Appendix A-3
Hydrology

Fargo-Moorhead Metropolitan Area Flood Risk Management

Supplemental Draft Feasibility Report and Environmental Impact Statement

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Preface

This Appendix describes the development of coincidental flow-frequency curves for major tributaries that reach their confluence with the Red River of the North between Grand Forks, ND and Emerson, Manitoba, Canada. Included in this Appendix is also a description of how annual instantaneous peak flow-frequency curves were determined for the WET portion (1942-2009) for three locations along the mainstem of the Red River of the North: Oslo, MN, Drayton, ND, and Emerson, Manitoba Canada. By interpolating between the adopted flow-frequency curves for the mainstem of the Red River, utilizing the coincidental flow-frequency curves for the tributaries, flow-frequency values could be determined for ungaged locations along the mainstem of the Red River. Flow-frequency values could then be utilized to develop balanced hydrographs patterned after the 2006 Spring Flood Event. This Appendix also includes a justification for selecting the 2006 event as the pattern event for the study.

1. Analysis for Halstad to Grand Forks

1.1 FLOW FREQUENCY CURVES BETWEEN HALSTAD & GRAND FORKS

This section summarizes flow-frequency analysis conducted downstream of Halstad, Minnesota to Grand Forks, North Dakota and balanced hydrographs generated at computation points along the mainstem of the Red River of the North between Halstad, MN and Thompson, ND. A schematic of this reach of the Red River of the North can be found in **Figure 1**. All coincident flow records contained in this report are based on the 1988 USACE *Timing Analysis*. All analysis carried out in this phase of the study is for the WET portion of the period of record from 1942 to 2009.

1.1.1 Coincidental Flows for the Goose River

Coincidental flows from the Goose River tributary for corresponding peak flows on the Red River of the North at Halstad are derived from the mean daily flow recorded by USGS gage 05083000 located at Hillsboro, North Dakota. The period of record associated with the mean daily flow record at the Hillsboro gage is 1931 to 2011. For this analysis only the WET portion (1942-2009) of the period of record was used for analysis. It is assumed that coincident flows at Hillsboro occur on the same day as the instantaneous peak at Halstad. The Hillsboro gage is located on the Goose River upstream of its confluence with the Red River. **Table 1** lists the coincident flow data series.

Table 1. Goose River @ Hillsboro WET (1942-2009) Coincidental Flow Record

Water Year	Coincidental Flow, cfs[1]	Water Year	Coincidental Flow, cfs[1]
1942	155	1986	417
1943	78	1987	1,310
1944	5	1988	996
1945	135	1989	1,890
1946	214	1990	39
1947	962	1991	12
1948	770	1992	750
1949	1,100	1993	2,160
1950	6,920	1994	484
1951	330	1995	1,450
1952	149	1996	3,830
1953	260	1997	4,180
1954	132	1998	110
1955	523	1999	5,450
1956	350	2000	1,600
1957	15	2001	1,790
1958	36	2002	2,630
1959	5	2003	235
1960	1,220	2004	4,630
1961	16	2005	4,280
1962	154	2006	2,410
1963	12	2007	1,310
1964	185	2008	170
1965	4,410	2009	2,860
1966	1,660		
1967	2,540		
1968	233		
1969	2,150		
1970	2,670		
1971	647		
1972	297		
1973	758		
1974	3,050		
1975	92		
1976	997		
1977	24		
1978	1,650		
1979	12,000		
1980	548		
1981	4		
1982	847		
1983	101		
1984	1,400		
1985	24		

[1]Source: USGS Mean Daily Flow Record

The flow-frequency curve for the WET portion (1942-2009) of the period of record at Hillsboro is developed using the observed coincidental flows at Hillsboro. A graphical curve can be fit to coincident peak flow data, plotted using the Weibull plotting position. The graphical curve can be found in **Figure 2**.

The frequency curve values at Hillsboro have to be transferred to the confluence of the Goose River with the Red River. This is done using general relations methodology. This technique uses a drainage area ratio relating the drainage area at Hillsboro to the drainage area associated with the confluence of the Goose River with the Red River. This drainage area ratio is raised to an exponent based on the logarithmic relationship between the WET instantaneous annual peak flow-frequency curves at Hillsboro and Portland and their associated drainage area ratio. As can be seen in **Figure 1**, USGS gage 05065500 near Portland, ND is located on the Goose River upstream of Hillsboro.

Analytical flow-frequency curves at Hillsboro and Portland are generated using a weighted skew value based on station skew and a regional skew of -0.4 and a MSE of 0.302 (source: Plate I of Bulletin 17b). The analytical curves are computed in HEC-SSP and plots are generated using the median plotting position. Since the USGS gage at Portland has a relatively short period of record (1942-1988) it is necessary to augment the flow-frequency analysis at Portland by carrying out a two station comparison with the Hillsboro gage. The resulting flow-frequency values, as well as the resulting exponent can be found in **Table 2.**

Table 2 contains the values required to transfer coincidental flows from Hillsboro to the confluence of the Goose River with the Red River for the WET flow-frequency curve.

Table 2. Goose River- Coincidental Flow-Frequency Curve- WET Analysis (1942-2009)

				WET Flow Frequency Curves (1942-2009)	
% Chance Exceedance	Hillsboro Annual Inst. Peak Discharge (cfs)	Portland Annual Inst Peak Discharge (cfs)	Exponent[1]	**Hillsboro Coin. Peak Discharge[4] (cfs)**	**Peak Discharge at the Confluence[2, 3] (cfs)**
0.2	21,453	18,300	0.16	13,000	13,125
0.5	17,975	13,908	0.26	10,500	10,663
1	15,325	11,025	0.33	9,000	9,180
2	12,687	8,501	0.41	7,800	7,990
5	9,274	5,685	0.50	5,550	5,716
10	6,801	3,928	0.56	4,000	4,134
20	4,480	2,470	0.60	2,300	2,384
50	1,760	968	0.61	630	653
	Hillsboro	**Portland**	**Goose R. Mouth**	[1] **Exponent (e) =** $\log(Q_{Hillsboro}/Q_{Portland})/\log(DA_{Hillsboro}/DA_{Portland})$	
DA sq. mi	1,093	407	1,160	[2] $Q_{confluence} = Q_{Hillsboro} * (DA_{Conf}/DA_{Hillsboro})^e$	

[3] The exponent 'e' was carried out to more significant figures in computation to minimize rounding error
[4] Based on USGS mean daily flow data

1.1.2 Coincidental Flows for the Marsh River

Coincidental peak flows from the Marsh River tributary for corresponding peak flows on the Red River at Halstad, MN are derived from mean daily flows recorded by USGS gage 05067500 near Shelly, MN. The period of record for the Shelly gage is 1944-2011. Only the period of record from 1944 to 2009 is utilized for the WET analysis. The Shelly gage is located upstream of the confluence of the Marsh River with the Red River. It is assumed that the coincident peak at Shelly occurs on the same day as the instantaneous peak at Halstad. **Table 3** lists the coincident flow data series.

Table 3. Marsh River @ Shelly, WET (1944-2009) Coincidental Flow Record

Water Year	Coincidental Flow, cfs[1]	Water Year	Coincidental Flow, cfs[1]
1944	905	1990	13
1945	773	1991	8.5
1946	661	1992	300
1947	3,190	1993	160
1948	950	1994	580
1949	160	1995	814
1950	4,640	1996	1,700
1951	2,070	1997	3,000
1952	654	1998	500
1953	128	1999	1,380
1954	365	2000	1,130
1955	210	2001	1,200
1956	912	2002	1,180
1957	180	2003	278
1958	38	2004	1,690
1959	4.8	2005	875
1960	153	2006	2,470
1961	40	2007	892
1962	359	2008	240
1963	12	2009	1,310
1964	393		
1965	480		
1966	720		
1967	266		
1968	17		
1969	490		
1970	926		
1971	580		
1972	1,220		
1973	182		
1974	2,140		
1975	136		
1976	774		
1977	Missing		
1978	2,220		
1979	2,200		
1980	413		
1981	175		
1982	329		
1983	238		
1984	Missing		
1985	1,120		
1986	1,280		
1987	90		
1988	150		
1989	1,900		

[1]Source: USGS Mean Daily Flow Record

The flow-frequency curve for the WET portion (1942-2009) of the flow record at Shelly is developed using the observed coincident flows. A graphical curve can be fit to the coincident peak flow data plotted using the Weibull plotting position. The graphical curve can be found in **Figure 3.**

The frequency curve at Shelly has to be transferred to the confluence of the Marsh River with the Red River. This is done using general relations methodology. This technique uses a drainage area ratio relating the drainage area at Shelly to the drainage area associated with the confluence of the Marsh River with the Red River. This drainage area ratio is raised to an exponent based on the analysis done between the Portland and Hillsboro gages on the Goose River.

Table 4 contains the values used to transfer flows from Shelly to the confluence of the Marsh River with the Red River for the WET flow-frequency curve. The values corresponding to the Wet Flow-Frequency Curve for Coincident Flows at the mouth of the Marsh River can also be found in **Table 4**.

Table 4. Marsh River- Coincidental Flow-Frequency Curve- WET Analysis (1942-2009)

		WET (1942-2009) Flow Frequency Curves	
% Chance Exceedance	Exponent[1]	**Shelly Coin. Peak Discharge[4] (cfs)**	**Peak Discharge at the Confluence[2] (cfs)**
0.2	0.16	5,500	5,782
0.5	0.26	5,000	5,419
1	0.33	4,500	4,990
2	0.41	3,800	4,309
5	0.50	2,900	3,382
10	0.56	2,200	2,614
20	0.60	1,600	1,929
50	0.61	590	712
	Shelly	**Marsh R. Mouth**	**[1] Exponent (e) = Log $(Q_{Hillsboro}/Q_{Portland})$/ Log $(DA_{Hillsboro}/DA_{Portland})$**
DA sq. mi	220[3]	300[3]	**[2] $Q_{confluence} = Q_{Shelly} * (DA_{Conf} / DA_{Shelly})^e$**

[3] Contributing Area could not be found at Shelly so total area was utilized
[4]Based on USGS Mean Daily Flow Record

1.1.3 Coincidental Flows for the Sand Hill River

Coincidental peak flows from the Sand Hill River tributary for corresponding peak flows on the Red River at Grand Forks are derived from the mean daily flows recorded at USGS gage 05069000 at Climax, MN. The period of record associated with the mean daily flow record at

Climax, MN is 1943 to 2011. Only the portion of the period of record from 1943 to 2009 is adopted for the WET analysis. The Climax gage is located upstream of the confluence of the Sand Hill River and the Red River. It is assumed that the coincident peak at Climax occurs two days before the peak at Grand Forks. **Table 5** lists the coincident flow data series.

Table 5. Sand Hill River @ Climax, WET (1943-2009) Coincidental Flow Record

Water Year	Coincidental Flow, cfs[1]	Water Year	Coincidental Flow, cfs[1]
1943	621	1988	550
1944	60	1989	2,300
1945	378	1990	200
1946	320	1991	65
1947	1,790	1992	120
1948	1,600	1993	1,250
1949	240	1994	1,120
1950	2,240	1995	600
1951	1,000	1996	4,230
1952	233	1997	2,000
1953	102	1998	1,410
1954	400	1999	3,300
1955	500	2000	700
1956	1,260	2001	1,600
1957	450	2002	3,360
1958	112	2003	380
1959	210	2004	1,500
1960	250	2005	913
1961	110	2006	3,530
1962	523	2007	906
1963	180	2008	206
1964	477	2009	2,800
1965	3,700		
1966	4,120		
1967	608		
1968	590		
1969	3,850		
1970	421		
1971	1,110		
1972	1,860		
1973	640		
1974	1,670		
1975	280		
1976	1,130		
1977	65		
1978	2,900		
1979	3,230		
1980	745		
1981	63		
1982	300		
1983	483		
1984	1,500		
1985	Missing		
1986	1,300		
1987	400		

[1]Source: USGS Mean Daily Flow Record

The flow-frequency curve for the WET portion (1942-2009) of the period of record at Climax is developed using the observed coincidental flows at Climax. A graphical curve can be fit to the coincident peak flow data using the Weibull plotting position. The graphical curve can be found in **Figure 4**.

The frequency curve at Climax has to be transferred to the confluence of the Sand Hill River with the Red River. This is done using the general relations methodology. This technique uses a drainage area ratio relating the drainage area at Climax to the drainage area associated with the confluence of the Sand Hill River with the Red River. This drainage area ratio is raised to an exponent based on the analysis done between the Portland and Hillsboro gages on the Goose River.

Table 6 contains the values used to transfer flows from Climax to the confluence of the Sand Hill River with the Red River for the WET flow-frequency curve. The values corresponding to the Wet Flow-Frequency Curve for Coincident Flows at the mouth of the Sand Hill River can also be found in **Table 6**.

