developed for gaged locations at Grand Forks, Hickson, and Halstad.

Table 7. Summary Table Statistics – WET With Dams, Instantaneous Peak Discharge Frequency

Location	Mean Log	Standard Deviation	Adopted Skew	Discharge-Frequency (cfs) % Chance Exceedance				
				10	2	1	0.5	0.2
Hickson[1,2,3]		Graphical		10,500	19,000	22,000	28,500	37,000
Fargo[2]		Graphical		17,000	29,300	34,700	46,200	61,700
Halstad[1]	4.099	0.356	-0.2940	34,871	59,306	70,798	82,872	99,713
Grand Forks	4.352	0.320	-0.2870	56,354	91,026	106,838	123,201	145,675

[1] Two-station comparison; [2]With-dams condition; [3]Revised with Hydraulics Guidance

Table 8. Summary Table Statistics – 25-yr Look-Ahead *With Dams*, Instantaneous Peak Discharge Frequency

Location	Mean Log	Standard Deviation	Adopted Skew	Discharge-Frequency (cfs) % Chance Exceedance				
				10	2	1	0.5	0.2
Hickson[1,2]		Graphical		9,555	19,709	23,757	26,164	30,016
Fargo[2]		Graphical		15,394	27,441	32,921	42,242	57,641
Halstad[1]	4.0408	0.3740	-0.3070	32,771	57,006	68,501	80,649	97,734
Grand Forks	4.2990	0.3362	-0.2976	53,213	87,782	103,682	120,244	143,205

[1] Two-station comparison; [2]With-dams condition

Table 9. Summary Table Statistics – 50-yr Look-Ahead *With Dams*, Instantaneous Peak Discharge Frequency

Location	Mean Log	Standard Deviation	Adopted Skew	Discharge-Frequency (cfs) % Chance Exceedance				
				10	2	1	0.5	0.2
Hickson[1,2]		Graphical		8,710	18,543	22,626	24,116	28,246
Fargo[2]		Graphical		13,965	25,764	31,304	38,787	54,034
Halstad[1]	3.9880	0.3970	-0.3407	30,963	54,989	66,482	78,692	95,991
Grand Forks	4.2517	0.3569	-0.3308	50,530	84,960	100,932	117,667	141,059

[1] Two-station comparison; [2]With-dams condition

Table 10. Summary Table Statistics – WET *Without Dams*, Instantaneous Peak Discharge Frequency

Location	Mean Log	Standard Deviation	Adopted Skew	Discharge-Frequency (cfs) % Chance Exceedance				
				10	2	1	0.5	0.2
Fargo	3.802	0.415	-0.307	20,808	38,445	47,153	56,524	69,914
Halstad	4.099	0.356	-0.294	34,871	59,306	70,798	82,872	99,713
Grand Forks	4.352	0.320	-0.287	56,354	91,026	106,838	123,201	145,675

Table 11. Summary Table Statistics – 25-yr Look-Ahead *Without Dams*, Instantaneous Peak Discharge Frequency

Location	Mean Log	Standard Deviation	Adopted Skew	Discharge-Frequency (cfs) % Chance Exceedance				
				10	2	1	0.5	0.2
Fargo	3.6879	0.4680	-0.3791	18,627	35,744	44,250	53,407	66,504
Halstad	4.0408	0.3740	-0.3070	32,771	57,006	68,501	80,649	97,734
Grand Forks	4.2990	0.3362	-0.2976	53,213	87,782	103,682	120,244	143,205

Table 12. Summary Table Statistics – 50-yr Look-Ahead Without Dams, Instantaneous Peak Discharge Frequency

Location	Mean Log	Standard Deviation	Adopted Skew	Discharge-Frequency (cfs) % Chance Exceedance				
				10	2	1	0.5	0.2
Fargo	3.5874	0.5146	-0.4349	16,720	33,326	41,640	50,596	63,420
Halstad	3.988	0.397	-0.3407	30,963	54,989	66,482	78, 692	95,991
Grand Forks	4.2517	0.3569	-0.3308	50, 530	84,960	100,932	117,667	141,059

5.1.3 Flow Frequency Analysis at Grand Forks

As stated in **Appendix A-1,** USGS gaging station 05082500 at Grand Forks, ND is the long-term station on the Red River below the Canadian border. It can be assumed as stated in **Appendix A-1**, that the flows at Grand Forks are not affected by the regulatory effects of the upstream dams. **Table 13** lists annual instantaneous peak flows for the Red River at Grand Forks and **Figure 7** graphically displays this record. Like Fargo, the observed streamflow record at Grand Forks post-1900 suggests an upward trend. However, large events prior to the turn of the century support the theory that cycles between wet and dry periods have been experienced in the Red River of the North basin.

To reflect the cyclic nature of the flow regime at Grand Forks, flow-frequency analysis at Grand Forks was carried out using the same methodology as used in the analysis at Fargo, ND. The annual instantaneous peak discharge-frequency curves for future conditions for the Red River of the North at Grand Forks were based upon the observed streamflows from 1882 through 2009. Historic values for 1826, 1852, and 1861 were not incorporated into the analysis, but were used to further substantiate the cyclic nature of the flow regime in the region.

Table 13. Annual Inst. Peak flows for USGS gaging station 05082500 the Red River at Grand Forks.

Water Year	Stream-flow (cfs)	Water Year	Stream-flow (cfs)	Water Year	Stream-flow (cfs)
1882	75,000	1927	10,600	1972	31,400[6]
1883	38,600	1928	12,200	1973	11,300[6]
1884	20,600	1929	17,100	1974	34,300[6]
1885	13,040	1930	9,610	1975	42,800[6]
1886	10,800	1931	1,630	1976	23,600[6]
1887	7,300	1932	10,400	1977	2,190[6]
1888	19,000	1933	4,380	1978	54,200[6]
1889	3,000	1934	3,210	1979	82,000[6]
1890	3,470	1935	2,920	1980	22,000[6]
1891	6,000	1936	14,500	1981	6,710[6]
1892	23,000	1937	4,180	1982	23,900[6]
1893	53,300	1938	6,660	1983	14,300[6]
1894	16,450	1939	6,720	1984	32,300[6]
1895	2,000	1940	10,000	1985	17,800[6]
1896	21,600	1941	13,400[6]	1986	31,900[6]
1897	85,000	1942	11,000[6]	1987	17,500[6]
1898	4,500	1943	28,200[6]	1988	8,500[6]
1899	9,000	1944	10,400[6]	1989	39,600[6]
1900	4,000	1945	21,300[6]	1990	5,040[6]
1901	14,000	1946	22,000[6]	1991	4,870[6]
1902	15,000	1947	35,000[6]	1992	8,000[2,6]
1903	18,800	1948	34,200[6]	1993	26,200[6]
1904	33,000	1949	15,200[6]	1994	26,800[6]
1905	16,800	1950	54,000[6]	1995	34,800[6]
1906	27,600	1951	23,600[6]	1996	58,400[6]
1907	30,400	1952	23,900[6]	1997	137,000[6]
1908	20,500	1953	14,600[6]	1998	29,700[6]
1909	9,260	1954	9,620[6]	1999	50,000[6]
1910	18,500	1955	15,400[6]	2000	31,500[6]
1911	3,520	1956	21,400[6]	2001	57,800[6]
1912	4,730	1957	14,700[6]	2002	38,000[6]
1913	17,200	1958	7,500[6]	2003	17,000[6]
1914	8,240	1959	6,300[6]	2004	34,300[6]
1915	21,500	1960	17,200[6]	2005	38,300[6]
1916	29,000[2]	1961	3,400[6]	2006	72,800[6]
1917	19,800	1962	26,600[6]	2007	35,300[6]
1918	4,480	1963	10,800[6]	2008	17,700[6]
1919	13,600	1964	13,200[6]	2009	80,000[6]
1920	30,300	1965	52,000[6]		
1921	11,500	1966	55,000[6]	**Superscripts**	
1922	19,000[2]	1967	28,200[6]	[6]Effected by regulation	
1923	16,200	1968	9,420[6]	[2]Discharge is estimate	
1924	2,530	1969	53,500[6]		
1925	9,690	1970	23,700[6]		
1926	7,720	1971	15,800[6]		

Notes: 1997 was recorded at 137,000 cfs but 114,000 cfs adopted for Q-frequency analysis & 2009 estimated by COE

As described in the HEC Appendix A-1C, the non-parametric Pettitt test (***reference 7***) was used to determine the best break point in the data record at Grand Forks. **Figure 8** displays the p-value or significance of a possible break point at each year. The results suggest that the year 1942 is the break point with the greatest evidence of the record containing two different flow regimes. This analysis was done as a sensitivity test to confirm that other gages in the basin had a similar statistically determined change point as the flow record at the Fargo, ND gage.

To be consistent with the analysis done at Fargo, 1941 was used as the change point for the analysis at Grand Forks. The wet portion of the curve consisted of the portion of the record from 1942 to 2009 and the dry portion of the record consisted of the portion of the record from 1882 to 1941. Flow-frequency analysis was done for the wet and dry portions of the period of record using a Log Pearson Type III distribution. It is appropriate to use a Log Pearson Type III distribution because flows at Grand Forks are considered unaffected by upstream regulation. Station skew and the median plotting position were used to generate the curves. The wet and dry portions of the record were weighted using the method described in the HEC Appendix A-1C and combined using interpolation in order to produce the 25-year and 50-year look-ahead curves. The flow frequency curve for both wet and dry conditions and the 25-year future condition and the 50-year future condition are plotted in **Figure 9, Figure 10**, and **Figure 11**, respectively.

5.1.4 Flow Frequency Analysis at Hickson

As described in **Section 4.3** of **Appendix A-1** the USGS gage for the Red River at Hickson, has a relatively short period of record (from 1976 to present). The record at Hickson was back-extended using HEC-5 (***reference 2***) output for regulated flows from 1942 to 1975. The back-extended record was combined with the observed streamflow record to develop an equivalent streamflow record for the wet portion of the period of record (1942-2009). These values are in **Table 14**. The regulated flows in this table vary slightly from those presented in **Appendix A-1, Table 22** because a correction was made for the routing parameters between Wahpeton and Hickson. This affected flows that were reconstituted from 1942 to 1975. Flows since 1975 were unadjusted and used as recorded. The flows in the following table are now the adopted flows.

Table 14. Equivalent Annual Instantaneous Peak Flow Record at Hickson

Water Year	Stream-flow (cfs)	Water Year	Stream-flow (cfs)	Water Year	Stream-flow (cfs)
1942	4,318	1965	7,152	1988	826
1943	6,631	1966	5,945	1989	12,900
1944	5,851	1967	3,320	1990	857
1945	5,041	1968	954	1991	2,820
1946	4,049	1969	11,639	1992	1,750
1947	5,990	1970	1,870	1993	6,400
1948	2,950	1971	1,172	1994	6,320
1949	3,003	1972	4,438	1995	8,000
1950	5,477	1973	1,607	1996	6,290
1951	7,556	1974	1,706	1997	13,300
1952	9,248	1975	5,098	1998	4,590
1953	3,854	1976	2,500	1999	3,700
1954	2,381	1977	408	2000	2,750
1955	1,475	1978	9,200	2001	11,500
1956	2575	1979	9,600	2002	3,780
1957	3,017	1980	3,250	2003	4,390
1958	1,150	1981	544	2004	3,140
1959	1,368	1982	4,200	2005	7,090
1960	2,950	1983	824	2006	14,400
1961	720	1984	5,100	2007	9,410
1962	6,834	1985	3680	2008	3,910
1963	5,150	1986	6,720	2009	22,600
1964	2,092	1987	2,460		

The regulated peak flow frequency curve for the wet portion of the period of record for the Red River of the North at Hickson was developed iteratively. For the first iteration the curve was determined graphically using the equivalent streamflow record described above and synthetic floods (based on the output from the HEC-HMS model). This first iteration was used as a starting point and then was revised during a second iteration using guidance received from the hydraulic modeling team.

The flow gages at Hickson and Fargo are located in hydrologically similar areas. Model based synthetic events were only generated for the POR at Hickson. The percent differences between the magnitudes of the synthetic events at Fargo for the POR and the wet portion of the period of record were determined. The percent differences were applied to the synthetic results for POR at Hickson to determine the equivalent synthetic events for the wet portion of the period of record at Hickson. **Table 15** contains the equivalent synthetic events for the wet portion of the record at Hickson.

Table 15. Peak flows at Hickson derived from peak flows at Fargo for the Wet portion of the period of Record.

Red River of the North @ Hickson	
Annual Instantaneous Peaks	
Computed Synthetic Results- Wet Portion of Record*	
Exceedance Frequency	
Event	Flow (cfs)
0.2 %	32,618
0.5 %	30,056
1.0 %	24,317
2.0 %	21,399

The regulated WET peak flow frequency curve for the Red River at Hickson was developed graphically by fitting a curve to the equivalent observed annual maximum peaks plotted against empirical frequency estimates and the equivalent synthetic floods plotted against their specified frequencies.

No "dry" curve exists for the flow record at Hickson so the method used at Fargo cannot be used for the gage at Hickson to get the 25-year and 50-year look-ahead curves. In order to generate the combined curves it was again necessary to use the assumption that Hickson and Fargo are located in hydrologically similar areas. Based on this assumption the percent differences between the wet curve at Fargo and the combined curves at Fargo could be used to translate the wet curve at Hickson into the 25-year combined curve and the 50-year combined curve at Hickson. The graphically fit regulated curves at Fargo were used for this purpose. The flow frequency curve for the WET condition at Hickson is plotted in **Figure 12.** The future scenario frequency curves are shown in **Figure 13** and **Figure 14**.

Based on guidance provided by unsteady HEC-RAS modelers, the upper end of the graphical WET flow-frequency curve at Hickson was revised to reflect insight gained from hydraulic modeling. The final adopted curve is displayed in **Figure 15**.

5.1.5 Flow-Frequency Analysis at Halstad, MN

Annual Instantaneous Peak Flow data is recorded by USGS gage 05064500 at Halstad, MN. As can be seen in **Table 16**, the observed instantaneous annual peak flow record at Halstad only extends back to 1936.

Table 16. Recorded Annual Peak Discharges for Red River @ USGS Gage 05064500 at Halstad, ND

Water Year	Stream-flow (cfs)	Water Year	Stream-flow (cfs)	Water Year	Stream-flow (cfs)
1936	7,670	1963	5,850[6]	1986	17,400[6]
1937	2,660	1964	7,820[6]	1987	9,860[6]
1942	5,060[6]	1965	25,600[6]	1988	5,010[6]
1943	21,800[6]	1966	26,800[6]	1989	26,000[6]
1944	7,200[6]	1967	13,800[6]	1990	2,880[6]
1945	13,300[2,6]	1968	2,350[6]	1991	3,700[6]
1946	10,000[6]	1969	35,700[6]	1992	5,200[2,6]
1947	24,500[6]	1970	11,600[6]	1993	22,500[6]
1948	16,000[6]	1971	5,480[6]	1994	16,600[6]
1949	7,710[6]	1972	16,200[6]	1995	23,300[6]
1950	18,700[6]	1973	6,200[6]	1996	25,200[6]
1951	12,900[6]	1974	17,800[6]	1997	71,500[6]
1952	20,700[6]	1975	39,900[6]	1998	19,200[6]
1953	13,600[6]	1976	9,950[6]	1999	18,100[6]
1954	4,660[6]	1977	2,050[6]	2000	29,100[6]
1955	7,200[6]	1978	28,800[6]	2001	37,900[6]
1956	12,900[6]	1979	42,000[6]	2002	15,000[6]
1957	4,980[6]	1980	12,900[6]	2003	11,900[6]
1958	4,420[6]	1981	3,920[6]	2004	18,200[2,6]
1959	3,780[6]	1982	13,200[6]	2005	21,300[6]
1960	8,600[6]	1983	7,800[6]	2006	43,100[6]
1961	1,900[6]	1984	21,900[6]	2007	24,700[6]
1962	15,900[6]	1985	10,400[6]	2008	15,300[6]
				2009	68,800

[2]*Discharge is an Estimate*
[6]*Discharge is affected by Regulation or Diversion*

A "Wet" flow-frequency curve could be developed at Halstad using the observed peak streamflow record from 1942 to 2009. The "Wet" curve at Halstad was plotted using a Log-Pearson Type III as outlined in Bulletin 17b. Median plotting positions and station skew were used for analysis. Due to the abbreviated POR at Halstad no "Dry" curve can be developed from the flow record, so the method used at Fargo cannot be used for get the 25-year and the 50-year combined look-ahead curves.

The USGS gage on the Red River of the North at Halstad is located downstream of the USGS gage at Fargo and upstream of the USGS gage at Grand Forks. To develop the combined curves at Halstad a linear regression was performed using the <u>unregulated</u> flow-frequency curves at

Fargo and the flow-frequency curves at Grand Forks. This regression relationship is displayed in **Figure 16**.

Relationships were developed between the difference between the “Wet” and “Combined” flow frequency curves and the logarithm of the drainage area associated with these two locations. An example of the regression analysis can be found in A linear relationship was developed at each exceedance probability. Using the drainage area at Halstad and the known “Wet” flow-frequency curve at Halstad these relationships could be used to determine the combined flow-frequency curves at Halstad. The WET and the combined 25-year and 50-year look-ahead curves at Halstad can be found in **Figure 17**, **Figure 18**, and **Figure 19**, respectively.

5.2 ANNUAL PEAK FLOW-FREQUENCY ANALYSIS – TRIBUTARIES

To build an adequate steady state HEC-RAS model ***(reference 8)*** for the project area it was necessary to develop flow-frequency curves based on the annual instantaneous peak flows for the Wild Rice Tributary, ND. Peak flows from the Wild Rice were derived from flows at the Abercrombie gage just upstream of the confluence. As indicated by **Table 17,** the observed streamflow record at Abercrombie extends back to 1933.

Table 17. Annual Instantaneous Streamflow Data for USGS Gage 05053000 Wild Rice River-ND near Abercrombie, ND

Water Year	Stream-flow (cfs)	Water Year	Stream-flow (cfs)	Water Year	Stream-flow (cfs)
1933	57.0	1959	222[6]	1985	1,210[6]
1934	15.0	1960	640[6]	1986	2,210[6]
1935	513	1961	36.0[6]	1987	701[6]
1936	415	1962	3,610[6]	1988	105[6]
1937	540	1963	1,460[6]	1989	7,150[6]
1938	318	1964	415[6]	1990	74.0[6]
1939	1,350	1965	2,820[6]	1991	410[6]
1940	300	1966	2,850[6]	1992	1,000[6]
1941	608	1967	2,050[6]	1993	3,630[6]
1942	579	1968	127[6]	1994	2,430[6]
1943	5,500	1969	9,540[6]	1995	3,730[6]
1944	956	1970	556[6]	1996	3,260[6]
1945	2,840	1971	508[6]	1997	9,470[6]
1946	2,320	1972	2,100[6]	1998	3,770[6]
1947	2,450[1]	1973	426[6]	1999	1,690[6]
1948	729	1974	630[6]	2000	676[6]
1949	650[2]	1975	3,500[6]	2001	9,320[6]
1950	2,300	1976	870[6]	2002	1,010[6]
1951	1,890	1977	91.0[6]	2003	2,250[6]
1952	5,400	1978	4,900[6]	2004	2,630[6]
1953	2,500	1979	6,000[6]	2005	2,810[6]
1954	800	1980	1,800[6]	2006	9,180[6]
1955	550[2]	1981	25.8[6]	2007	6,030[6]
1956	750	1982	1,550[6]	2008	1,480[6]
1957	408	1983	265[6]	2009	14,100[6]
1958	262[6]	1984	2,970[6]		

[2]Discharge is an Estimate
[6]Discharge is affected by Regulation or Diversion

A flow-frequency analysis was carried out using HEC-SSP **(*reference 9*)** for both the POR and the WET portion of the record (1942-2009) at Abercrombie. A weighted skew coefficient was used to carry out this analysis. The regional skew at Abercrombie was set at -0.23, based on the St. Paul District Army Corps. Of Engineers regional skew map **(*reference 10*)**. The mean squared error associated with this skew is 0.125. The median plotting position was used.

Because of the short period of record, a "dry" curve cannot be generated for the peak flow record at Abercrombie so the method used at Fargo cannot be used to determine the 25-year and 50-year look-ahead curves. In order to generate these combined curves it was necessary to use the assumption that Abercrombie and Fargo are located in hydrologically similar areas. Based on this assumption the percent differences between the wet curve at Fargo and the combined curves at Fargo could be used to translate the wet curve at Abercrombie into the 25-year combined curve and the 50-year combined curve at Abercrombie. The analytically fit unregulated curves at Fargo were used for this purpose. **Table 18** lists the flow-frequency values and statistics (where generated) for the POR, WET and weighted combined curves. The corresponding POR, WET, 25-yr look-ahead and 50-yr look-ahead plots can be found in **Figure 20, Figure 21, Figure 22, and Figure 23**, respectively.

Table 18. Peak Annual Flow-Frequency Curves for the Wild Rice Tributary, ND

Exceed. Prob	Wild Rice Tributary, ND Annual Inst. Peaks, cfs			
	POR	Wet Period	Comb- 25 yr	Comb- 50 yr
0.99	30	46	36	27
0.9	180	248	184	120
0.5	1,196	1,459	1,193	825
0.2	3,508	3,983	3,524	2,766
0.1	5,852	6,415	5,818	4,808
0.05	8,705	9,283	8,571	7,334
0.02	13,250	13,716	12,844	11,300
0.01	17,264	17,538	16554	14,797
0.005	21,765	21,743	20,646	18,670
0.002	28,440	27,863	26,614	24,346
LPIII Statistics				
Years of Record	78	68		
Mean	3.037	3.126		
St. Dev.	0.594	0.555		
Adopted Skew	-0.413	-0.419		

5.3 FLOW-FREQUENCY ANALYSIS- COINCIDENT FLOWS-TRIBUTARIES

Coincidental peak flows from the Wild Rice Tributary, ND, Wild Rice Tributary, MN and the Buffalo River for corresponding peak flows on the Red River were determined and flow-frequency curves were developed for the POR, WET, and future conditions (25-year look-ahead and 50-year look-ahead). The values associated with these curves can be found in **Table 19**.

Table 19. Flow-Frequency Curves for Coincident Flows for Corresponding Peaks on the Red River

Combined Coincidental Flows											
Exceedance Frequency	Wild Rice River, MN USGS Gage 05064000 at Hendrum, MN			Buffalo River Reference Gage USGS Gage 05062000 NR Dilworth, MN				Wild Rice River, ND USGS Gage 05053000 NR Abercrombie, ND			
	Wet POR Period (cfs)	25 yr (cfs)	50 yr (cfs)	POR	Wet Period (cfs)	25 yr (cfs)	50 yr (cfs)	POR	Wet Period (cfs)	25 yr (cfs)	50 yr (cfs)
0.90	682	480	400		246	183	157		9	8	8
0.75	1,263	937	765		579	443	370		240	190	163
0.50	2,348	1,894	1,569	1,096	1,312	1,076	903	950	1,419	1,148	957
0.25	4,089	3,550	3,095		2,615	2,288	2,009		2,587	2,245	1,958
0.2	4,647	4,102	3,618	2,701	3,061	2,719	2,413	3,700	3,021	2,691	2,375
0.1	6,393	5,798	5,272	4,073	4,431	4,036	3,684	5,900	6,185	5,658	5,185
0.05	8,165	7,547	6,993	5,550	5,809	5,385	5,004	8,400	8,649	8,057	7,520
0.02	10,547	9,894	9,304	7,623	7,604	7,149	6,738	11,700	11,655	10,980	10,367
0.01	12,373	11,703	11,096	9,256	8,923	8,457	8,033	13,500	13,780	13,134	12,545
0.005	14,211	13,524	12,900	10,928	10,198	9,721	9,288	15,000	15,801	14,577	13,500
0.002	16,652	15,942	15,296	13,174	11,804	11,318	10,875	18,000	18,342	17,264	16,300

5.3.1 Coincident Flows from the Wild Rice Tributary, ND

Coincidental peak flows from the Wild Rice tributary for corresponding peak flows on the Red River at Fargo were derived from flows at the Abercrombie gage just upstream of the confluence with the Wild Rice River and the Red River (as is described in **Appendix A-1**). **Table 20** in **Appendix A-1** lists the coincident data flow series. Coincident flows at Abercrombie can be assumed to be representative of the flow record at the mouth of the Wild Rice River because of Abercrombie's close proximity to the confluence of the Red River and the Wild Rice River (ND).

The coincidental flow frequencies for the POR for the Wild Rice Tributary can be found in **Table 19.** The corresponding flow-frequency curve can be found in **Figure 24**.

The coincident flow record at Abercrombie is limited to 1933-2009. A graphical flow-frequency curve for the WET portion of the record was developed using the observed coincident flow record plotted using Weibull plotting positions. The values corresponding to the WET flow-frequency curve for the Wild Rice Tributary, ND can be found in **Table 19**. The corresponding flow-frequency curve is displayed in **Figure 25**.

Because of the short period of record, a "dry" curve cannot be generated for the coincident flow record at Abercrombie, so the method used at Fargo cannot be used to get the 25-year and 50-year look-ahead curves. To generate the combined curves, it was necessary to use the assumption that Abercrombie and Fargo are located in hydrologically similar areas. Based on this assumption the percent differences between the wet curve at Fargo and the combined curves at Fargo could be used to translate the wet curve at Abercrombie to the 25-year combined curve and the 50-year combined curve at Abercrombie. The graphically fit regulated curves at Fargo were used for this purpose. The values corresponding to the 25-year and 50-year look-ahead flow-frequency curves can be found in **Table 19**. The future scenario frequency curves are shown in **Figure 26** and **Figure 27**.

5.3.2 Coincidental Flows from the Buffalo River Tributary

Coincidental peak flows from the Buffalo River tributary for corresponding peak flows on the Red River at Fargo were derived from flows at USGS gage 0506200 at Dilworth, MN upstream of the confluence of the Buffalo River and the Red River. **Table 20** lists the coincident flow data series.

The flow-frequency curve for the POR at Dilworth was developed using the observed coincidental flows at Dilworth. The coincident flow record at Dilworth is limited to 1931-2009. A flow-frequency curve for the WET portion of the Record could be developed using the observed coincident flow record. It was found that a Log-Pearson Type III distribution fit the observed coincident flow record when plotted using the median plotting position.

Because Dilworth is located a significant distance upstream of the Buffalo River's confluence with the Red River of the North as can be seen in **Figure 28,** for both the POR and the WET flow frequency curves at Dilworth the curves had to be transferred to the mouth of the Buffalo River. This was done using the general relations methodology. This technique uses a drainage area ratio relating the drainage area at Dilworth to the drainage area associated with the confluence of the Buffalo River with the Red River. This drainage area ratio was raised to an exponent based on the logarithmic relationship between the POR flow-frequency curves at the Dilworth USGS gage and USGS gage 05061500 on the South Branch of the Buffalo River at Sabin and their associated drainage area ratio**.** The locations of these two USGS gages are displayed in **Figure 28.**

Table 21 contains the values used to transfer flows from Dilworth to the confluence of the Buffalo River with the Red River for both the POR and the WET flow-frequency curves.

Because of the short period of record, a “dry” curve cannot be generated for the coincident flow record at Dilworth so the method used at Fargo cannot be used to generate the 25-year and 50-year look-ahead curves. To generate the combined curves it was necessary to use the assumption that the confluence of the Buffalo River with the Red River and the Fargo gage are located in hydrologically similar areas. Based on this assumption the percent differences between the wet curve at Fargo and the combined curves at Fargo could be used to translate the wet curve at the mouth of the Buffalo River to the 25-year combined curve and the 50-year combined curves. Because an analytical curve had been used to fit the wet portion of the curve at Dilworth, the analytically fit unregulated curves at Fargo were used for this purpose. The values corresponding to the POR, 25-year and 50-year look-ahead flow-frequency curves can be found in **Table 19**. The WET and future scenario frequency curves are shown in **Figure 29, Figure 30, and Figure 31**.

Table 20. Coincidental Flows, based on the Mean daily flows recorded by USGS Gage 05062000 on the Buffalo River NR Dilworth, MN

Water Year	Coincidental Flow, cfs	Water Year	Coincidental Flow, cfs	Water Year	Coincidental Flow, cfs
1931	36	1961	64	1991	260
1932	276	1962	4,400	1992	385
1933	248	1963	511	1993	1,310
1934	374	1964	1,110	1994	971
1935	227	1965	2,950	1995	1,,310
1936	1,180	1966	3,390	1996	2,350
1937	295	1967	783	1997	5,410
1938	277	1968	186	1998	4,680
1939	1,200	1969	2,950	1999	640
1940	500	1970	691	2000	1,620
1941	750	1971	175	2001	4,650
1942	264	1972	1,410	2002	1,000
1943	1,980	1973	125	2003	1,240
1944	486	1974	1,940	2004	1,400
1945	2,180	1975	10,900	2005	1,950
1946	1,050	1976	760	2006	4,420
1947	2,620	1977	38	2007	1,230
1948	950	1978	4,680	2008	2,130
1949	178	1979	3,240	2009	6,430
1950	2,600	1980	1,480		
1951	1,630	1981	926		
1952	1,650	1982	1,820		
1953	350	1983	205		
1954	67	1984	2,020		
1955	1,230	1985	1,930		
1956	1,670	1986	2,090		
1957	1,080	1987	820		
1958	999	1988	480		
1959	300	1989	2,780		
1960	1,050	1990	330		

Table 21. Buffalo River Flow Transfer from USGS gage at Dilworth to the Confluence of the Buffalo River with the Red.

% Chance Exceedance	USGS 05062000 Mainstem Buffalo R. Dilworth, MN Peak Discharge (cfs)	USGS 05061500 S Branch Buffalo R. Sabin, MN Peak Discharge (cfs)	Exponent[1]	POR		WET	
				Dilworth Coin. Peak Discharge (cfs)	Peak Discharge at the Confluence[2] (cfs)	Dilworth Coin. Peak Discharge (cfs)	Peak Discharge at the Confluence[2,3] (cfs)
0.2	23,492	16,155	0.49	11,954	13,174	10,710	11,804
0.5	18,022	12,754	0.45	9,990	10,928	9,322	10,198
1	14,443	10,439	0.42	8,508	9,256	8,202	8,923
2	11,309	8,342	0.40	7,044	7,623	7,027	7,604
5	7,793	5,895	0.37	5,162	5,550	5,403	5,809
10	5,567	4,282	0.34	3,805	4,073	4,140	4,431
20	3,679	2,867	0.33	2,532	2,701	2,869	3,061
50	1,630	1,274	0.32	1,028	1,096	1,231	1,312
80	702	533	0.36	352	378	430	462
90	447	330	0.40	187	202	227	246
95	306	220	0.43	107	117	128	140
99	148	99	0.53	34	38	39	43
	Dilworth	**Sabin**	**Buffalo R. Mouth**		**[1] Exponent (e) = Log ($Q_{Dilworth}$/Q_{Sabin})/ Log ($DA_{Dilworth}$/DA_{Sabin})**		
DA sq. mi	975	454	1,189		**[2] $Q_{confluence} = Q_{Dilworth} * (DA_{Conf} / DA_{Dilworth})^e$**		

[3] *The exponent 'e' was carried out to more significant figures in computation to minimize rounding error*

5.3.3 Coincident Flows from the Wild Rice Tributary, MN

Coincidental peak flows from the Wild Rice tributary, MN were found for corresponding peak flows on the Red River at Halstad. Coincidental Peaks were derived from flows at the Hendrum gage on the Wild Rice River upstream of the confluence of the Wild Rice River and the Red River. No transfer of coincidental flows at Hendrum to the mouth of the Wild Rice-MN is necessary because of Hendrum's close proximity to the confluence of the Wild Rice-MN with the Red River of the North. **Table 22** lists the annual coincident flow data series.

The coincident flow record at Hendrum is limited to 1944-2009. A flow-frequency curve for the WET portion of the record could be developed using the observed coincident flow record. It was found that a Log-Pearson Type III distribution fit the observed coincident flow record when plotted using the median plotting position. The values corresponding to the WET flow-frequency curve for the Wild Rice tributary, MN can be found in **Table 19**. The corresponding flow-frequency curve is displayed in **Figure 32**.

Table 22. Coincidental Flows based on the Mean Daily Flows recorded by USGS Gage 05064000 on the Wild Rice River- MN at Hendrum, MN

Water Year	Coincidental Flow	Water Year	Coincidental Flow
1944	2, 170	1987	1,200
1945	1,800	1988	850
1946	1,500	1989	4,900
1947	4,200	1990	652
1948	2,000	1991	233
1949	550	1992	1,400
1950	2,800	1993	3,630
1951	1,600	1994	2,600
1952	880	1995	2,400
1953	1,470	1996	5,460
1954	1,560	1997	8,980
1955	1,700	1998	6,240
1956	4,150	1999	3,580
1957	897	2000	8,010
1958	544	2001	7,100
1959	357	2002	6,170
1960	1,400	2003	1,770
1961	808	2004	4,770
1962	2,070	2005	3,480
1963	710	2006	5,500
1964	2,570	2007	4,970
1965	4,340	2008	2,840
1966	3,560	2009	8,530
1967	2,960		
1968	273		
1969	3,120		
1970	2,880		
1971	850		
1972	2,800		
1973	980		
1974	5,210		
1975	6,720		
1976	2,050		
1977	92		
1978	9,110		
1979	7,600		
1980	1,770		
1981	509		
1982	1,500		
1983	2,090		
1984	2,100		
1985	4,370		
1986	3,800		

Because of the short period of record, a “dry” curve cannot be generated for the coincident flow record for the Wild Rice Tributary, MN so the method used at Fargo cannot be used to get the 25-year and 50-year look-ahead curves. To generate the combined curves, it was necessary to use the assumption that Hendrum and Fargo are located in hydrologically similar areas. Based on this assumption the percent differences between the wet curve at Fargo and the combined curves at Fargo could be used to translate the coincident wet curve at Hendrum to the 25-year combined curve and the 50-year combined curve coincident curve at Hendrum. The analytically fit unregulated curves at Fargo were used for this purpose. The values corresponding to the 25-year and 50-year look-ahead flow-frequency curves can be found in **Table 19**. The future scenario frequency curves are shown in **Figure 33** and **Figure 34**.

5.4 FLOW-FREQUENCY ANALYSIS- RED RIVER REACH BETWEEN GRAND FORKS & HICKSON

As described in **Section 4.7 of Appendix A-1** discharge-frequencies for this reach were based primarily on interpolations between adopted discharge-frequencies at Fargo and Hickson. It also incorporated the coincidental flow-frequencies from the Wild Rice River, ND, Wild Rice River, MN and the Buffalo Rivers. Interpolation was carried out for the POR, WET, and Future conditions (25-year look-ahead and 50-year look-ahead).

Flows were estimated between Fargo and Halstad using a drainage area ratio exponent between Halstad and Fargo as shown in **Table 23**. Flows upstream and downstream of the Sheyenne River were based on the generalized exponent. For the reach between Fargo and Hickson flows were varied only at locations upstream and downstream of the Wild Rice River, ND based on its corresponding coincidental flow. The resulting summaries of discharge-frequencies for the designated locations along the Red for the POR, WET, 25-year look-ahead period and 50-year look-ahead period can be found in **Table 24** through **Table 27**. **Figure 35** through **Figure 38** display the adopted POR, WET and combined discharge-frequency curves for designated locations on the Red.

The tables below indicate that the “Wet” scenario produces lower discharges than the “Period of Record Analysis” for the 0.2% exceedance frequency. This is because there is less variability within the flow record if you isolate the “Wet” period because you are now working with a homogenous flow record. Because there is less variability in the flows that are being considered, the standard deviation associated with the data set is smaller and thus one would expect the 0.2% event to deviate less from the series of observed flows for the WET period than you would when using the POR for analysis. Because there was so much variability in the POR flows due to the heterogeneity of the record one had to be excessively conservative in estimating the 0.2% event to account for this variability.

At Grand Forks, the WET analysis produces a flow frequency curve that reflects lower discharges than the POR analysis for events less frequent than the 10% event. Thus, according to the new hydrology adopted for this study the design level of protection for the Grand Forks flood Control Project is extremely conservative.