Table 6. Sand Hill River- Coincidental Flow-Frequency Curve- WET Analysis (1942-2009)

		WET (1942-2009) Flow Frequency Curve	
% Chance Exceedance	Exponent[1]	**Climax Coin. Peak Discharge[3] (cfs)**	**Peak Discharge at the Confluence[2] (cfs)**
0.2	0.16	5,100	5,119
0.5	0.26	4,950	4,980
1	0.33	4,800	4,838
2	0.41	4,300	4,341
5	0.50	3,850	3,895
10	0.56	3,300	3,343
20	0.60	2,100	2,130
50	0.61	700	710
	Climax	**Sand Hill R. Mouth**	**[1] Exponent (e) = Log $(Q_{Hillsboro}/Q_{Portland})$/ Log $(DA_{Hillsboro}/DA_{Portland})$**
DA sq. mi	420	430	**[2] $Q_{confluence} = Q_{Climax} * (DA_{Conf} / DA_{Climax})^e$**
[3]Based on USGS Mean Daily Flow data			

1.1.4 Coincidental Flows for the Red Lake River

Coincidental peak flows from the Red Lake River tributary for corresponding peak flows on the Red River at Grand Forks are derived from mean daily flows recorded at USGS gage 05079000 at Crookston, MN, located upstream of the confluence of the Red Lake River and the Red River. The period of record associated with the Crookston gage is 1901-2011. Only the portion of the period of record from 1942-2009 is adopted for WET analysis. It is assumed that the coincident peak at Crookston occurred one day before the peak at Grand Forks. **Table 7** lists the coincident flow data series.

Table 7. Red Lake River @ Crookston, WET (1942-2009) Coincidental Flow Record

Water Year	Coincidental Flow, cfs[1]	Water Year	Coincidental Flow, cfs[1]
1942	5,500	1987	4,000
1943	6,080	1988	2,100
1944	4,420	1989	4,400
1945	8,910	1990	700
1946	7,630	1991	1,030
1947	7,200	1992	1,600
1948	8,000	1993	3,440
1949	6,000	1994	10,900
1950	22,200	1995	9,060
1951	7,440	1996	21,400
1952	3,520	1997	24,500
1953	1,130	1998	8,090
1954	4,010	1999	14,000
1955	6,990	2000	5,950
1956	12,300	2001	11,500
1957	9,490	2002	9,870
1958	3,110	2003	4,110
1959	3,600	2004	5,700
1960	3,320	2005	7,630
1961	1,310	2006	16,700
1962	9,830	2007	7,770
1963	5,380	2008	3,160
1964	5,020	2009	10,800
1965	15,700		
1966	19,900		
1967	11,100		
1968	3,950		
1969	14,800		
1970	11,500		
1971	11,000		
1972	14,300		
1973	3,050		
1974	12,300		
1975	8,840		
1976	7,100		
1977	800		
1978	15,300		
1979	15,100		
1980	4,000		
1981	5,860		
1982	3,400		
1983	3,960		
1984	4,700		
1985	5,110		
1986	11,000		

[1]Source: USGS Mean Daily Flow Record

The flow-frequency curve for the WET portion (1942-2009) of the POR at Crookston is developed using the observed coincidental flows at Crookston.

Red Lake Dam is located upstream of Crookston, MN on the Red Lake River approximately 196 river miles above the mouth of the Red Lake River. Red Lake Dam impounds the Upper and Lower Red Lakes. The two lakes are connected by a small strait known as “the narrows.” The Upper and Lower Lakes provide flood control storage for the Red Lake River and subsequently the Red River of the North watersheds. Available storage for flood runoff is about 1,010,000 acre-feet. During flood events the Red Lake reservoir stores as much runoff as necessary, releasing between 0 and 1,000 cfs depending on downstream conditions. During the 2009 flood event releases from the reservoir were held under 250 cfs between 21 March 2009 and 15 May 2009. The Red Lake River peaked at Crookston on the 25th of March and the Red River peaked at Grand Forks on the 1st of April 2009.

The drainage area for Upper and Lower Red Lake is 1,950 square miles. According to the USGS the 1, 950 square miles in the headwaters of the Red Lake River is completely controlled by the dam outlet of Lower Red Lake. During Flood events flow from this drainage area is essentially cut off from reaching the USGS gage at Crookston and can be considered non-contributing area.

A graphical curve can fit to the coincident peak flow data at Crookston using the Weibull plotting position. The graphical curve can be found in **Figure 5**. By carrying out flow-frequency analysis graphically any regulatory effects caused by Red Lake Dam are accounted for.

The flow-frequency curve at Crookston has to be transferred to the confluence of the Red Lake River with the Red River. This is done using general relations methodology. This technique uses a drainage area ratio relating the drainage area at Crookston to the drainage area associated with the confluence of the Red Lake River with the Red River. This drainage area ratio is raised to an exponent based on the analysis done between the Portland and Hillsboro gages on the Goose River.

Table 8 contains the values used to transfer flows from Crookston to the confluence of the Red Lake River with the Red River for the WET flow-frequency curve. The values corresponding to the Wet Flow-Frequency Curve for coincident flows at the mouth of the Red Lake River can also be found in **Table 8**. The drainage area listed in the table for Crookston and the mouth of the Red Lake River is the area below Red Lake Dam. This is based on the assumption that during large flood events when the coincident peaks are occurring on Red Lake River, minimal flows are being released from the dam.

Table 8. Red Lake River- Flow Frequency Curve- WET Analysis (1942-2009)

		WET (1942-2009) Flow Frequency Curves	
% Chance Exceedance	Exponent[1]	**Crookston Coin. Peak Discharge[3] (cfs)**	**Peak Discharge at the Confluence[2] (cfs)**
0.2	0.16	30,000	30,659
0.5	0.26	28,000	28,999
1	0.33	26,000	27,197
2	0.41	25,000	26,406
5	0.50	20,050	21,437
10	0.56	17,000	18,325
20	0.60	13,000	14,102
50	0.61	6,800	7,379
	Crookston	**Red Lake R. Mouth**	[1] **Exponent (e) = Log $(Q_{Hillsboro}/Q_{Portland})$/ Log $(DA_{Hillsboro}/DA_{Portland})$**
DA sq. mi	3,320	3,800	[2] **$Q_{confluence} = Q_{Crookston} * (DA_{Conf} / DA_{Crookston})^e$**

[3]Based on USGS Mean Daily flow record

1.1.5 Rebalancing the Hydrographs Downstream of Halstad

The summation of the flow-frequencies at the confluences of the major tributaries along the Red River with the gaged flow-frequency values at Halstad is greater than the gaged based flow-frequency curve downstream at Grand Forks. The adopted analysis relies heavily on the assumption that the travel time/ lag time between recorded flows on the tributaries and when they reach a location on the Red River is the same for every event. This discrepancy could be due to the variability associated with the lag time in determining coincident peaks on the tributaries.

Results can be rebalanced by evenly redistributing the difference in flows at each exceedance interval between Halstad and Grand Forks between the major tributaries along the Red River using drainage area ratios. These revised flow-frequency curves are transferred back to gaged locations along the tributaries and re-plotted to ensure they are comparable to the original graphical curves generated at these locations. The re-plotted values were smoothed out where necessary to resemble the characteristics of the original curves. The curves are displayed in **Figure 6** through **Figure 9**.

Adjusted flow-frequency curve values are significantly less than the data based flow-frequency curves for the Sand Hill and Red Lake Rivers. This is reasonable because according to the National Weather Service Office of Hydrologic Development backwater effects are known to occur on tributaries located along this reach of the Red River of the North. The Red River of the North has a mild slope in the Grand Forks area (~0.5 ft/mi). Mild gradients may cause the river to experience backwater effects. As a result of backwater effects flow gets pushed upstream the tributaries causing a stage increase on the tributary at a time when the river discharge was actually falling (hysteresis).

During large events at Climax and Crookston USGS data is estimated from a stage discharge rating curve. According to the 2009 Water-Data Report estimated daily discharges are “poor.” This is most likely because a rating curve relationship is being used to estimate flow from stage. Since the stage is likely high due to backwater effects the rating curve relationship will over estimate the corresponding flow.

1.1.6 Flow-Frequency Curves at Un-gaged Locations

Discharge-frequencies for the reach between Halstad and Grand Forks are based primarily on interpolations between adopted discharge-frequencies at Halstad and Grand Forks and the adopted coincidental flow-frequencies from the Goose River, Marsh River, Sand Hill River and Red Lake River. Flows are estimated between Halstad and Grand Forks using a drainage area ratio. For the 2 and 10 year events the drainage area ratios are raised to exponents of 1.055 and 0.174, respectively. The flow-frequency values can be found in **Table 9**.

Table 9- Flow-Frequency values for ungaged locations between Halstad and Grand Forks

Red River of the North Mainstem Flow-Frequency Analysis WET Analysis (1942-2009)									
	Flow Frequency Values (cfs)								
LOCATION	**DA**	**2-YR**	**5-YR**	**10-YR**	**20-YR**	**50-YR**	**100-YR**	**200-YR**	**500-YR**
Grand Forks	20,015	23,295	42,139	56,354	70,956	91,026	106,838	123,201	145,675
d/s Red Lake	200,15	23,295	42,139	56,354	70,956	91,026	106,838	123,201	145,675
Red Lake Coinc.	3,800	7,379	11,604	13,399	15,437	18,128	20,073	22,200	24,595
u/s Red Lake	16,215	15,916	30,535	42,955	55,519	72,898	86,765	101,001	121,080
Thompson	16,095	15,792	30,535	42,899	55,519	72,898	86,765	101,001	121,080
d/s Sand Hill River	16,015	15,709	30,535	42,862	55,519	72,898	86,765	101,001	121,080
Sand Hill River Coinc.	430	763	1,801	2,700	3,451	4,000	4,226	4,367	4,532
u/s Sand Hill River	15,585	14,946	28,734	40,162	52,068	68,898	82,539	96,634	116,548
d/s Marsh River	15,375	14,734	28,734	40,067	52,068	68,898	82,539	96,634	116,548
Marsh River Coinc.	150	712	1,511	2,420	3,145	3,996	4,709	5,151	5,543
u/s Marsh River	15,225	14,022	27,223	37,648	48,922	64,902	77,830	91,484	111,005
d/s Goose River	15,225	14,022	27,223	37,648	48,922	64,902	77,830	91,484	111,005
Goose River Coinc.	1,160	657	1,964	2,650	3,908	5,596	7,032	8,612	11,292
u/s Goose River	14,065	13,365	25,259	34,997	45,014	59,306	70,798	82,872	99,713
Halstad	13,775	13,074	25,259	34,871	45,014	59,306	70,798	82,872	99,713

1.2 BALANCED HYDROGRAPHS BETWEEN HALSTAD & THOMPSON

Balanced hydrographs are developed at all pertinent computation points located on the reach of the Red River of the North between Halstad and Thompson, ND in support of the unsteady RAS model. Hydrographs are generated for the 0.2-, 0.5-, 1-, 2-, and 10-percent exceedance frequency events for the WET portion of the period of record.

Coincidental balanced hydrographs are required for the confluences of the Goose River, Marsh River, Sand Hill River and Red Lake River with the Red River of the North. Balanced hydrographs on the main stem of the Red River of the North are required upstream and downstream of each of the tributaries, as well as at Thompson, ND.

The Hydrologic Engineering Center's Flood Hydrograph Package, HEC-1, is used to construct balanced hydrographs using specified 1, 3, 7, 15 and 30-day volumes and a pattern event. Flood volume duration analysis provides for the volume at each duration and specified frequency. For the Fargo-Moorhead Metro Feasibility Study the 2006 Spring Flood Event has been adopted as the pattern event.

Coincident flood volume frequency curves are derived at the mouths of the tributaries and at specified locations on the mainstem. This is done by assuming the same proportional change in flood volume at a given duration as at that duration for a hydrologically similar gaged location.

1.2.1 Pattern Event Hydrograph

To develop balanced hydrographs along the mainstem of the Red River of the North, as well as at the confluence of its tributaries it is first necessary to identify an event hydrograph which can be used as a pattern for the balanced hydrographs. The pattern event helps establish the shape and timing of the hydrograph. The 2006 pattern event at gaged locations is acquired from USGS daily observed streamflow measurements. The 2006 pattern event at ungaged locations is determined by routing the closest upstream observed 2006 hydrograph downstream to the location of interest and adding in appropriate local flow hydrographs.

To account for the local flow associated with contributing drainage area between computation points along the Red River of the North, it is necessary to develop hydrographs which are representative of this additional flow. Local flow hydrographs are developed by using a reference USGS gage located in a hydrologically similar area. The 2006 event hydrographs at gaged locations can be modified using a drainage area ratio to generate the local flow hydrographs. The reference gages, along with the associated drainage area ratios, are listed in **Table 10**.

Table 10- Reference gages and drainage area ratios.

Ratios for Determining Flow Resulting from Contributing Areas				
Reach	**Ref Gage**	**DA ref Gage**	**DA Reach**	**Ratio**
Halstad to Just U/S Mouth of Goose	Hillsboro	1,093	290	0.265
Hillsboro to Mouth of Goose	Hillsboro	1,093	77	0.0704
Shelly to Mouth of Marsh River	Shelly	220	80	0.364
D/S Marsh R to U/S Sand Hill R	Climax	420	210	0.5
D/S Sand Hill R to U U/S Red Lake R	Climax	420	200	0.476
Crookston to Mouth of Red Lake	Crookston	3,320	480	0.145

1.2.2 2006 Spring Event Hydrograph Routing

1.2.2.1 Adopted Routing Parameters

The USACE 1988 *Timing Analysis* can be used to develop straddle stagger routing parameters to route the 2006 event hydrograph downstream from Halstad to Thompson. The adopted routing parameters can be found in **Table 11**.

Table 11. Straddle Stagger Routing parameters – Halstad to Thompson.

Straddle Stagger Routing Parameters	Average	Lag	Subreaches
Halstad to Upstream Goose River	3	1	1
Downstream Goose River to Upstream Marsh River	Direct Transfer Lag =0, attenuation is negligible		
Down Stream Marsh River to Upstream Sand Hill River	3	1	1
Downstream Sand Hill River to Thompson, ND	Direct Transfer Lag= 0 , attenuation is negligible		
Downstream Sand Hill River to Upstream Red Lake River/ Grand Forks	3	1	1

1.2.2.2 2006 Event Routing Calibration

Daily flow data was recorded by USGS gage 05070000 located on the Red River of the North near Thompson, MN for the 2006 event. The data based hydrograph depicted in **Figure 10** at Thompson is compared to the routed 2006 event hydorgraph just downstream of the Sand Hill River. As can be seen in the figure the routed flows downstream of the confluence of the Sand Hill River and the Red River are quite comparable to the actual gage based hydrograph at Thompson. The timing conforms to what might be expected, with both hydrographs peaking on the same day. The routed hydrograph may be underestimating the attenuation slightly, but is still quite accurate.

Routing parameters are based on the timing and attenuation for a typical event for this portion of the Red River. The actual recorded data for the 2006 event conforms to the modeled flows relatively well. Therefore, the 2006 is representative of a typical event and is thus a good pattern event.

The USGS recorded data for the 2006 event at Thompson, MN and Grand Forks, ND is displayed in **Figure 11**. As can be seen from **Figure 11**, the Red River at Grand Forks is peaking prior to the Red River at Thompson. This is unexpected because Grand Forks is downstream of Thompson, and is atypical for this portion of the river as is indicated by **Table 12**.

Table 12- Timing between Grand Forks and Thompson

WY	Instantaneous Annual Peaks (CFS)		Time Lag (days)
	Grand Forks (DS Station)	Thompson (US Station)	
2004	34,300	25,400	Thompson peaks 1-day before GF
2005	38,300	26,300	Peak on the Same Day
2006	72,800	53,500	GF peaks 1-day before Thompson
2007	35,300	27,900	Peak on the Same Day
2008	17,700	14,700	Thompson peaks 1-day before GF
2009	76,700	61,300	Peak on the Same Day

From **Table 12** one can conclude that Thompson usually peaks on the same day or one day prior to Grand Forks. However, in 2006 this was not the case. In 2006 the event hydrograph at Thompson peaks on April 7th, while the hydrograph at Grand Forks peaks on April 6th. The timing at Grand Forks is reflected in **Figure 12** by both the hydrograph generated using USGS observed flow data and the hydrograph developed using straddle stagger routing.

1.2.2.3 Discussion- 2006 Event as Pattern Event

The Red Lake River is a tributary of the Red River of the North that reaches its confluence with the main stem of Red River just upstream of Grand Forks. The routed hydrograph just upstream of the mouth of the Red Lake River on the Red River of the North is displayed in **Figure 13** in comparison to the observed event hydrograph at Thompson. At this point the timing still seems to be typical, with the Red River peaking just upstream of the Red Lake River one day after peaking at Thompson.

Based on this analysis, it can be concluded that the magnitude of inflows from the Red Lake River caused the timing on the main stem at Grand Forks to be atypical. The timing of the 2006 event is atypical for the Red Lake River and the Red River because the routed curve and the USGS curve yield similar curves. Thus, it must be the magnitude of the flow from the Red Lake River that is causing the Red River to peak earlier than what would be expected for a typical event.

The 2006 event at Oslo peaks on the same day as the peak at Grand Forks. Based on the timing that took place during other flood events as listed in **Table 13**, the Oslo timing of the peak at Oslo with respect to the peak at Grand Forks is reasonable.

Table 13- Timing between Grand Forks and Oslo

WY	Time Lag Between Grand Forks and Oslo (days)
2003	2
2004	0
2005	1
2006	0
2007	1
2008	1
2009	0
1969	3
2001	2
1996	1
1997	5

The timing of the 2006 event between Grand Forks (just downstream of the mouth of the Red Lake River) and Oslo is appropriate, however the magnitude of inflow from the Red Lake River is atypical and thus, the timing of the peak at Grand Forks arrives 2 days early.

No event selected based on observed data will conform completely to what is considered a "typical" flood event in the Red River Basin. Using this reach as a case study it is observed that between Halstad and the Red Lake River and between Grand Forks and Oslo the 2006 event accurately models a typical event on the Red River, but at Grand Forks the timing is atypical as a result of flow coming from the Red Lake River. Because the 2006 event mirrors the average timing and attenuation on the Red River for the majority of the river's reaches it is still appropriate to use it as a pattern event even if it doesn't conform exactly to what is considered typical at a few locations.

1.2.3 Volume Duration Analysis for Coincident Flows

The methodology used for points of interest upstream of Halstad involved using a regression between the mean daily annual peak flow-frequency curve and the annual instantaneous peak flow-frequency curve. In this stage of the study it was decided that it would be more appropriate to directly adopt the coincident flow-frequency curve as the 1-day duration frequency curve. As was done previously, the volume duration curves at other durations were derived by assuming the same proportional change in flow volume for each duration, as for the 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 14**.

Table 14. 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			
Hillsboro	Goose R.	Coincidental	Hillsboro Coincidental Peak with Halstad- No Shift
Shelly	Marsh R.	Coincidental	Shelly Coincidental Peak with Halstad- No Shift
Climax	Sand Hill R.	Coincidental	Climax Coincidental Peak with Grand Forks- +2 day Shift
Crookston	Red Lake R.	Coincidental	Crookston Coincidental Peak with Grand Forks- +1 day Shift
US & DS Goose R.	RRN	Mainstem	Halstad
US & DS Marsh R.	RRN	Mainstem	Halstad
US & DS of Sand Hill R	RRN	Mainstem	Grand Forks
US & DS of Red Lake R	RRN	Mainstem	Grand Forks

2. FLOW-FREQUENCY ANALYSIS DOWNSTREAM OF GRAND FORKS

This section contains flow-frequency analysis for the WET portion of the period of record (1942-2009) for the following locations located on the mainstem of the Red River of the North: Oslo, MN, Drayton, ND, and Emerson, Canada.

2.1 Initial Flow-Frequency Analysis

2.1.1 Oslo, MN

As is displayed in **Table 15**, there are only 42 years of instantaneous peak flow data between 1942 and 2009 for the USGS gage at Oslo.

Table 15. Annual Inst. Peak Flows at Oslo- WET Analysis (1942-2009)

Date	Flow (cfs)	Date	Flow (cfs)
4-Apr-42	11,900	6-Apr-88	11,500
13-Apr-43	31,500	14-Apr-89	33,500
26-Mar-45	24,000	5-Apr-90	4,900
22-Apr-47	33,800	10-Jul-91	5,200
17-Apr-48	41,400	15-Mar-92	8,200
10-Apr-49	18,700	7-Apr-93	28,100
10-May-50	63,000	13-Jul-94	26,600
12-Apr-51	24,800	1-Apr-95	35,000
21-Apr-52	24,800	22-Apr-96	59,200
25-Jun-53	14,900	23-Apr-97	120,000
15-Apr-54	9,790	22-May-98	29,000
10-Apr-55	16,400	2-Apr-99	53,000
24-Apr-56	22,500	29-Jun-00	31,000
2-Jul-57	14,900	16-Apr-01	51,000
10-Jul-58	7,890	15-Jul-02	34,000
7-Apr-59	7,200	30-Jun-03	16,500
12-Apr-60	17,100	1-Apr-04	36,000
4-Apr-66	59,000	19-Jun-05	36,100
19-Apr-69	56,500	6-Apr-06	77,600
12-Apr-78	56,200	23-Jun-07	37,200
20-May-85	17,800	17-Jun-08	18,000
3-Apr-86	30,000	1-Apr-09	80,600
30-Mar-87	18,500		

Because the flow record at Oslo is missing twenty-three years of record, a two station comparison is carried out between the USGS gage at Oslo and the USGS gage at Drayton. Based on this two station comparison the initial statistics at Oslo are adjusted to the values displayed in **Table 16**.

Table 16. Adjusted Statistics based on Oslo two-station comparison

	Statistics	
	Original	Adjusted
Length of Record (N)	45	66
Mean (X)	4.40	4.37
Standard Deviation (S)	0.319	0.331

An analytical flow-frequency analysis can then be carried out using the Hydraulic Engineering Center's Statistical Software Package (HEC-SSP). A Log Pearson Type Three Distribution, adjusted statistics (as defined in **Table 16**) and station skew are utilized to generate the flow-frequency curve.

2.1.2 Drayton, ND

The instantaneous annual peak flow record at Drayton as acquired from the USGS website is displayed in **Table 17**. Using this data, an analytical flow-frequency analysis can be carried out in HEC-SSP by applying a Log Pearson Type Three Distribution to the data. In this stage of analysis station skew is utilized.

Table 17. USGS annual instantaneous peak flow record at Drayton, WET Analysis (1942-2009)

Date	Flow (cfs)	Date	Flow (cfs)
7-Apr-42	21,900	21-May-85	17,700
17-Apr-43	28,700	7-Apr-86	29,700
18-Apr-44	12,300	7-Apr-87	27,600
2-Apr-45	24,600	7-Apr-88	13,900
30-Mar-46	23,000	19-Apr-89	41,800
28-Apr-47	29,300	7-Apr-90	5,080
21-Apr-48	57,000	11-Jul-91	4,940
12-Apr-49	27,900	16-Mar-92	8,800
12-May-50	86,500	14-Aug-93	27,600
15-Apr-51	24,600	6-Apr-94	27,900
25-Apr-52	23,900	1-Apr-95	37,800
26-Jun-53	14,700	25-Apr-96	61,300
15-Apr-54	11,100	24-Apr-97	124,000
11-Apr-55	18,000	24-May-98	28,400
27-Apr-56	28,000	9-Apr-99	59,500
4-Jul-57	14,100	30-Jun-00	29,300
12-Jul-58	7,850	19-Apr-01	55,300
8-Apr-59	11,200	18-Jun-02	34,800
14-Apr-60	24,700	2-Jul-03	15,300
31-Mar-61	3,600	2-Apr-04	37,400
24-Apr-62	32,300	21-Jun-05	31,200
12-Apr-63	12,900	10-Apr-06	78,800
20-Apr-64	15,600	23-Jun-07	30,400
22-Apr-65	47,200	17-Jun-08	18,600
8-Apr-66	67,500	5-Apr-09	85,500
8-Apr-67	32,200		
23-Jul-68	12,500		
19-Apr-69	59,000		
29-Apr-70	31,700		
11-Apr-71	23,400		
20-Apr-72	31,100		
25-Mar-73	13,400		
25-Apr-74	43,900		
4-May-75	44,000		
7-Apr-76	27,600		
9-Apr-77	3,400		
16-Apr-78	56,200		
28-Apr-79	92,900		
10-Apr-80	22,400		
3-Jul-81	7,520		
17-Apr-82	35,500		
9-Apr-83	21,300		
6-Apr-84	32,400		

2.1.3 Emerson, Manitoba, Canada

The instantaneous annual peak flow record at Emerson is displayed in **Table 18**. Using this data, an analytical flow-frequency analysis can be carried out in HEC-SSP by applying a Log Pearson Type Three Distribution to the data. In this stage of analysis station skew is utilized.

Table 18. Annual Instantaneous Peak Flow data at Emerson- WET Analysis (1942-2009)

Date	Flow (cfs)	Date	Flow (cfs)
10-Apr-42	27,900	18-Apr-78	50,300
20-Apr-43	29,500	1-May-79	92,400
19-Apr-44	12,300	10-Apr-80	21,700
4-Apr-45	29,400	4-Jul-81	6,110
5-Apr-46	24,100	18-Apr-82	34,000
28-Apr-47	28,400	9-Apr-83	24,600
27-Apr-48	51,800	8-Apr-84	30,200
15-Apr-49	29,200	29-Mar-85	16,700
13-May-50	94,400	7-Apr-86	34,200
15-Apr-51	26,600	9-Apr-87	37,400
24-Apr-52	24,200	8-Apr-88	15,700
28-Jun-53	14,500	23-Apr-89	42,400
17-Apr-54	11,500	10-Apr-90	5,470
10-Apr-55	23,400	12-Jul-91	5,690
26-Apr-56	33,700	4-Apr-92	15,700
4-Jul-57	15,300	17-Aug-93	31,900
12-Jul-58	7,880	8-Apr-94	26,900
10-Apr-59	15,700	2-Apr-95	42,400
13-Apr-60	30,500	26-Apr-96	66,000
30-Mar-61	4,290	26-Apr-97	133,000
25-Apr-62	33,300	12-Mar-98	27,500
13-Apr-63	13,700	12-Apr-99	58,600
25-Jun-64	17,500	2-Jul-00	31,800
25-Apr-65	46,100	25-Apr-01	57,600
11-Apr-66	66,300	18-Jun-02	35,700
30-Apr-67	33,200	3-Jul-03	14,200
24-Jul-68	13,900	7-Apr-04	45,200
26-Apr-69	54,700	7-Apr-05	38,200
29-Apr-70	39,600	12-Apr-06	72,400
16-Apr-71	26,600	4-Apr-07	34,500
23-Apr-72	30,700	19-Jun-08	16,527
27-Mar-73	14,200	15-Apr-09	88,200
28-Apr-74	43,400		
7-May-75	42,700		
7-Apr-76	31,300		
10-Apr-77	4,440		

2.2 Adopted Flow Frequency Curves

The flow-frequency curves generated at Oslo, Drayton, and Emerson are plotted alongside the previously adopted flow-frequency curves at Fargo, Halstad, and Grand Forks. In order to produce a family of nested curves for the mainstem of the Red River, smoothing functions have to be developed and applied to the skew and standard deviation associated with the flow-frequency curves at Oslo, Drayton, and Emerson.