Table 23. Drainage Area Exponent for Red River reach between Fargo and Halstad

	Exceedance Frequencies, %							
n- values	**50**	**20**	**10**	**5**	**2**	**1**	**0.5**	**0.2**
POR	0.653	0.467	0.383	0.320	0.389	0.365	0.273	0.059
WET	0.602	0.483	0.400	0.397	0.392	0.410	0.272	0.167
25-yr	0.778	0.512	0.461	0.443	0.434	0.444	0.355	0.233
50-yr	0.927	0.621	0.526	0.493	0.478	0.479	0.435	0.297

Table 24. Summary Table Red River Flow-Frequencies – POR With Dams, Annual Instantaneous Peak Discharge Frequency

Location	POR DISCHARGE-FREQUENCY, cfs								
	Drainage Area Sq mi	Exceedance Frequency %							
		50	20	10	5	2	1	0.5	0.2
Grand Forks	**20,015**	**17,000**	**35,300**	**50,500**	**67,300**	**91,700**	**112,000**	**134,000**	**165,000**
u/s Red Lake R	16,215	11,090	24,600	36,100	48,900	67,600	83,700	100,000	124,000
Halstad	**13,755**	**9,850**	**20,700**	**29,800**	**39,900**	**54,600**	**66,900**	**80,200**	**99,200**
d/s Wild Rice R	13,735	9,831	20,672	29,767	39,863	54,538	66,829	80,136	99,183
Wild Rice R, MN coincidental	**1,650**	**2,348**	**4,650**	**6,395**	**8,162**	**10,529**	**12,335**	**14,147**	**16,544**
u/s Wild Rice R, MN	12,085	7,483	16,022	23,372	31,701	44,009	54,494	65,989	82,639
d/s Elm R	12,055	7,471	16,003	23,350	31,676	43,967	54,444	65,945	82,627
u/s Elm R	11,655	7,308	15,753	23,050	31,335	43,393	53,777	65,339	82,461
d/s Buffalo R	11,305	7,164	15,530	22,782	31,031	42,881	53,181	64,797	82,312
Buffalo R coincidental	**1,190**	**1,096**	**2,701**	**4,073**	**5,550**	**7,623**	**9,256**	**10,928**	**13,174**
u/s Buffalo R	10,115	6,068	12,829	18,709	25,481	35,258	43,925	53,869	69,138
d/s Sheyenne R	9,905	5,986	12,704	18,559	25,310	34,971	43,590	53,561	69,052
u/s Sheyenne R	5,055	3,857	9,277	14,345	20,404	26.915	34,090	44,569	66,349
Fargo	**3,220**	**3,639**	**8,900**	**13,865**	**19,831**	**26,000**	**33,000**	**43,500**	**66,000**
d/s Drain 53	3,165	3,639	8,900	13,865	19,831	25,999	32,999	43,499	65,999
u/s Drain 53	3,135	3,639	8,900	13,865	19,831	25,999	32,999	43,499	65,998
d/s Wild Rice R, ND	3,080	3,638	8,900	13,864	19,830	25,999	32,998	43,498	65,997
Wild Rice R, ND coincidental	**1,640**	**950**	**3,700**	**5,900**	**8,400**	**11,700**	**13,500**	**15,000**	**18,000**
u/s Wild Rice R, ND	1,440	2,688	5,200	7,964	11,430	14,299	19,498	28,498	47,997
d/s Wolverton Cr	1,430	2,729	5,021	7,861	11,321	13,639	18,993	28,504	46,881
u/s Wolverton Cr	1,325	2,573	5,778	8,328	11,910	18,202	22,522	28,326	36,339
Hickson	**1,310**	**2,550**	**5,900**	**8,400**	**12,000**	**19,000**	**23,100**	**28,300**	**35,000**
Wahpeton	**1,020**	**2,280**	**4,720**	**6,690**	**8,550**	**10,950**	**13,300**	**16,000**	**19,600**

Table 25. Summary Table Red River Flow-Frequencies – WET With Dams, Annual Instantaneous Peak Discharge Frequency

Location	Drainage Area Sq mi	WET SCENARIO DISCHARGE-FREQUENCY, cfs								
		Exceedance Frequency %								
		50	25	20	10	5	2	1	0.5	0.2
Grand Forks	**20,015**	**23,295**	**37,605**	**42,139**	**56,354**	**70,956**	**91,026**	**106,838**	**123,201**	**145, 675**
u/s Red Lake R	16,215	17,385	26,905	27,739	41,954	52,556	66,926	78,538	89,201	104,675
Halstad	**13,755**	**13,074**	**22,261**	**25,260**	**34,871**	**45,014**	**59,306**	**70,798**	**82,872**	**99,713**
d/s Wild Rice R	13,735	13,051	22,232	25,225	34,830	44,962	59,238	70,714	82,806	99,665
Wild Rice R, MN coincidental	**1,650**	**2,348**	**4,089**	**4,102**	**6,393**	**8,165**	**10,547**	**12,373**	**14,211**	**16,652**
u/s Wild Rice R, MN	12,085	10,703	18,143	21,123	28,437	36,797	48,691	58,341	68,595	83,013
d/s Elm R	12,055	10,687	18,123	21,097	28,409	36,761	48,644	58,281	68,549	82,978
u/s Elm R	11,655	10,472	17,854	20,756	28,028	36,271	48,004	57,480	67,923	82,513
d/s Buffalo R	11,305	10,282	17,614	20,452	27,688	35,834	47,433	56,765	67,361	82,095
Buffalo R coincidental	**1,190**	**1,312**	**2,615**	**2,719**	**4,431**	**5,809**	**7,604**	**8,923**	**10,198**	**11,804**
u/s Buffalo R	10,115	8,970	14,999	17,733	23,257	30,025	39,829	47,842	57,163	70,291
d/s Sheyenne R	9,905	8,857	14,860	17,555	23,062	29,776	39,503	47,432	56,838	70,046
u/s Sheyenne R	5,055	5,908	11,026	12,683	17,616	22,791	30,340	35,989	47,331	62,621
Fargo	**3,220**	**5,600**	**10,600**	**12,150**	**17,000**	**22,000**	**29,300**	**34,700**	**46,200**	**61,700**
d/s Drain 53	3,165	5,600	10,600	12,150	17,000	22,000	29,299	34,699	46,199	61,699
u/s Drain 53	3,135	5,599	10,600	12,150	17,000	21,999	29,299	34,699	46,199	61,699
d/s Wild Rice R, ND	3,080	5,599	10,600	12,150	16,999	21,999	29,298	34,698	46,198	61,698
Wild Rice R, ND coincidental Abercrombie	**1,640**	**1,419**	**2,587**	**3,021**	**6,185**	**8,648**	**11,655**	**13,780**	**15,801**	**18,342**
u/s Wild Rice R, ND	1,440	4,180	8,013	9,129	10,814	13,351	17,643	20,918	30,397	43,356
d/s Wolverton Cr	1,430	4,166	7,899	8,952	10,791	13,453	17,872	21,196	30,252	42,385
u/s Wolverton Cr	1,325	4,021	6,756	7,227	10,537	14,618	20,566	24,472	28,720	33,177
Hickson	**1,310**	**4,000**	**6,600**	**7,000**	**10,500**	**14,000**	**19,000**	**22,000**	**28,500**	**37,000**

Table 26. Summary Table Red River Flow-Frequencies – 25-Yr Look-Ahead With Dams, Annual Instantaneous Peak Discharge Frequency

Location	25-YR LOOK-AHEAD SCENARIO DISCHARGE-FREQUENCY, cfs									
	Drainage Area Sq mi	Exceedance Frequency, %								
		50	25	20	10	5	2	1	0.5	0.2
Grand Forks	**20,015**	**20,684**	**34,694**	**39,157**	**53,213**	**67,723**	**87,782**	**103,682**	**120,244**	**143,205**
u/s Red Lake R	16,215	14,774	23,994	24,757	38,813	49,323	63,682	75,382	86,244	102,205
Halstad	**13,755**	**11,480**	**20,392**	**23,330**	**32,771**	**42,799**	**57,006**	**68,501**	**80,649**	**97,734**
d/s Wild Rice R	13,735	11,454	20,359	23,295	32,727	42,744	56,934	68,413	80,566	97,668
Wild Rice R, MN coincidental (Hendrum)	**1,650**	**1,894**	**3,550**	**4,102**	**5,798**	**7,547**	**9,894**	**11,703**	**13,524**	**15,942**
u/s Wild Rice R, MN	12,085	9,560	16,809	19,193	26,929	35,197	47,040	56,710	67,042	81,726
d/s Elm R	12,055	9,542	16,785	19,169	26,898	35,158	46,989	56,647	66,983	81,679
u/s Elm R	11,655	9,294	16,471	18,841	26,483	34,636	46,306	55,805	66,186	81,040
d/s Buffalo R	11,305	9,076	16,192	18,549	26,114	34,171	45,697	55,054	65,474	80,467
Buffalo R coincidental (confluence)	**1,190**	**1,076**	**2,288**	**2,719**	**4,036**	**5,385**	**7,149**	**8,457**	**9,721**	**11,317**
u/s Buffalo R	10,115	8,000	13,904	15,830	22,078	28,786	38,548	46,597	55,753	69,150
d/s Sheyenne R	9,905	7,871	13,741	15,661	21,865	28,519	38,198	46,165	55,340	68,814
u/s Sheyenne R	5,055	4,664	9,426	11,102	16,038	21,163	28,521	34,246	43,595	58,846
Fargo	**3,220**	**4,352**	**8,968**	**10,608**	**15,394**	**20,345**	**27,441**	**32,921**	**42,242**	**57,641**
d/s Drain 53	3,165	4,352	8,968	10,608	15,394	20,345	27,440	32,920	42,241	57,640
u/s Drain 53	3,135	4,352	8,968	10,608	15,394	20,345	27,440	32,920	42,241	57,640
d/s Wild Rice R, ND	3,080	4,351	8,968	10,608	15,393	20,344	27,440	32,919	42,240	57,639
Wild Rice R, ND coincidental (Abercrombie)	**1,640**	**1,148**	**2,245**	**2,691**	**5,658**	**8,057**	**10,980**	**13,134**	**14,577**	**17,264**
u/s Wild Rice R, ND	1,440	3,203	6,723	7,917	9,735	12,287	16,460	19,785	27,663	40,375
d/s Wolverton Cr	1,430	3,198	6,636	7,772	9,722	12,388	16,680	20,055	27,549	39,492
u/s Wolverton Cr	1,325	3,147	5,753	6,349	9,577	13,547	19,288	23,242	26,339	31,093
Hickson	**1,310**	**3,139**	**5,632**	**6,160**	**9,555**	**13,729**	**19,709**	**23,757**	**26,164**	**30,016**

Table 27. Summary Table Red River Flow-Frequencies – 50-Yr Look-Ahead With Dams, Annual Instantaneous Peak Discharge Frequency

Location	50-YR LOOK-AHEAD SCENARIO DISCHARGE-FREQUENCY, cfs									
	Drainage Area Sq mi	Exceedance Frequency, %								
		50	25	20	10	5	2	1	0.5	0.2
Grand Forks	**20,015**	**18,679**	**32,287**	**36,666**	**50, 530**	**64,931**	**84,960**	**100,932**	**11,7667**	**141,059**
u/s Red Lake R	16,215	12,769	21,587	22,266	36,130	46,531	60,860	72,632	83,667	100,059
Halstad	**13,755**	**10,264**	**18,836**	**21,697**	**30,963**	**40,872**	**54,989**	**66,482**	**78,692**	**95,991**
d/s Wild Rice R	13,735	10,236	18,799	21,658	30,916	40,813	54,913	66,390	78,592	95,908
Wild Rice R, MN coincidental Hendrum	**1,650**	**1,569**	**3,095**	**3,618**	**5,272**	**6,993**	**9,304**	**11,096**	**12, 900**	**15,296**
u/s Wild Rice R, MN	12,085	8,667	15,704	18,040	25,644	33,820	45,609	55,294	65,692	80,612
d/s Elm R	12,055	8,647	15,677	18,012	25,610	33,779	45,555	55,228	65,621	80,553
u/s Elm R	11,655	8,381	15,321	17,638	25,160	33,222	44,826	54,343	64,665	79,750
d/s Buffalo R	11,305	8,147	15,007	17,308	24,759	32,727	44,178	53,556	63,812	79,032
Buffalo R coincidental (confluence)	**1,190**	**903**	**2,009**	**2,413**	**3,684**	**5,004**	**6,738**	**8,034**	**9,288**	**10,875**
u/s Buffalo R	10,115	7,244	12,998	14,895	21,075	27,723	37,440	45,522	54,524	68,157
d/s Sheyenne R	9,905	7,105	12,813	14,702	20,844	27,438	37,067	45,067	54,029	67,734
u/s Sheyenne R	5,055	3,807	8,106	9,681	14,633	19,699	26,882	32,664	40,317	55,478
Fargo	**3,220**	**3,506**	**7,630**	**9,161**	**13,965**	**18,855**	**25,764**	**31,304**	**38,787**	**54,034**
d/s Drain 53	3,165	3,506	7,630	9,027	13,965	18,855	25,763	31,303	38,786	54,033
u/s Drain 53	3,135	3,506	7,630	8,953	13,965	18,855	25,763	31,303	38,786	54,033
d/s Wild Rice R, ND	3,080	3,505	7,630	8,819	13,964	18,854	25,763	31,302	38,786	54,032
Wild Rice R, ND coincidental Abercrombie	**1,640**	**957**	**1,958**	**2,375**	**5,185**	**7,520**	**10,367**	**12,545**	**13,450**	**16,299**
u/s Wild Rice R, ND	1,440	2,548	5,672	6,444	8,779	11,334	15,396	18,757	25,336	37,733
d/s Wolverton Cr	1,430	2,548	5,605	6,358	8,774	11,434	15,609	19,019	25,243	36,927
u/s Wolverton Cr	1,325	2,550	4,925	5,485	8,718	12,582	18,134	22,123	24,258	29,236
Hickson	**1,310**	**2,550**	**4,831**	**5,366**	**8,710**	**12,762**	**18,543**	**22,626**	**24,116**	**28,246**

6. Balanced Hydrographs

The Corps developed balanced hydrographs at all pertinent computation points within the study area in support of the unsteady RAS model. These events are the 0.2-, 0.5-, 1-, 2-, and 10-percent exceedance frequency events for the POR, WET, 25-yr, and 50-yr look-ahead periods. To configure these synthetic events, flood volume duration frequency analyses provided the volume, for each duration, and specified frequency. The Corps HEC-1 model ***(reference 11)*** used this information along with the 2006 event as a pattern event to configure the balanced hydrographs. The pattern event helps establish the shape and timing of the hydrograph in regard to volume.

The spring 2006 flood event was selected as the pattern event for all balanced hydrographs developed for the Fargo-Moorhead Metro Study. This is consistent with the methodology used for the Wild Rice Study, ND, which also uses 2006 as the pattern event. At the time that hydrologists began work on the Fargo Moorhead Metro Study the USGS discharge measurements associated with 2009 spring flood event were still listed as estimates and the 2010 spring flood had not yet occurred. With 2009 and 2010 data unavailable, the next largest event in terms of peak magnitude and volume was 1997. In 1997 spring snowmelt was interrupted by a blizzard. The blizzard caused runoff to recess for a week before resuming. As a result of atypical hydro meteorological conditions, the 1997 event could not be used as a pattern event. The 2006 event was deemed to be most representative of a typical flood event in the Red River Basin.

The procedure involved two approaches; direct and indirect analysis. POR and WET period analyses at gaged locations employed direct analysis of the available data. Indirect analysis was employed for the ungaged locations as well as the 25-yr and 50-yr look-ahead conditions. This is because mean daily flow series are not available for a direct analysis for these conditions. Indirect analysis was also employed for the "coincidental" balanced hydrographs for the tributaries as direct analysis for this type of event is not possible.

6.1 Flood Volume Frequency Curves - Direct Analysis

The first step in developing the balanced hydrographs was to develop flood volume frequency relationships for the period of record at pertinent gaged stations on the Red River and its tributaries. This was done using observed mean daily flow data. The Hydrologic Engineering Center's Statistical Software Package (HEC-SSP) ***(reference 9)*** was used to compute the volume-duration frequency curves. In some cases the skew and standard deviation were manually modified so that frequency curves did not cross one another. This was done by plotting the lognormal of skew or standard deviation associated with each duration versus the lognormal of the mean associated with each duration and applying a linear regression. The resulting linear regression was utilized to smooth the skew and standard deviation for each duration. The period-of-record varied at each gage with some gages becoming active after 1942. For those gages that were active prior to 1942, the POR analysis used the total record that was available, whereas the WET analysis used the period since 1942. If the gages became active after 1942, the analysis used the record that was available. This information can be found in **Table 28**.

Table 28: Flood Volume Frequency Pertinent Information

LOCATION	PERIOD OF RECORD	PROGRAM USED	STATISTICS SMOOTHED?
Red River at Fargo, ND	1901-2009	HEC-SSP	Yes
Wild Rice River at Abercrombie, ND	1932-2009	HEC-SSP	Yes
Buffalo River at Dilworth, MN	1931-2009	HEC-SSP	Yes
Red River at Halstad, MN	1962-2009	HEC-SSP	Yes
Wild Rice River at Hendrum, MN	1944-2009	HEC-SSP	Yes
Red River at Hickson, ND	1942-2009	HEC-SSP	Yes
Red River at Amenia, ND	1947-2009	HEC-SSP	Yes

Flood volume-duration frequency curves were developed for main stem gaged flows at Halstad, Fargo and Hickson on the Red River. These curves can be found in **Figure 39**, **Figure 42**, and **Figure 44,** respectively. Flood volume-duration frequencies were also required for tributary gages. These were: Wild Rice River-ND at Abercrombie, Buffalo River at Dilworth, Wild Rice River-MN at Hendrum, and the Rush River at Amenia. These curves can be found in **Figure 40**, **Figure 41, Figure 43, and Figure 45,** respectively**.**

6.2 Flood Volume Frequency Curves- Indirect Analysis

6.2.1 Gaged Locations

As described above, flood volume frequency analysis for the POR and WET curve at gaged points of interest (Fargo, Hickson, and Halstad), were developed using direct analysis. In regard to the indirect analysis, annual instantaneous peak flood frequency relations were developed at these locations for the POR and WET, 25-year look-ahead and 50-year look-ahead periods as described in the preceding sections of this appendix. An annual mean daily peak flow frequency curve was also generated for the POR. The 1-day duration for the future period curves were determined by correlating the POR annual mean daily peak flow-frequency curve with the annual instantaneous peak flows curve (1-day duration = annual mean daily peak flow at that exceedance probability). This relation was assumed to also apply between instantaneous peak and mean daily peak, flow frequencies for the WET, 25-yr and 50-yr combined curves. To configure the other durations, the volume duration curves at other durations were derived by assuming the same proportional change in flow volume, for each duration, as for the POR and WET flood volume frequency curves.

6.2.2 Tributaries Coincident Flows

The unsteady RAS model also requires discharges and volumes from the intervening tributaries that contribute flow to the Main Stem. These are the significant tributaries in terms of flow and are presented as “coincidental” balanced hydrographs. This is to maintain consistency throughout the Main Stem with respect to the magnitude of the event for each duration and specified exceedance frequency. Coincident Flow-Frequency analyses for the POR, WET, 25-yr and 50-yr condition were done for each of these tributaries in the same manner as described in early sections of this Appendix.

To match with the Main Stem, coincidental balanced hydrographs were required for the Buffalo River, the Wild Rice River, MN, the Wild Rice River, ND, Upstream and Downstream of the Sheyenne River's confluence with the Red River, the Maple River and the Rush River. The Corps derived coincident flood volume frequency curves at these tributaries by assuming the same proportional change in flood volume, for each duration, as at the most hydrologically similar gaged station.

For the indirect analysis, the Corps developed both the instantaneous and annual mean daily peak flow-frequency curves at these gaged locations for the POR and WET portion of the period of record. The 1-day duration for the WET and future period coincident curves were determined by correlating the WET mean daily peak flow-frequency curve with the instantaneous peak flows curve for the POR period at these hydrologically similar gaged stations (1-day duration = annual mean daily peak flow at that exceedance probability). This relation was assumed to also apply between instantaneous peak and mean daily peak, flow frequencies for the WET, 25-yr and 50-yr combined curves. To configure the other durations, the volume duration curves at other durations were derived by assuming the same proportional change in flow volume, for each duration, as for the POR and WET flood volume frequency curves at the hydrologically similar gaged locations.

The hydrologically similar location identified for each point of interest and the method used to produce to the volume duration curve is listed in **Table 29**. A sample set of the coincident flow volume duration curves for the WET, 25-yr and 50-yr periods generated indirectly using the gaged location at Hendrum, ND which was used to develop the balanced hydrographs for the Wild Rice River, ND can be found in **Figure 46, Figure 47, and Figure 48**, respectively.

Table 29. Hydrologically similar location/ methodology used to produce balanced hydrographs.

Location	River	Volume Type	Hydrologically Similar Location used for generating Flood Volume Frequency Curve or alternate method used to obtain Balanced hydrograph
Gaged			
Halstad	Red River	Main Stem	Halstad
Fargo	Red River	Main Stem	Fargo
Hickson	Red River	Main Stem	Hickson
Hendrum	Wild Rice River, MN	Coincidental	Hendrum
Dilworth	Buffalo River	Coincidental	Dilworth
Abercrombie	Wild Rice River, ND	Coincidental	Abercrombie
Ungaged			
Red DS Wild Rice, MN	Red River	Main Stem	Halstad
Red River DS Buffalo River	Red River	Main Stem	Halstad
Red River DS of Sheyenne River	Red River	Main Stem	Halstad
Red River US of Sheyenne River	Red River	Main Stem	Fargo
Buffalo River at Mouth	Buffalo River	Coincidental	Dilworth
Sheyenne River at Mouth	Sheyenne River	Coincidental	Subtract: Red DS of Sheyenne River - Red US Sheyenne River
Sheyenne River DS of Rush River	Sheyenne River	Coincidental	-1 Day shift translation from Sheyenne River at Mouth
Rush River at Mouth	Rush River	Coincidental	Amenia
Sheyenne River US of Rush	Sheyenne River	Coincidental	Subtract: Sheyenne DS of Rush River - Rush River at Mouth
Sheyenne River DS of Maple River	Sheyenne River	Coincidental	-1 Day shift from Sheyenne River US of Rush River
Maple River at Mouth	Maple River	Coincidental	Dilworth
Sheyenne River US of Maple River	Sheyenne River	Coincidental	Subtract: Sheyenne DS of Maple River - Maple River at Mouth

6.3 Balanced Hydrographs

6.3.1 Gaged Based

After producing the volume duration curves as described above, the 1-day, 3-day, 7-day, 15-day, and 30-day values could be used to configure balanced hydrographs. Once these durations were estimated, they were inputted into HEC-1 (**reference 11**) to configure a hydrograph that reflects these volumes per duration, patterned after the 2006 event hydrograph at that location. All balanced hydrographs were smoothed using the graphical capabilities of HEC-DSSVue (**reference 12**).

A sample set of the balanced hydrographs for the WET, 25-yr and 50-yr periods generated using the indirect methodology of producing coincident flood volume duration curves for the gaged location at Hendrum, ND can be found in **Figure 49, Figure 50, and Figure 51**, respectively.

6.3.2 Sheyenne River

To determine coincidental hydrographs on the Sheyenne, the analysis began at the downstream end at the confluence with the Red River. The balanced hydrographs on the Red River upstream of the Sheyenne were subtracted from the balanced hydrographs downstream of the Sheyenne to arrive at the corresponding coincident balanced hydrographs on the Sheyenne at the confluence of the Sheyenne River and the Red River. This method hinges on the correct assumption of the Red River development of discharge-frequencies, upstream and downstream of the Sheyenne and the resulting development of balanced hydrographs at those locations.

To determine the coincident balanced hydrograph on the Sheyenne River just downstream of the confluence of the Rush River with the Sheyenne, DSSVue was used to shift the coincident balanced hydrograph at the confluence of the Sheyenne with the Red River back one day.

The coincident balanced hydrograph at the confluence of the Rush River with the Sheyenne River was determined using the gaged location on the Rush River at Armenia. Coincident flows for the Amenia gage with peaks at the Fargo gage on the Red River were determined for the WET portion of the period of record from 1947-2009. The coincident flow record at Amenia can be found in **Table 30**.

This coincidental flow record was used to generate a flow-frequency curve for the WET portion of the period of record at Amenia using a graphical fit. This curve was then translated to the mouth of the Rush River using a drainage area ratio. The percent difference between the regulated WET flow-frequency curve and combined curves at Fargo was used to translate the WET curve at Amenia into the 25-yr and 50-yr combined curves at Amenia. The corresponding combined coincidental flow-frequency values can be found in **Table 31.**

Table 30. Coincident Flows derived from Mean Daily Streamflows Recorded by USGS gage 05060500 on the Rush River at Amenia, ND

Amenia- Coincident with Peaks at Fargo			
Water Year	Flow (cfs)	Water Year	Flow (cfs)
1947	1,180	1985	4
1948	100	1986	48
1949	13	1987	269
1950	400	1988	1
1951	19	1989	95
1952	25	1990	1
1953	27	1991	3
1954	0	1992	13
1955	31	1993	61
1956	93	1994	33
1957	11	1995	147
1958	56	1996	199
1959	0	1997	1,450
1960	224	1998	127
1961	0	1999	750
1962	5	2000	4
1963	8	2001	429
1964	42	2002	30
1965	195	2003	110
1966	220	2004	308
1967	3	2005	238
1968	6	2006	425
1969	302	2007	7
1970	141	2008	9
1971	1	2009	670
1972	35		
1973	65		
1974	565		
1975	168		
1976	90		
1977	0		
1978	120		
1979	1,360		
1980	46		
1981	0		
1982	570		
1983	88		
1984	211		

Table 31. Coincidental Flow-Frequency Curves Developed for USGS gage 05060500 Site on the Rush River at Amenia, ND

Combined Coincidental Flows			
Exceed. Prob	Amenia- Graphical Fit		
	Wet Flow (cfs)	25-yr Flow (cfs)	50-yr flow (cfs)
0.99	0	0	0
0.9	2	2	2
0.75	17	15	14
0.5	123	107	95
0.2	598	545	494
0.1	1,212	1,127	1,050
0.05	1,934	1,823	1,721
0.02	2,980	2,832	2,696
0.01	3,815	3,659	3,517
0.005	4,674	4,356	4,074
0.002	5,840	5,535	5,261

The coincident balanced hydrograph for the Sheyenne River Upstream of its confluence with the Rush River was determined by subtracting the balanced hydrograph at the confluence with the Rush River from the balanced hydrograph downstream of the confluence of the Rush River with the Sheyenne River. To determine the coincident balanced hydrograph on the Sheyenne just downstream of the confluence of the Maple River with the Sheyenne, DSSVue was used to shift the coincident balanced hydrograph just upstream of the Sheyenne River's confluence with the Rush River back one day.

The coincident balanced hydrograph at the mouth of the Maple River was determined by transferring the annual instantaneous flow-frequency peaks at Dilworth to the mouth of the Maple River by using a ratio of 1.276 based on drainage area. The process described in **Section 6.2.2** was then used to develop the coincident volume duration curve at the confluence of the Maple River with the Sheyenne River using Dilworth as the hydrologically similar gage point. After producing the volume duration curve as described above the 1-day, 3-day, 7-day, 15-day, and 30-day values could be used to configure balanced hydrograph at the mouth of the Maple River using HEC-1.

The coincident balanced hydrograph for the Sheyenne River Upstream of its confluence with the Maple River was determined by subtracting the balanced hydrograph at the confluence of the Sheyenne with the Maple River from the balanced hydrograph downstream of the confluence of the Maple River with the Sheyenne.

The balanced hydrographs generated using this methodology were used to determine the flow-frequency inputs for the unsteady RAS model by identifying the peak value off the balanced hydrographs generated for each exceedance probability for the WET, 25-year look-ahead and 50-year look-ahead curves. These values can be found in **Table 32, Table 33,** and **Table 34**. A sample set of the balanced hydrographs for the 100-yr Wet condition that demonstrate this process can be found in **Figure 52, Figure 53,** and **Figure 54**.

Table 32. Summary Table Sheyenne River Flow-Frequencies – WET With Dams, Annual Instantaneous Peak Discharge Frequency

Location	WET SCENARIO DISCHARGE-FREQUENCY, cfs					
	Drainage Area sq mi	Exceedance Frequency, %				
		10	2	1	0.5	0.2
Red R u/s Conf Sheyenne R	5,055	17,616	30,340	35,989	47,331	62,621
Sheyenne R at Conf w/ Red R	4,850	11,755	22,317	26,594	31,433	38,795
Rush R at Conf w/ Sheyenne R	172	1,212	2,980	3,815	4,674	5,840
Sheyenne R u/s Conf w/ Rush R	4, 611	11,291	21,207	25,183	29,712	36,649
Maple R at Conf w/ Sheyenne R	1,518	5,654	9,703	11,386	13,012	15,062
Sheyenne R u/s Conf Maple R	3,092	7,933	15,856	18,962	22,202	29,180
Red R d/s Conf Sheyenne R	11, 335	23,062	39,503	47,449	56,838	70,046

Table 33. Summary Table Sheyenne River Flow-Frequencies – 25-yr Look-ahead *With Dams*, Annual Instantaneous Peak Discharge Frequency

Location	25-yr Look-ahead SCENARIO DISCHARGE-FREQUENCY, cfs					
	Drainage Area sq mi	Exceedance Frequency, %				
		10	2	1	0.5	0.2
Red R u/s Conf Sheyenne R	5,055	16, 038	28,521	34, 246	43, 595	58,846
Sheyenne R at Conf w/ Red R	4,850	11,489	21,414	25,542	29,769	36,800
Rush R at Conf w/ Sheyenne R	172	1,127	2,832	3,659	4,356	5,535
Sheyenne R u/s Conf w/ Rush R	4, 611	11,058	20,359	24,189	28,165	34,766
Maple R at Conf w/ Sheyenne R	1,518	5,150	9,123	10,791	12,404	14,442
Sheyenne R u/s Conf Maple R	3,092	7,711	14,713	18,452	19,858	25,472
Red R d/s Conf Sheyenne R	11, 335	21,865	38,198	46, 165	55,340	68,814

Table 34. Summary Table Sheyenne River Flow-Frequencies – 50-yr Look-Ahead With Dams, Annual Instantaneous Peak Discharge Frequency

Location	50-yr Look-ahead SCENARIO DISCHARGE-FREQUENCY, cfs					
	Drainage Area Sq mi	Exceedance Frequency, %				
		10	2	1	0.5	0.2
Red R u/s Conf Sheyenne R	5,055	14633	26,882	32,664	40,317	55,478
Sheyenne R at Conf w/ Red R	4,850	11,104	20,557	24,973	28,811	34,391
Rush R at Conf w/ Sheyenne R	172	1,050	2,696	3,517	4,074	5,261
Sheyenne R u/s Conf w/ Rush R	4, 611	10,701	19,552	23,672	27,310	32,458
Maple R at Conf w/ Sheyenne R	1,518	4,701	8,597	10,250	11,851	13,877
Sheyenne R u/s Conf Maple R	3,092	7,460	14,092	17,244	19,573	24,431
Red R d/s Conf Sheyenne R	11, 335	20,844	37,067	45,067	54,029	67,734

6.3.3 Lower Bound of True Balanced Hydrograph Volumes

The coincident balanced hydrographs, derived using the methodology as described in the preceding sections for development of the tributary inputs, can only be considered as an initial starting point or "lower bound" as flood volume may be under-estimated due to the fact that the historic coincident peaks were on the rising or falling limb of the recorded hydrographs. This could lead to mean 3-day, mean 7-day, etc., flows that are higher than the "peak" coincident flow. Because ratios are used to decrease the "peak" coincident flow into the mean daily flow, mean 3-day flow, etc., the method does not take into account this possibility, and the balanced hydrographs have the potential to underestimate the true flow volumes. The HEC-RAS model initially used these hydrographs and then were modified or calibrated along with local flow along the reach to match downstream balanced hydrographs on the Main Stem. Modelers are aware of this issue and will be adjusting for this throughout the modeling process.

6.4 Unsteady vs. Steady RAS modeling Inputs

The peak discharge values at various exceedance probabilities will be different for the unsteady and steady RAS models for the coincident flows at the mouth of Sheyenne River. To determine the steady RAS coincident discharge-frequencies at the mouth of the Sheyenne, the flow-frequency discharges upstream and downstream of the confluence of the Sheyenne and the Red Rivers were subtracted from each other at each exceedance probability.

The Unsteady RAS model coincident flow-frequency values at the mouth of the Sheyenne River are based on the balanced hydrograph methodology described in **Section 6.3.2**. This methodology involves subtracting the balanced hydrographs upstream of the confluence with the Sheyenne from the balanced hydrographs downstream of the confluence at each exceedance probability to generate the balanced hydrographs at the mouth of the Sheyenne River at the various exceedance probabilities. The peak discharge at each frequency was then determined to be equivalent to the peak of the balanced hydrograph at for that frequency of event. These values are listed in **Table 32, Table 33, and Figure 34.**

These two methodologies won't produce the same discharge-frequencies. The difference in timing between the upstream and downstream hydrographs will produce a hydrograph at the confluence with a greater peak (using the methodology described in **Section 6.3.2** for the Unsteady-RAS model), then if one had simply subtracted the peaks associated with the upstream and downstream balanced hydrograph (for the steady RAS model). This is made clearer by **Figure 55**.

7. Confidence Intervals

Confidence Limit curves are sometimes referred to as error limit curves about the adopted Log-Pearson Type III discharge-probability function developed using the non-central t distribution. Confidence limit curves are used to define the discharge-exceedance probability function's uncertainty.

The Corps calculated ninety percent confidence interval, limit curves for the unregulated and regulated conditions at Fargo. This was done for each of the climate futures; WET, 25-, and 50-yr, look-ahead periods. Equivalent years of record for the WET period were based on the 68 years that were available for that period. The DRY period had 40 equivalent years. The Corps's Flood Damage Analysis program ***(*HEC-FDA*, reference 13)*** calculates the limit curves based on the equivalent number of years for each period and the three moments of the Log Pearson Type III statistical distribution.

The WET and Dry period curves can be calculated directly based on the actual number of years in their respective periods. The combined curves for the 25-yr and 50-yr periods had to be estimated. Initially, the Corps calculated limit curves based on equivalent years for the 25-yr and 50-yr look-ahead conditions by weighting the respective years with the probability that each component would occur, (i.e. WET & DRY). For the 25-yr future period, the WET equivalent years were given a weight of 0.8 and the corresponding DRY condition years were assigned a weight of 0.2. The Corps assigned the 50-yr future a weight of 0.65 and 0.35 respectively. This computation generated equivalent years of 62 and 58 for the 25- and 50-yr look-ahead periods, respectively. Previous analysis described in this report determined the three moments of each future period.

The 25- and 50-yr look-ahead periods were deemed to have as much uncertainty in the upper limit as the WET period. Therefore, an adjustment to the upper 0.05 limit was computed by adjusting the equivalent years of record until the 2 percent exceedance frequency limit flows were the same for all three conditions. This resulted in equivalent years of record equal to 59 and 52 for the 25-yr and 50-year look-ahead periods. This was done to match the upper limit 0.05 limit curve for the WET future as close as possible for each combined future condition. As can be seen in **Figure 56**, the combined curves have different slopes so there cannot be a perfect match. Therefore, the Corps selected the 2 percent exceedance frequency as the best match point that would render equivalent economic impact to the WET 0.05 limit curve. **Table 35** lists the adopted 0.05 limit curve flow values for each exceedance frequency and future condition.

Table 35. Five % Confidence Limits for Climate Future and Equivalent Years

5 % CONFIDENCE LIMIT FOR CLIMATE FUTURE AND EQUIVALENT YEARS			
Exceedance Frequency	**WET 68 yrs Flow, cfs**	**25-yr 59 yrs Flow, cfs**	**50-yr 52 yrs Flow, cfs**
0.002	108,987	113,187	117,406
0.004	90,904	93,588	96,382
0.010	69,566	70,558	71,764
0.020	55,163	55,081	55,283
0.040	42,296	41,375	40,801
0.100	27,620	26,003	24,802
0.200	18,257	16,465	15,122
0.300	13,457	11,720	10,437
0.500	8,078	6,601	5,556
0.700	4,843	3,693	2,924
0.800	3,552	2,593	1,974
0.900	2,302	1,576	1,134
0.950	1,599	1,034	708
0.990	789	454	281
0.999	342	170	92

8. References

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2. Department of Defense, U.S. Army Corps of Engineers, Hydrologic Engineering Center, ***"HEC-5, Simulation of Flood Control and Conservation Systems***", Oct 1998.

3. Department of Defense, St. Paul District U.S. Army Corps of Engineers, "***Volume I, Timing Analysis" for the Technical Resource Service, Red River of the North",*** March 1988.

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5. Department of Defense, U.S. Army Corps of Engineers, Hydrologic Engineering Center, ***"HEC-HMS, Hydrologic Modeling System"***, ***Version 2.2***, September 1998.

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7. Pettitt, A.N. (1979), "A non-parametric approach to the change-point problem", *Appl. Stat*., 28, 126-135.

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11. Department of Defense, U.S. Army Corps of Engineers, Hydrologic Engineering Center, ***"HEC-1, Flood Hydrograph Package,*** September1990.

12. Department of Defense, U.S. Army Corps of Engineers, Hydrologic Engineering Center, "***HEC-DSSVue, Data Storage System Visual Utility Engine", Version 2.0,*** August 2009.

13. Department of Defense, U.S. Army Corps of Engineers, Hydrologic Engineering Center, ***"HEC-FDA, Flood Damage Reduction Analysis",*** November 2008.

FIGURES

Figure 1. Boise de Sioux and Red River of the North

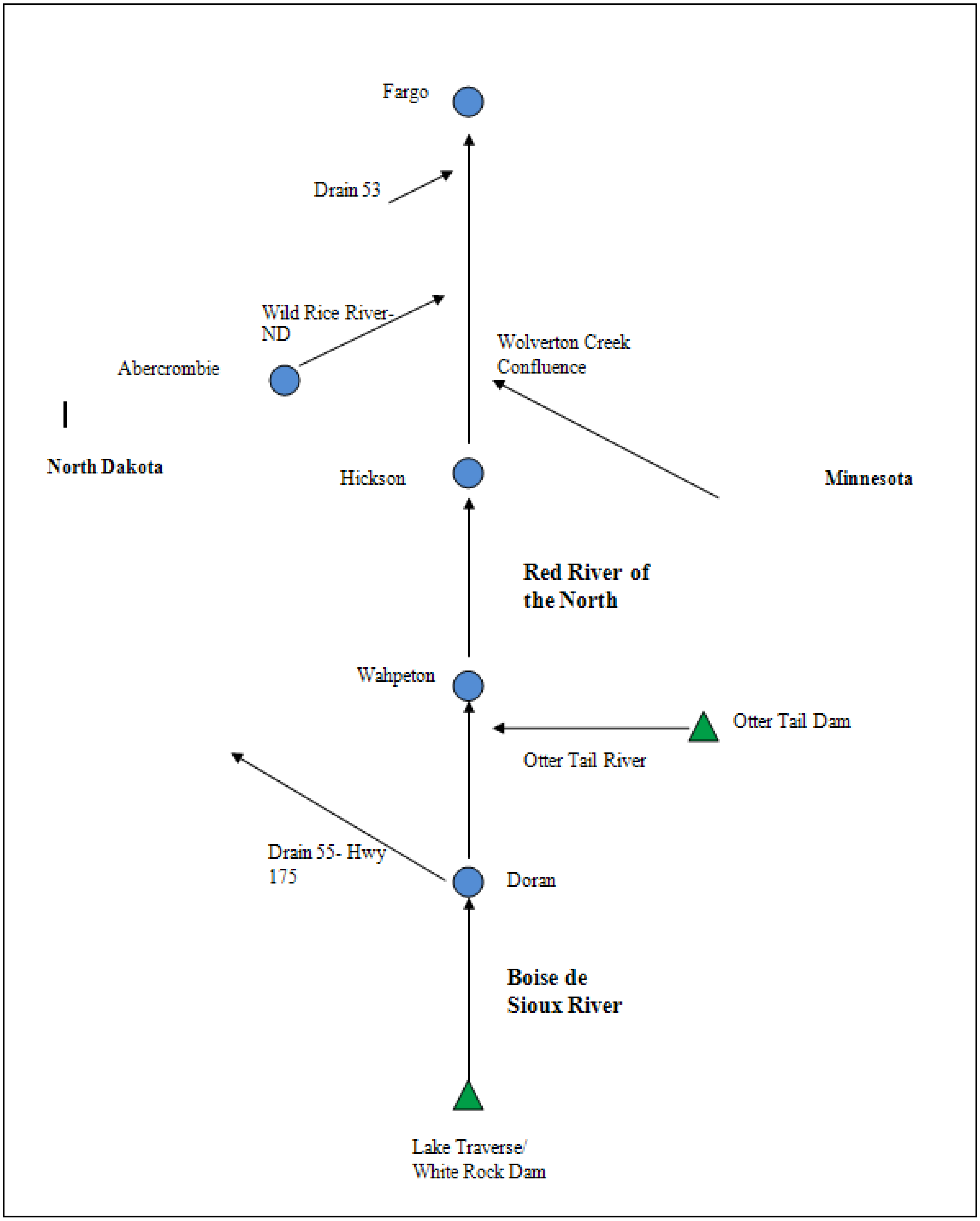


Figure 2. Red River Reach Fargo to Halstad

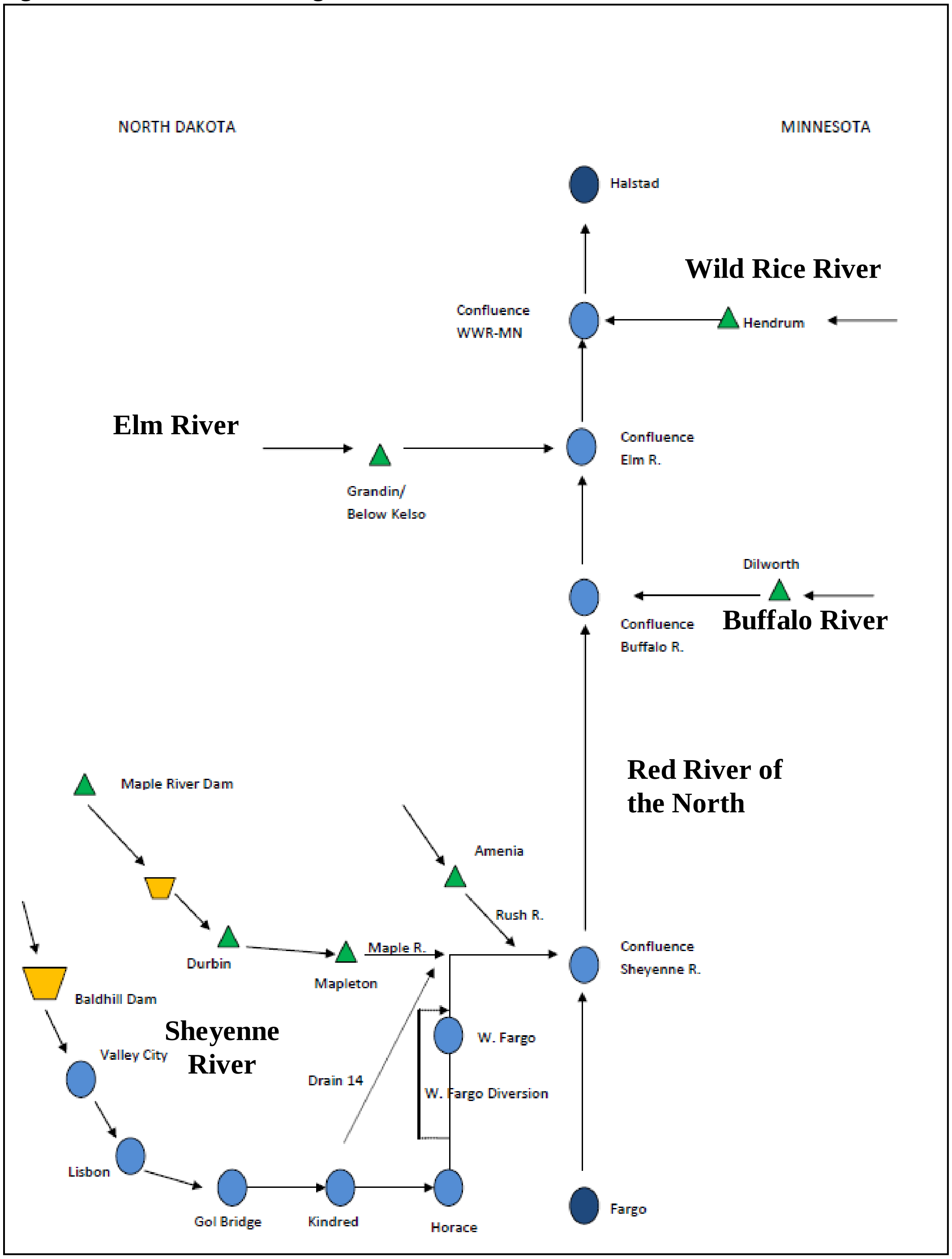


Figure 3. Red River Reach Halstad to Grand Forks

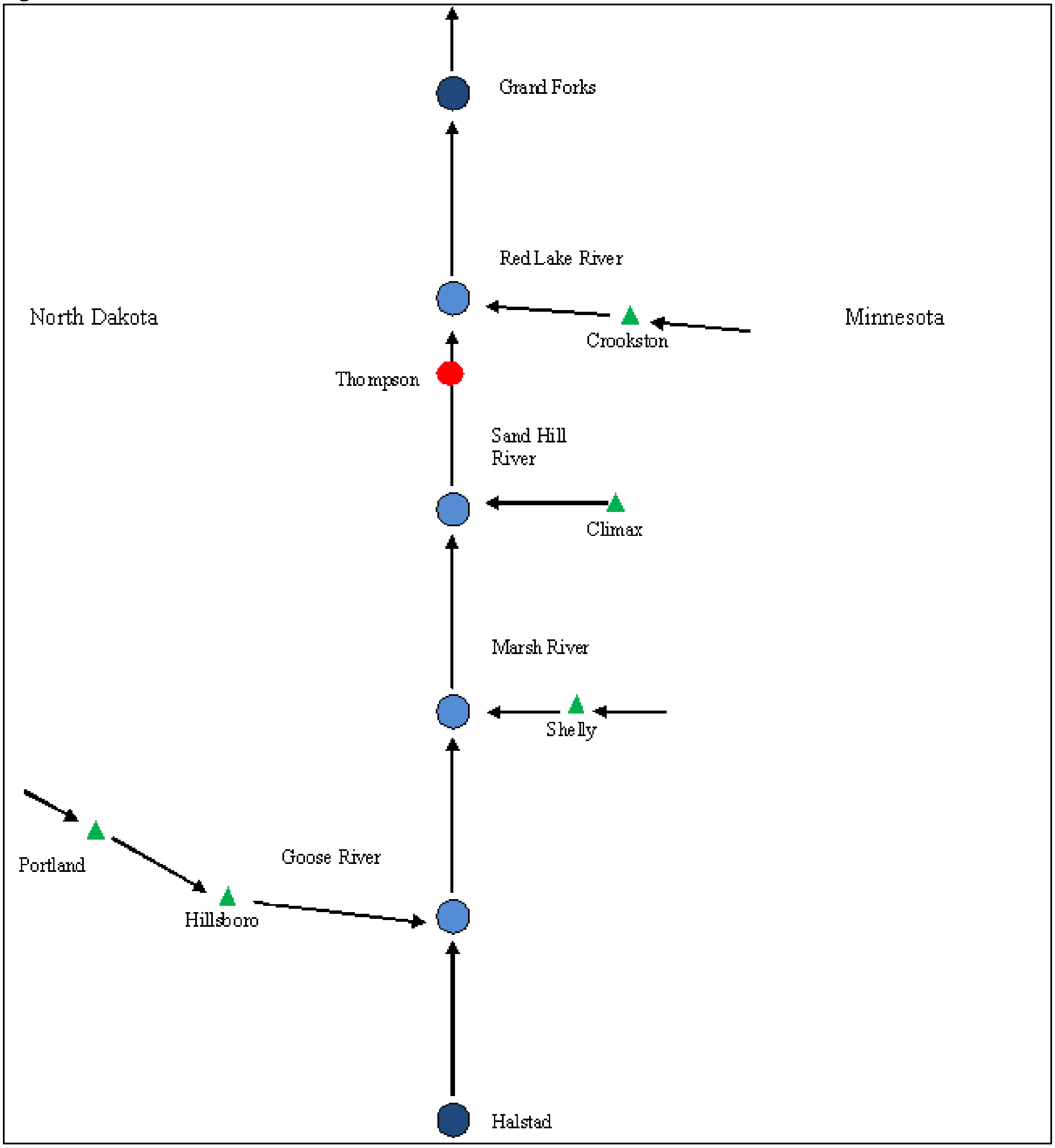


Figure 4- Red River at Grand Forks Peak Flow Frequency Curve- Full Period

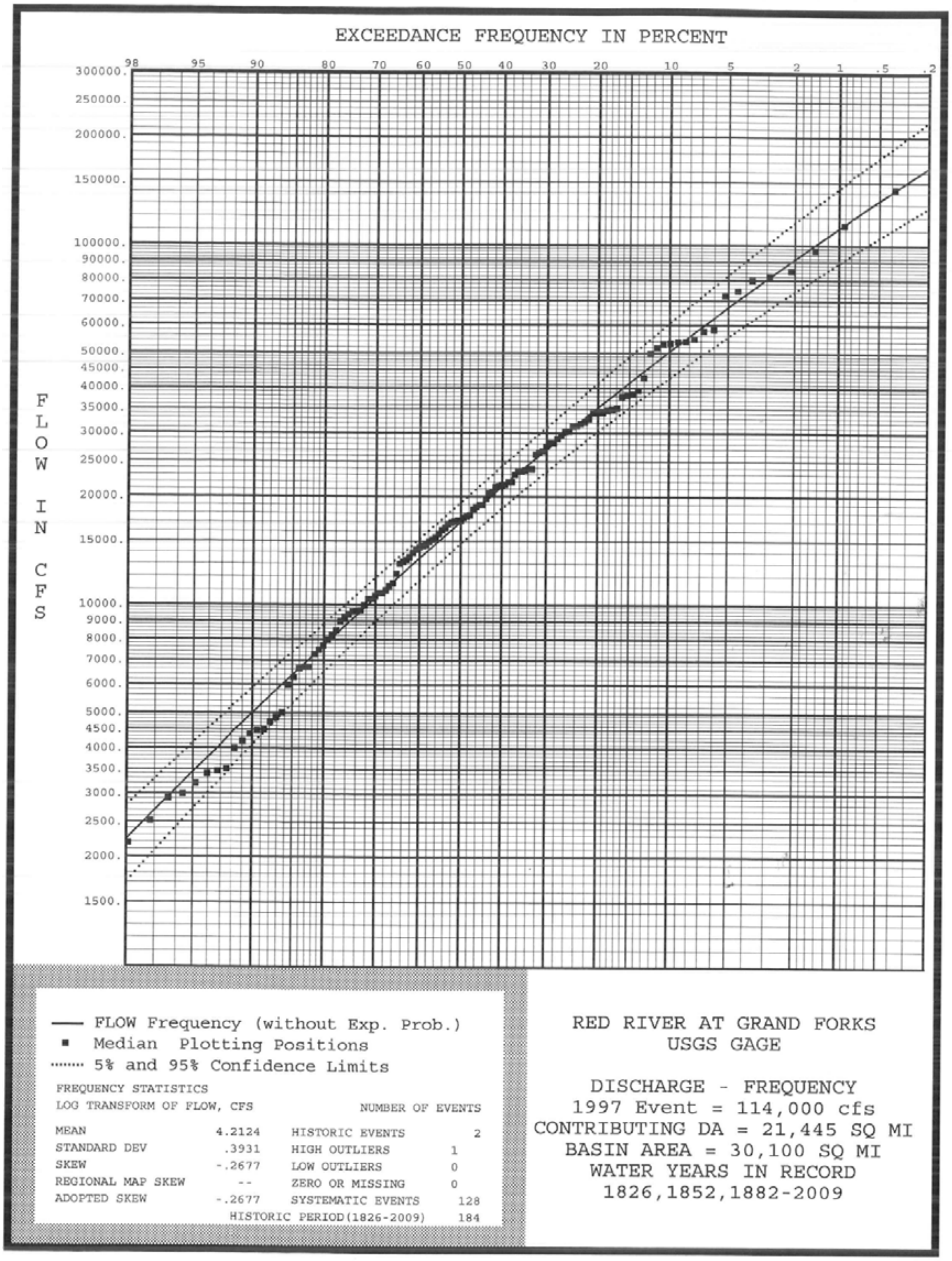


Figure 5- Red River at Halstad Peak Flow Frequency Curve- Full Period

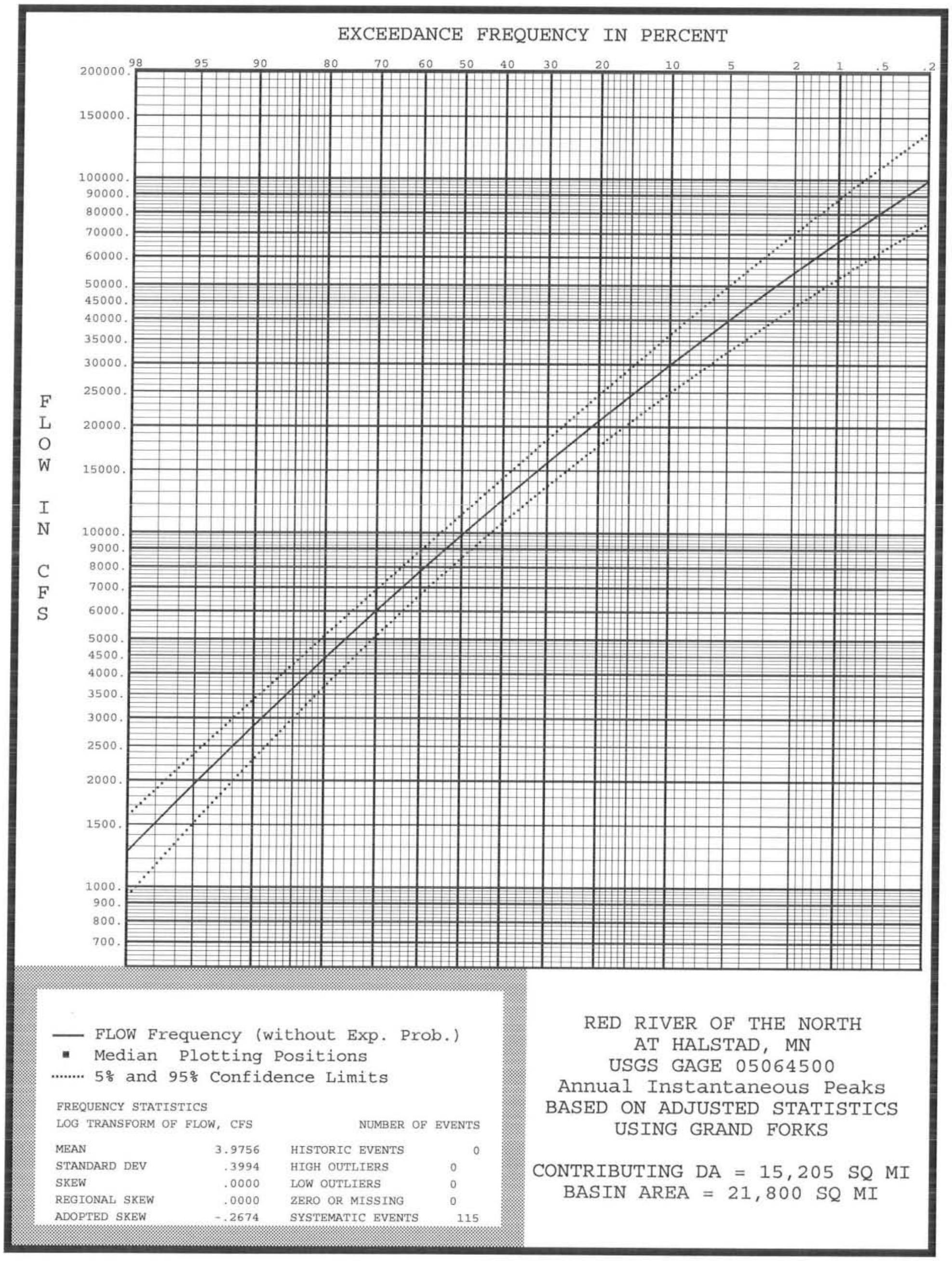
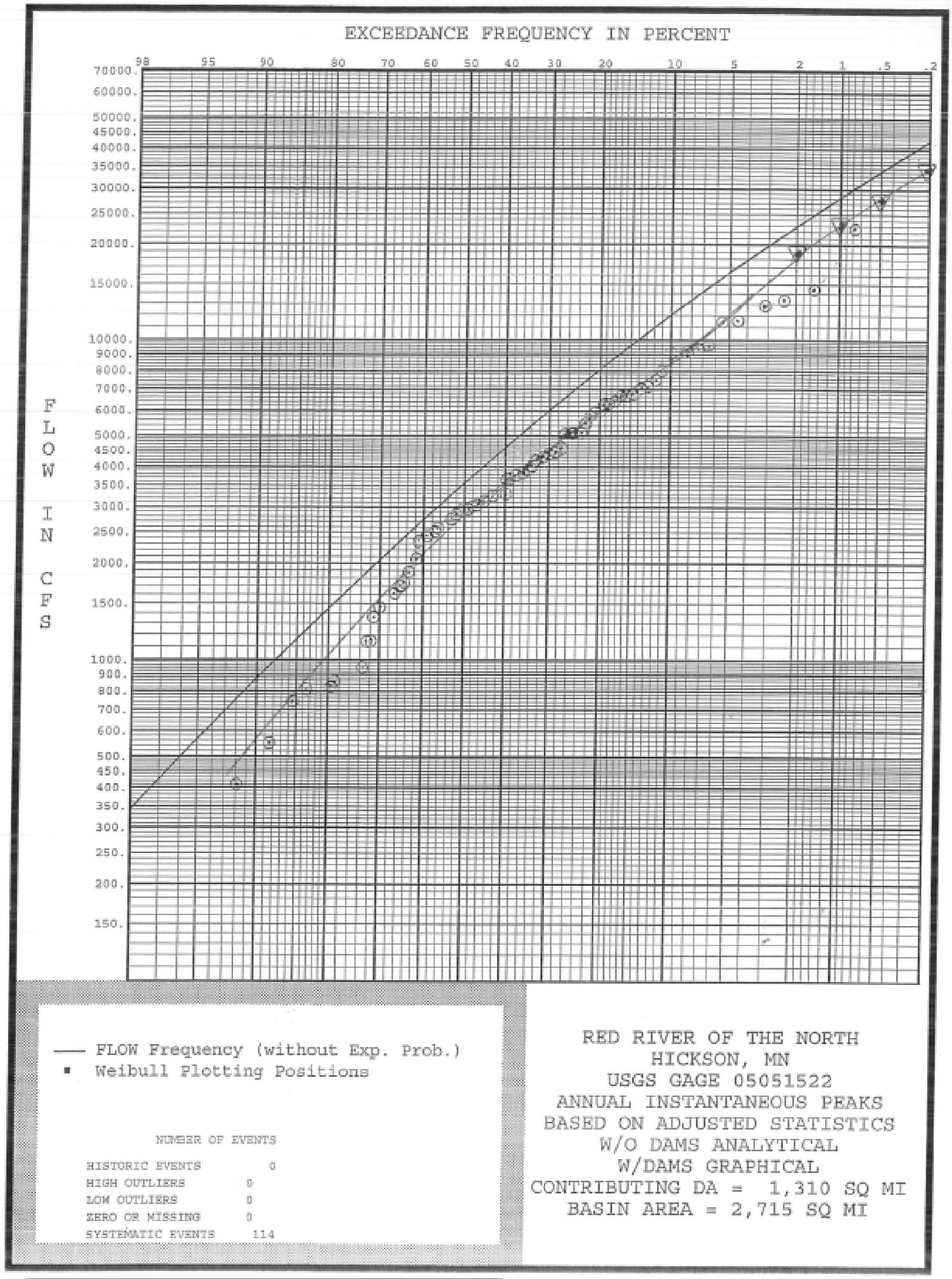


Figure 6- Red River at Hickson Peak Flow Frequency Curve- Full Period



Pencil Line = Graphical Flow Frequency Curve

Figure 7. Unregulated annual peak flows at Grand Forks

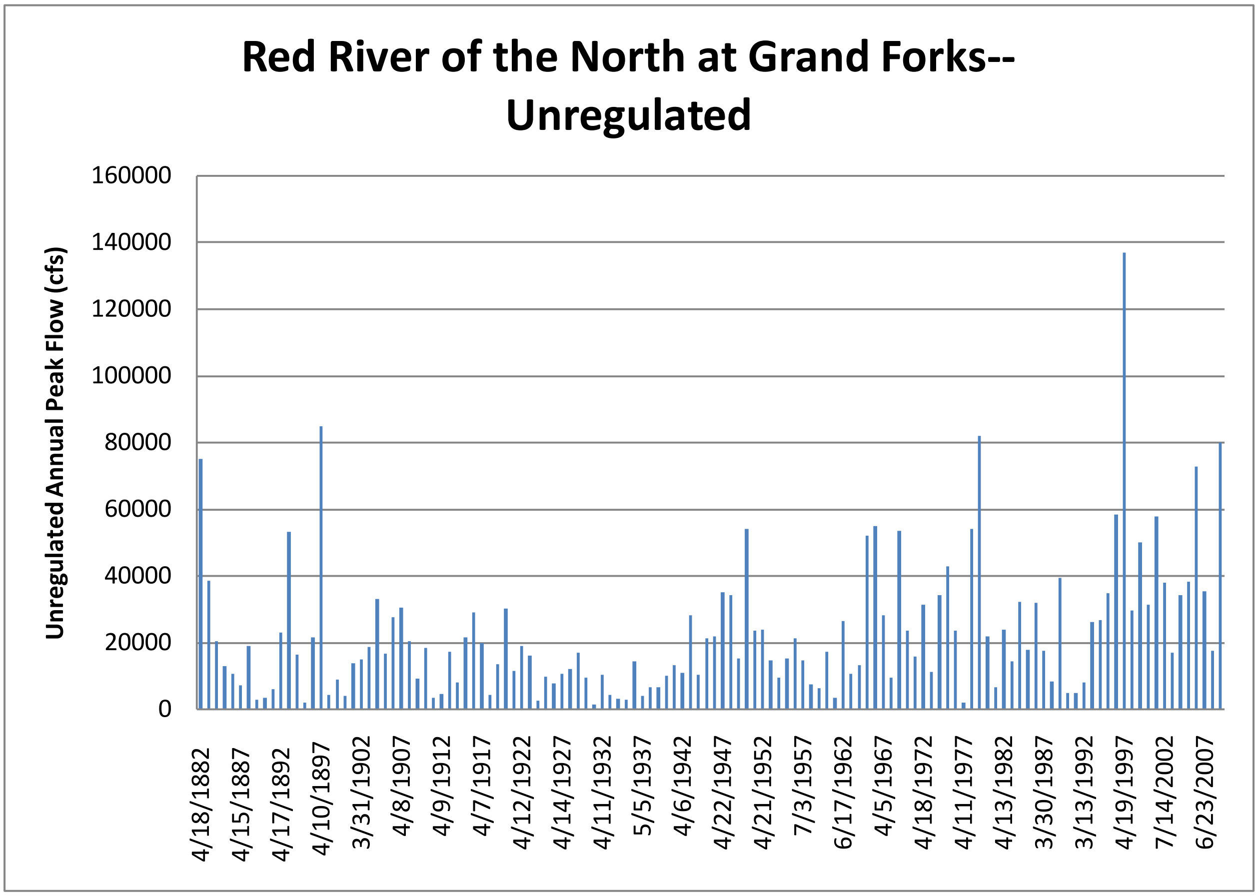


Figure 8. Change Point Analysis for Grand Forks, ND

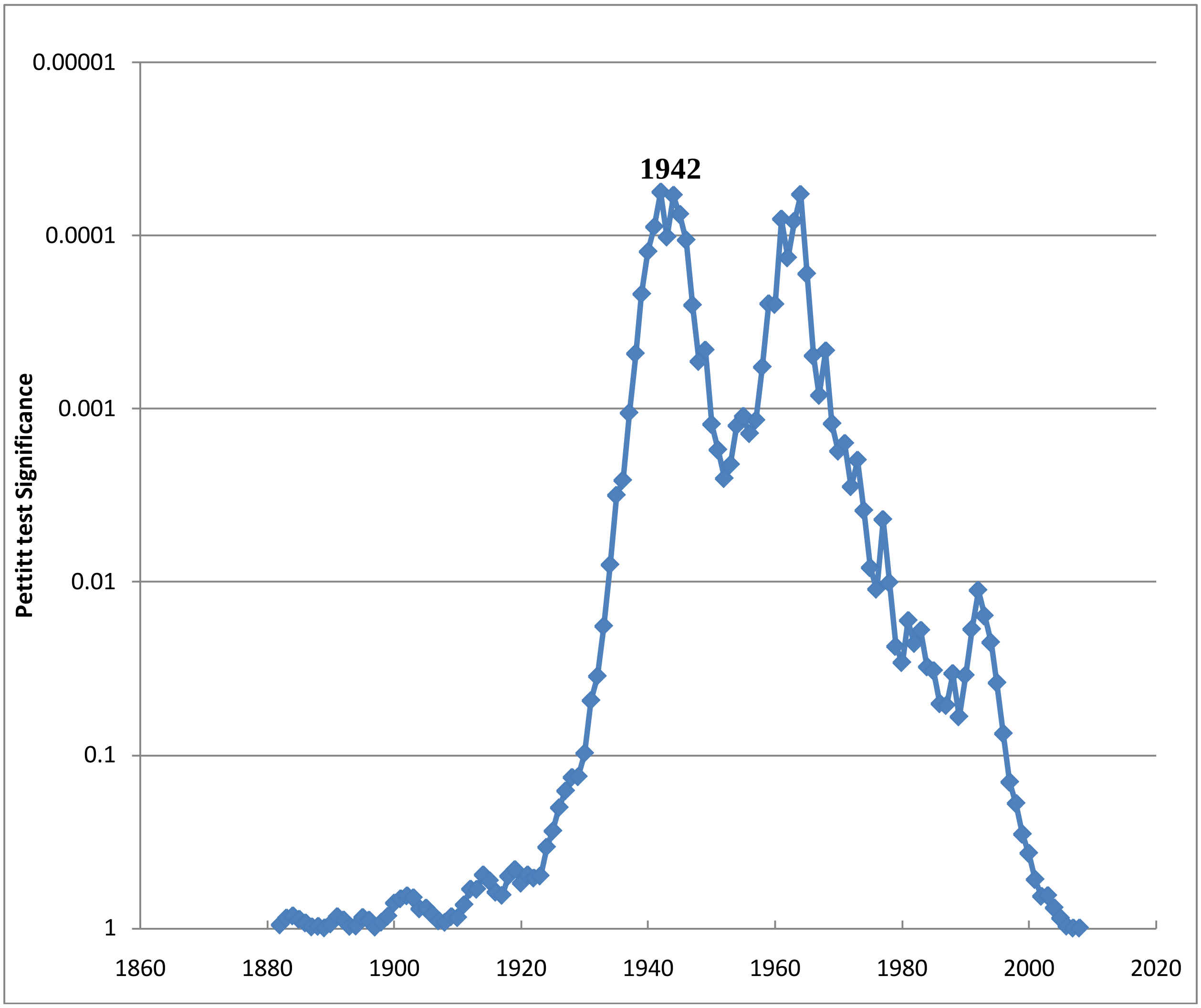


Figure 9. Red River of the North at Grand Forks- Flow Frequency Curves for Wet (1942-2009) and Dry Periods (1882-1941) with Median Plotting Positions

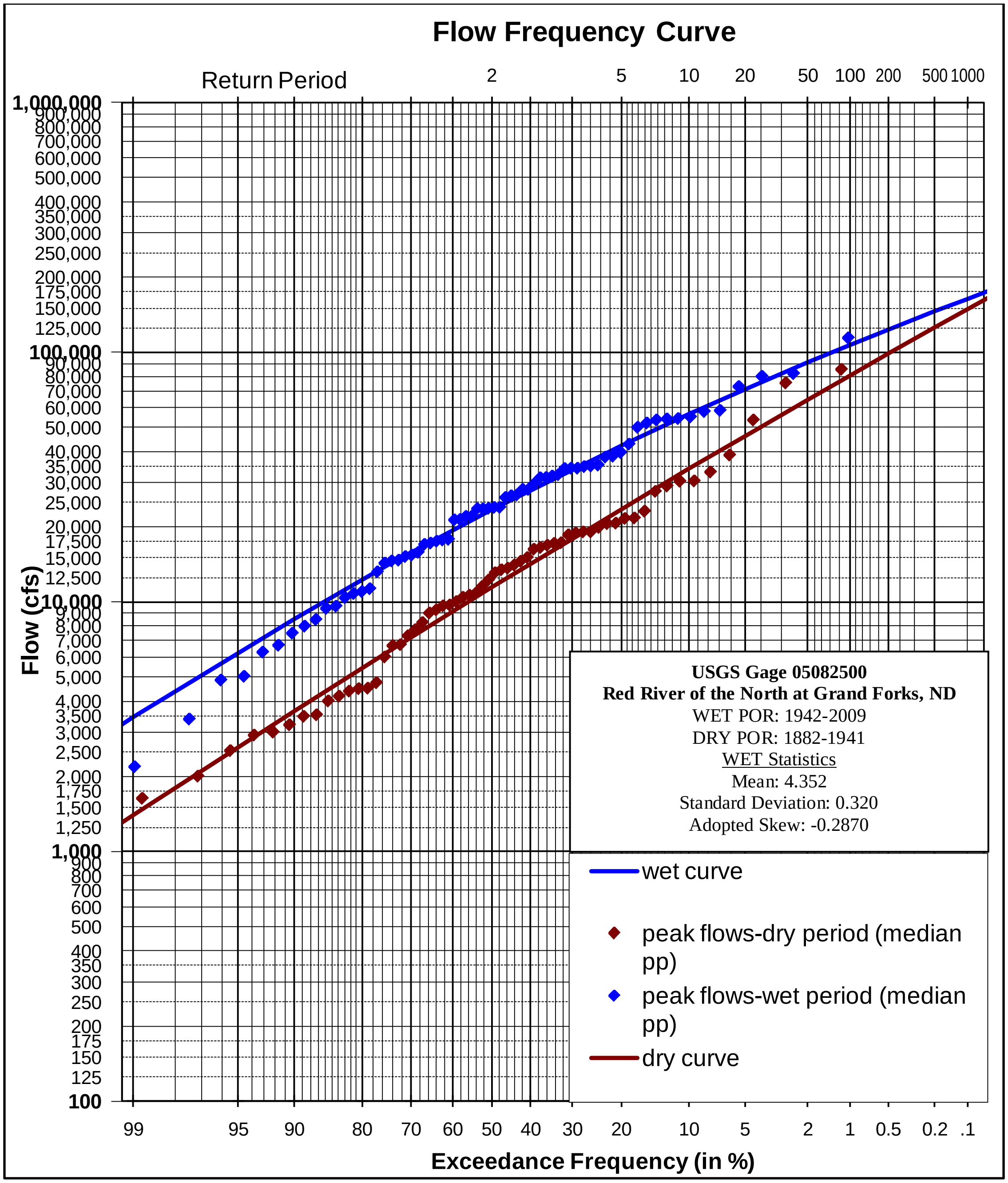


Figure 10. Grand Forks Peak Flow Frequency Curves for Wet and Dry Periods with 25-year Look Ahead Curve (0.8 wet and 0.2 dry weighting).