The mean squared error (MSE) associated with the adopted skew is found using the methodology described in Bulletin 17b (Equation 6). The initial statistics, along with the adopted statistics for the flow-frequency curves at Oslo, Emerson, and Drayton, can be found in **Table 19**. The linear relationships used to smooth out the statistics can be found in **Figure 14** and **Figure 15.**

Table 19. Initial and adjusted statistics for the flow-frequency curves Upstream of Grand Forks

	Mean Log	Standard Deviation		Skew		
		Initial	Adopted	Initial	Adopted	MSE
Drayton	4.400	0.327	0.320	-0.511	-0.292	0.094
Emerson	4.431	0.314	0.315	-0.530	-0.291	0.094
Oslo[1]	4.365	0.331	0.325	-0.300	-0.292	0.097

1 The statistics at this station were adjusted based on a two station comparison

The values for station skew at Emerson and Drayton are not used to develop the function used to smooth skew. The station skew values computed from observed data at Emerson and Drayton deviate significantly from the observed trend produced by skew values in the rest of the basin. This can be seen in **Figure 15**.

The adjusted statistics listed in **Table 19** are used to develop the adopted flow-frequency curves at Oslo, Emerson and Drayton. The flow frequency values at these locations can be found in **Table 20**. The corresponding family of curves can be found in **Figure 16**.

Table 20 Adopted Flow-Frequency Curves Downstream of Grand Forks- WET Analysis (1942-2009)

Red River of the North Mainstem Flow-Frequency Analysis WET Analysis (1942-2009)			
Exceedance Frequency in %	Mainstem Locations		
	USGS Gage Site 05083500 at Oslo, MN (cfs)	USGS Gage Site 05092000 at Drayton (cfs)	USGS Gage Site 05102500 at Emerson (cfs)
0.2	153,811	161,486	169,000
0.5	129,950	136,789	143,483
1	112,569	118,757	124,815
2	95,773	101,292	106,697
5	74,459	79,061	83,572
10	58,970	62,847	66,650
20	43,920	47,027	50,081
50	24,056	26,009	27,937
80	12,513	13,674	14,827
90	8,706	9,571	10,434
95	6,381	7,051	7,722
99	3,466	3,869	4,276

3. Balanced Hydrographs: Grand Forks to Drayton

3.1 Grand Forks to Oslo

As can be seen in **Figure 17**, there is one major tributary to the Red River of the North between Grand Forks and Oslo: the Turtle River. Balanced hydrographs are required for upstream of the Turtle River's confluence with the Red River of the North, at the mouth of the Turtle River and at Oslo (which is also assumed to be representative of conditions just downstream of the Turtle River).

3.1.1 Volume Duration Analysis

Developing volume duration curves is the first step in developing balanced hydrographs. A mean daily flow record is required to carry out volume duration analysis. The USGS gage at Oslo only records mean daily flow data during flood events. Because a continuous flow record does not exist for Oslo, the volume duration curve at Oslo has to be developed indirectly.

Volume duration curves at Grand Forks are used to determine the proportional change in volume between the 1-day volume duration curve and the curves corresponding to other durations of interest. The 1-day volume duration curve is equivalent to the adopted flow-frequency curve at a location. The relationship developed at Grand Forks can be applied to the adopted flow-frequency curve at Oslo in order to develop volume duration curves for Oslo.

Because there is no gaged record just upstream of the Turtle River's confluence with the Red River, the flow-frequency curve at the mouth of the Turtle River is found using interpolation. A drainage area ratio raised to an exponent "n" is used to interpolate between the known flow-frequency curves at Oslo and Grand Forks. The "n" values used for this analysis can be found in **Table 21**. The drainage areas used in this analysis are based on the contributing areas found in the Red River FIS study and on the USGS website. The flow-frequency curve representative of conditions upstream of the Turtle River's confluence with the Red River can be found in **Table 21**.

A volume duration curve cannot be developed directly for upstream of the mouth of the Turtle River. Instead, the volume duration curve at Grand Forks is used to determine the proportional change in volume between the 1-day duration (the flow-frequency values) and the other durations. In this way a volume duration relationship is developed for upstream of the mouth of the Turtle River based on the adopted flow-frequency curve at that location.

Table 21. Interpolation Table to find flow-frequency values at ungaged locations – WET Analysis (1942-2009)

Red River of the North Mainstem Flow-Frequency Analysis WET Analysis (1942-2009)									
Flow-Frequency Values (cfs)									
LOCATION	**DA (sq mi)**	**2-YR**	**5-YR**	**10-YR**	**20-YR**	**50-YR**	**100-YR**	**200-YR**	**500-YR**
USGS Gage Site 05083500 at Oslo, MN	21,105	24,056	43,920	58,970	74,459	95,773	112,569	129,950	153,811
n		0.61	0.78	0.86	0.91	0.96	0.99	1.01	1.02
D/S Turtle River, MN	21,105	24,056	43,920	58,970	74,459	95,773	112,569	129,950	153,811
Mouth of the Turtle River-Coincident Flows	635	547	1,282	1,885	2,524	3,422	4,132	4,867	5,868
U/S Turtle River, MN	20,319	23,509	42,638	57,086	71,935	92,351	108,437	125,083	147,943
USGS Gage Site 05082500 at Grand Forks, ND	20,015	23,295	42,139	56,354	70,956	91,026	106,838	123,201	145,675

3.1.2 Balanced Hydrographs

3.1.2.1 Explicit Derivation of Balanced Hydrographs

Balanced hydrographs are developed at Oslo and just upstream of the mouth of the Turtle River by using HEC-1. To utilize HEC-1, a pattern hydrograph must be identified. The 2006 spring flood event is utilized as the pattern event for this study. The same pattern hydrograph is used for Oslo as for the location just upstream of the mouth of the Turtle River. This assumption can be made because the Turtle River has a relatively small drainage area. As a result of having a small drainage area, the amount of flow entering the Red River from the Turtle River will have little effect on the shape and timing of the hydrograph on the mainstem of the Red River of the North.

No observed daily discharge data is available at the USGS gage located on the Red River of the North at Oslo for the 2006 spring event. USGS mean daily stage data is available for the 2006 spring flood event at Oslo. The National Weather Service (NWS) provided a rating curve relating stage and flow at Oslo, as well as a flow record generated at Oslo using a model. The resources provided by the NWS, USGS mean daily stage data and the adopted USGS annual instantaneous peak flow for 2006 at Oslo can be used to develop a 2006 pattern event hydrograph at Oslo.

The discharge hydrograph produced by the NWS model appears to be a bit flashy. The discharge hydrograph based on the rating curve appears more realistic. A comparison of both hydrographs can be found in **Figure 18** and **Figure 19**. For this reach, the rating curve based discharge data set was utilized as the 2006 pattern event.

By using the 2006 pattern hydrograph, the volume duration relationships and the HEC-1 Software package, balanced hydrographs can be generated for Oslo and just upstream of the mouth of the Turtle River.

3.1.2.2 Implicit Derivation of Balanced Hydrographs

There are only two USGS gages on the Turtle River: one located at Turtle River State Park near Arvilla, ND and one located downstream at Manvel, ND. Neither gage is continuous for the WET portion of the period of record. The instantaneous annual peak flow records at Arvilla and Manvel extend from 1993 to 2009 and 1946 to1982, respectively. Data based flow-frequency curves cannot be generated along the Turtle River. The flow-frequency relationship and corresponding balanced hydrographs at the mouth of the Turtle River have to be developed implicitly. This is done by subtracting the balanced hydrographs developed for the point upstream of the Turtle River from the balanced hydrographs developed at Oslo to produce the balanced hydrographs for the mouth of the Turtle River. A flow-frequency curve can be developed for the mouth of the Turtle River by identifying the peaks of the resulting balanced hydrographs and can be found in **Table 21**.

3.2 Flow Frequency Curves between Oslo and Drayton

There are three significant tributaries that flow into the Red River between Oslo and Drayton: the Forest River, the Snake River and the Park River. The Tamarac River also reaches its confluence the Red River, but due to its relatively small contributing area, a detailed flow analysis is not necessary for the Tamarac River. A schematic describing this portion of the Red River can be found in **Figure 17**. USGS gage data available for the Red River tributaries between Oslo and Drayton is displayed in **Figure 20**. Coincident flow frequency curves are developed for the WET portion of the period of record (1942-2009) at the mouth of each these tributaries as well as for just upstream and downstream of the confluence of the tributaries with the Red River of the North. The adopted flow-frequency curves for these locations are displayed in **Table 22**. Coincident timing is selected based on the the *1988 USACE Timing Analysis*.

Table 22. Adopted Flow-Frequency Curves between Oslo and Drayton- WET Analysis (1942-2009)

Red River of the North Mainstem Flow-Frequency Analysis WET Analysis (1942-2009)									
	Flow-Frequency Values (cfs)								
Location	**DA (sq mi)**	**2-YR**	**5-YR**	**10-YR**	**20-YR**	**50-YR**	**100-YR**	**200-YR**	**500-YR**
USGS Gage Site 05092000 at Drayton	24,670	26,009	47,027	62,847	79,061	101,292	118,757	136,789	161,486
n		1.13	-0.37	-1.20	-1.87	-2.22	-2.28	-2.10	-1.87
D/S Park River, ND	24,100	25,329	47,441	64,630	82,603	10,6697	125,252	143,672	168,702
Park River Coincidental Flows	1,010	550	1,700	2,800	4,300	6,000	7,000	7,500	8000
U/S Park River, ND	23,090	24,779	45,741	61,830	78,303	100,697	118,252	136,172	160,702
D/S Snake River, MN	23,060	24,743	45,763	61,927	78,494	100,989	118,602	136,545	161,094
Snake River Coincidental Flows	950	342	1,174	2,004	2,921	3,912	4,592	5,084	5,694
U/S Snake River, MN	22,110	24,400	44,589	59,923	75,573	97,077	114,010	131,460	155,399
D/S Forest River, ND	22,080	24,363	44,611	60,020	75,765	97,370	114,363	131,836	155,794
Forest River Coincidental Flows	900	210	750	1,300	1,800	2,350	2,700	2,850	3,000
U/S Forrest River, ND	21,180	24,153	43,861	58,720	73,965	95,020	111,663	128,986	152,794
USGS Gage Site 05083500 at Oslo, MN	21,105	24,056	43,920	58,970	74,459	95,773	112,569	129,950	153,811

3.2.1 Forest River Tributary

Coincidental peak flows from the Forest River tributary for corresponding peak flows on the Red River of the North at Oslo are derived from combining the USGS mean daily flow records at USGS gages 05084500 and 0508500 located on the Forest River at Minto, ND. It is assumed that the coincident flows at Minto occurred on the same day as the instantaneous peak at Oslo. This assumption is based on the results of the *Timing Analysis* developed for the Red River Basin by the Corps of Engineers in 1988. **Table 23** lists the coincident flow data series.

Table 23. Forest River at Minto, Coincidental Flow Record, WET Analysis (1942-2009)

Water Year	Coincidental Flows (cfs)[1]	Water Year	Coincidental Flows (cfs)[1]
1942	1,200	1988	200
1943	85	1989	35
1945	214	1990	23
1947	33	1991	12
1948	1,400	1992	150
1949	1,680	1993	199
1950	4,290	1994	60
1951	127	1995	420
1952	48	1996	800
1953	20	1997	1,310
1954	55	1998	31
1955	161	1999	443
1956	769	2000	35
1957	10	2001	413
1958	18	2002	65
1959	260	2003	54
1960	733	2004	1,890
1966	680	2005	188
1969	454	2006	803
1978	551	2007	284
1985	35	2008	65
1986	190	2009	506
1987	650		

[1]Data Based on USGS mean daily flow record

The flow-frequency curve for the WET portion (1942-2009) of the period of record at Minto is developed using the observed coincidental flows at Minto. A graphical curve can be fit to the coincident peak flow data, plotted using the Weibull plotting position. The graphical curve can be found in **Figure 21**.

The frequency curve determined at Minto is assumed to be equivalent to the flow-frequency curve at the mouth of the Forest River. This assumption can be made because Ardoch Dam is located downstream of the Minto gage. Ardoch dam was constructed in 1938. The dam is owned by the Department of the Interior: U.S Fish and Wildlife Service. The dam consists of an earthen structure with a length of 2,500 feet and a maximum discharge of 10,380 cfs. Its storage capacity is 13,630 acre-feet. Normal storage for this dam is 3,939 acre-feet. The dam has a drainage area of approximately 793 square miles. The regulatory effects of Ardoch Dam are assumed to effectively cancel out any added flow that might enter the Forest River between Minto and its confluence with the Red River. The adopted flow-frequency curve at the mouth of the Forest River can be found in **Table 22**.

3.2.2 Snake River

Coincidental peak flows from the Snake River tributary for corresponding peak flows on the Red River of the North at Oslo are derived from the USGS mean daily flow record at the Argyle gage on the Middle River. The USGS gage at Argyle only started recording flows in 1951. The portion of the WET period of record from 1942-1950 is unknown for the Snake River. The Middle River is a tributary of the Snake River. As is displayed in **Figure 20** there are two USGS gages on the mainstem of the Snake River: Alvarado, MN and Warren, MN. Neither gage has a significant period of record.

It is assumed that the coincident flows at Argyle occur one day later then the instantaneous peaks at Oslo. This assumption is based on the results of the *Timing Analysis* developed for the Red River Basin by the Corps of Engineers in 1988. **Table 24** contains the coincident flow data series.