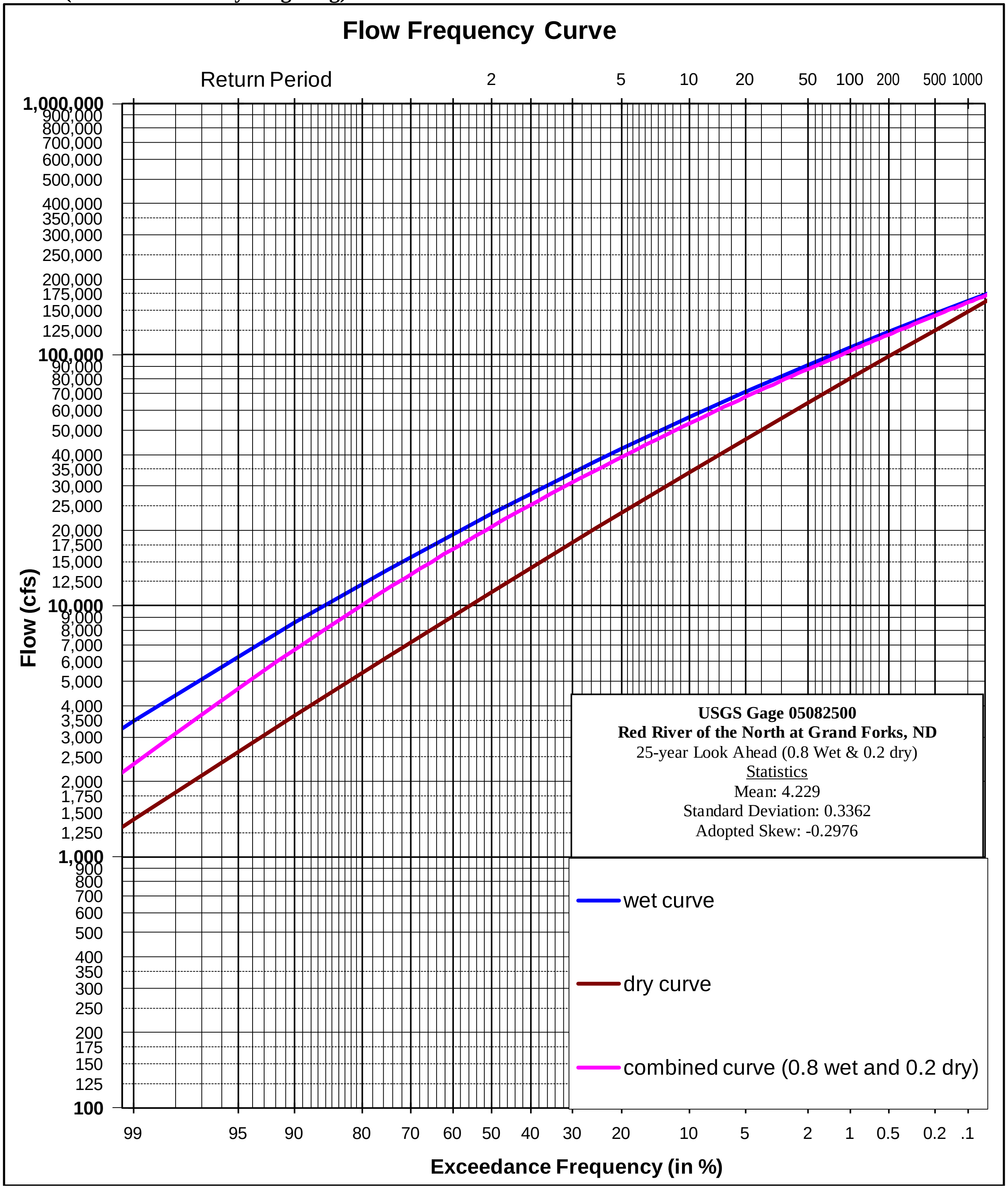


Figure 11. Grand Forks Peak Flow Frequency Curves for Wet and Dry Periods with 50-year Look Ahead Curve (0.65 wet and 0.35 dry weighting).

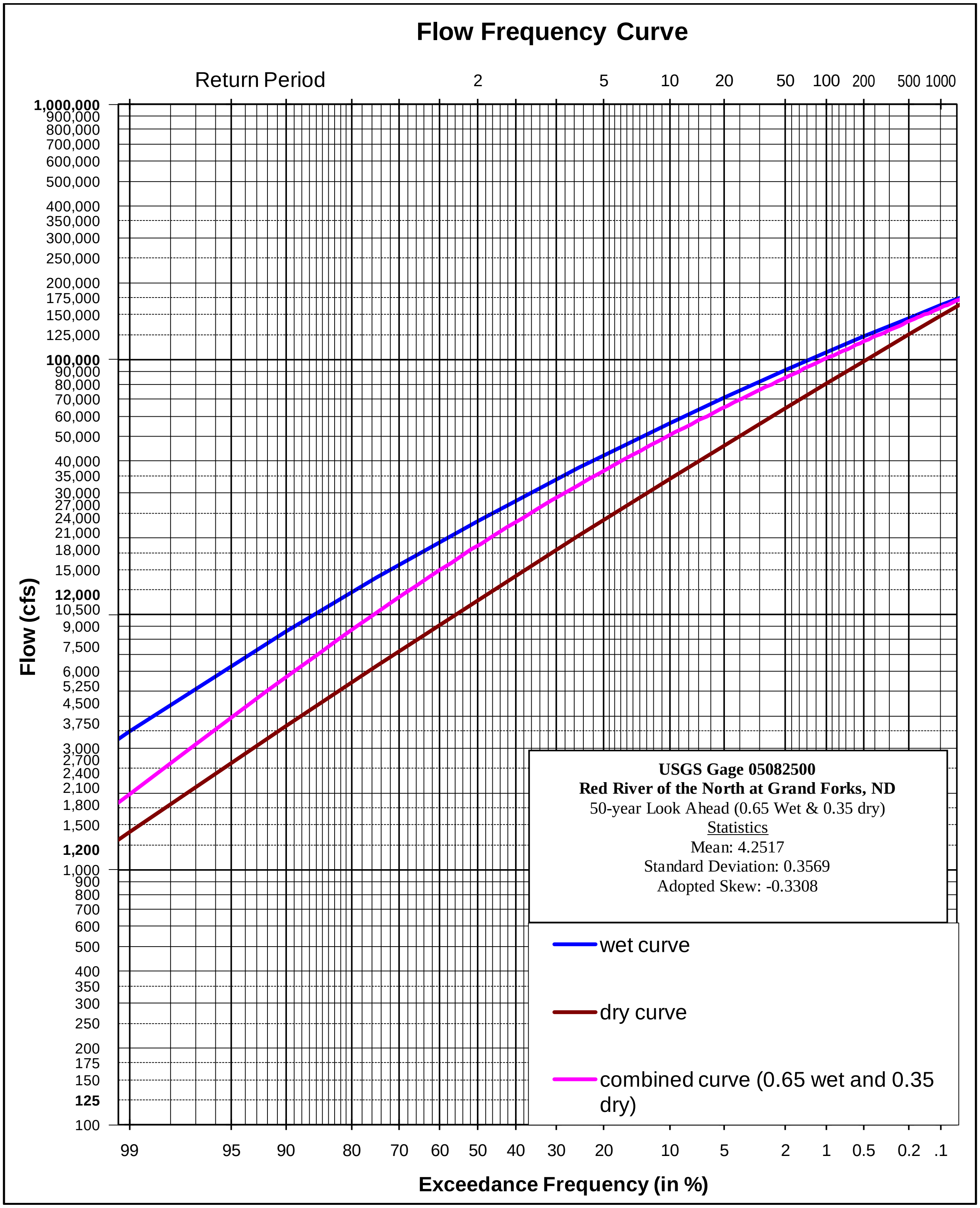


Figure 12. USGS Gage 05051522- Red River of the North at Hickson-Initial Peak Flow Frequency Curve for Wet Period (1942-2009) with Weibull plotting positions and synthetic events

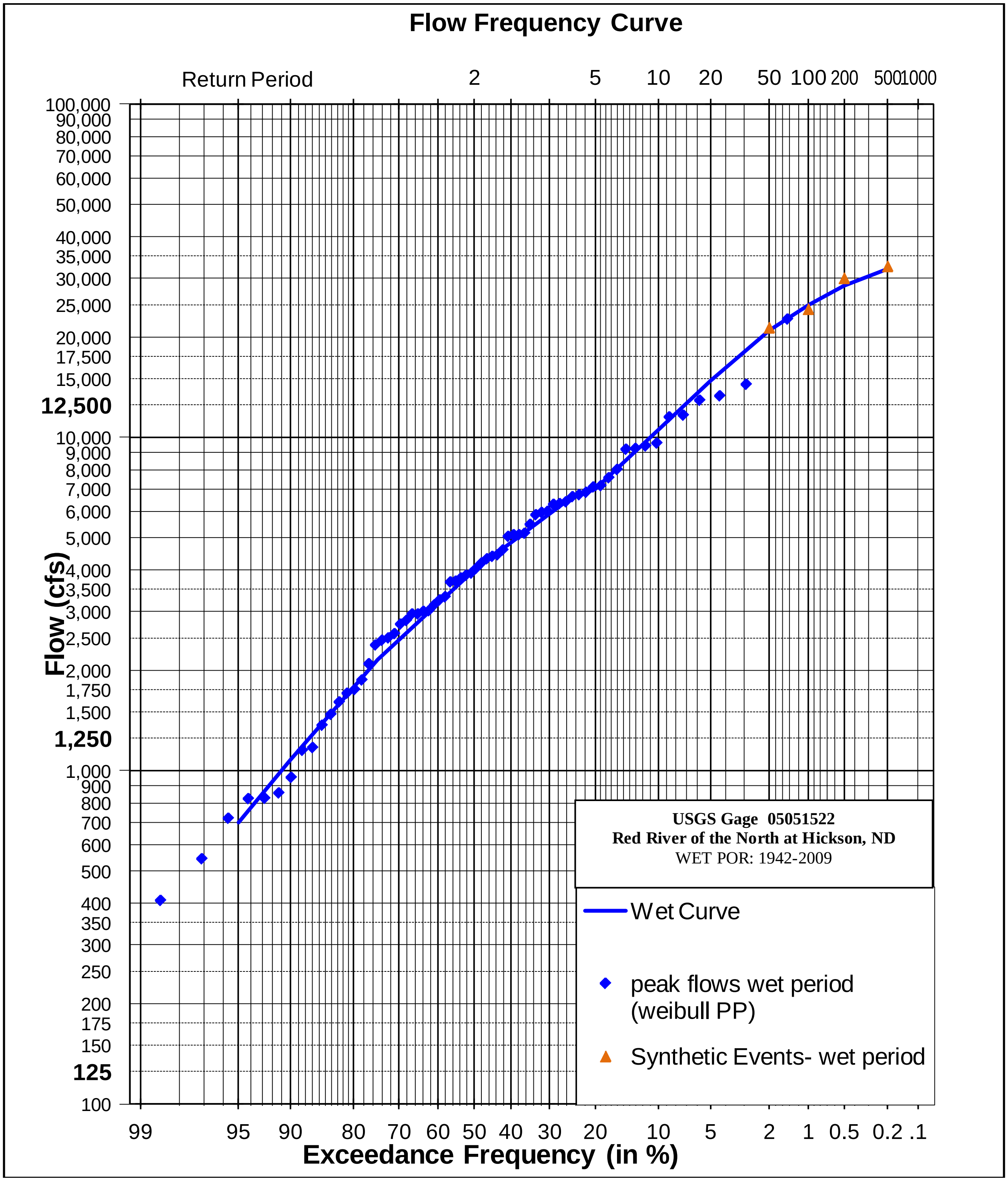


Figure 13. Hickson Peak Flow Frequency Curves for Wet Period and 25- year Look Ahead Curve (0.8 wet and 0.2 dry weighting)

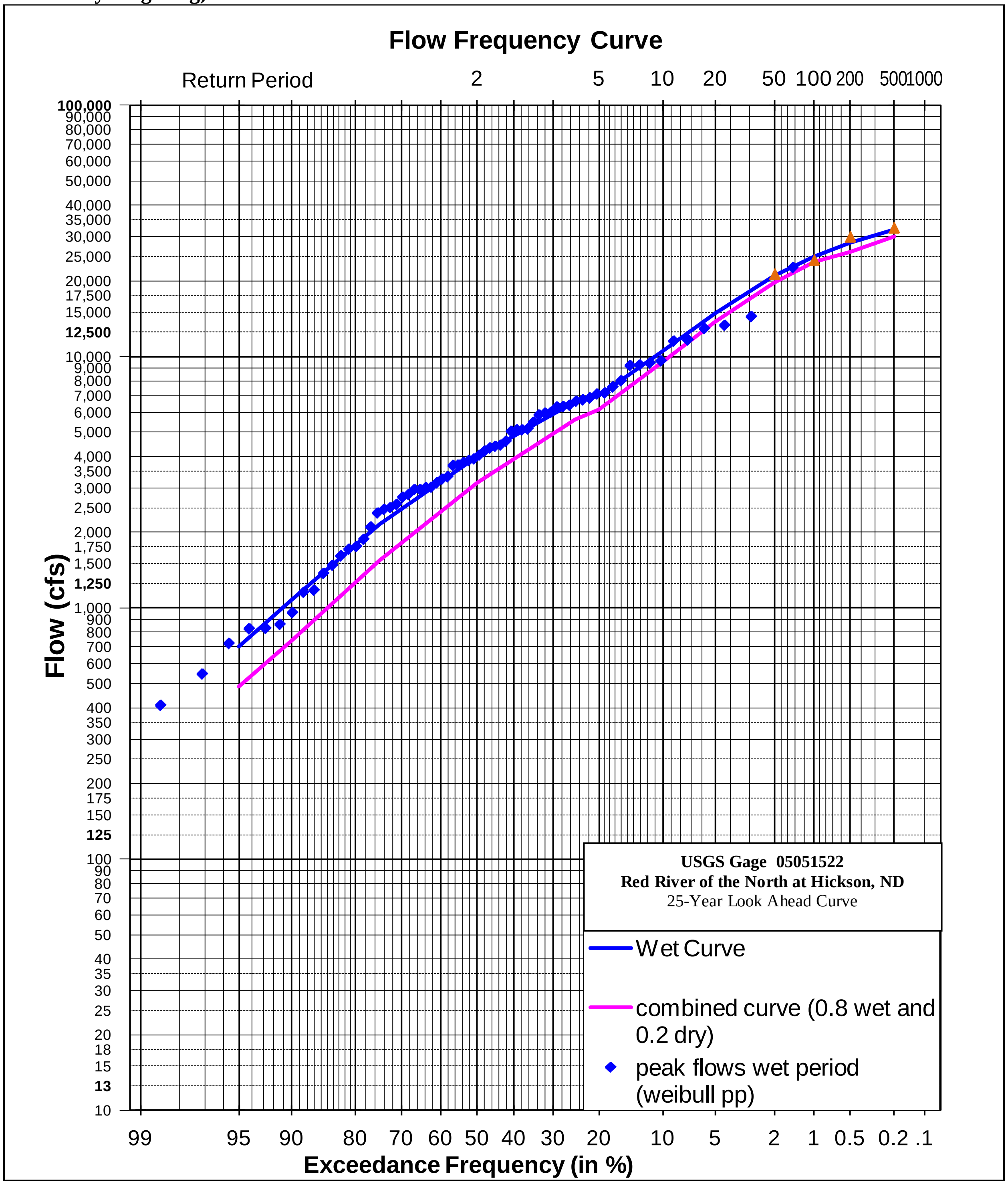


Figure 14. Hickson Peak Flow Frequency Curves for Wet and 50-year Look Ahead Curve (0.65 wet and 0.35 dry weighting).

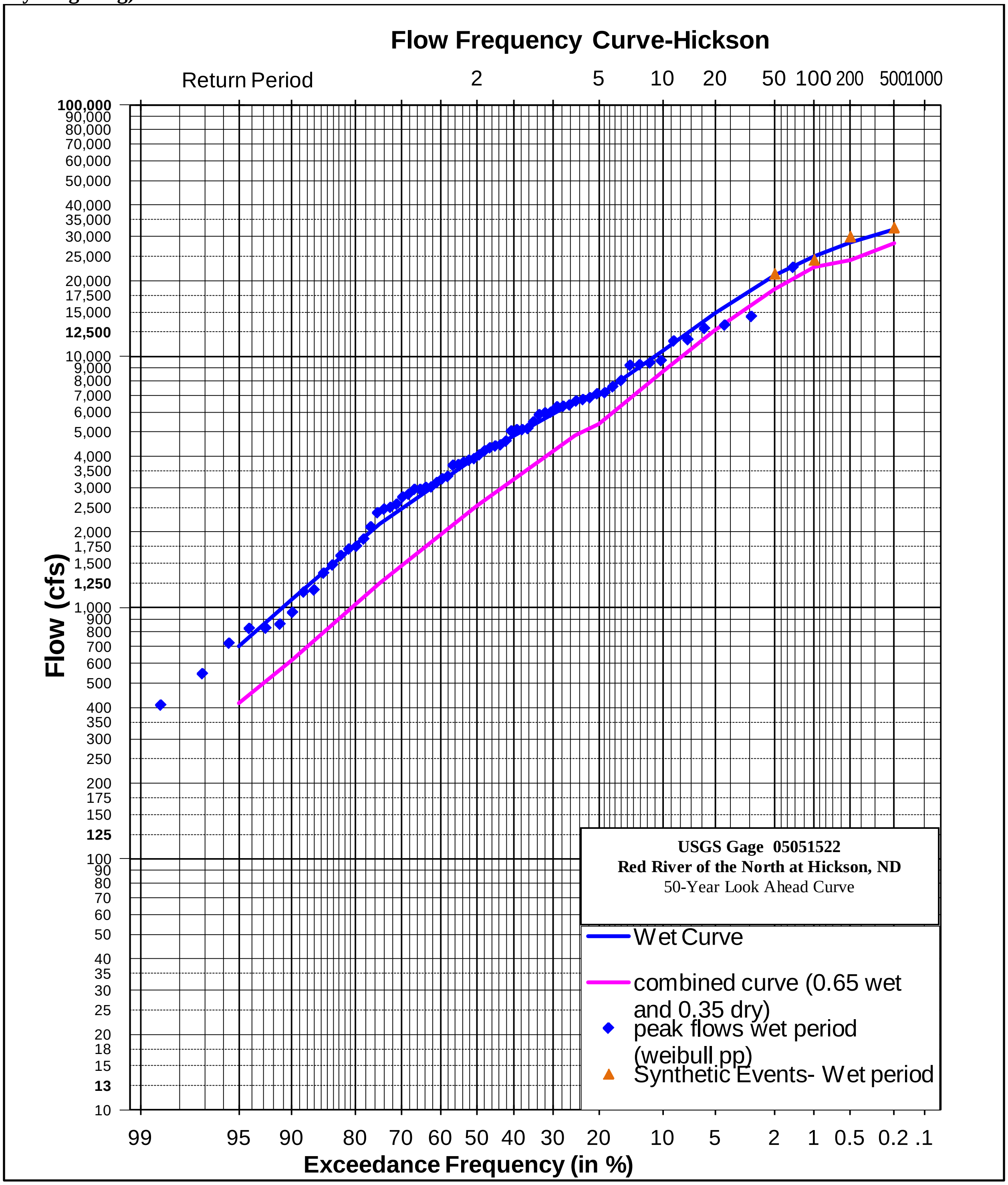


Figure 15. USGS Gage 05051522- Red River of the North at Hickson-Adopted Peak Flow Frequency Curve for Wet Period (1942-2009) with Weibull plotting positions

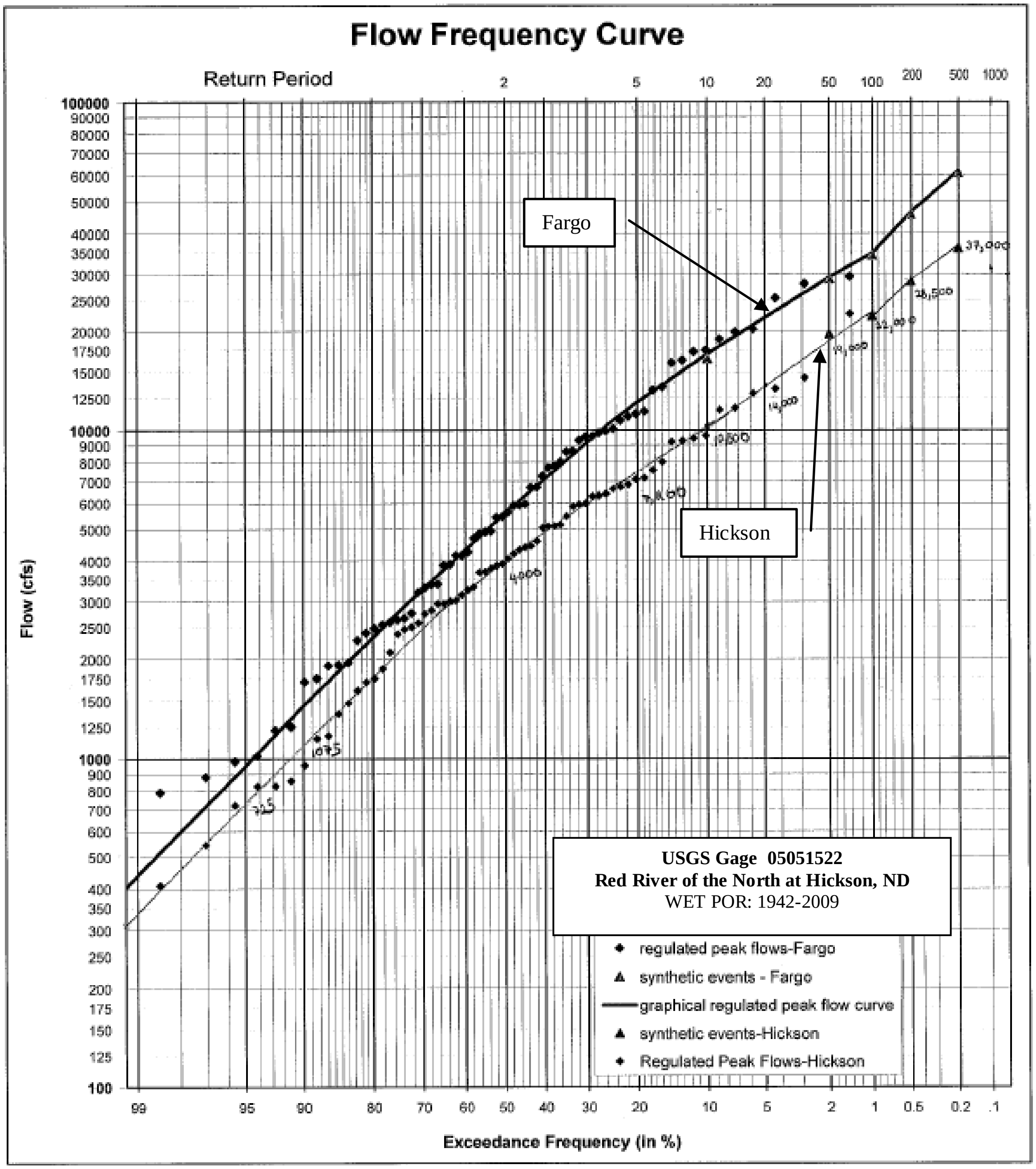


Figure 16. Example of Regression used to develop the combined curves at Halstad (5-year event, 25-year look-ahead period).

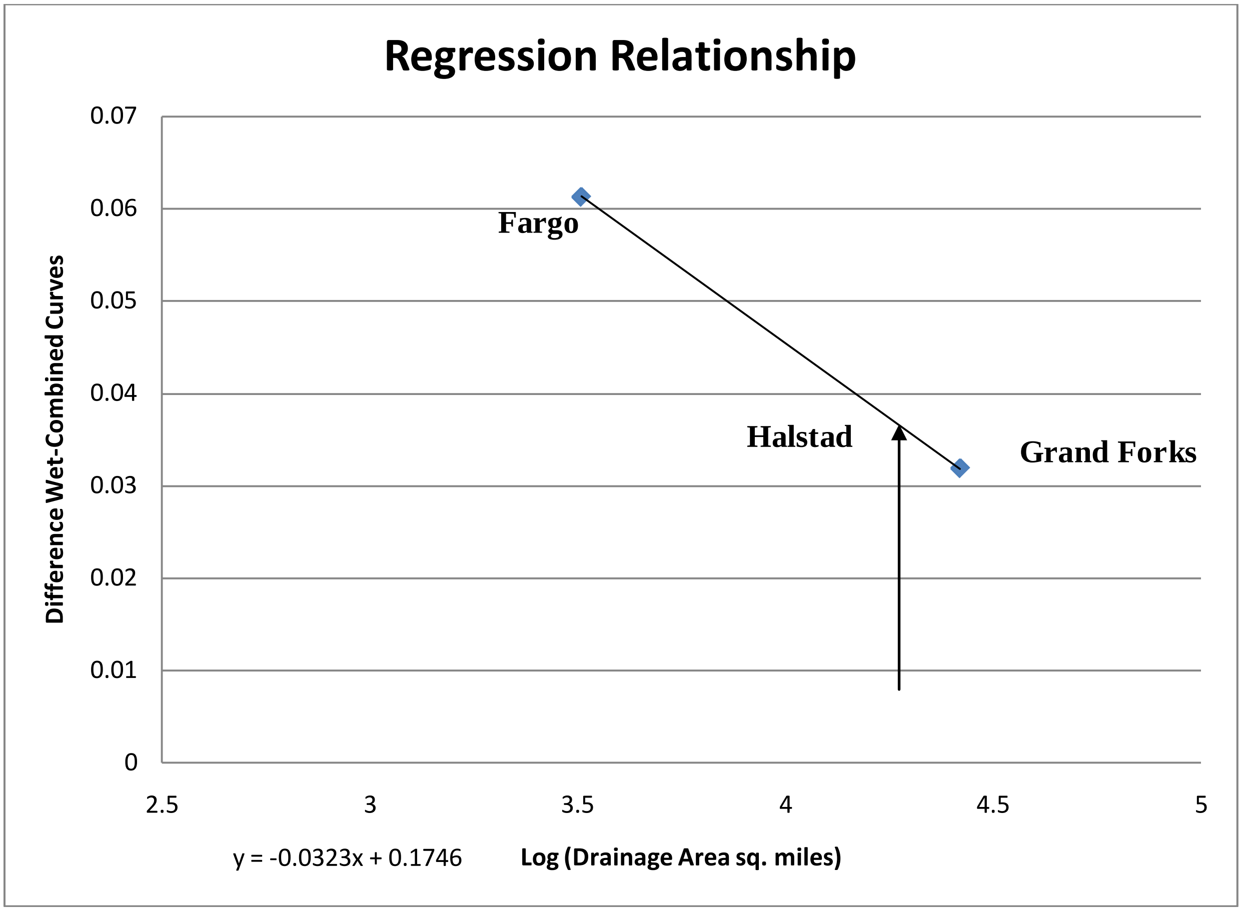


Figure 17. USGS gage 05064500 Red River of the North at Halstad, MN- Peak Flow Frequency Curve for Wet Period (1942-2009) with Median Plotting Position

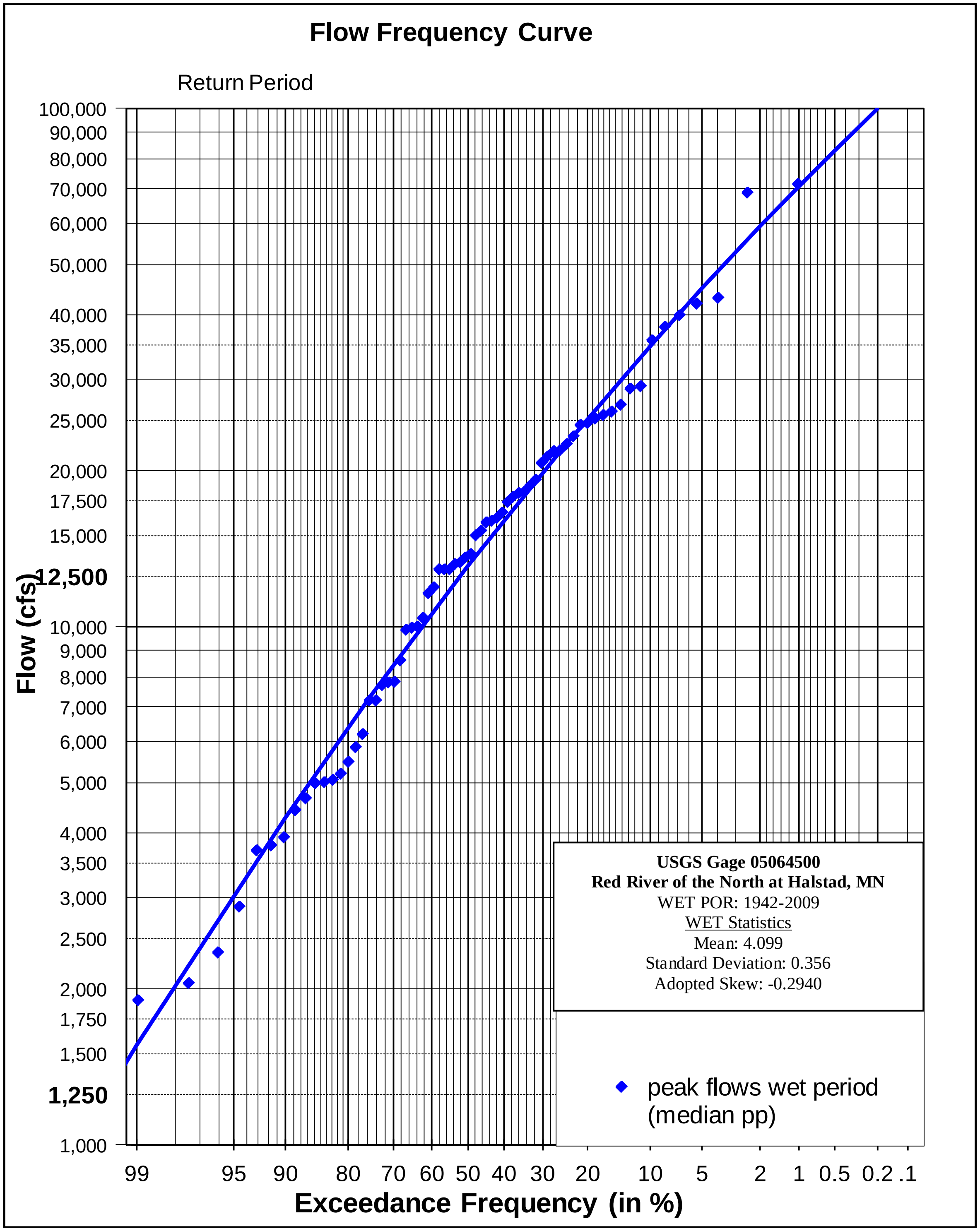


Figure 18. Halstad Peak Flow Frequency Curves for Wet and 25-year Look Ahead (0.8 wet and 0.2 dry weighting).

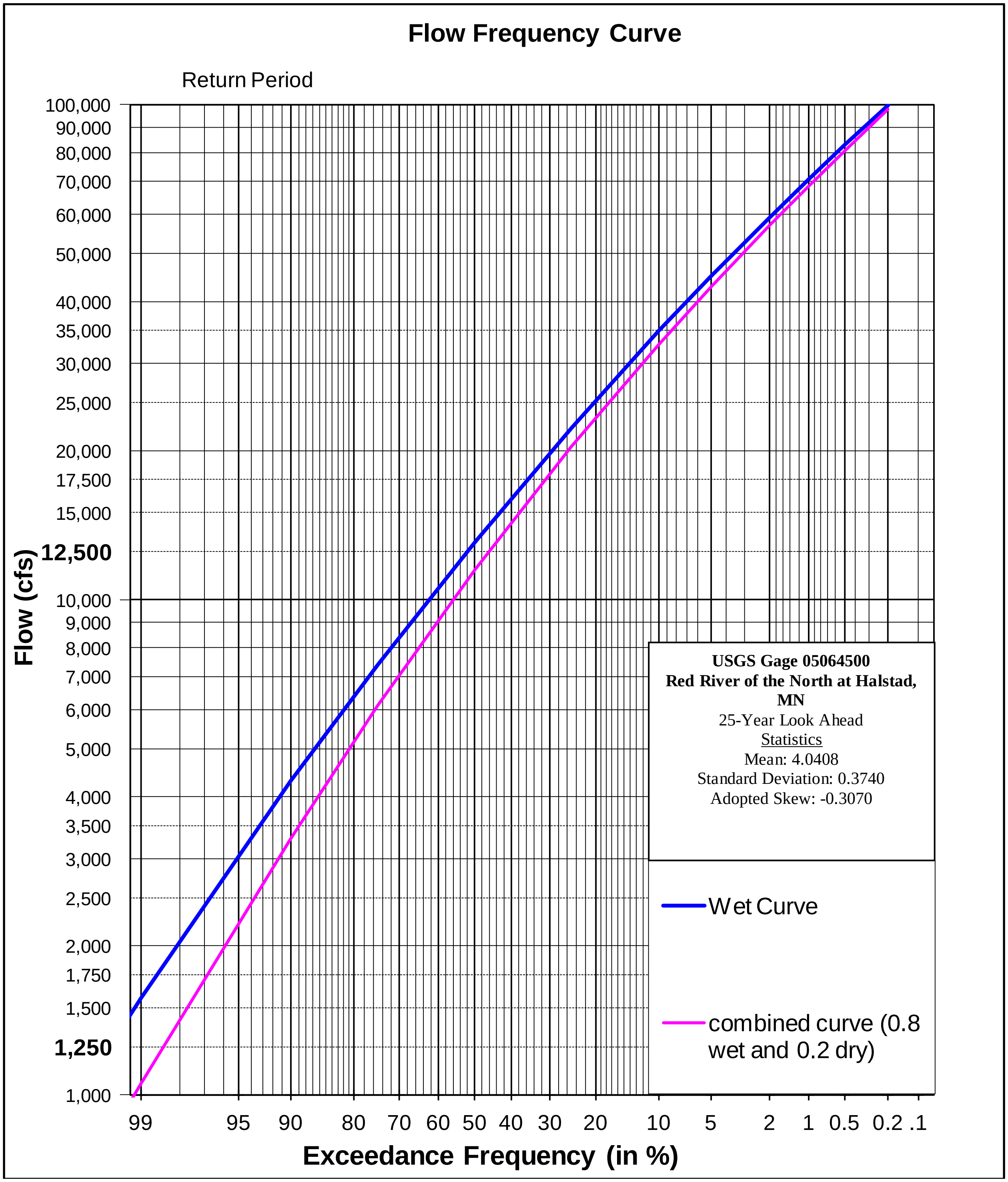


Figure 19. Halstad Peak Flow Frequency Curves for Wet and 50-year Look Ahead Curve (0.65 wet and 0.35 dry weighting).

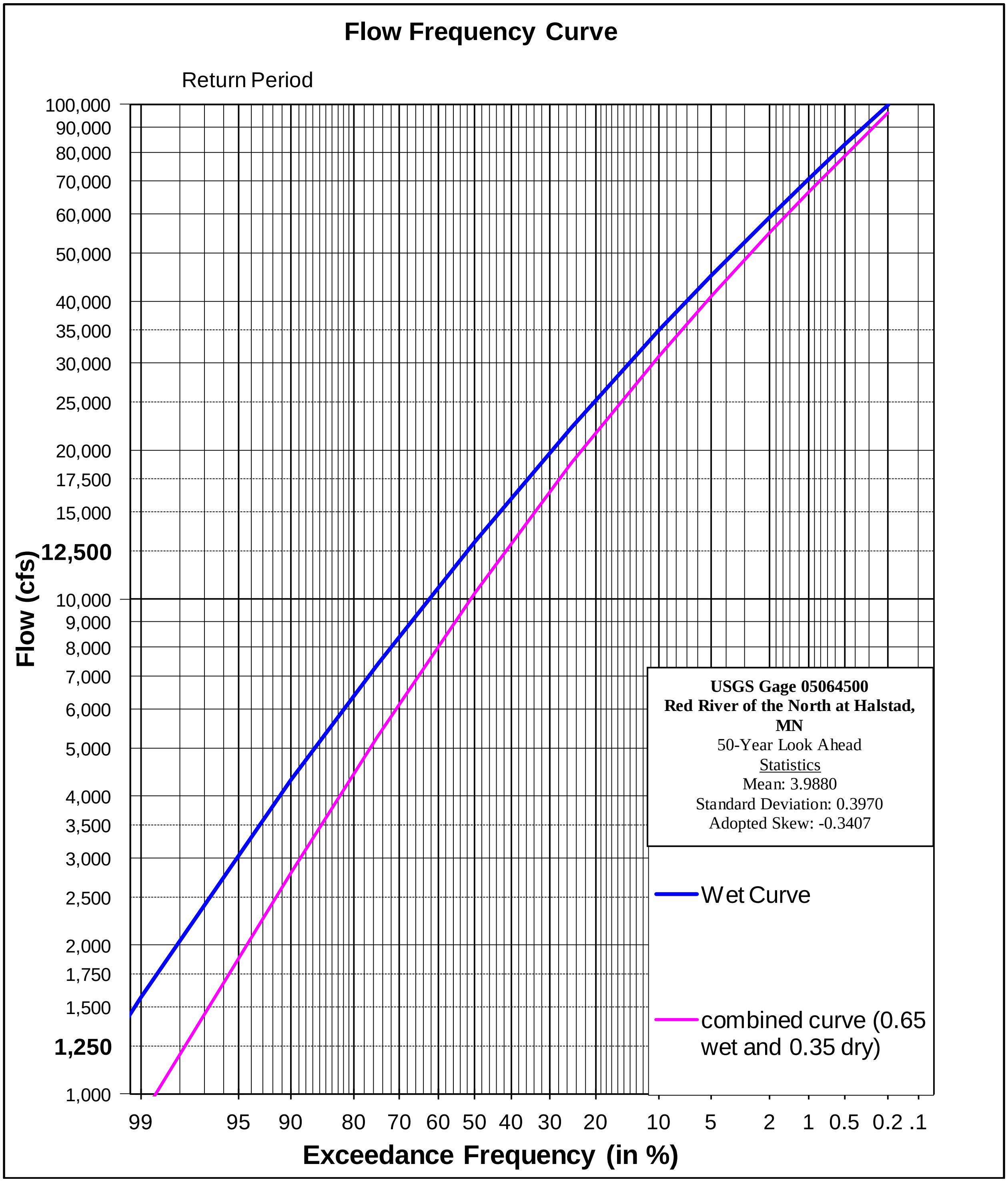


Figure 20. USGS Gage 05053000, Wild Rice River (ND) near Abercrombie, ND- Annual Instantaneous Peak Flow Frequency Curve- Full Period of Record.