Table 24. Middle River (Snake River Trib.) at Argyle, Coincidental Flow Record- Wet Analysis (1942-2009), USGS gage at Argyle POR: 1951-2009

Water Year	Coincidental Flows (cfs)[1]	Water Year	Coincidental Flows (cfs)[1]
1951	694	1991	74
1952	96	1992	90
1953	5	1993	213
1954	106	1994	72
1955	180	1995	458
1956	716	1996	1,400
1957	224	1997	1,650
1958	542	1998	203
1959	490	1999	1,600
1960	546	2000	175
1966	1,570	2001	748
1969	530	2002	120
1978	950	2003	21
1985	87	2004	562
1986	559	2005	432
1987	400	2006	1,700
1988	261	2007	285
1989	300	2008	83
1990	29	2009	420

[1]Data Based on USGS mean daily flow record

The flow-frequency curve for the WET portion (1942-2009) of the period of record at Argyle is developed using the observed coincidental flows at Argyle. A graphical curve can be fit to the coincident peak flow data, plotted using the Weibull plotting position. The graphical curve can be found in **Figure 22**.

The frequency curve at Argyle must be transferred to the confluence of the Snake River with the Red River. This is done using general relations methodology as described in **Table 25**. This technique uses a drainage area ratio relating the drainage area at Argyle to the drainage area associated with the confluence of the Snake River with the Red River. This drainage area ratio is raised to an exponent based on the relationship between analytically based Annual Instantaneous Flow-Frequency curves for the Minto and Argyle gages. HEC-SSP is used to develop the analytical flow frequency curves at Minto and Argyle, using weighted skew. Regional skew values are acquired from the USGS Generalized skew Coefficient Report published in 1997.

Table 25. Flow Frequency Curve Transferred to the Mouth of the Snake River

Freq	Argyle Peak Q (POR) cfs	Minto Peak Q (POR) cfs	Log(Flow Ratio)/ Log(DA Ratio)	Coin @ Argyle (wet)	Argyle coin @ mouth (wet)
0.2	8,067	21,996	1.13	1,850	8,166
0.5	6,920	16,514	0.98	1,800	6,524
1	6,027	12,958	0.86	1,750	5,434
2	5,119	9,881	0.74	1,700	4,499
5	3,907	6,498	0.57	1,600	3,397
10	2,992	4,422	0.44	1,300	2,317
20	2,091	2,730	0.30	900	1,336
50	939	1,033	0.11	320	368
Snake R	**Argyle**	**Minto**			
DA	Gage DA	Gage DA			
sq. mi.	sq. mi.	sq. mi.			
950	255	620			
Regional Skew:	-0.481	-0.413			

The flow-frequency curve at Argyle must be adjusted significantly in order to transfer the curve to the mouth of the Snake River. It is necessary to further adjust the resulting curve in order to ensure that the adopted flow-frequency curve for the mouth of the Snake River reflects a similar pattern as the other coincidental flow frequency curves developed for the reach of the Red River between Oslo and Drayton. The coincidental flow frequency curves at the mouths of the Forest and the Park Rivers are used to carry out this analysis. A relationship can be developed between flow and drainage area at significant exceedance probabilities for the pertinent coincidental flow-frequency curves. The resulting relationships between exceedance probability, drainage area and discharge are displayed in **Figure 23**. These relationships are used to determine the adopted flow-frequency curve at the mouth of the Snake River. The adopted flow-frequency for the mouth of the Snake River can be found in **Table 22**.

3.2.3 Park River

Coincidental peak flows from the Park River tributary for corresponding peak flows on the Red River of the North at Drayton are derived from the USGS mean daily flow record at the Grafton gage. It is assumed that the coincident flows at Grafton occur three days prior to the instantaneous peak at Drayton. This assumption is based on the results of the *Timing Analysis* developed for the Red River Basin by the Corps of Engineers in 1988. The Grafton gage is located on the Park River, just upstream of its confluence with the Red River.
Table 26 lists the coincident flow data series.

Table 26. Park River @ Grafton, Coincidental Flow Record- WET Analysis (1942-2009)

Water Year	Coincidental Flow (cfs)[1]	Water Year	Coincidental Flow (cfs)[1]
1942	21,900	1976	27,600
1943	28,700	1977	3,400
1944	12,300	1978	56,200
1945	24,600	1979	92,900
1946	23,000	1980	22,400
1947	29,300	1981	7,520
1948	57,000	1982	35,500
1949	27,900	1983	21,300
1950	86,500	1984	32,400
1951	24,600	1985	17,700
1952	23,900	1986	29,700
1953	14,700	1987	27,600
1954	11,100	1988	13,900
1955	18,000	1989	41,800
1956	28,000	1990	5,080
1957	14,100	1991	4,940
1958	7,850	1992	8,800
1959	11,200	1993	27,600
1960	24,700	1994	27,900
1961	3,600	1995	37,800
1962	32,300	1996	61,300
1963	12,900	1997	124,000
1964	15,600	1998	28,400
1965	47,200	1999	59,500
1966	67,500	2000	29,300
1967	32,200	2001	55,300
1968	12,500	2002	34,800
1969	59,000	2003	15,300
1970	31,700	2004	37,400
1971	23,400	2005	31,200
1972	31,100	2006	78,800
1973	13,400	2007	30,400
1974	43,900	2008	18,600
1975	44,000	2009	85,500

[1]Data Based on USGS mean daily flow record

The flow-frequency curve for the WET portion (1942-2009) of the period of record at Grafton can be developed using the observed coincidental flows at Grafton. A graphical curve is fit to the coincident peak flow data, plotted using the Weibull plotting position. The graphical curve can be found in **Figure 24**. Because Grafton is located close to the mouth of the Park River, it is unnecessary to use general relations to transfer the Grafton flow-frequency curve to the mouth of the Park River. The graphical curve at Grafton is directly adopted as the coincidental flow frequency curve at the mouth of the Park River as displayed in **Table 22**.

3.2.4 Upstream and Downstream Flow-Frequency Analysis

It was necessary to develop flow-frequency curves for points of interest upstream and downstream of the tributaries along the reach between Oslo and Drayton. Flow-frequency analysis at these ungaged locations is developed using drainage area based interpolation between adopted discharge-frequencies at Oslo, Drayton, and the adopted coincidental flow-frequency curves developed at the mouths of the Forest River, Snake River, and Park River. Interpolation is carried out using a drainage area ratio and raised to an exponent 'n' as shown in **Table 22**.

The summation of the inflows coming off the tributaries in conjunction with the flows at Oslo, exceed the downstream flows at Drayton. This implies that flow is being attenuated throughout the reach between Oslo and Drayton. A comparison made between the annual instantaneous peak flow records at Oslo and Drayton indicated that for 34% of the period of record, annual instantaneous peak flows at Oslo exceeded the peak flows at Drayton. This confirms that attenuation occurs between Oslo and Drayton. This is reflected within the adopted flow-frequency curves found in **Table 22**.

3.2.5 Balanced Hydrographs between Oslo and Drayton

3.2.5.1 Pattern Event Hydrograph

The 2006 spring flood event is being utilized as the pattern event for the Fargo-Moorhead Metro Feasibility Study. In order to develop pattern hydrographs for ungaged locations along the Red River reach between Oslo and Drayton, the Hydraulic Engineering Center's Hydrologic Modeling Software package (HEC-HMS) is utilized to route the 2006 Spring Flood Event hydrograph downstream from Oslo to Drayton.

Daily flow values were not continuously recorded for the 2006 event at Oslo. As a result, a hydrograph must be generated at Oslo for the 2006 event. Initially a rating curved provided by the National Weather Service (NWS) was utilized to convert stage values to a mean daily discharge record (this was the methodology used for the reach between Grand Forks and Oslo). Calibration runs in HEC-HMS indicate that the modeled flows that the NWS had also provided produce a better result than the flow record generated using the rating curve. NWS modeled discharges at Oslo for the 2006 event are adopted and routed downstream.

The reach between Oslo and Drayton is broken up into subreaches as described in **Table 27**.

With the exception of two subreaches, straddle stagger routing can be utilized to route the 2006 event at Oslo downstream to Drayton. For the subreaches between the mouth of the Park River and the Snake River and between the Park River and the Tamarac River, a direct lag should be used to route flows. Routing parameters are based on the *USACE 1988 Timing Analysis*. Adopted parameters are displayed in **Table 27**.

Table 27. Routing parameters Oslo to Drayton

HMS Routing Oslo to Emerson				
	Based on Timing Study			
Subreaches	Average (Day)	(min)	Lag (day)	(min)
Oslo to Forest R	5	6000	1.333	1920
Minto to Mouth of Forest R	2	2560	0.500	720
Forest R to Snake R	3	4000	0.556	800
Argyle to Mouth of Snake R	3	4000	0.889	1280
Snake R to Park R	Lag Only		0.333	480
Grafton to Mouth of Park R	2	3200	0.889	1280
Park R to Tamarac R	Lag Only		0.444	640
Tamarac R to Drayton	6	8000	1.111	1600

Routing requires that local inflows be assigned to the subreaches between Oslo and Drayton. Local flows are determined using a drainage area ratio and 2006 observed flows associated with hydrologically similar gaged locations. **Table 28** displays the hydrologically similar references gages, along with the drainage area ratios that can be used to develop the local flows associated with the subreaches between Oslo and Drayton.

Table 28. Local Flow Parameters

Local Area	Reference Gage	DA Ratio
Oslo to US Forest R	Minto (Forest R)	0.12
Minto to Conf Forest R w/ RRN	Minto (Forest R)	0.45
DS Forest R to US Snake R	Minto (Forest R)	0.048
Argyle to Conf Snake R w/ RRN	Argyle (Middle R)	1.32
DS Snake R to US Park R	*Assume Local Flow Negligible*	
Grafton to Conf Park R w/ RRN	Grafton (Park R)	0.45
DS Park R to US Tamarac R	*Assume Local Flow Negligible*	
US Tamarac R to Drayton	Grafton (Park R)	0.82

3.2.5.2 Volume Duration Analysis

To develop balanced hydrographs for ungaged points of interest upstream and downstream of the tributaries along the mainstem of the Red River between Oslo and Drayton, it is necessary to develop volume duration curves at these locations. Volume duration curves cannot be generated directly because no mean daily flow record exists at ungaged sites. To develop these curves, a volume duration curve generated for the gaged location at Drayton is used to determine the proportional change in volume between the 1-day duration (flow frequency values) and the other durations of interest. This proportional change in volume is applied to the adopted flow-frequency curves at the ungaged locations in order to generate the volume duration curves.

Volume duration curves also must be developed at the confluences of the tributaries with the Red River. Because volume duration curves cannot be directly developed for coincidental flows, the volume duration curves at these locations are generated by using volume duration curves generated from gaged locations along the tributaries. The volume duration curves at these gaged locations are used to determine the proportional change in volume between the 1-day duration and other durations of interest. This proportional change in volume is then applied to the adopted flow-frequency curves for the mouths of the tributaries in order to generate the volume duration curves.

The points of interest along the Red River reach between Oslo and Drayton, along with the hydraulically similar site used to generate the volume duration curves, are listed in **Table 29**.

Table 29. Volume Duration Curves for ungaged locations

Location	River	Volume Type	Hydrologically Similar Location used for generating Flood Volume Frequency Curve or alternate method used to obtain Balanced hydrograph
Oslo	Red River	Main Stem	Grand Forks
Red River US of Forest River	Red River	Main Stem	Drayton
Forest River at Mouth	Red River	Coincidental	Minto
Red River DS of Forest River	Red River	Main Stem	Drayton
Red River US of Snake River	Red River	Main Stem	Drayton
Snake River at Mouth	Red River	Coincidental	Argyle
Red River DS of Snake River	Red River	Main Stem	Drayton
Red River US of Park River	Red River	Main Stem	Drayton
Park River at Mouth	Red River	Coincidental	Grafton
Red River DS of Park River	Red River	Main Stem	Drayton

3.2.5.3 Balanced Hydrographs

The Hydrologic Engineering Center's Flood Hydrograph Package, HEC-1, is used to construct balanced hydrographs using specified 1, 3, 7, 15 and 30-day volumes and a pattern event. Balanced hydrographs are developed at the locations identified in **Table 29** using HEC-1. Flood volume duration analysis provides for the volume at each duration and specified frequency. For the Fargo-Moorhead Metro Feasibility Study the 2006 Spring Flood Event has been adopted as the pattern event.

4. Analysis between Drayton and Emerson

The reach between Emerson and Drayton includes two significant tributaries: the Pembina River and Two Rivers. A schematic of this reach of the Red River can be found in **Figure 25.**

4.1 Red River of the North-Mainstem

4.1.1 Available Data & Hydrologic Properties

According to the USGS, the reach of the Red River of the North between Drayton and Emerson lies in a glacial lakebed. Consequently, the floodplain is relatively flat (less than 0.5- foot drop in elevation per mile). Because of the flat floodplain, shallow river channel, and the river's northerly flow, the timing of spring snowmelt greatly facilitates flooding in this part of basin. Since flows tend to breakout into the floodplains during flood events, significant attenuation of channel flow occurs between Drayton and Emerson. These overland breakouts are evident in the photograph from the 1979 flood event displayed in **Figure 26**.

4.1.2 2006 Event Hydrograph Routing

The USGS recorded 2006 spring flood hydrograph is routed from Drayton to Emerson in order to develop pattern hydrographs at ungaged locations of interest along this reach of the Red River.