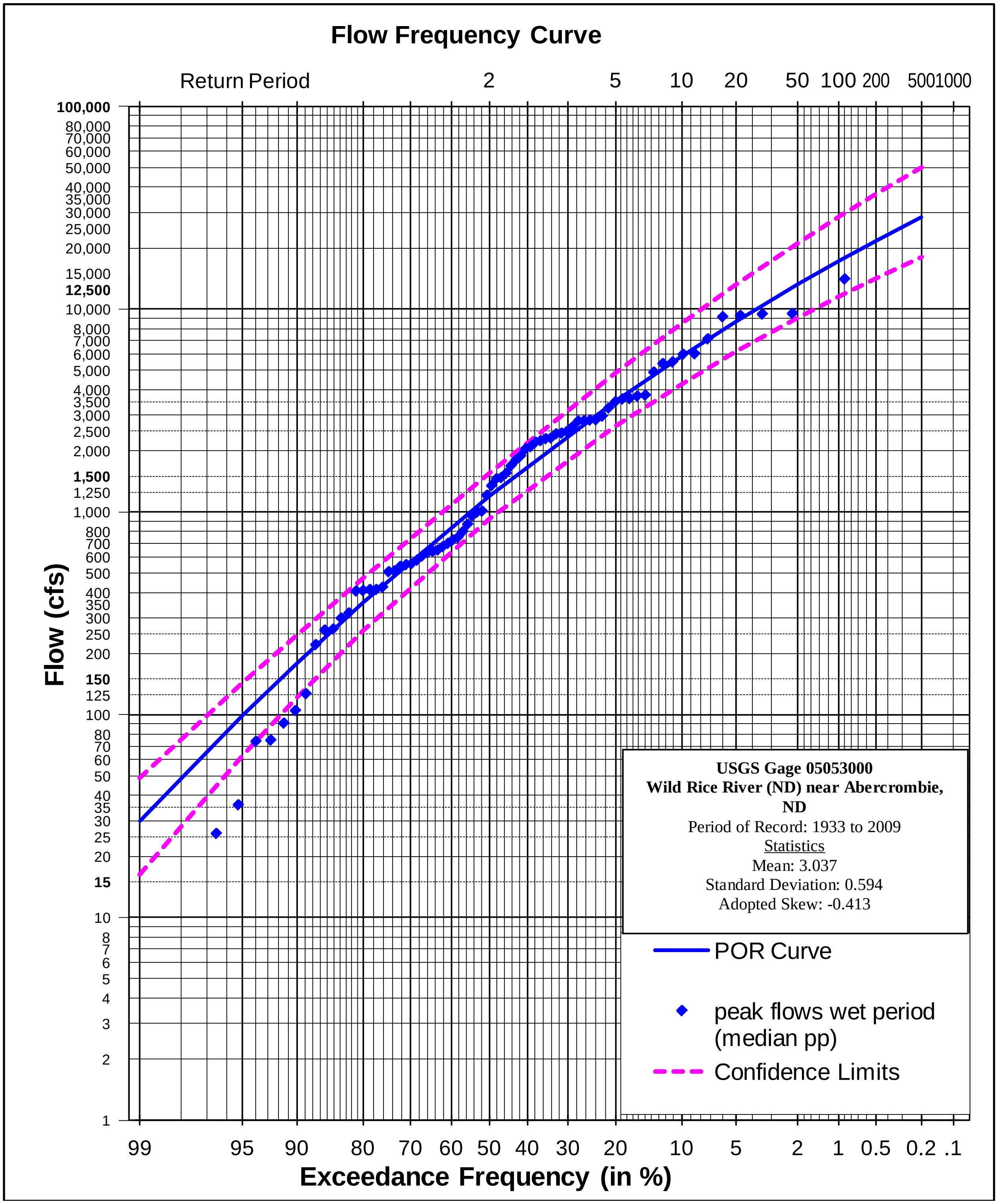


Figure 21. USGS Gage 05053000, Wild Rice River (ND) near Abercrombie, ND Peak Flow-frequency Curve for Wet Period (1942-2009) with median plotting positions.

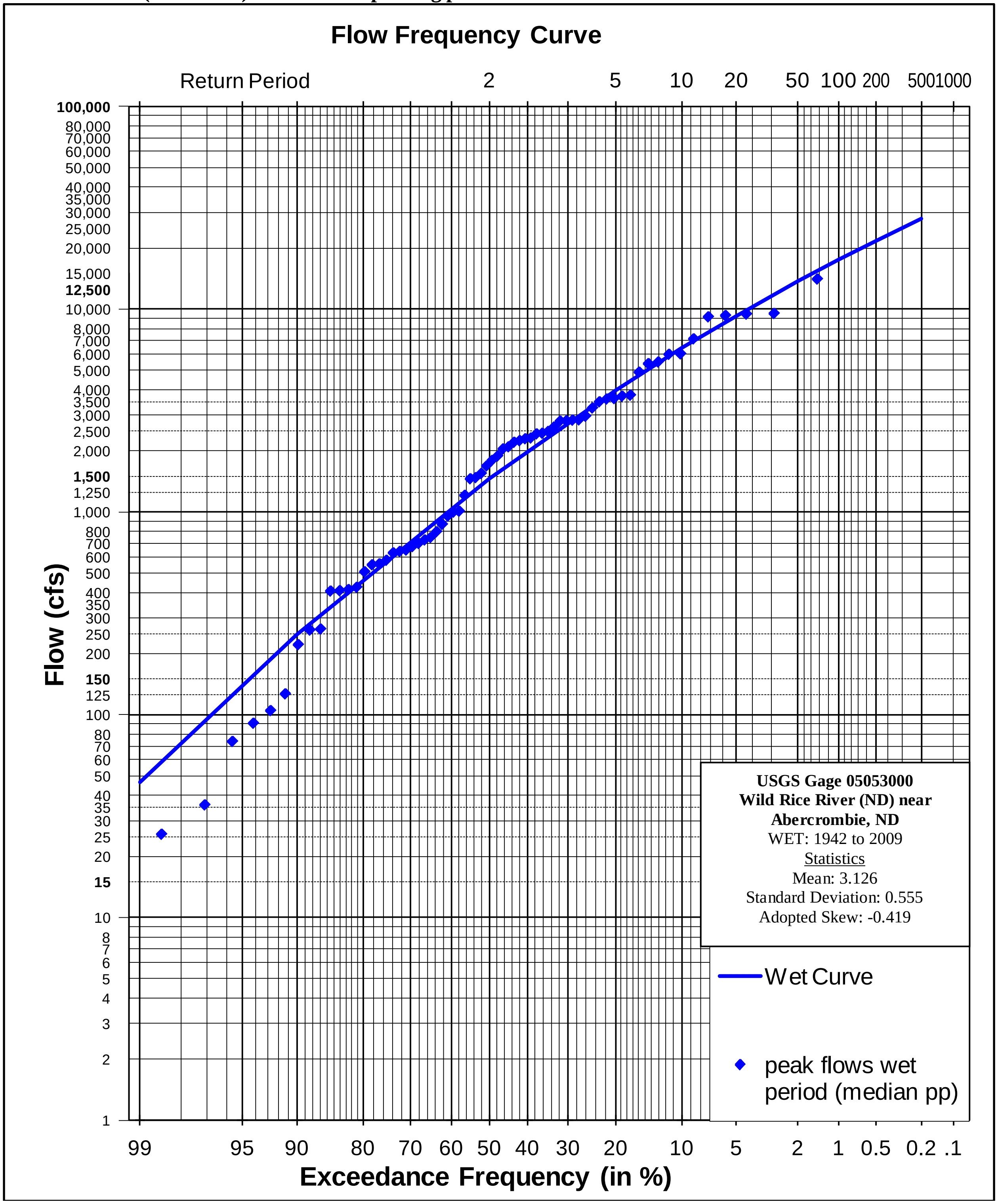


Figure 22. USGS Gage 05053000, Wild Rice River (ND) near Abercrombie, ND- Peak Flow Frequency Curves for Wet and 25-year Look Ahead Curve (0.8 wet and 0.2 dry weighting)

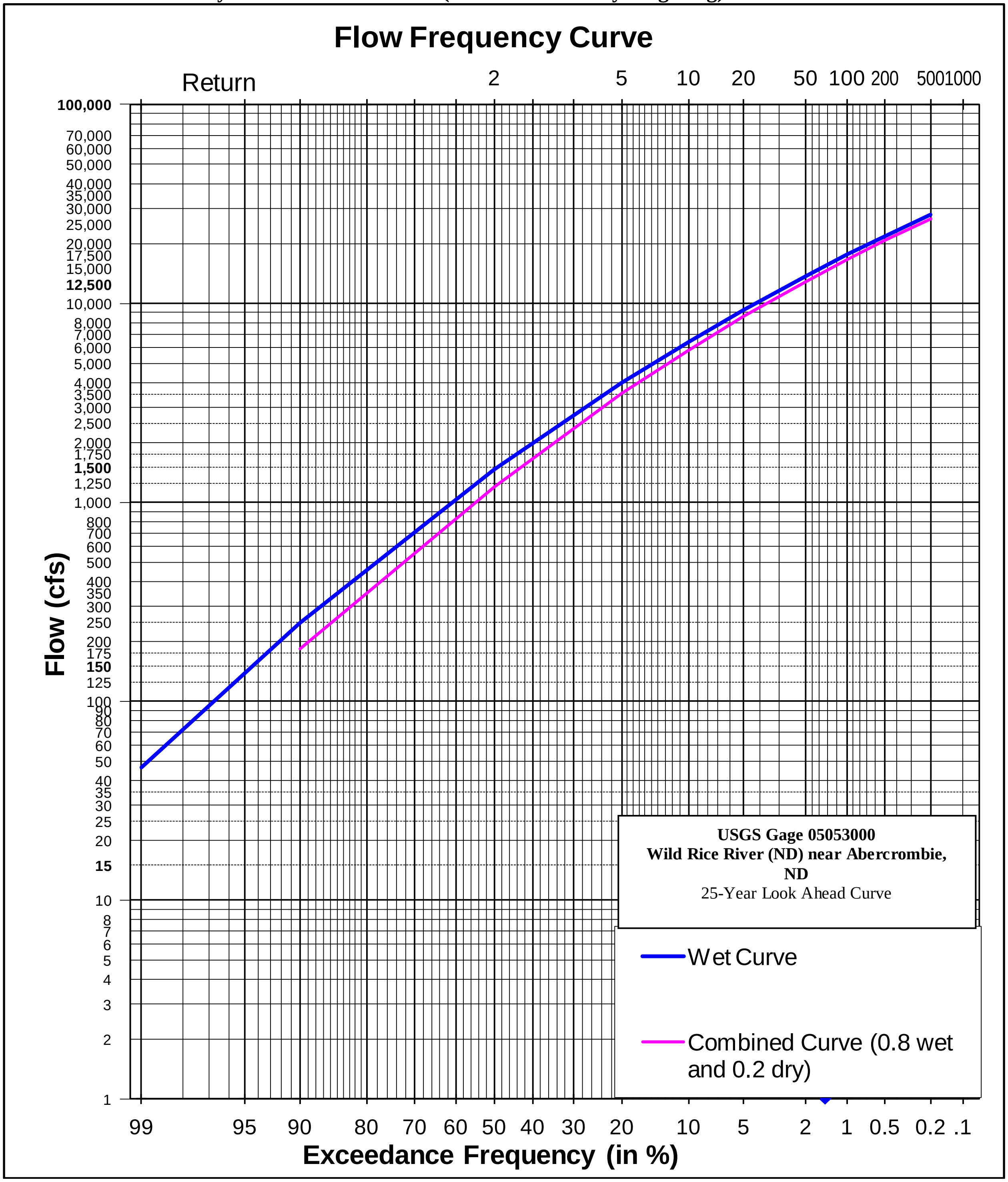


Figure 23. USGS Gage 05053000, Wild Rice River (ND) near Abercrombie, ND- Peak Flow frequency curves for Wet and 50-year Look-Ahead Curves (0.65 wet and 0.35 dry weighting).

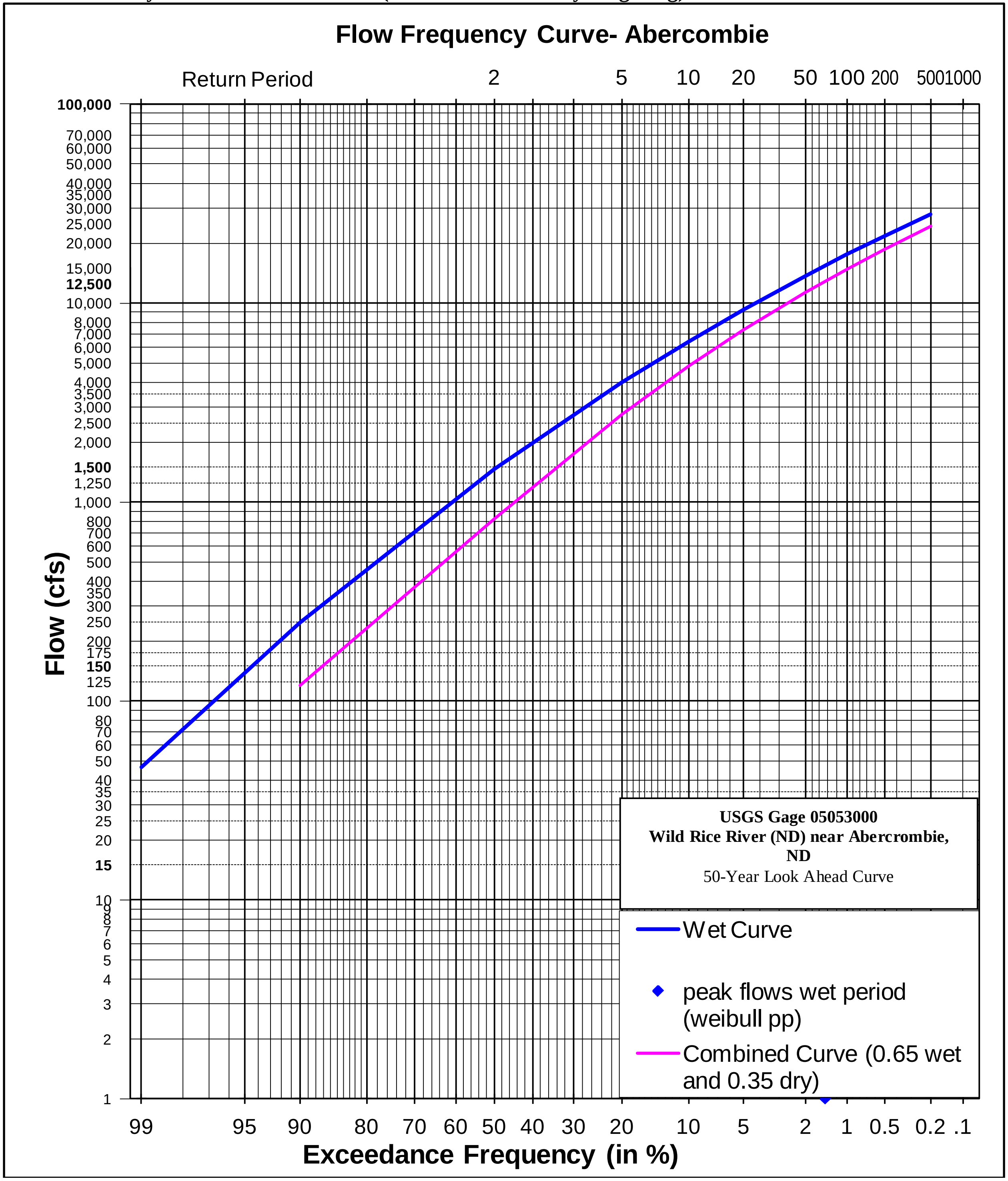
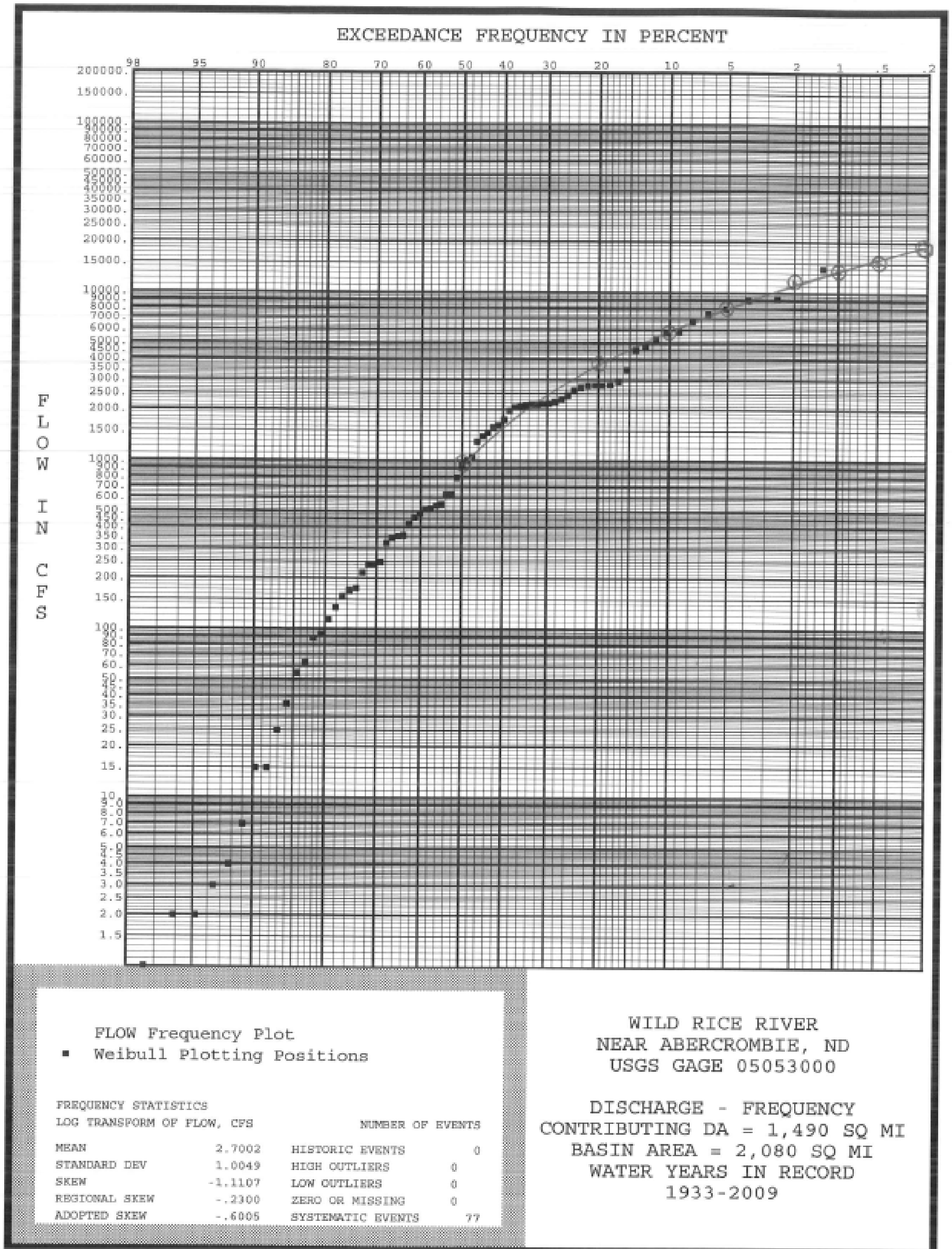


Figure 24. Wild Rice River near Abercrombie, ND Coincidental Peak Flow Frequency Curve- Full Period.



Pencil Line = Graphical Flow Frequency Curve

Figure 25. Coincidental Flow-Frequency Curve for the WET (1942-2009 portion of the POR at the Mouth of the Wild Rice River (ND) - Based on the Coincidental Flow Record at USGS Gage 05053000 Wild Rice River (ND) near Abercrombie, ND

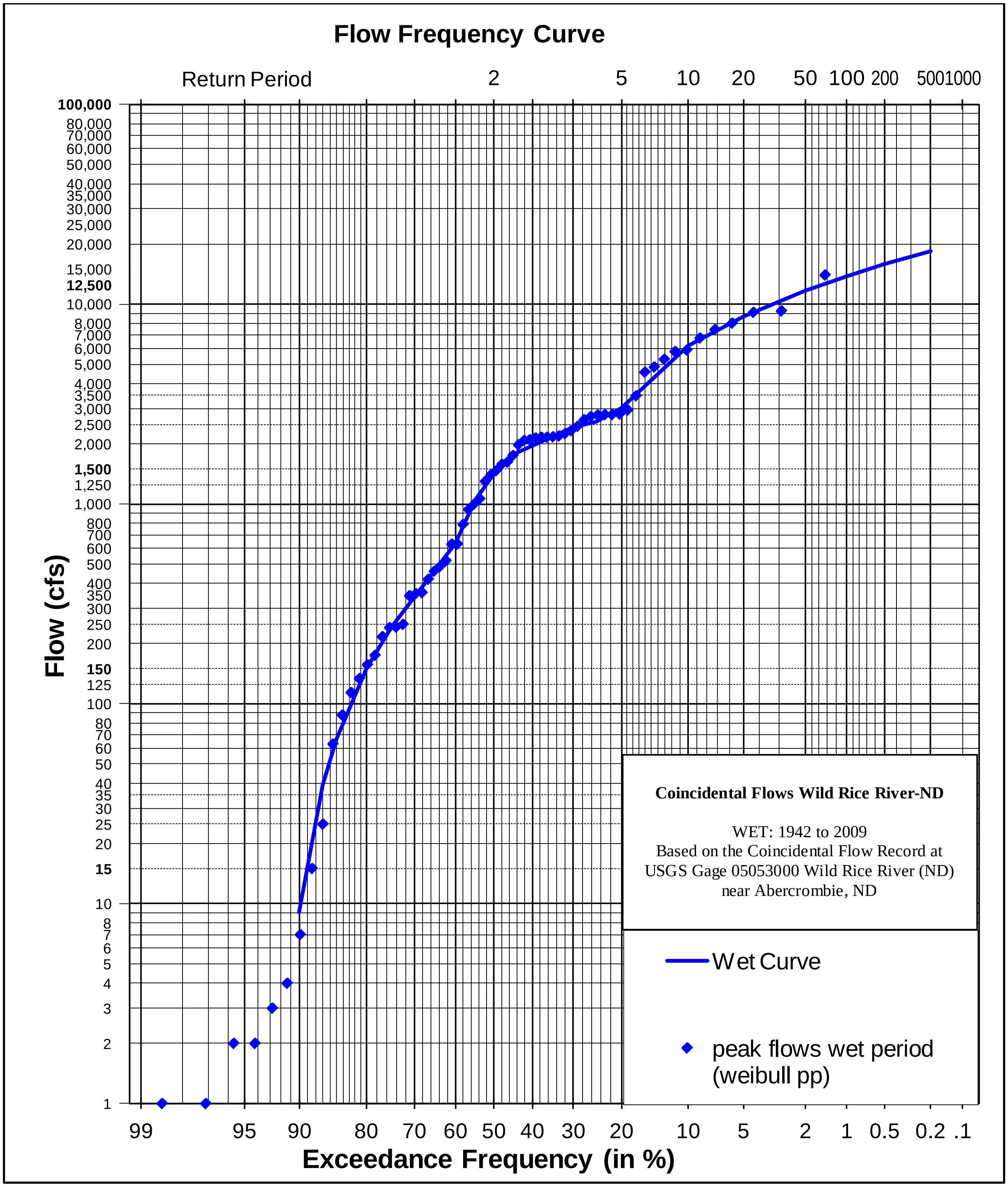


Figure 26. Mouth of the Wild Rice River (ND) near Abercrombie, ND Coincidental Flow Frequency for Wet and 25-year Look Ahead Curves (0.8 wet and 0.35 dry weighting).

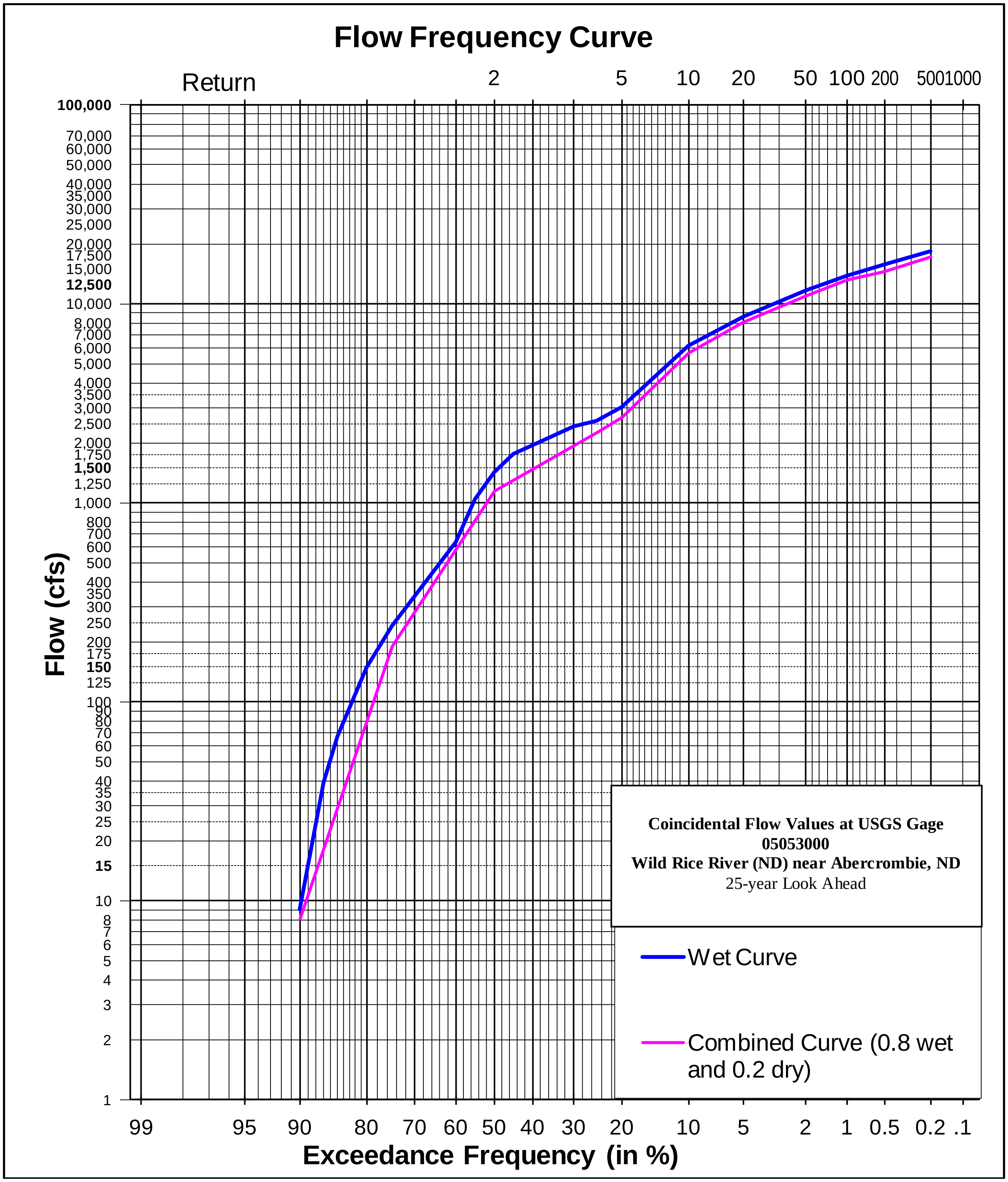


Figure 27. Mouth of the Wild Rice River near Abercrombie, ND Coincidental flow frequency for Wet and 50 year Look Ahead curves (0.65 wet and 0.35 dry).

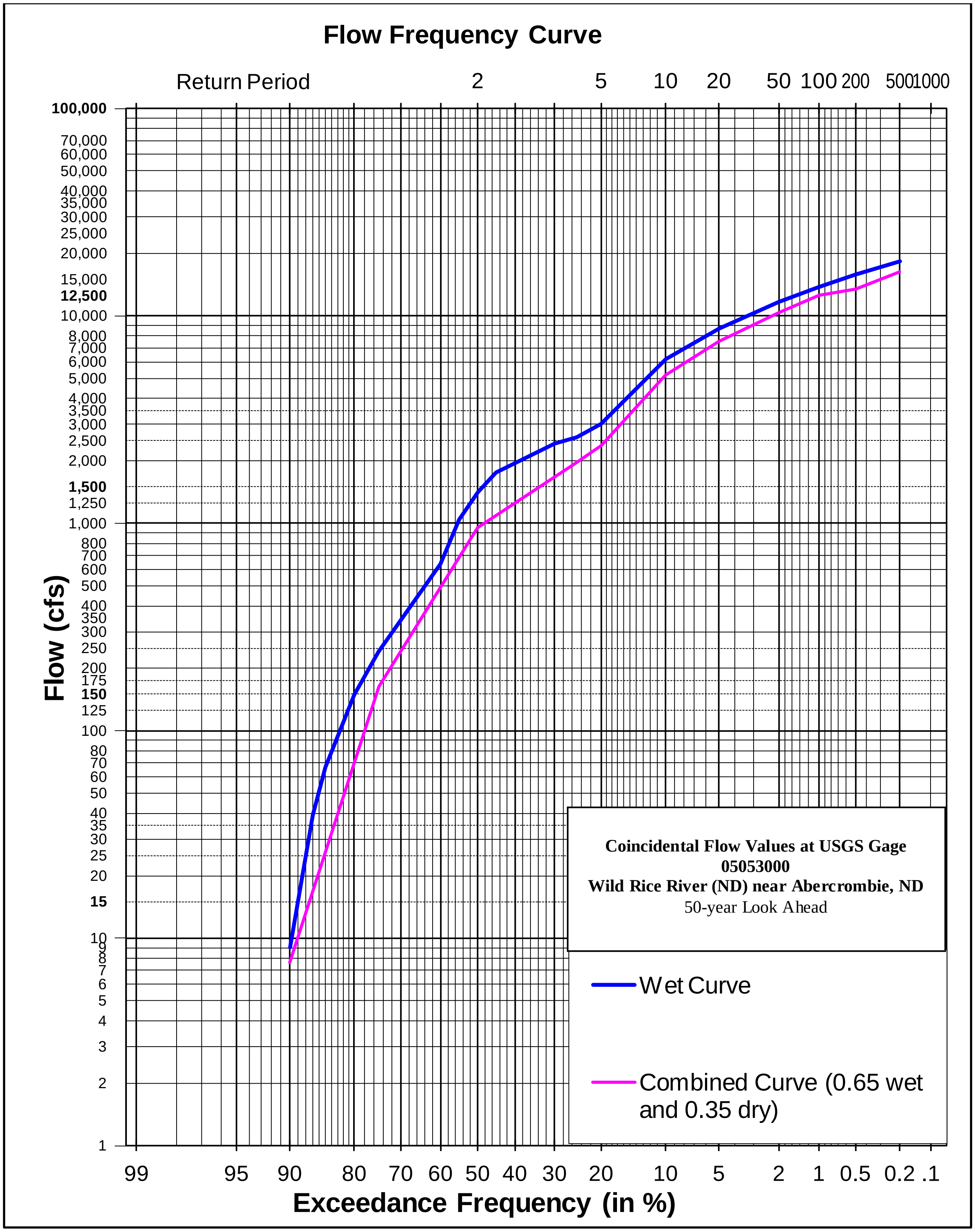


Figure 28. Schematic of the Buffalo River (2011 Google Image- USDA Farm Service Agency)

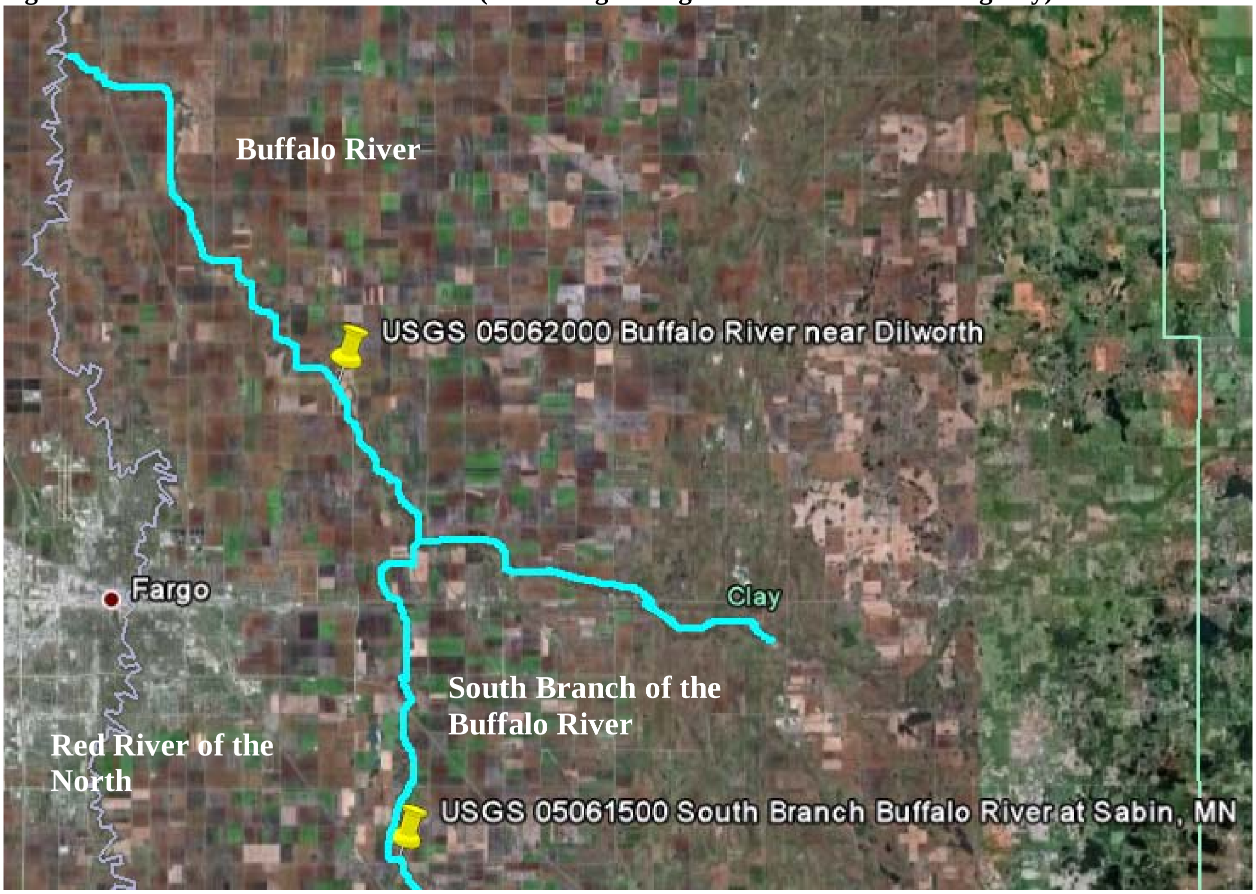


Figure 29. Coincidental Flow-Frequency Curve for the WET (1942-2009) portion of the POR at the Mouth of the Buffalo River - Based on the Coincidental Flow Record at USGS Gage 05062000 Buffalo River Near Dilworth, MN

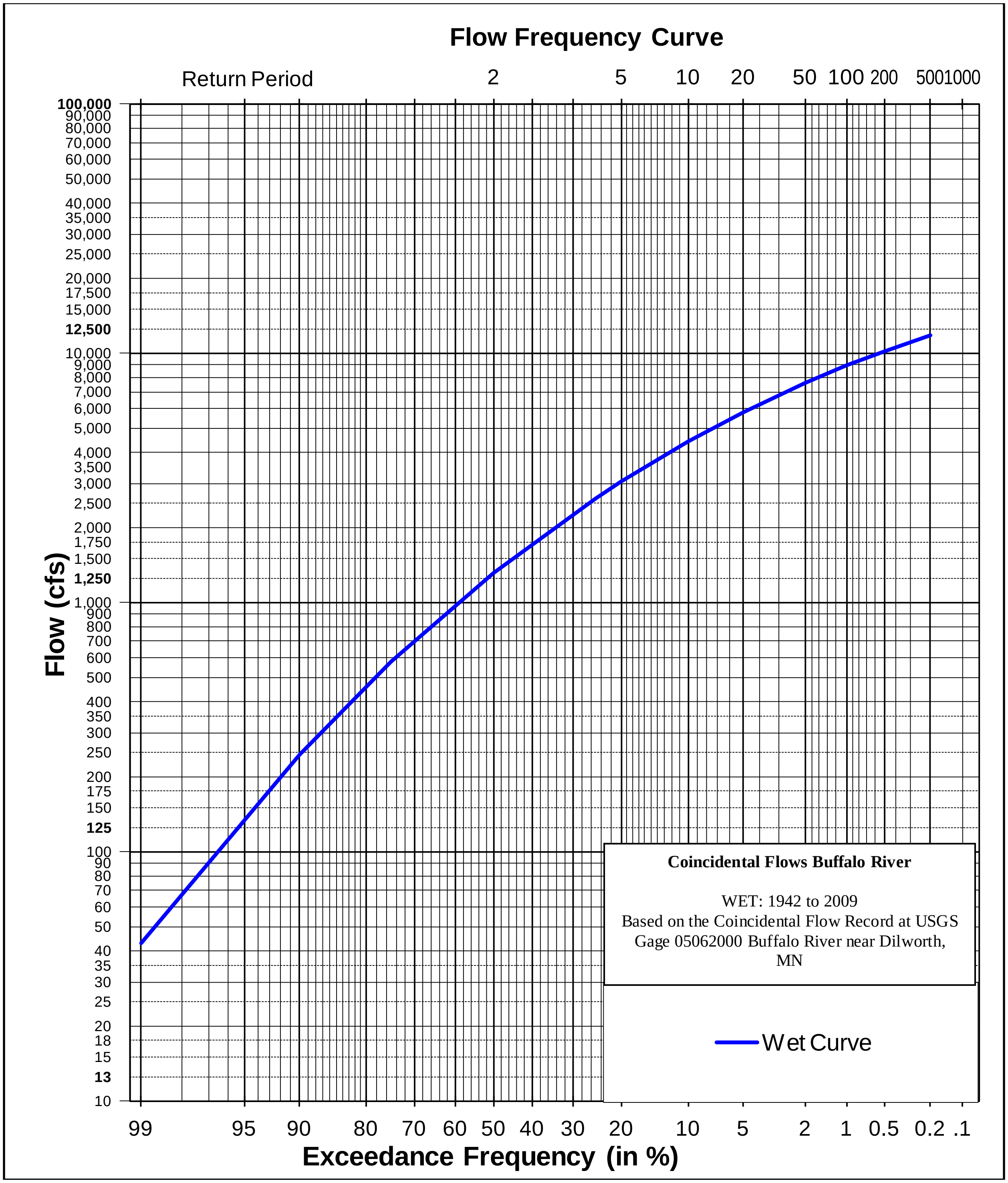


Figure 30. Buffalo River Coincident Flow Frequency Curve for Wet and 25-year Look Ahead (0.8 wet and 0.2 dry) Curves.

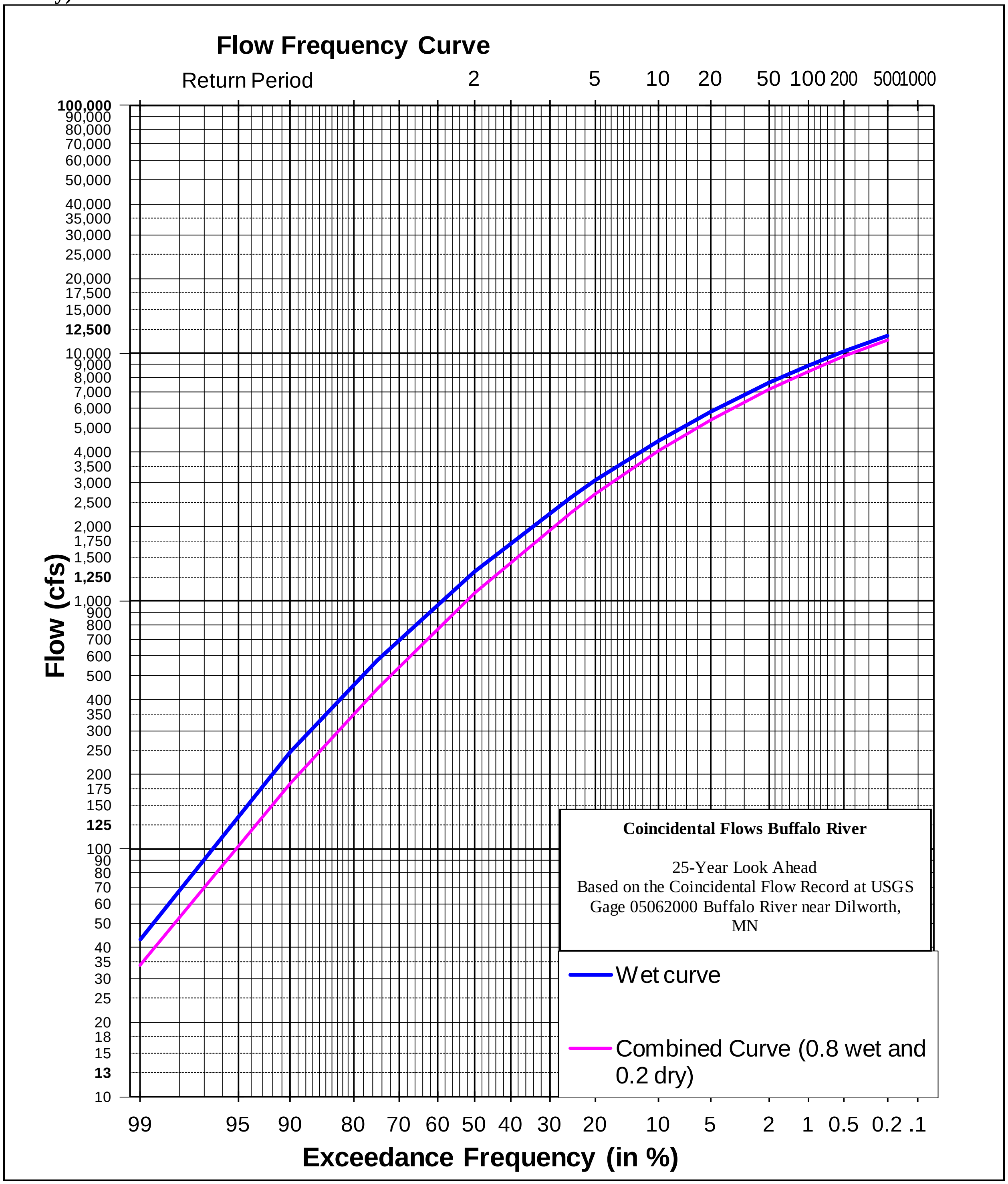


Figure 31. Buffalo River Coincident Flow Frequency Curve for Wet and 50-year Look Ahead (0.65 wet and 0.35 dry) Curves.

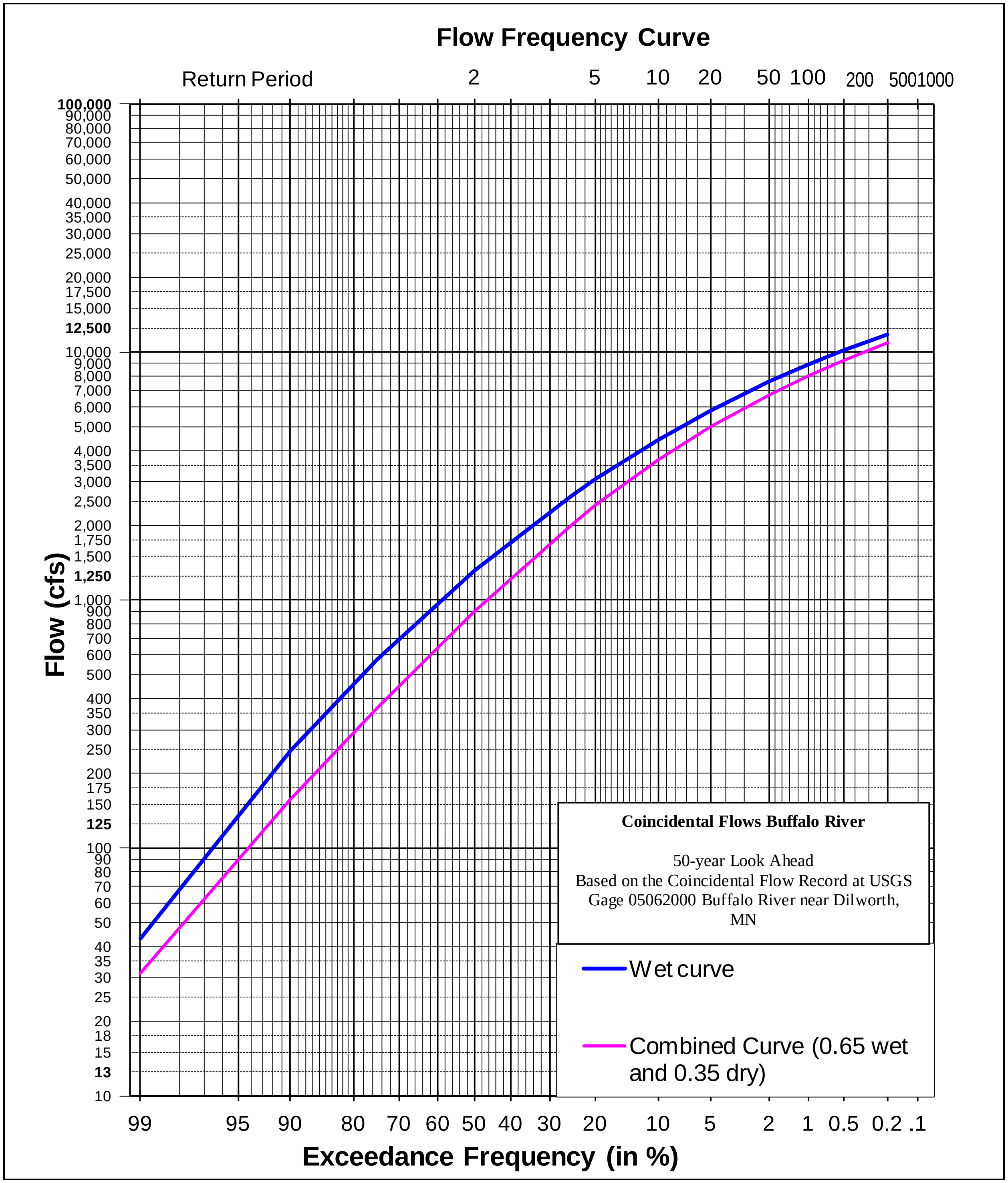


Figure 32. Coincidental Flow-Frequency Curve for the WET portion of the POR (1944-2009) at the Mouth of the Wild Rice River (MN) - Based on the Coincidental Flow Record at USGS Gage 05064000 Wild Rice River (MN) at Hendrum, MN

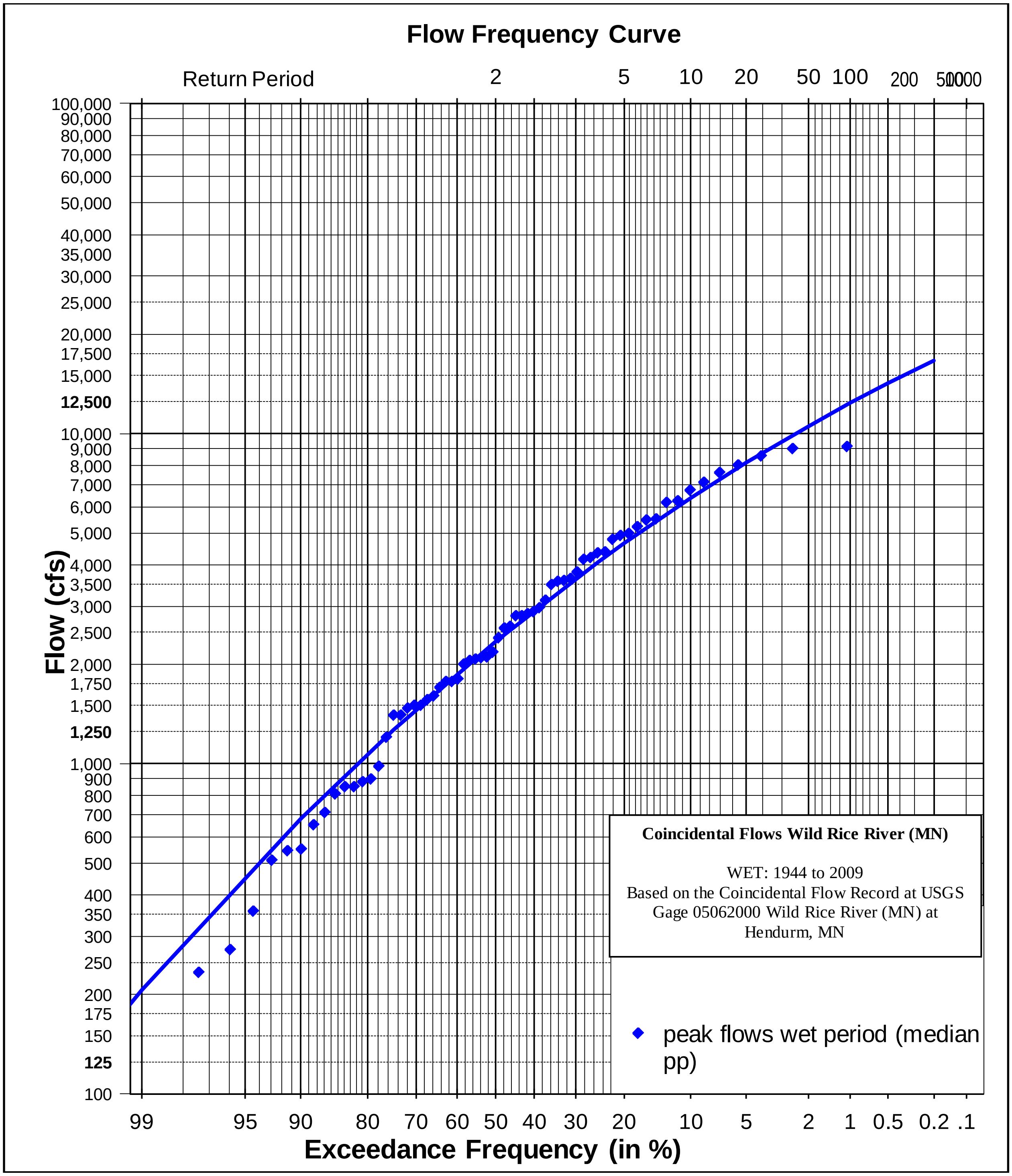


Figure 33. Wild Rice River, MN coincident Flow Frequency for Wet and 25-year Look Ahead (0.8 wet and 0.2 dry) curves.

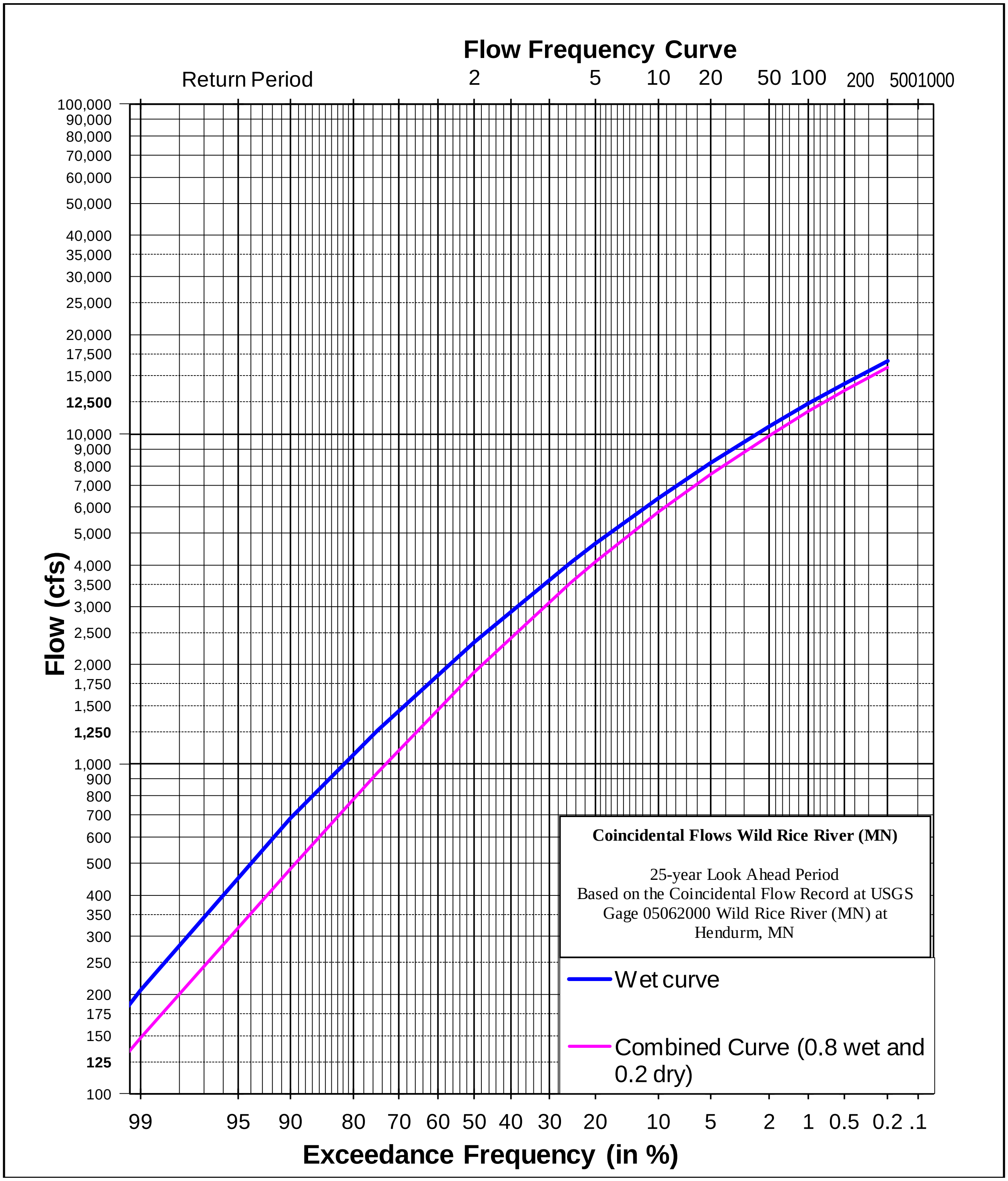


Figure 34. Wild Rice River, MN coincident Flow Frequency for Wet and 50-year Look Ahead Period (0.65 wet and 0.35 dry) curves.

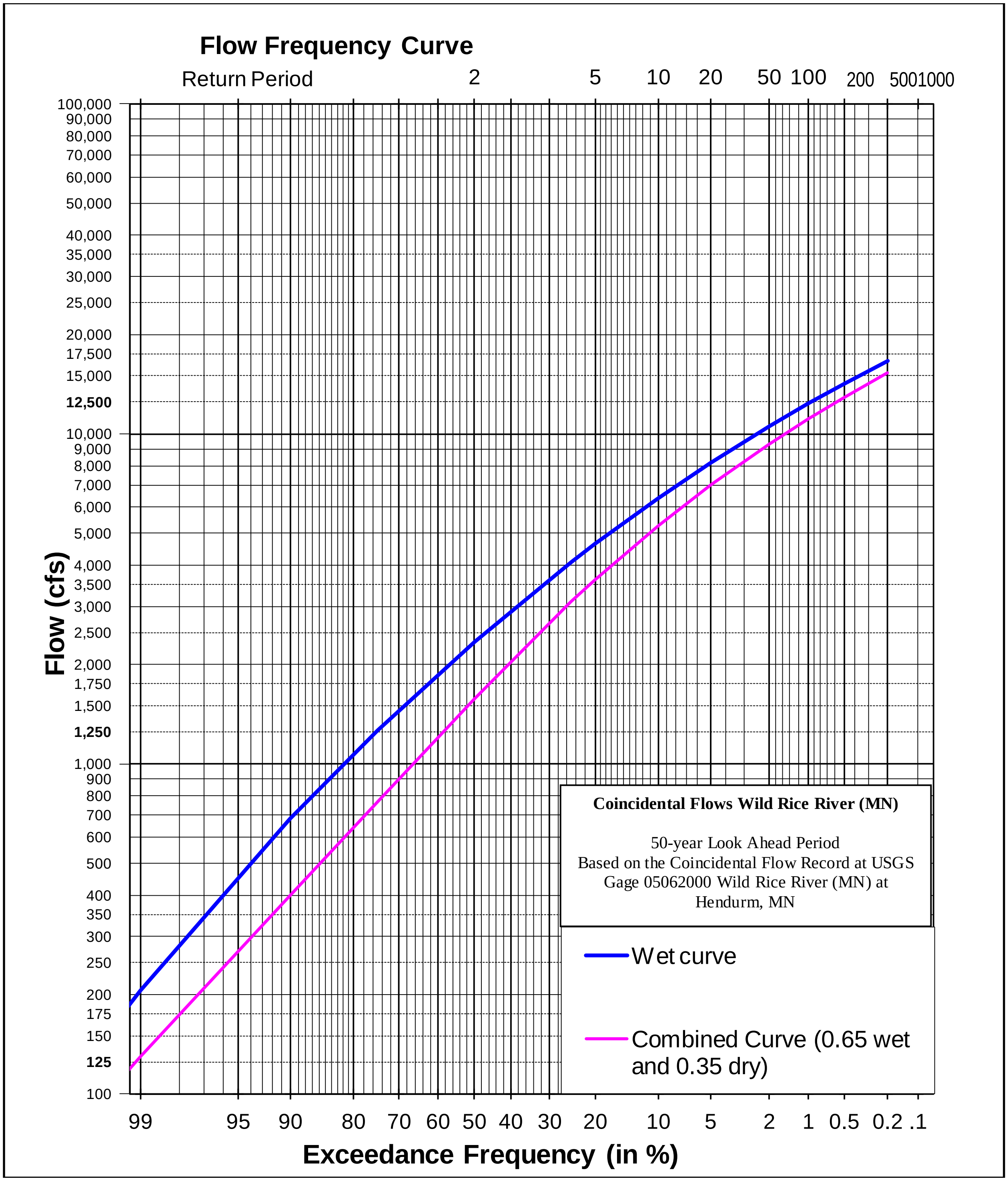


Figure 35. Red River of the North Discharge Frequency Curves- POR

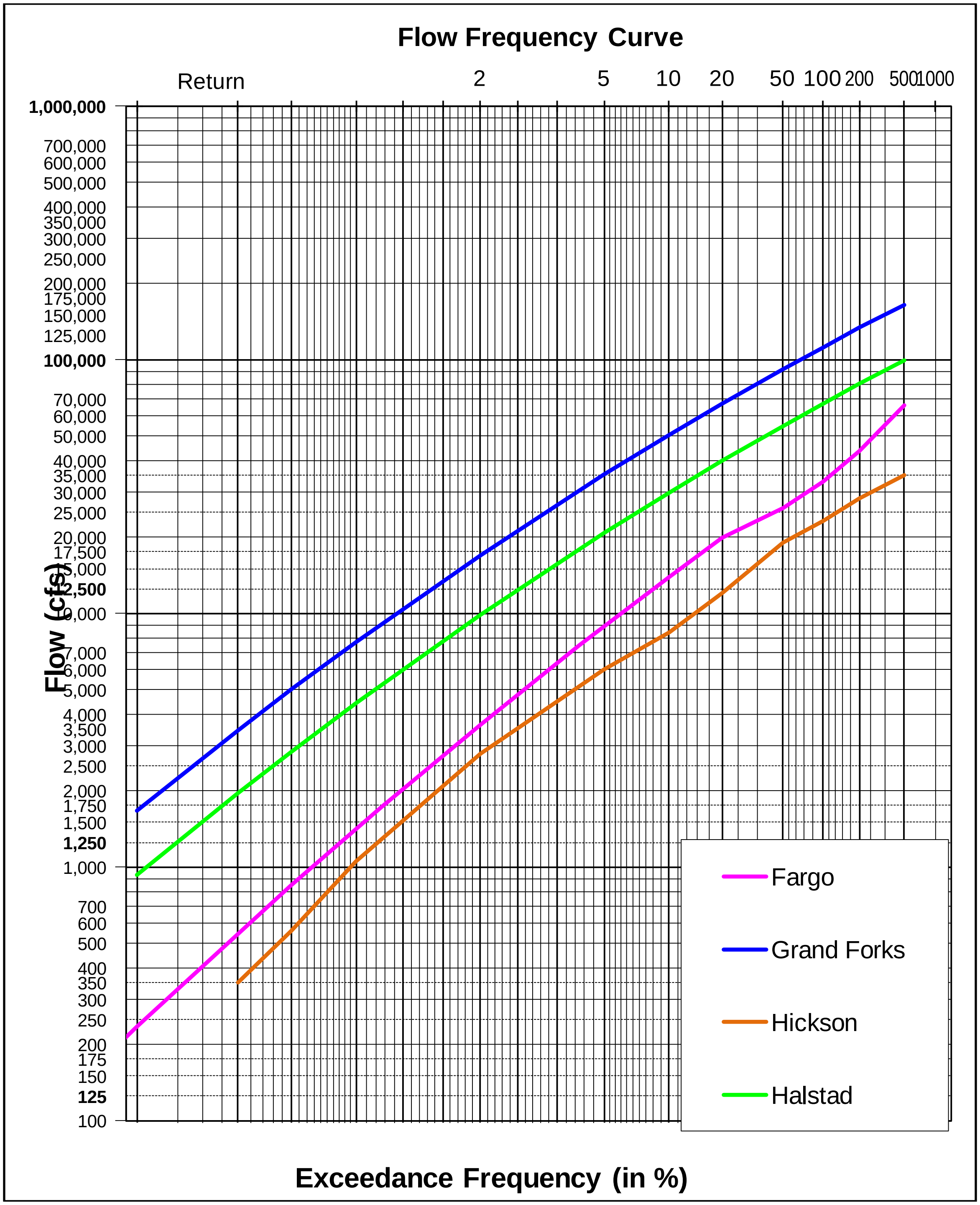


Figure 36. Red River of the North Discharge Frequency Curves- WET (1942-2009)

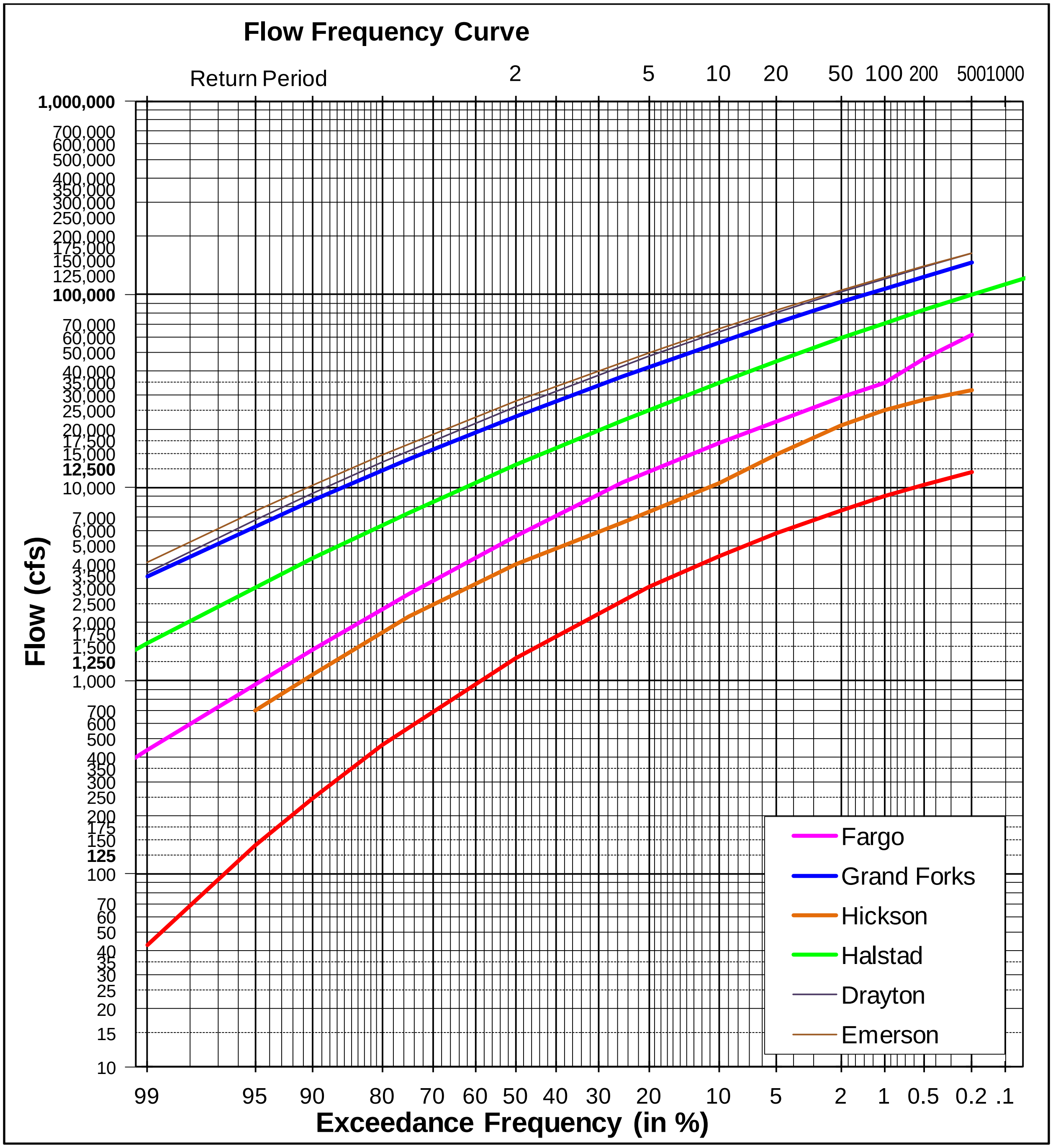


Figure 37. Red River of the North Discharge Frequency Curves- 25- yr Look Ahead Combined Curves

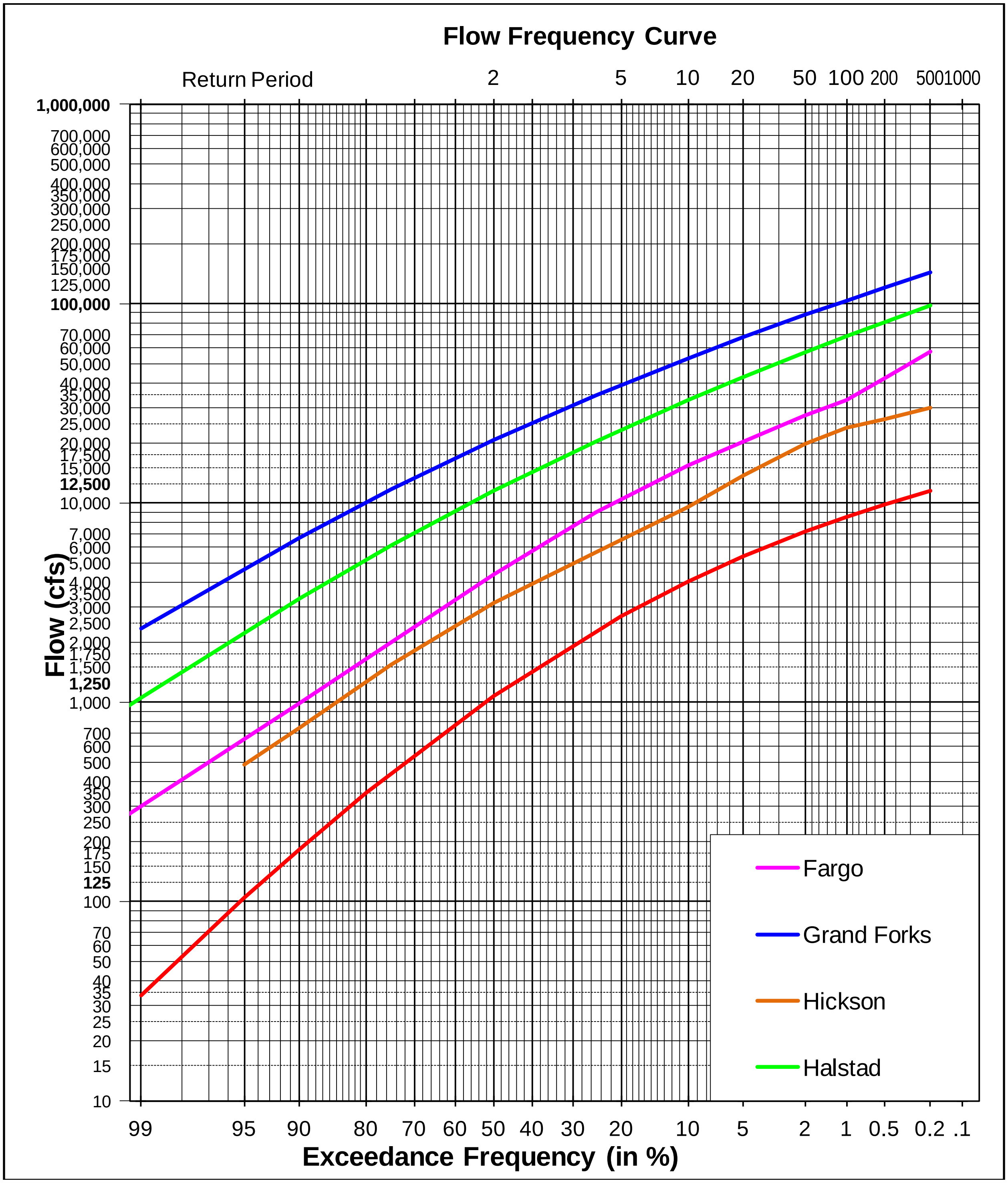


Figure 38. Red River of the North Discharge Frequency Curves- 50- yr Look Ahead Combined Curves