As can be seen in **Table 30,** the 2006 event peak flow decreased 7% between Drayton and Emerson. Adopted routing parameters are based on the *U.S Army Corps of Engineers 1988 Timing Study*. The 1948, 1969, 1975 (spring) and 1978 flood events can be used to develop Straddle Stagger routing parameters for the reach. These events are significant because attenuation in the peak between Drayton and Emerson was observed for these years. The peak flow values associated with these locations are recorded in **Table 30.**

Table 30. Comparison between flows at Drayton and Emerson (USGS)

Water Year	Peak Flow at Drayton (cfs)	Peak Flow at Emerson (cfs)	% Total Change in Peak (cfs)
1948	57, 000	51, 800	- 9
1950	86, 000	95, 500	+ 11
1965	47, 200	46, 200	-2
1966	67, 500	66, 800	-1
1969	59, 000	54, 700	-7
1975 (Spring)	44, 000	42, 800	-3
1978	56, 200	50, 600	-9
1979	92, 900	92, 700	0
2006	78, 800	73, 500	-7

The routing parameters associated with each of these four events are modeled using the observed flows at Drayton and the routed flows associated with Two Rivers and the Pembina River. The resulting flows at Emerson are compared to the actual observed flows at Emerson for the 2006 event. The routing parameters associated with the 1975 (spring) event, as displayed in **Table 30**, most closely reproduced the 2006 flood event at Emerson as can be seen in **Table 31.**

Table 31. Straddle Stagger Routing Parameters: Drayton to Emerson

Reach	Average	Lag
Drayton to Two Rivers	12	2
Two Rivers to Emerson/ Pembina River	10	1

DSS-VUE has to be used to carry out straddle stagger routing. The hydrographs have to be averaged (straddle) and lagged (stagger) in two steps in order to preserve the correct timing. The resulting hydrograph at Emerson compared to the hydrograph based on observed flow at Emerson is displayed in **Figure 27**. No local flow is added in because it is assumed that local flow ran off before the peak arrived on the Red River of the North.

4.2 Two Rivers

4.2.1 Available Data & Hydrologic Properties

As can be seen in **Figure 28**, the Two Rivers tributary is made up of three branches: the North Branch, Middle Branch and South Branch.

There are four USGS daily stream flow gages located within the Two Rivers watershed. There is one USGS observed streamflow measurement near the confluence of the Two Rivers with the Red River of the North. Available USGS gage data can be found in **Table 32** and their corresponding geographical locations can be found in **Figure 28**.

Table 32. USGS gages Located within the Two Rivers Watershed

Gage Location	USGS Gage #	Period of Record
South Branch of the Two Rivers at Lake Bronson, MN	05094000	1928- Present
Two Rivers at Hallock, MN	05095000	1911-1943
Two Rivers below Hallock, MN	05095500	1945-1955
North Branch of the Two Rivers near Northcote, MN	05097500	1941- 1951

The two gages near Hallock are located close together on the same branch of the Two Rivers. The recorded flow records at these two locations can be combined in order to create a more complete streamflow record at Hallock. USGS gage 05097500 located near Northcote has a short period of record from 1941 to 1951. Because of its abbreviated flow record, the Northcote gage is not used in this study. The Two Rivers long term gaging station is located on the South Branch of the Two Rivers downstream of Lake Bronson, MN.

On Dec 12, 1991, the USGS took an observed streamflow measurement of 64.2 cfs near the confluence of the Two Rivers with the Red River. It can be assumed that backwater effects from the Red River of North did not effect this measurement. This measurement can be used in calibrating HMS routing of the 2006 event for use as a pattern event for developing balanced hydrographs.

A flow record can be developed for the WET portion of the period of record at Hallock (1942-2009) by developing a linear relationship for the concurrent portion of the period of record between the USGS gage at Lake Bronson and the USGS gage at Hallock. A relatively good correlation exists between the two gages as can be seen in **Figure 29**.

4.2.2 Coincidental Flow Frequency Analysis

Coincident timing is selected based on the *Timing Analysis* published in the Technical Resource Service of the Red River of the North.

Coincidental peak flows from the Two Rivers tributary for corresponding peak flows on the Red River of the North at Drayton, ND are derived from the USGS mean daily flow record at the Hallock gage. It is assumed that the coincident flow at Hallock occurred one day prior to the instantaneous peak at Drayton. The Hallock gage is located on the South Branch of the Two Rivers, upstream of its confluence with the Red River. **Table 33** lists the coincident flow data series.

Table 33. Two Rivers @ Hallock, WET (1942-2009) Coincidental Flow Record

Water Year	Coincidental Flow, cfs[1]	Water Year	Coincidental Flow, cfs[1]
1942	1,300	1976	248
1943	740	1977	115
1944	Missing	1978	1,460
1945	500	1979	1,697
1946	500	1980	572
1947	70	1981	117
1948	1,600	1982	0
1949	1,000	1983	0
1950	3,400	1984	0
1951	1,350	1985	128
1952	39	1986	845
1953	16	1987	709
1954	321	1988	233
1955	639	1989	1,573
1956	1,157	1990	61
1957	537	1991	2,169
1958	228	1992	200
1959	867	1993	2,349
1960	1,258	1994	132
1961	16	1995	403
1962	683	1996	3,294
1963	514	1997	2,619
1964	396	1998	164
1965	723	1999	3,553
1966	3,035	2000	194
1967	917	2001	1,483
1968	1,016	2002	944
1969	1,224	2003	35
1970	2,642	2004	1,088
1971	1,303	2005	500
1972	974	2006	2,045
1973	62	2007	314
1974	1,517	2008	99
1975	1,280	2009	1,005

[1]Source: USGS Mean Daily Flow Record

The flow-frequency curve for the WET portion (1942-2009) of the period of record at Hallock is developed using the observed coincidental flows at Hallock. A graphical curve is fit to the coincident peak flow data, plotted using the Weibull plotting position. The graphical curve can be found in **Figure 30**.

The coincidental flow-frequency curve at Hallock must be transferred to the confluence of the Two Rivers with the Red River. This is done using general relations methodology. This technique uses a drainage area ratio relating the drainage area at Hallock to the drainage area associated with the confluence of the Two Rivers with the Red River. The drainage area ratio is applied to the Hallock flow frequency curve in order to generate the projected coincident flows at the confluence of the Two Rivers and Red River of the North. **Table 34** contains the values used to transfer coincidental flows from Hallock to the confluence of the Two Rivers with the Red River for the WET flow-frequency curve.

Table 34. Flow Transfer from Hallock Gage- WET Analysis (1942-2009)

Exceedance Probability	Hallock Coincidental Discharge (cfs)	Drainage Area Ratio	Coincident Flows at Confluence (cfs)
0.002	3,550	1.968	6986
0.005	3,500	1.968	6888
0.01	3,450	1.968	6790
0.02	3,400	1.968	6691
0.05	2,950	1.968	5806
0.1	2,350	1.968	4625
0.2	1600	1.968	3149
0.5	550	1.968	1082
	Hallock		Mouth
Drainage Area (sq. mi)	625		1230

4.2.3 2006 Event Hydrograph Routing

The USGS recorded 2006 spring flood hydrograph is routed from Drayton to Emerson in order to develop pattern hydrographs at ungaged locations of interest along this reach of the Red River.

The flows associated with the North Branch of the Two Rivers, as well as the local runoff between Hallock and the mouth of the Two Rivers can be estimated using a drainage area ratio and the flow record at Grafton. The drainage area ratio utilized, as well as the drainage areas used to determine this ratio, can be found in **Table 35**.

Table 35. Drainage Areas used to Determine Local Flow

Area	Total D.A (sq. miles)	Source
Two Rivers Watershed	1,230	USACE 1988 Timing Analysis
Hallock	605	USGS
Local Flow D.A	625	Computed
Grafton (ref. flow record)	695	USGS
D.A Ratio	0.871	

Because Hallock is relatively close to the confluence of the Two Rivers with the Red River of the North, the flows at Hallock can be routed directly to the confluence. The flows at Hallock are combined with the local flow record. The local flow record is lagged one day to account for travel time. From these routed flows, a coincident flow record can be developed at the confluence of Two Rivers with the Red River of the North. This coincident flow record is used to develop a coincident flow-frequency curve at this location. The 2006 spring flood event can also be determined from the routed flow record.

Based on this methodology, a flow of 60.3 cfs is produced on Dec. 12, 1991. This is reasonably close to the recorded flow value of 64.2 cfs.

4.3 Pembina River

4.3.1 Available Data & Hydrologic Properties

The headwaters of the Pembina River are located in Manitoba, Canada. The Pembina River flows southeasterly and crosses into the United States about 15 miles northwest of Walhalla, North Dakota. The confluence of the Pembina River with the Red River of North is located near Pembina, North Dakota.

4.3.1.1 Hydrology & Geomorphology

The flow characteristics associated with the Pembina River during flood events can be attributed to the region's geomorphology. Near Wahalla, the river flows upon what was formerly Lake Agassiz lakebed. Between Wahalla and Neche the river valley disapears. Downstream of Neche the riverbed is perched, meaning that the riverbed is higher than the floodplains. The terrain between Wahalla and the mouth of the Pembina River is very flat which makes the area suseptible to flooding. The Tongue River enters the Pembina River a few miles upstream of the Pembina River's confluence with the Red Rver of the North.

4.3.1.2 Available Flow Data

As can be seen in **Figure 31**, the USGS has flow gages located on the Pembina River at Walhalla, ND (USGS Gage 05099600) and at Neche, ND (USGS Gage 05100000). Both the Wahalla and Neche gages have daily flow records for the period of record between 1942 and 2009.

4.3.1.3 Breakout Flows

Water Management Consultants' *Hydrodynamic Modeling of the Lower Pembina River Report,* published for the International Joint Commission (IJC), indicates that breakout flows occur on the Pembina River upstream and downstream of Neche.

The USGS record at Neche has sporatically been adjusted to include upstream breakout flows. The IJC report indicates that only minor breakout flows occur above Neche (~ 5% of the flow).

According to model reports generated for the IJC and antedotal reports provided by area residents, major breakouts occur downstream of Neche. This was confirmed by the North Dakota State Water Commission (NDSWC). The photograph taken during the spring flood event of 2009, displayed in **Figure 32**, illustrates the magnitude of these breakout flows.

According to the NDSWC, breakout flows ocurr on the Pembina River about one mile downstream of Neche, ND. These breakout flows were historically contained by agricultural dikes. The majority of these dikes have since been removed. Flows leave the Pembina River and breakout equally north and south of the river. The NDSWC stated that the flows that breakout from the Pembina River to the south enter the London Coulee and then enter a large innundated area south of the Pembina River. The flows that breakout to the north flow to the international border and follow the border dike eastward until they re-enter the Pembina River near Pembina, ND. According to the NDSWC the majority of these flows only re-enter the system after the Red River of the North had peaked.The IJC report includes the estimated magnitudes of breakout flows downstream of Neche for the 1996 and 1997 flood events. These magnitudes are visually displayed in **Figure 33** and **Figure 34**.

According to the U.S Army Corps of Engineer's Environmental Impact Statement for Flood Control for the Pembina River, bankfull flow for the Pembina River near Neche, ND is 3,500 cfs. By adopting 3,500 cfs as the bankfull condition for the Pembina River and by using the values provided for in the IJC report, a curve can be developed relating the observed flows at Neche, ND to downstream breakout flows as can be seen in **Figure 35**.

The relationship displayed in **Figure 35** can be applied to the observed flow record at Neche to accound for breakout flows. It is assumed that by the time the breakout flows re-enter the Red River of the North/ Pembina River system they would no longer affect the magnitude of the peak on the Red and thus it is not necessary to re-route the breakout into the Pembina or Red River.

4.3.1.4 Tongue River

There is a USGS gage located on the Tongue River at Akra, ND (USGS 05101000). The flow record at Akra includes missing data points and only extends back to 1950.

4.3.2 Coincidental Flow Frequency Analysis

Coincident timing is selected based on the *Timing Analysis* published in the Technical Resource Service of the Red River of the North.

Coincidental peak flows from the Pembina River tributary for corresponding peak flows on the Red River at Emerson, ND are derived from flows at the Walhalla gage upstream of the confluence of the Pembina River with the Red River. It is assumed that the coincident peak at Walhalla occurred three days prior to the instantaneous peak at Emerson. **Table 36** lists the coincident flow data series.

Table 36. Pembina River @Walhalla, Coincidental Flows- WET Analysis (1944-2009)

Water Year	Coincidental Flow, cfs[1]	Water Year	Coincidental Flow, cfs[1]
1944	2,890	1977	980
1945	386	1978	2,400
1946	320	1979	60
1947	1,560	1980	866
1948	911	1981	3,170
1949	379	1982	355
1950	2,180	1983	26
1951	3,740	1984	750
1952	4,040	1985	1,370
1953	721	1986	135
1954	221	1987	1,120
1955	199	1988	920
1956	120	1989	4,420
1957	2,400	1990	241
1958	5,080	1991	401
1959	55	1992	434
1960	16	1993	-
1961	800	1994	-
1962	1,600	1995	-
1963	200	1996	806
1964	1,880	1997	1,550
1965	170	1998	-
1966	175	1999	-
1967	565	2000	-
1968	1,190	2001	-
1969	550	2002	49
1970	39	2003	4,490
1971	6,370	2004	906
1972	4,120	2005	64
1973	7,160	2006	3,700
1974	1,780	2007	4,270
1975	155	2008	6,580
1976	5,540	2009	1,600

[1] Based on USGS Mean Daily Flow Record

The flow-frequency curve for the WET portion (1942-2009) of the flow record at Walhalla is developed using the observed coincident flows. A graphical curve is fit to the coincident peak flow data plotted using the Weibull plotting position. The graphical curve can be found in **Figure 36.**

The frequency curve at Walhalla has to be transferred to the confluence of the Pembina River with the Red River. This is done using general relations methodology. This technique uses a drainage area ratio relating the drainage area at Walhalla to the drainage area associated with the confluence of the Pembina River with the Red River. The drainage area ratio is applied to the Walhalla flow frequency curve in order to generate the projected coincident flows at the confluence of the Pembina River and Red River of the North. **Table 37** contains the values used to transfer coincidental flows from Walhalla to the confluence of the Pembina River with the Red River for the WET flow-frequency curve.