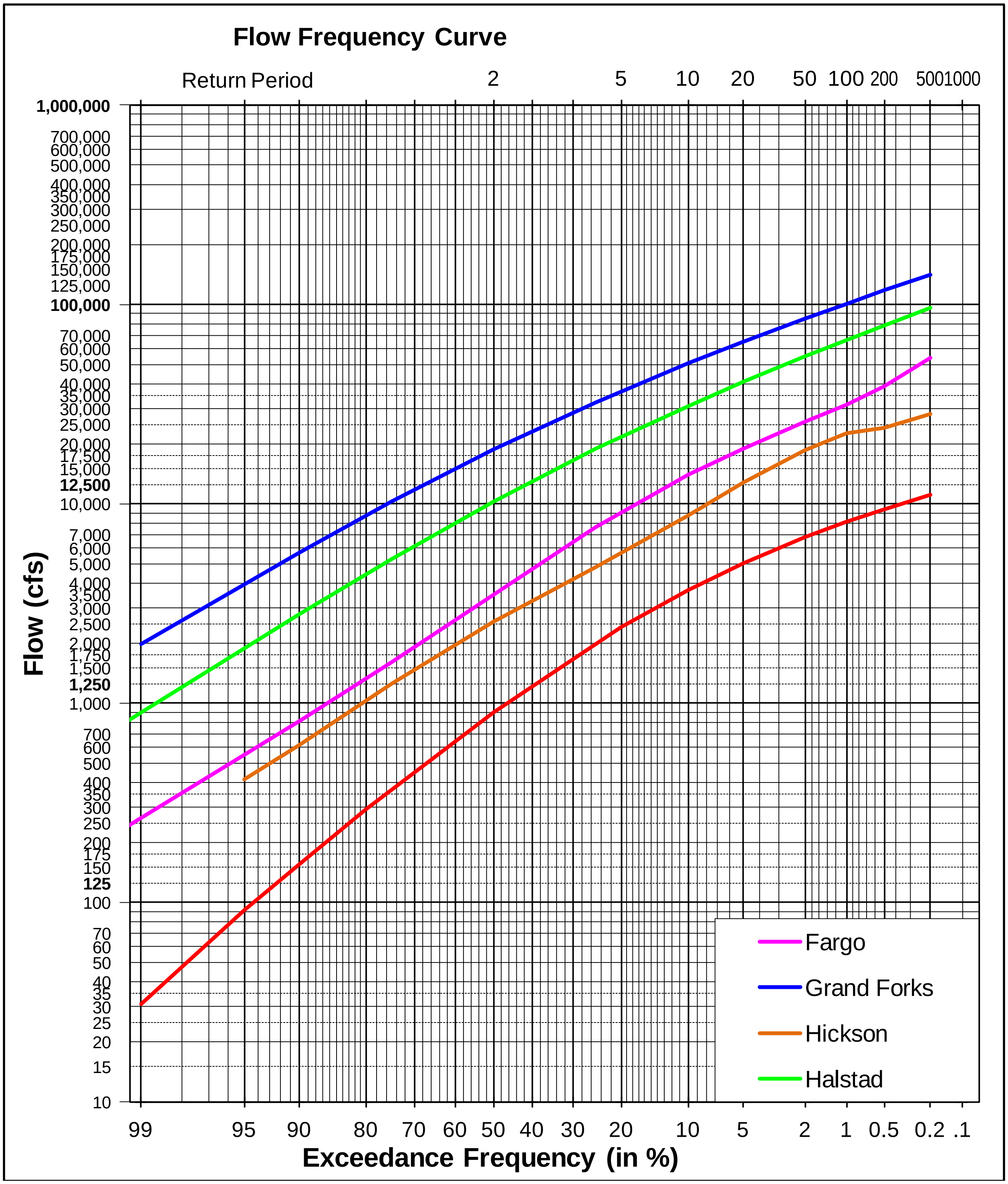


Figure 39 Volume Duration Frequency Analytical Plot for Red River at Fargo, ND Flood Volume Frequency

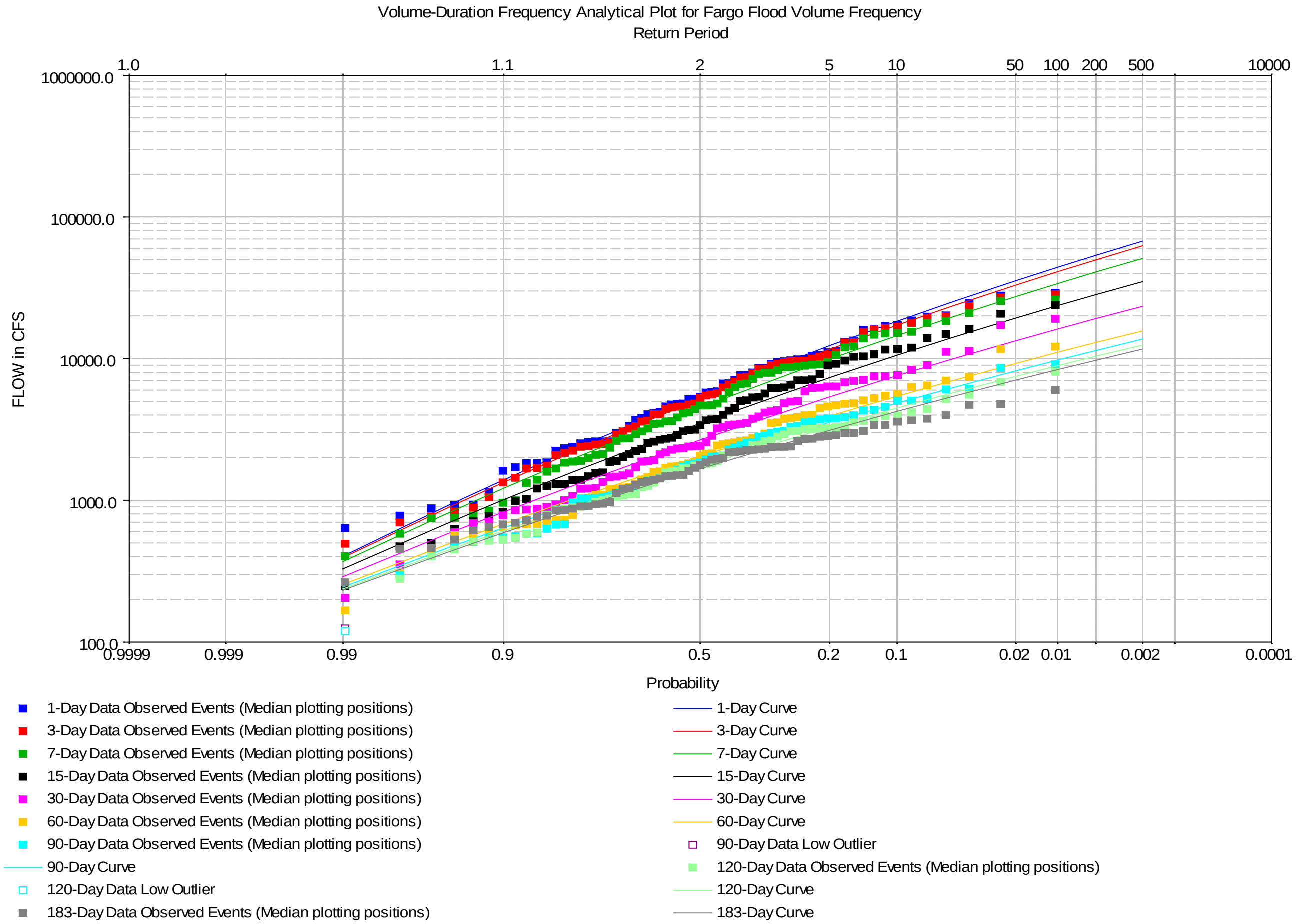


Figure 40- Volume Duration Frequency Analytical Plot for Wild Rice River at Abercrombie, ND Flood Volume Frequency

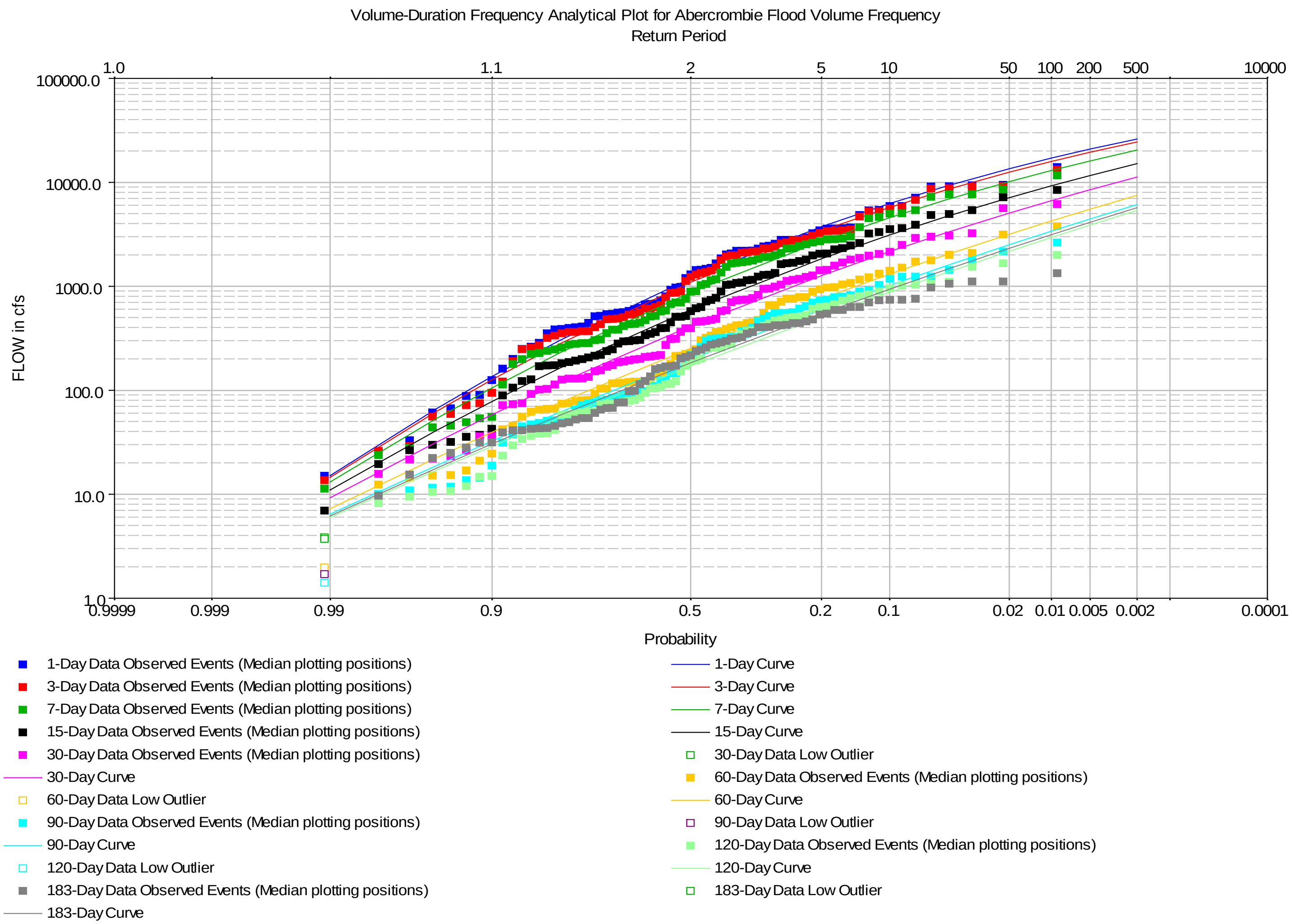


Figure 41- Volume Duration Frequency Analytical Plot for Buffalo River at Dilworth, MN Flood Volume Frequency

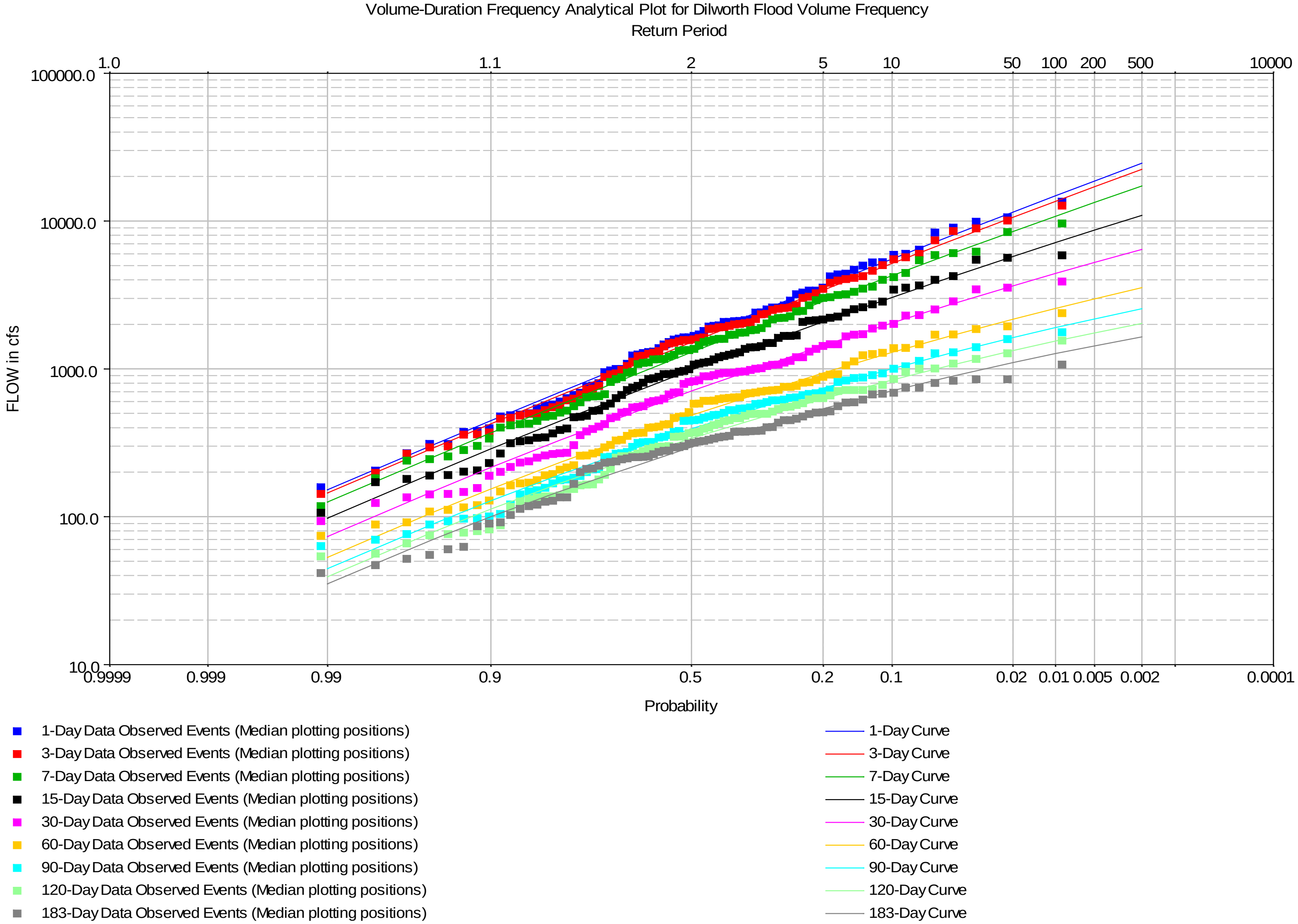


Figure 42- Volume Duration Frequency Analytical Plot for Red River at Halstad, MN Flood Volume Frequency

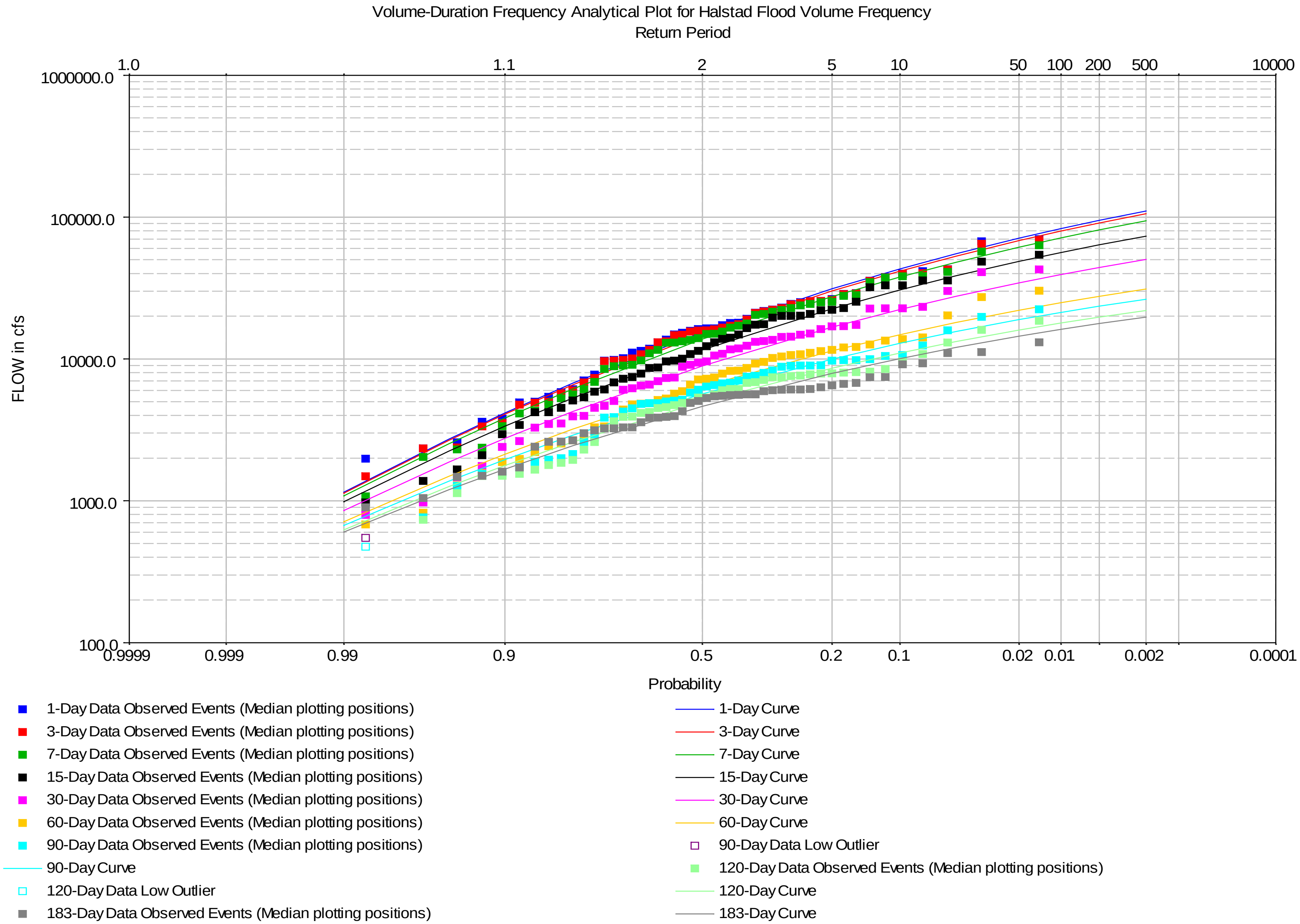


Figure 43- Volume Duration Frequency Analytical Plot for Wild Rice River at Hendrum, MN Flood Volume Frequency

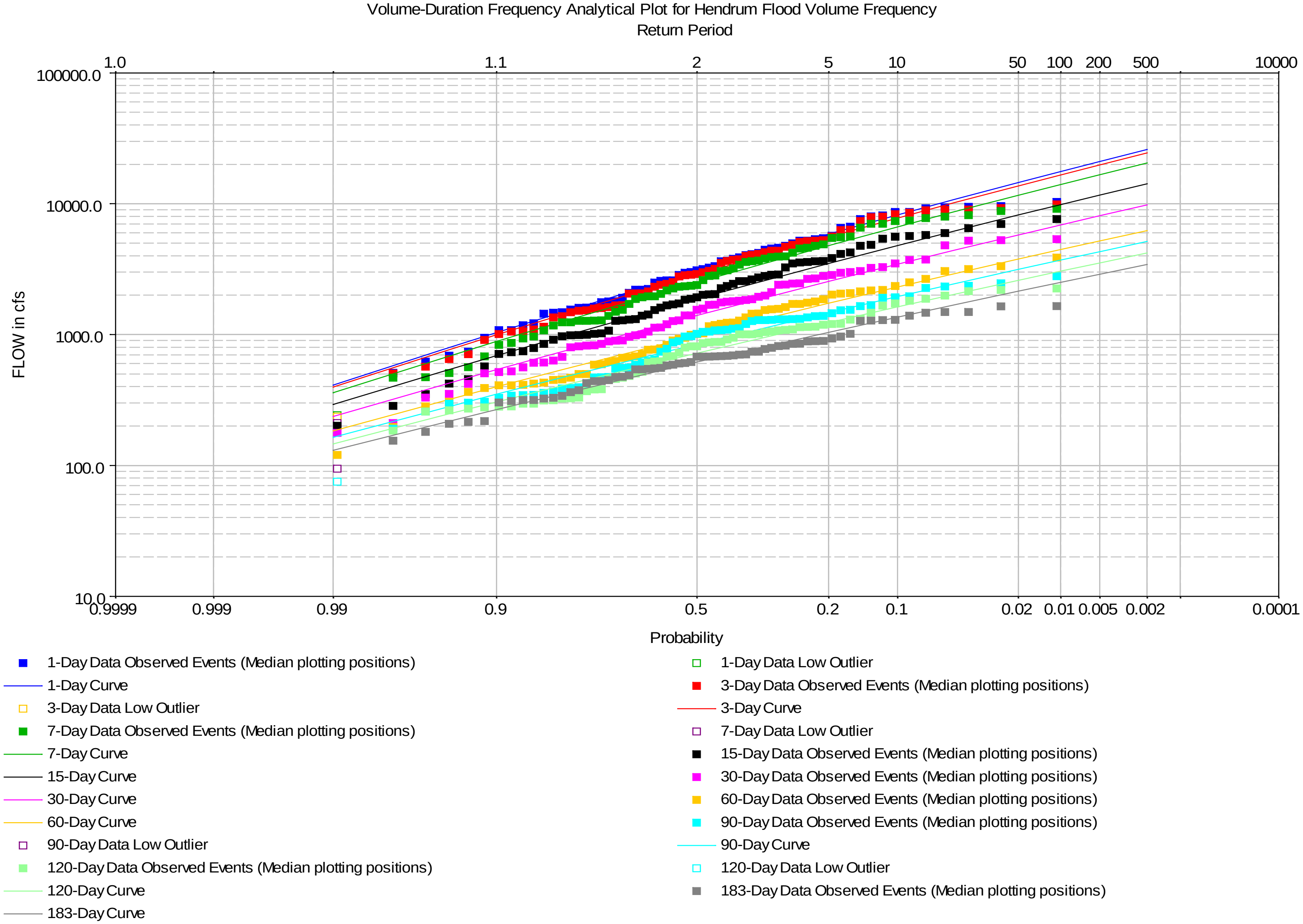


Figure 44- Volume Duration Frequency Analytical Plot for Red River at Hickson, ND Flood Volume Frequency

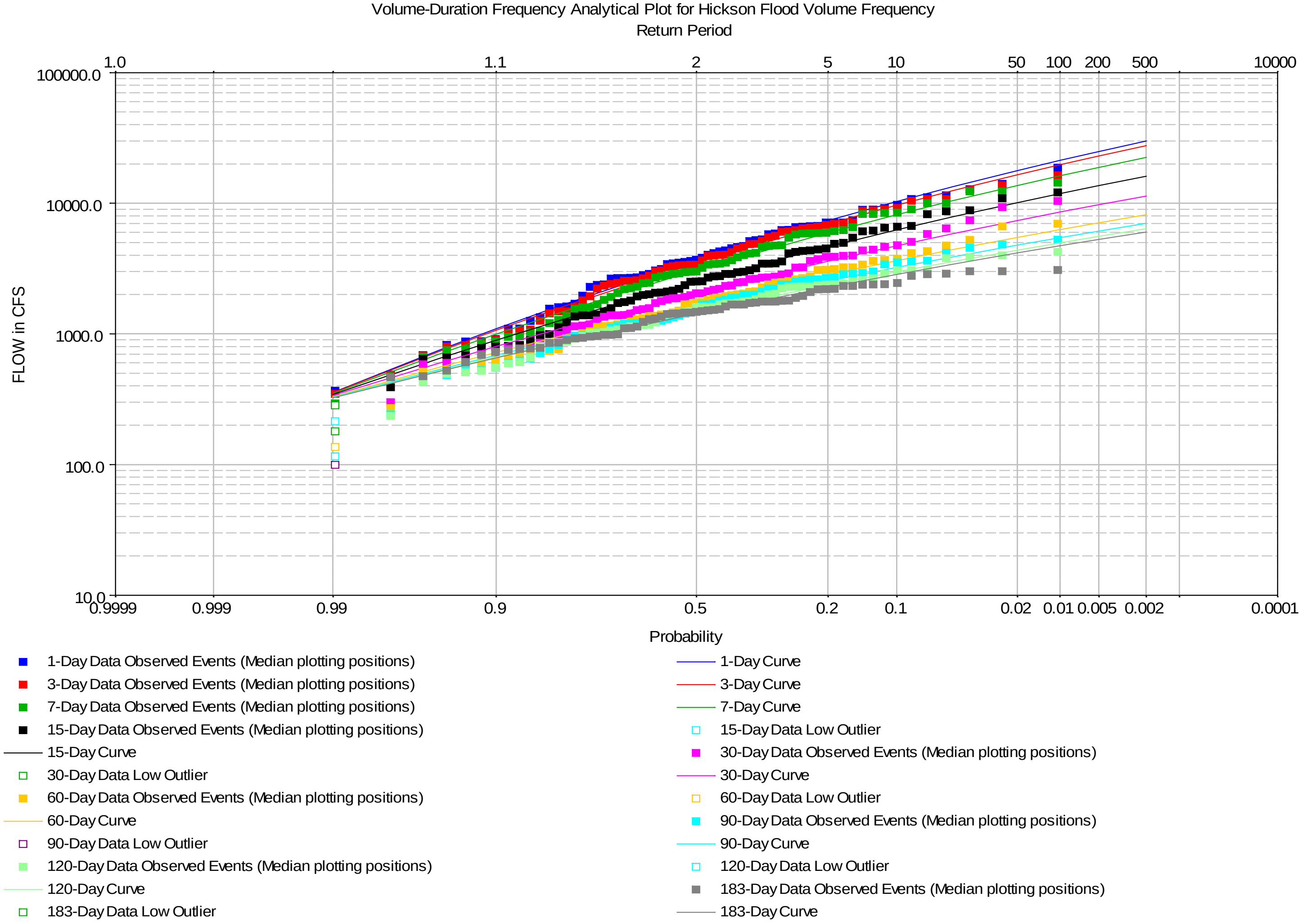


Figure 45 Volume Duration Frequency Analytical Plot for Red River at Amenia Flood Volume Frequency

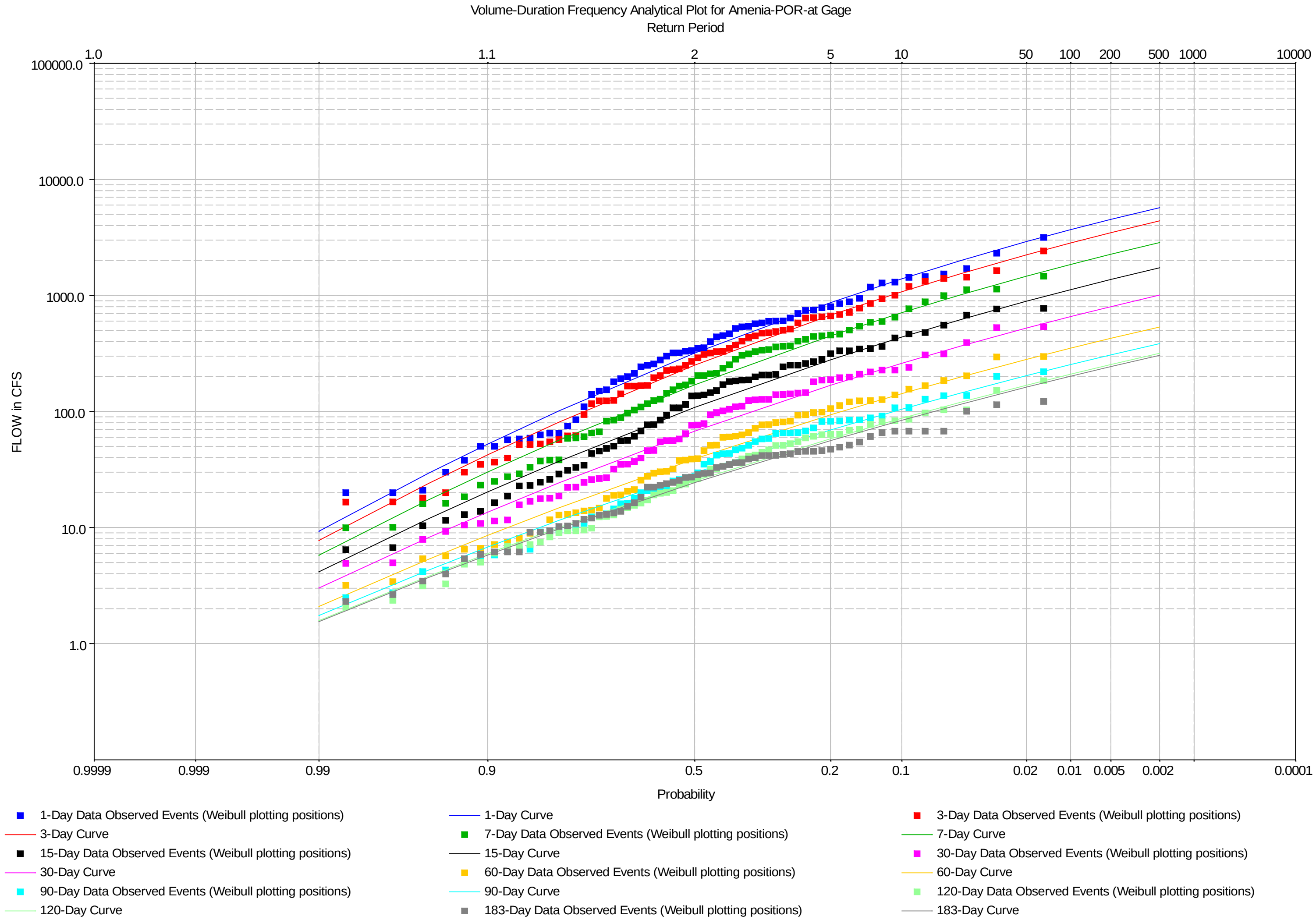


Figure 46- Wild Rice River-ND at Hendrum, ND Flow Volume-Frequency Curves, Wet Condition

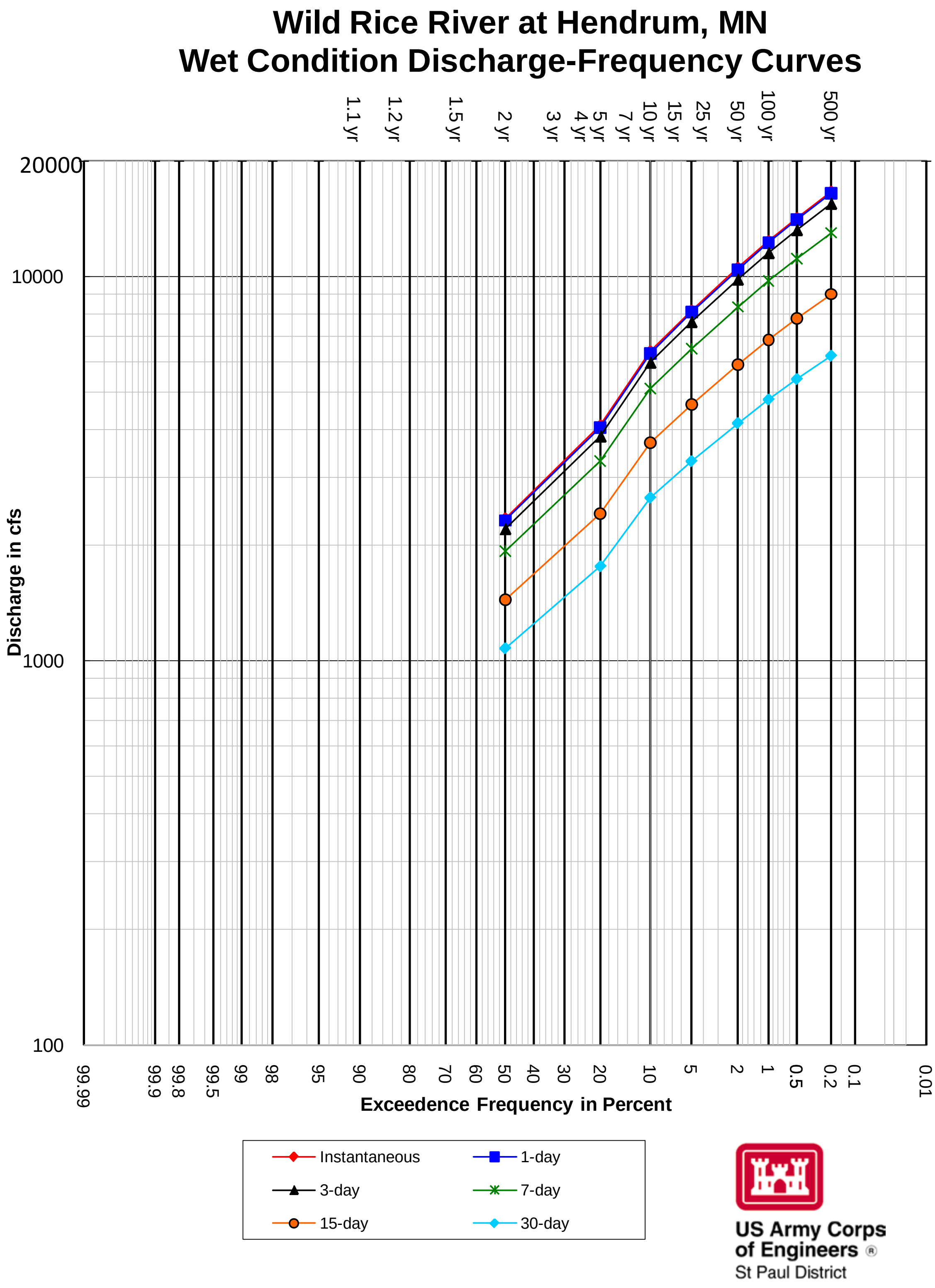


Figure 47- Wild Rice River at Hendrum, ND Flow Volume-Frequency Curves, 25 Year Look Ahead Condition (80% Wet, 20% Dry)

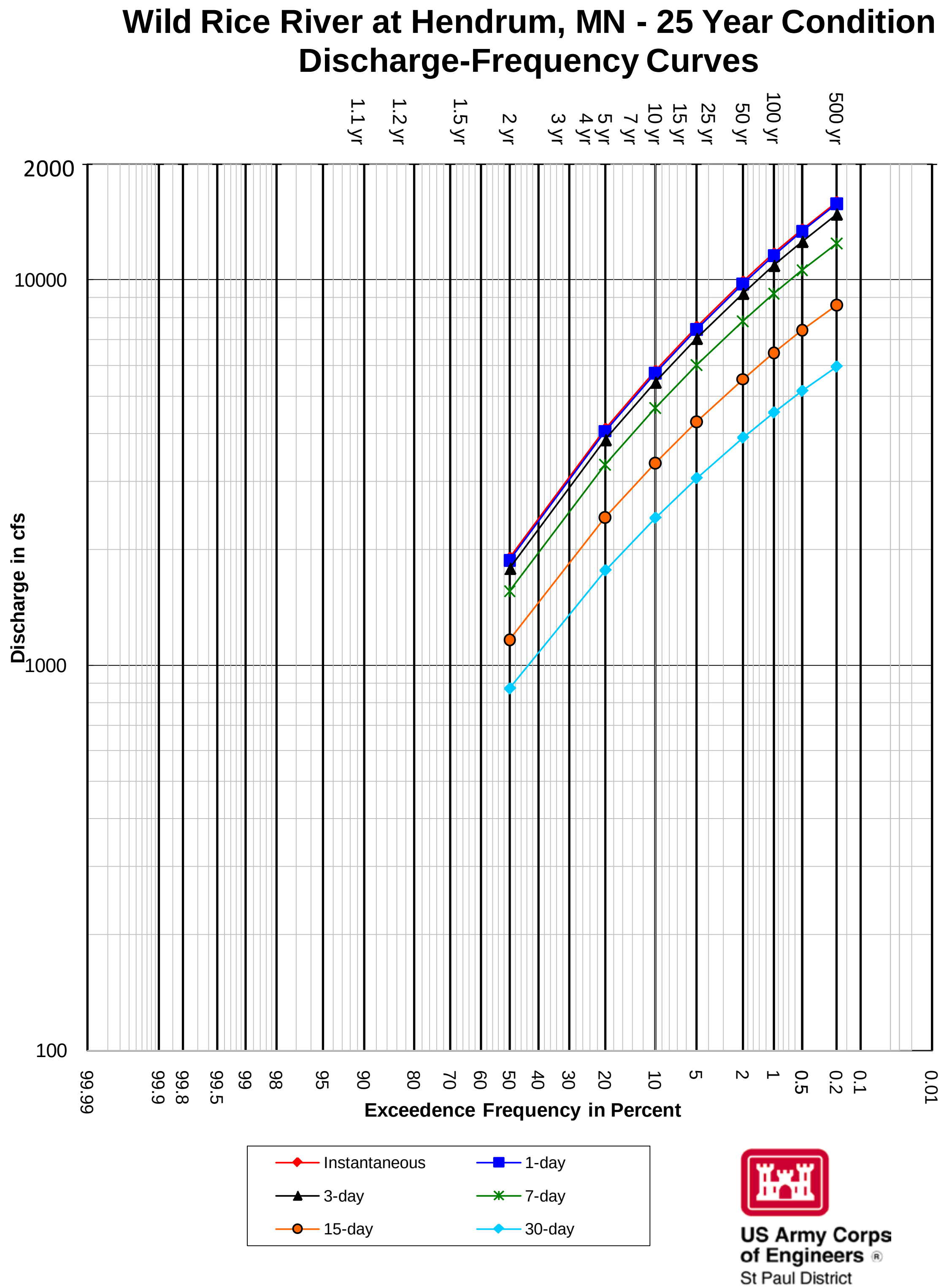


Figure 48- Wild Rice River at Hendrum, ND Flow Volume-Frequency Curves, 50 Year Look Ahead Condition (65% Wet, 35% Dry)