Table 37. Flow Transfer from Walhalla to the Confluence of the Pembina River with the Red.

% Chance Exceedance	Walhalla Peak Discharge (cfs)	Drainage Area Ratio	Coincident Flows at Confluence (cfs)
0.002	7,900	1.19	9427
0.005	7,800	1.19	9308
0.01	7,700	1.19	9189
0.02	7,400	1.19	8831
0.05	6,200	1.19	7399
0.1	4,800	1.19	5728
0.2	3050	1.19	3640
0.5	840	1.19	1002
	Walhalla		Mouth
Drainage Area (sq. mi)	3310		3950

4.3.3 2006 Event Hydrograph Routing

The USGS recorded 2006 spring flood hydrograph is routed from Drayton to Emerson in order to develop pattern hydrographs at ungaged locations of interest along this reach of the Red River.

Observed flows at Neche are routed through the breakout flow transform and then downstream using Straddle Stagger routing parameters. Parameters are based on the U.S Army Corps of Engineers *1988 Timing Analysis*. The daily flow record at Akra is routed to the mouth of the Pembina River using Straddle Stagger routing parameters based on the U.S Army Corps of Engineers 1988 *Timing Analysis*.

The flows associated with the Pembina River and Tongue River are combined and added to an estimate of the local area runoff associated with the drainage area between Neche and the mouth of the Pembina River (exculding the Tongue River drainage area). Local flow are determined using a drainage area ratio and the observed flow record at Neche. The drainage area ratio utilized, as well as the drainage areas used to determine this ratio, can be found in **Table 38**.

Table 38. Drainage Areas used to develop local flows for Pembina River

Local Area	Total D.A (sq. miles)	Source
Pembina River	3,950	Timing Analysis
Neche	3,410	USGS
Local Area Neche to Mouth (WO Tongue R)	380	Calculated
Akra (Tongue R)	160	USGS
Reference Gage	**Ratio**	
Neche	0.11	

The resulting flow record at the confluence of the Pembina River with the Red River of the North is used to develop a coincident annual peak flow record at the mouth of the Pembina River, as well as to develop the 2006 hydrograph at this location. The coincident peak flow record can be used to develop a coincidental peak flow-frequency curve representative of the confluence of the Pembina River with the Red River of the North.

4.4 BALANCED HYDROGRAPHS BETWEEN DRAYTON & EMERSON

The St. Paul District Corps of Engineers developed balanced hydrographs at all pertinent computation points located on the reach of the Red River of the North between Drayton, ND and Emerson, Manitoba, Canada in support of the unsteady RAS model. Hydrographs were generated for the 0.2-, 0.5-, 1-, 2-, and 10-percent exceedance frequency events for the WET portion of the period of record.

Coincidental balanced hydrographs are required for the confluences of the Two Rivers and Pembina River with the Red River of the North. Balanced hydrographs on the main stem of the Red River of the North are required upstream and downstream of each of the tributaries.

4.4.1. Volume Duration Analysis

In order to develop balanced hydrographs for ungaged points of interest upstream and downstream of the tributaries along the mainstem of the Red River between Drayton and Emerson, it is necessary to develop volume duration curves at these locations. Volume duration curves cannot be generated directly because no mean daily flow record exists at ungaged sites. In order to develop these curves, a volume duration curve generated for the gaged locations at Drayton and Emerson are used to determine the proportional change in volume between the 1-day duration (flow frequency values) and the other durations of interest. This proportional change in volume is applied to the adopted flow-frequency curves at the ungaged locations in order to generate the volume duration curves.

Volume duration curves also must be developed at the confluences of the tributaries with the Red River. Because volume duration curves cannot be directly developed for coincidental flows, the volume duration curves at these locations are generated by using volume duration curves generated from gaged locations along the tributaries. The volume duration curves at these gaged locations are used to determine the proportional change in volume between the 1-day duration and other durations of interest. This proportional change in volume is then applied to the adopted flow-frequency curves for the mouths of the tributaries in order to generate the volume duration curves.

The points of interest along the Red River reach between Drayton and Emerson, along with the hydraulically similar site used to generate the volume duration curves, are listed in **Table 39**.

Table 39. Reference Gages

Location	River	Volume Type	Hydrologically Similar Location used for generating Flood Volume Frequency Curve or alternate method used to obtain Balanced hydrograph
Drayton	Red River	Mainstem	Drayton
Red River US of Two Rivers	Red River	Main Stem	Drayton
Two Rivers at Mouth	Two Rivers	Coincidental	Hallock
Red River DS of Two Rivers	Red River	Main Stem	Drayton
Red River US of Pembina	Red River	Main Stem	Emerson
Pembina at Mouth	Pembina River	Coincidental	Walhalla
Emerson	Red River	Mainstem	Emerson

4.2 Balanced Hydrographs

The Hydrologic Engineering Center's Flood Hydrograph Package, HEC-1 is used to configure balanced hydrographs. To configure these balanced hydrographs, flood volume duration frequency analysis provides for the volume at each duration and specified frequency. HEC-1 also requires a pattern event. For the Fargo-Moorhead Metro Feasibility Study, the 2006 Spring Flood Event is the pattern event. The pattern event helps establish the shape and timing of the hydrograph.

5. References

1. " Ardoch, North Dakota," *FindLakes,* http://findlakes.com/ardoch_north-dakota~nd00337.htm, September 2010.
2. Bulletin 17B, "Guidelines for Determining Flood Flow Frequency Analysis", U.S Department of the Interior, Geological Survey, March 1982.
3. Connelly, Brian, Senior Hydrologic Forecaster, North Central River Forecast Center, National Weather Service, July 2010.
4. Fay, James T., Water Development, North Dakota State Water Commission, September 2010.
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6. HEC-HMS "Hydrologic Modeling System", U.S Army Corps of Engineers, Hydrologic Engineering Center, Version 2.2, September 1998.
7. HEC-SSP "Statistical Software Package", U.S Army Corps of Engineers, Hydrologic Engineering Center, Version 1.1, May 2009.
8. "Hydrologic Analyses for Flood Insurance Studies, The Red River of the North Main Stem, from Wahpeton/ Breckenridge to Emerson, Manitoba:, St. Paul District , Corps of Engineers, May 2000.
9. "Hydraulic Analysis in Grand Forks Vicinity," Appendix B, Office of Hydrologic Development, National Weather Service.
10. "International Joint Commission: Hydrodynamic Modeling of the Lower Pembina River," Water Management Consultants INC, March 2000.
11. Lorenz, D.L. "Generalized Skew Coefficients for Flood-Frequency Analysis in Minnesota," USGS Water Resources Investigations Report 97-4089, 1997.
12. "Phase I of the General Design Memorandum and Final Supplement to the Final Environmental Impact Statement for Flood Control," St. Paul District, US Army Corps of Engineers, September 1983.
13. "05069000 Sand Hill River at Climax, MN". Water Data Report 2009. USGS.
14. "05079000 Red Lake River at Crookston, MN". Water Data Report 2009. USGS.
15. "Technical Resource Service Red River of the North, Volume I: Timing Analysis," St. Paul District, US Army Corps of Engineers, March 1988.

FIGURES

Figure 1- Flow Chart for the Red River of the North between Halstad and Grand Forks

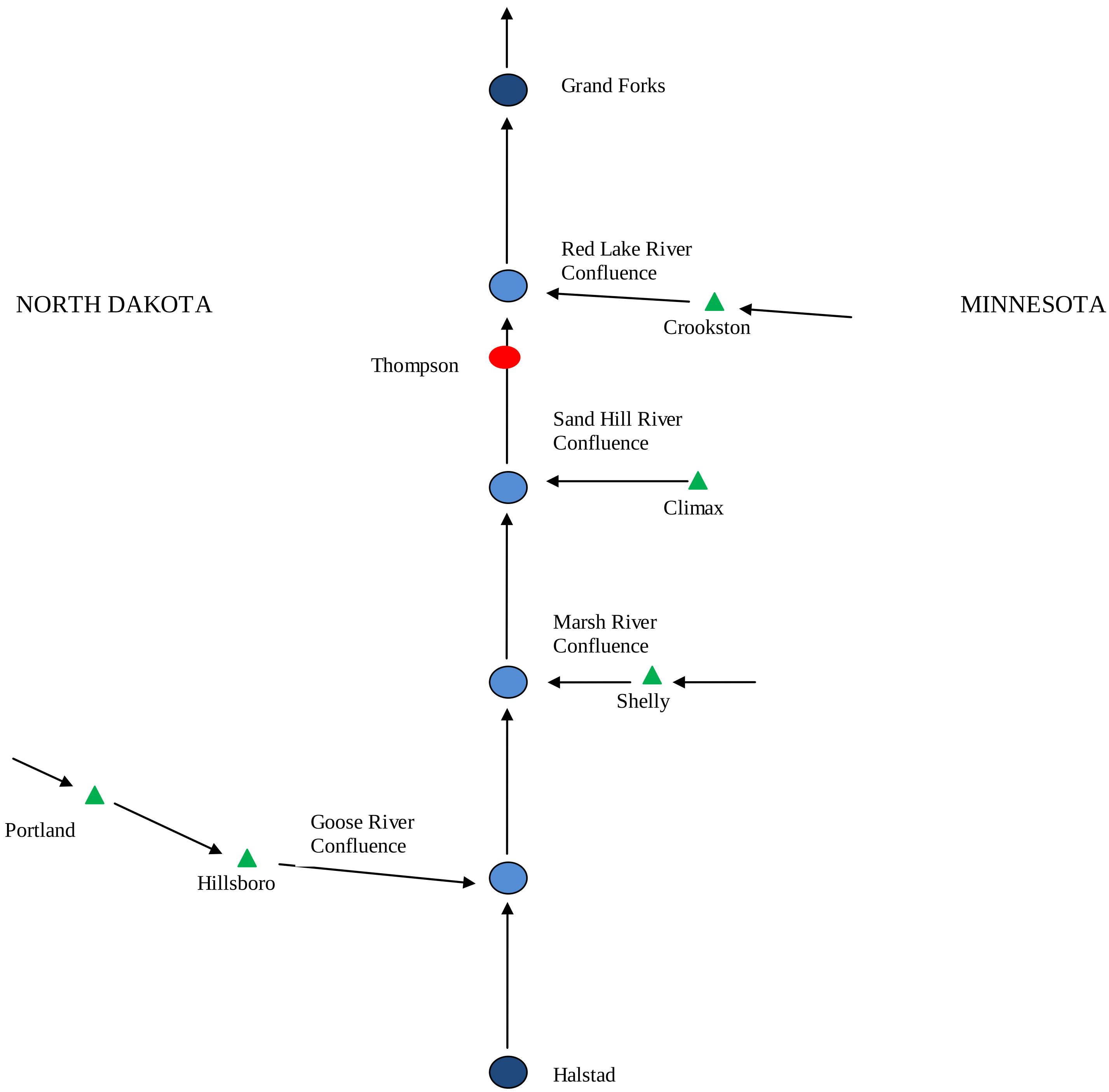
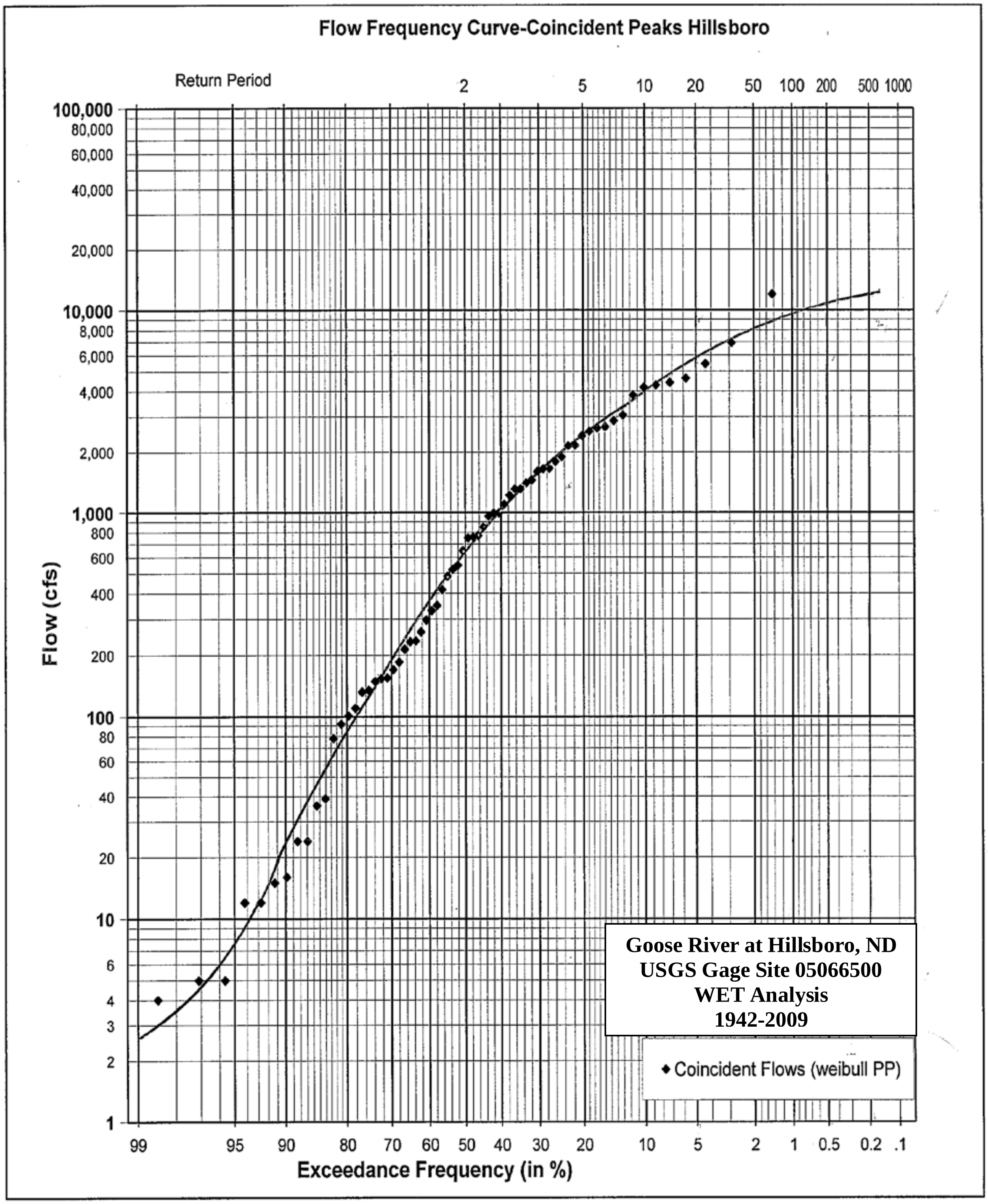
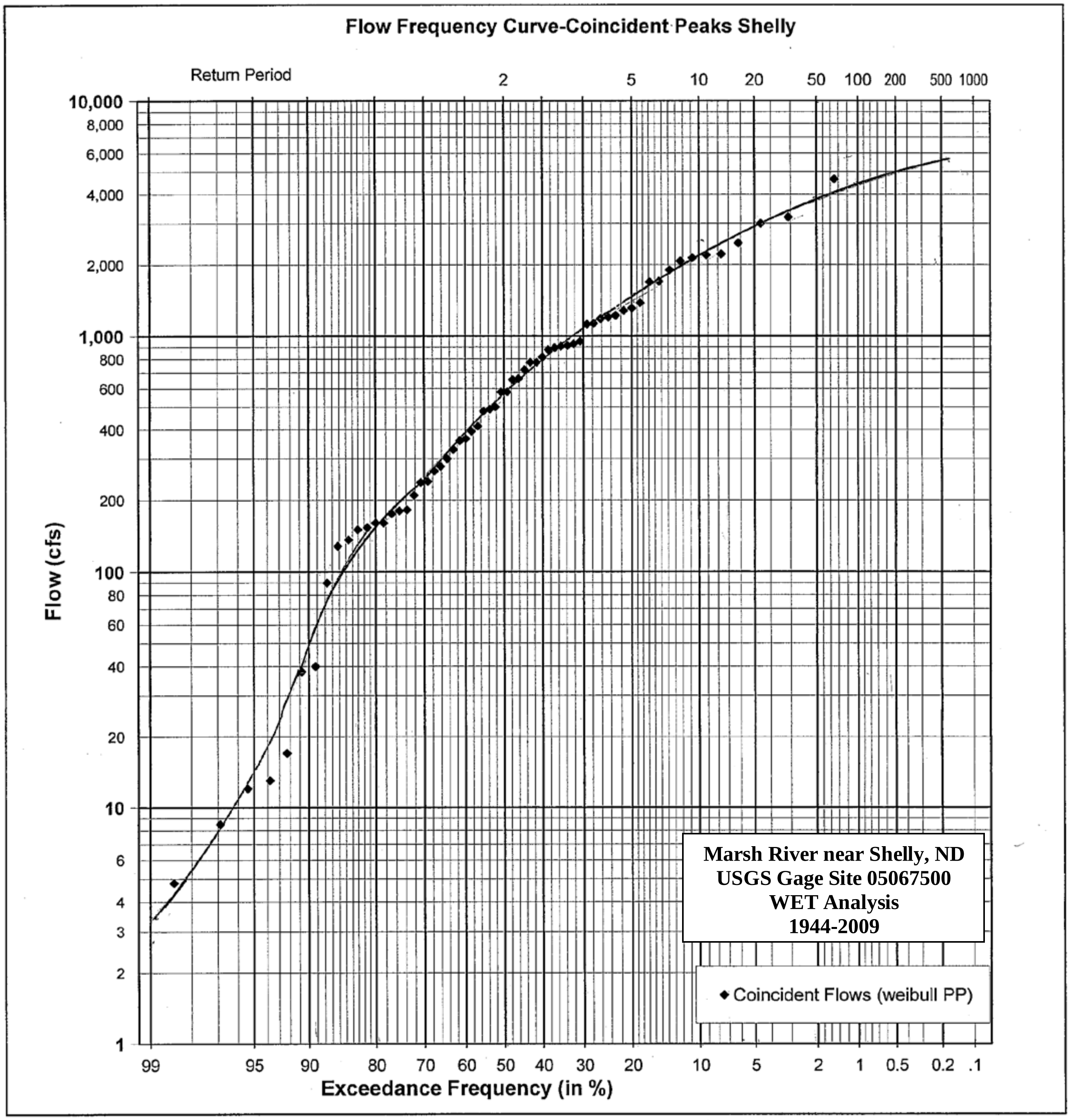