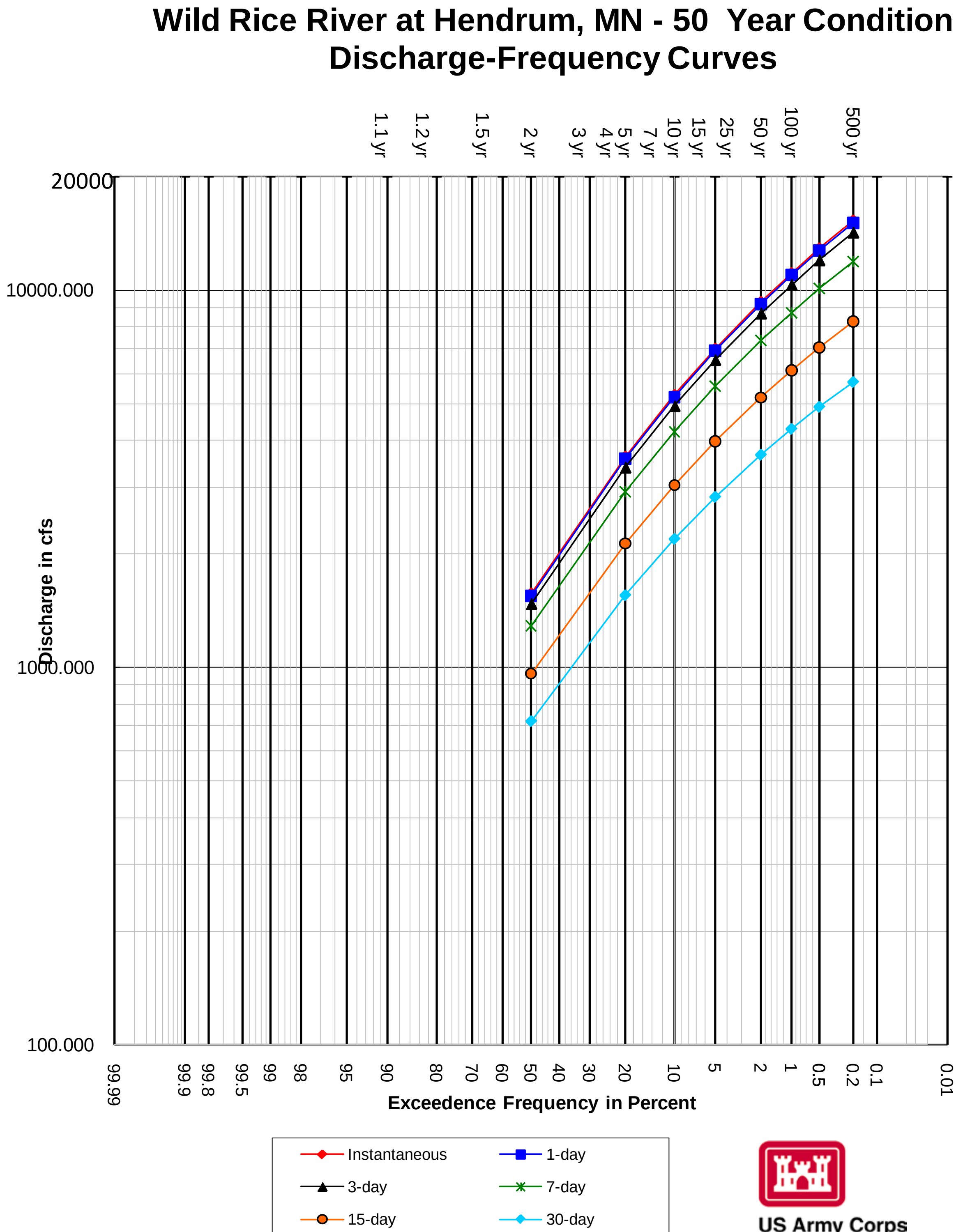


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Figure 49- Balanced Hydrograph, Wild Rice River at Hendrum, MN, Wet Condition

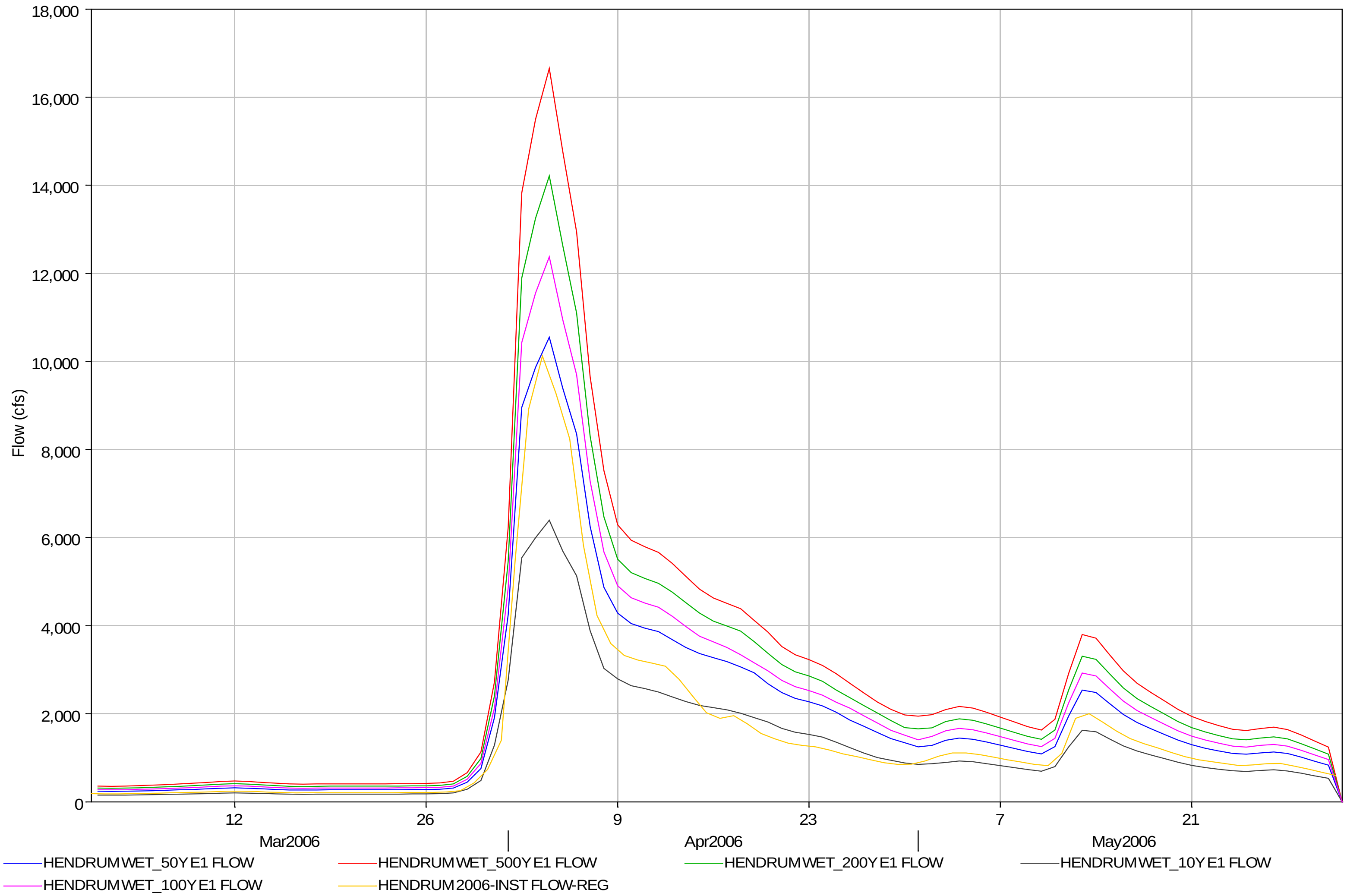


Figure 50- Balanced Hydrograph, Wild Rice River at Hendrum, MN, 25 Year Look Ahead Condition (80% Wet, 20% Dry)

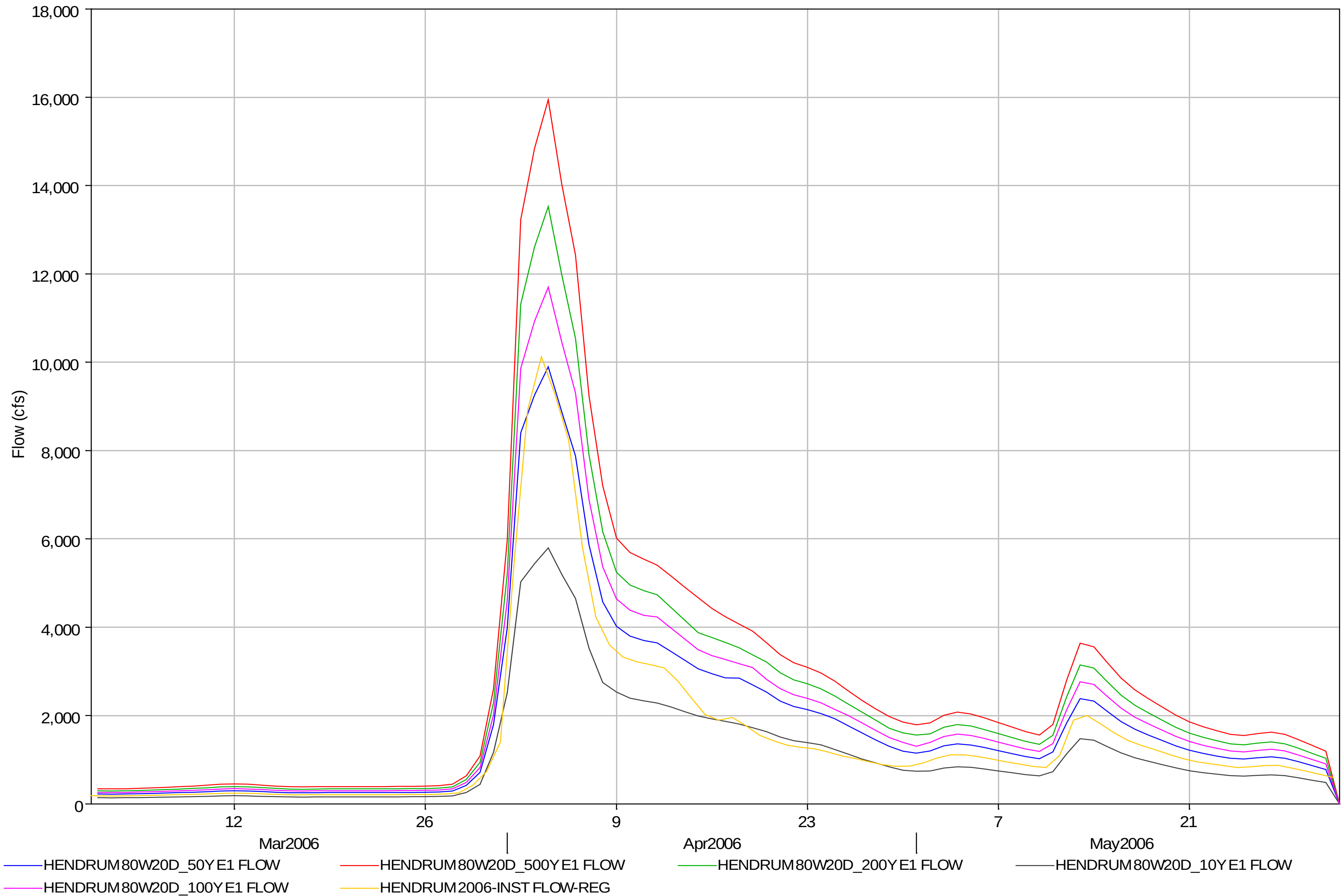


Figure 51- Balanced Hydrograph, Wild Rice River at Hendrum, MN, 50 Year Look Ahead Condition (65% Wet, 35% Dry)

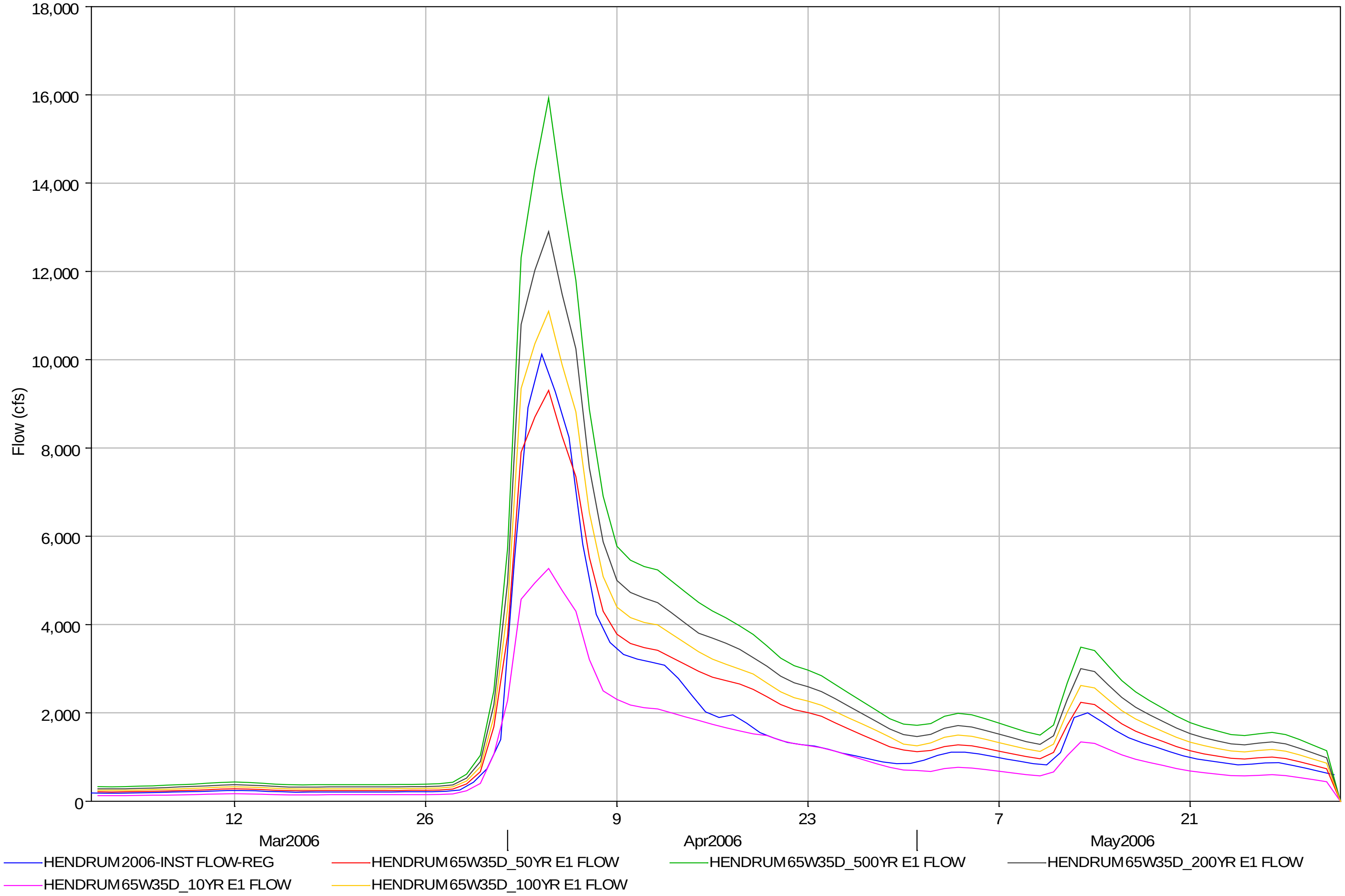


Figure 52- 100 Year Balanced Hydrographs Wet Condition, Red River US and DS of Sheyenne River and Sheyenne River at Mouth

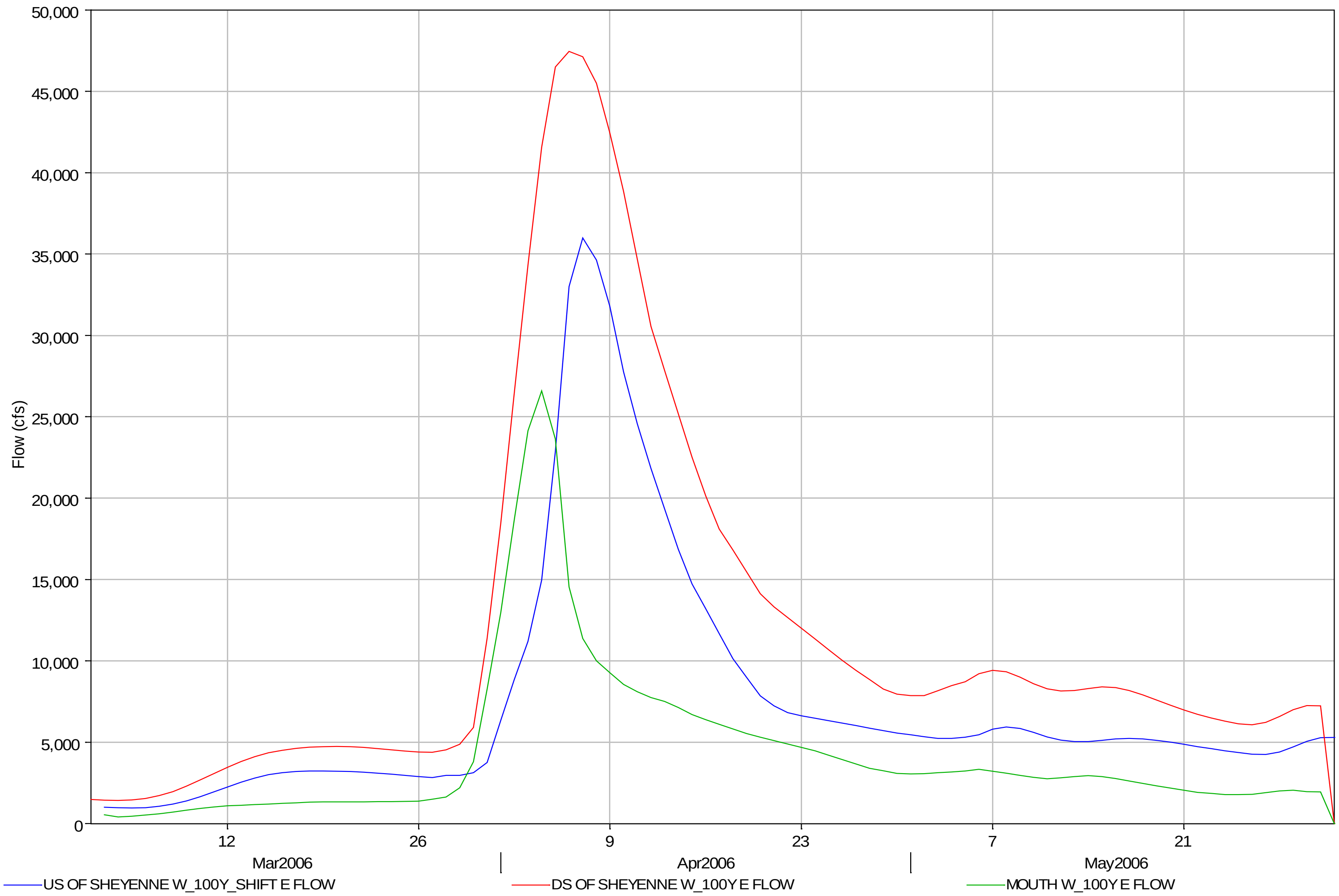


Figure 53- 100 Year Balanced Hydrographs Wet Condition, Sheyenne US and DS of Rush River and Rush River at Mouth

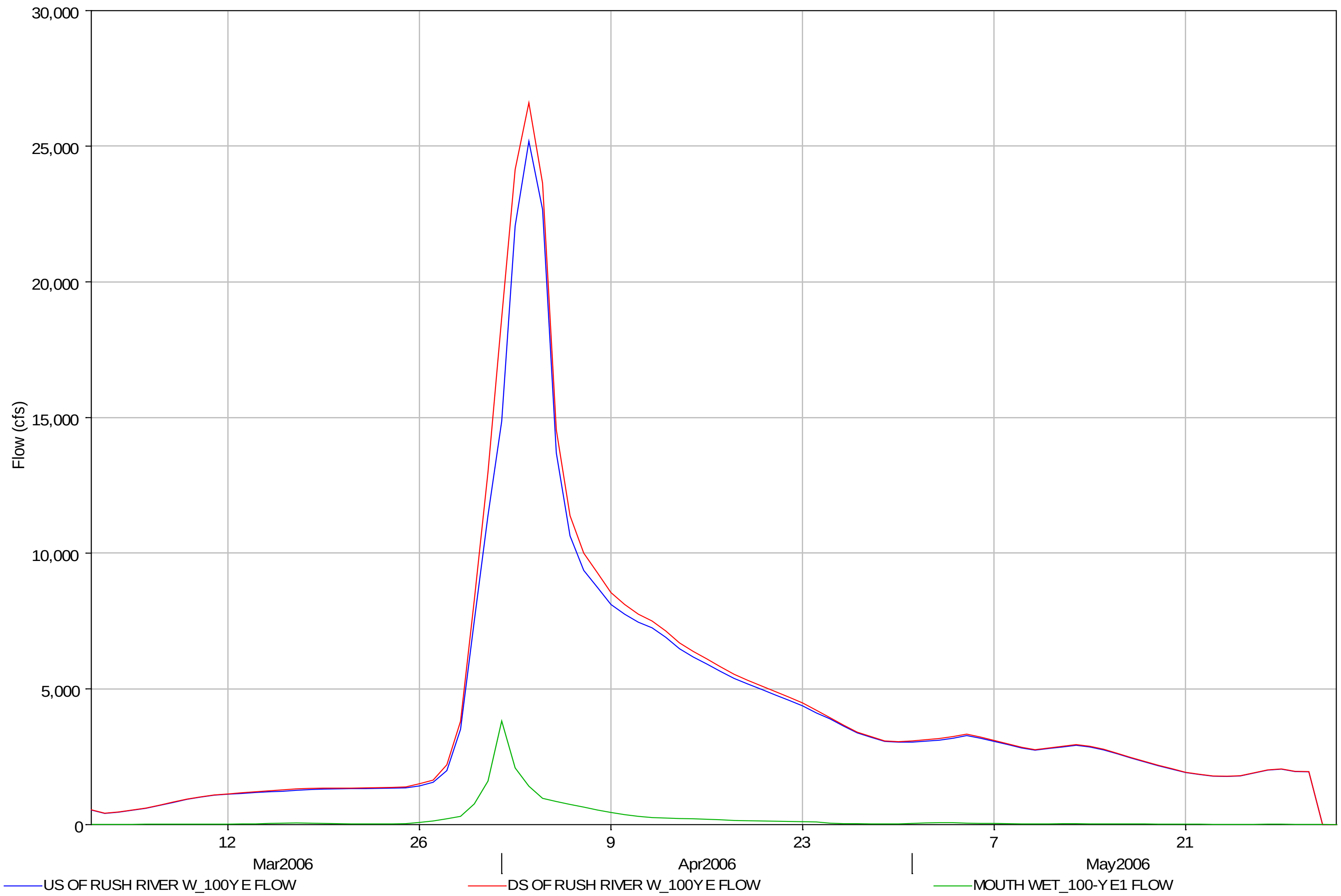


Figure 54- 100 Year Balanced Hydrographs Wet Condition, Sheyenne US and DS of Maple River and Maple River at Mouth

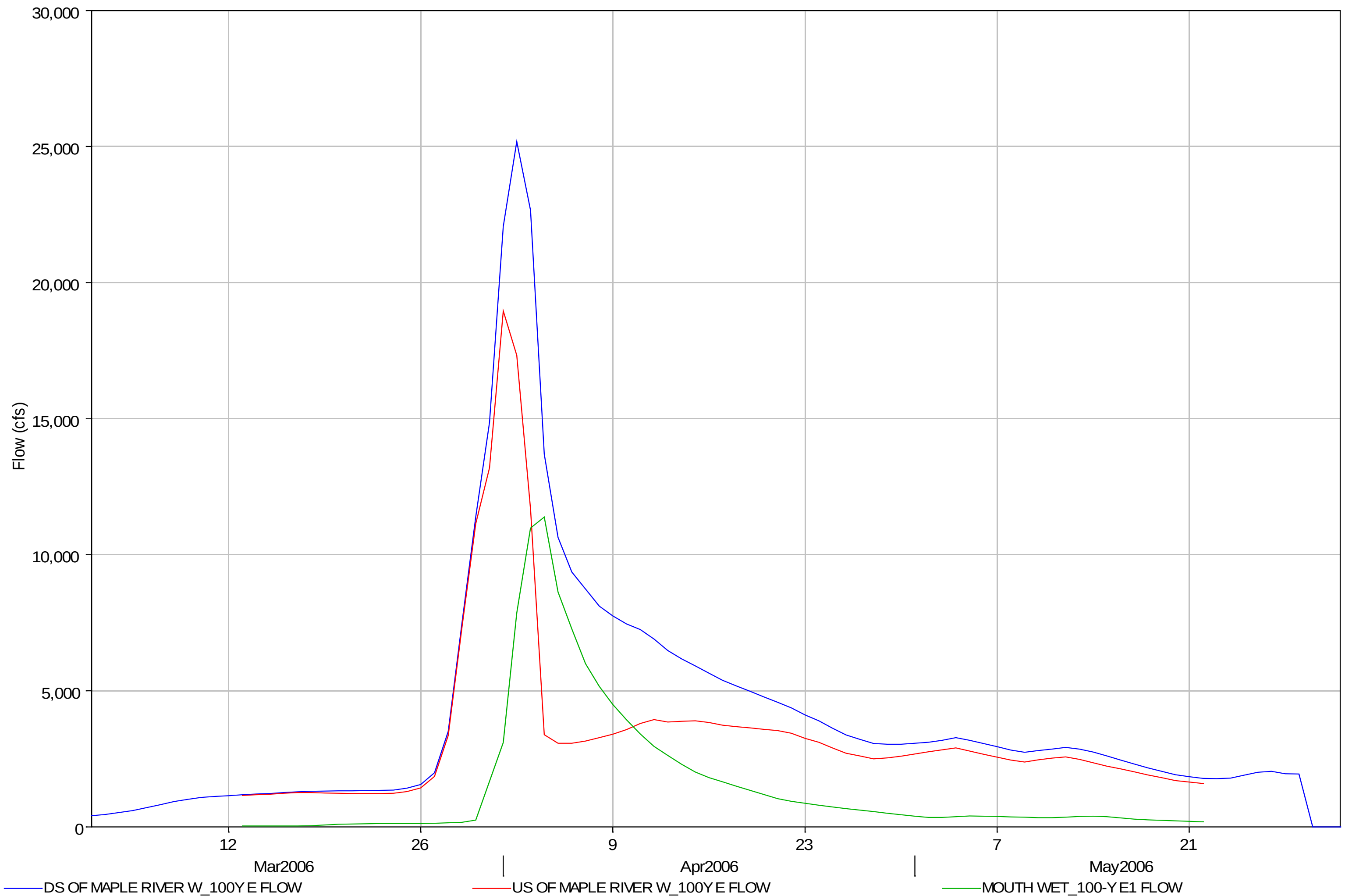


Figure 55- Diagram describing the difference in the flow-frequencies at the mouth of the Sheyenne River for the Unsteady vs. Steady RAS model

The coincident hydrograph at the mouth of the tributary (green) is obtained by subtracting the hydrograph upstream of the confluence on the main stem (blue) from the hydrograph downstream of the confluence (red) for the Steady RAS Model. The peak of the resulting coincident hydrograph may be larger than the differences in the peaks of the upstream and downstream hydrographs on the main stem due to the individual timing of the hydrographs for the Unsteady RAS model.

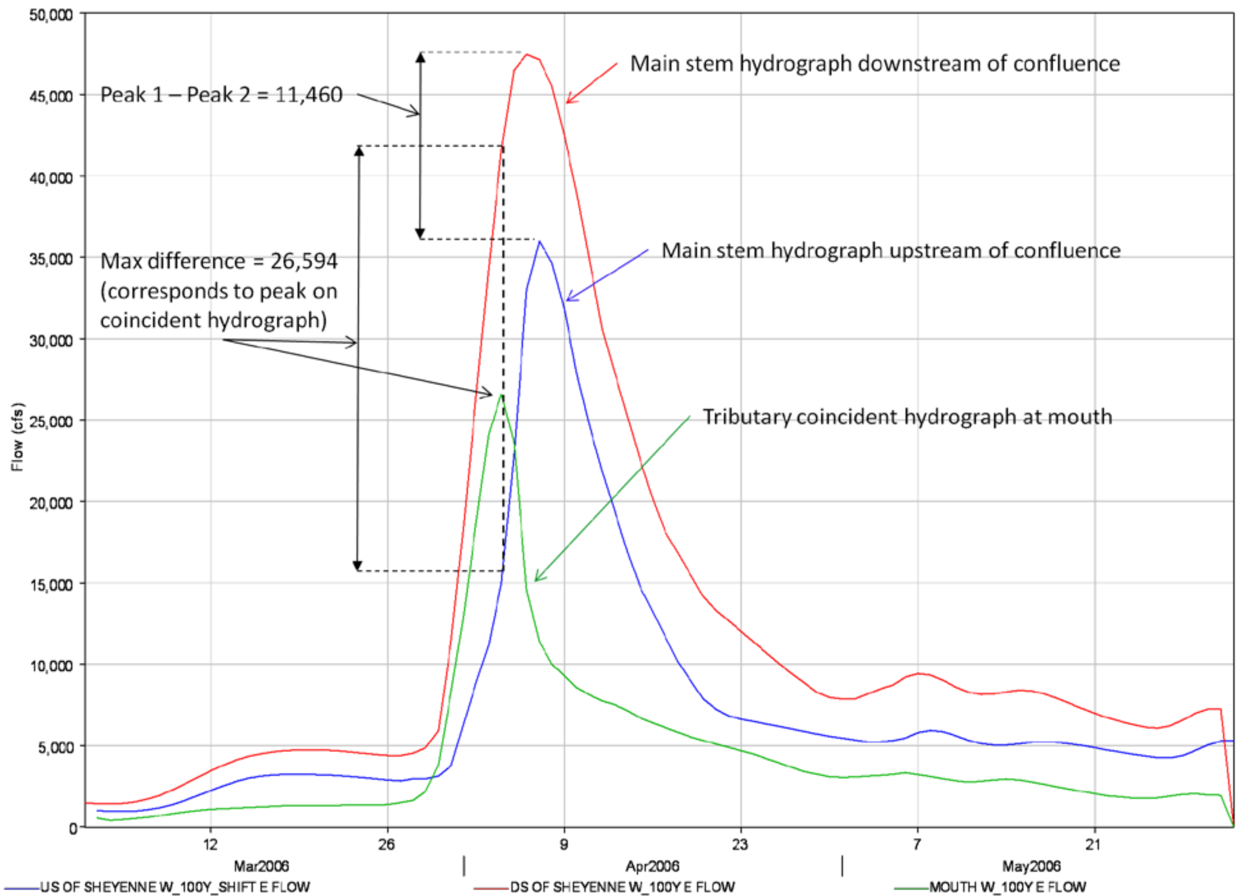
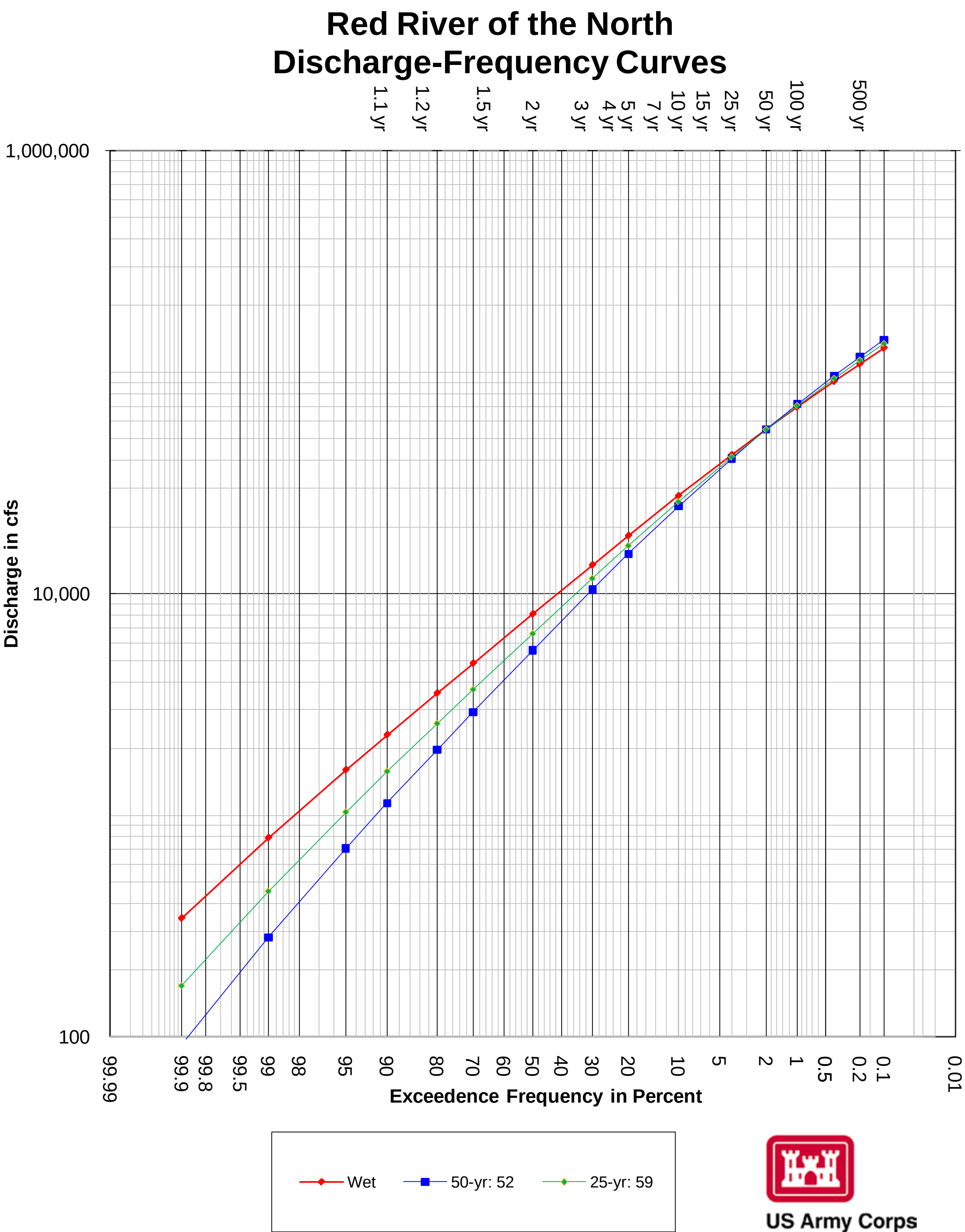


Figure 56. Five % Confidence Limits for WET, 25-yr, & 50-yr Look-Ahead Periods



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