Figure 2- Graphical Coincident Flow-Frequency Curve at Hillsboro, ND



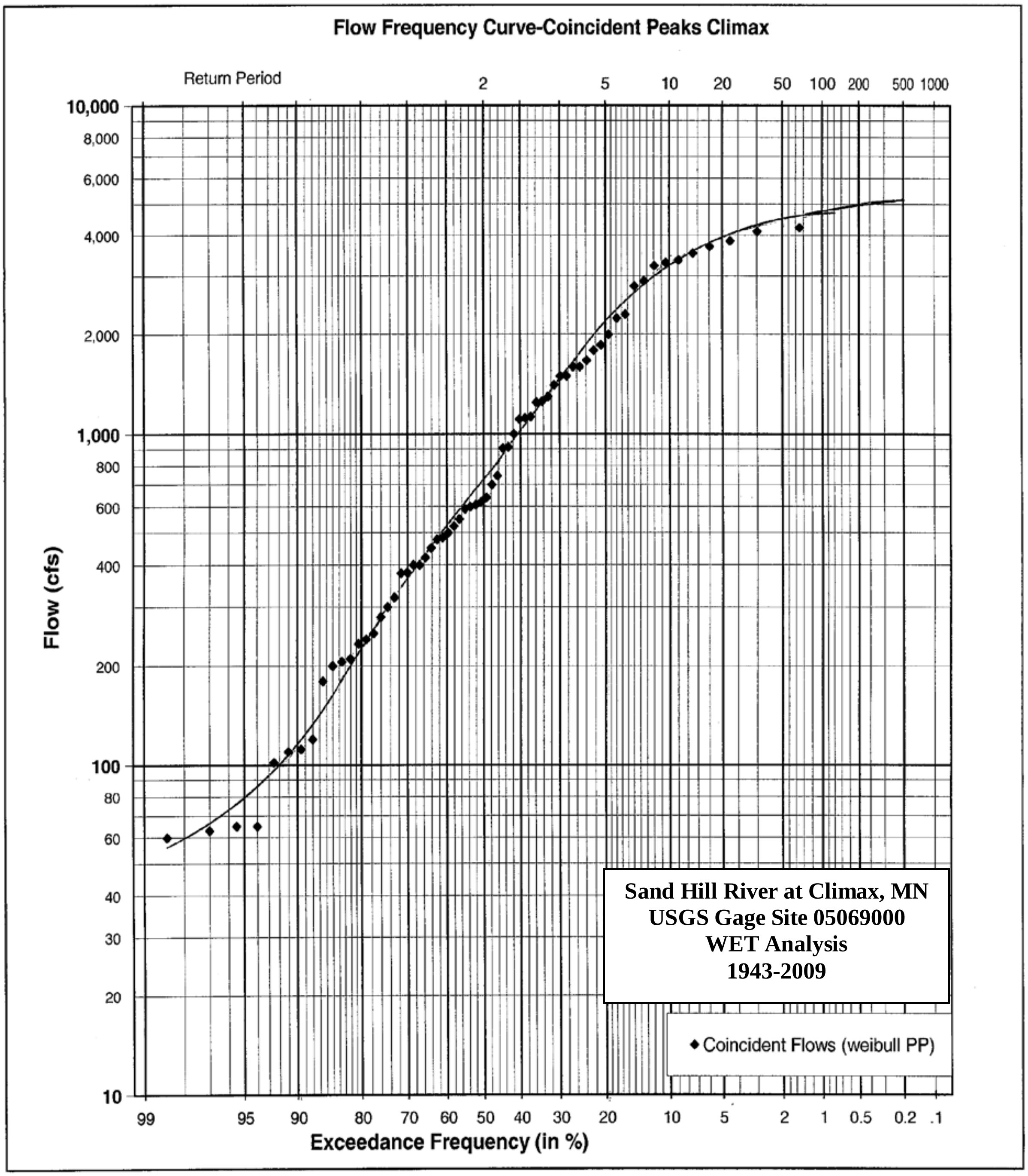
Pencil Line = Graphical Flow Frequency Curve

Figure 3- Graphical Coincident Flow-Frequency Curve at Shelly, MN



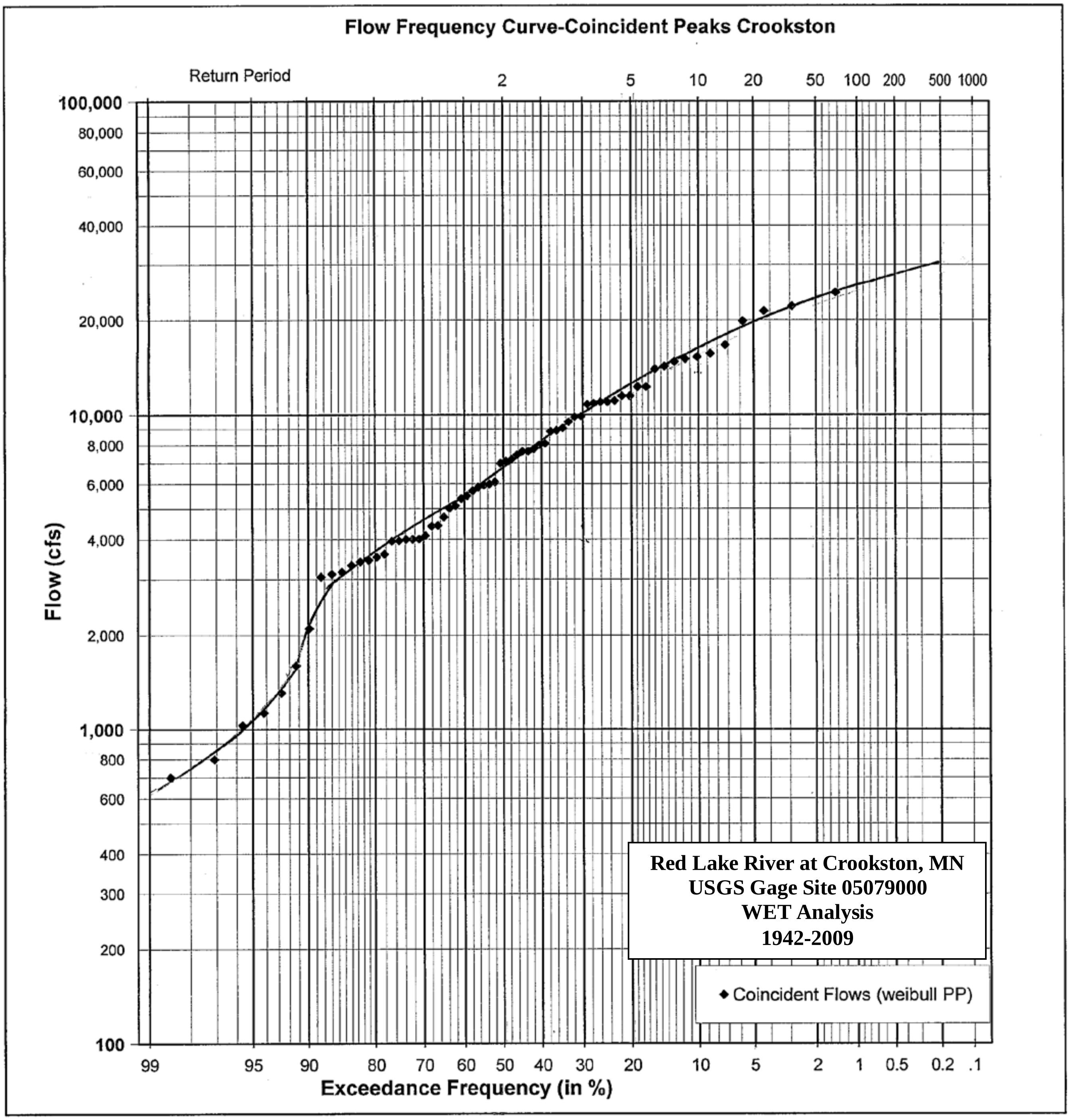
Pencil Line = Graphical Flow Frequency Curve

Figure 4- Graphical Coincident Flow-Frequency Curve at Climax, MN



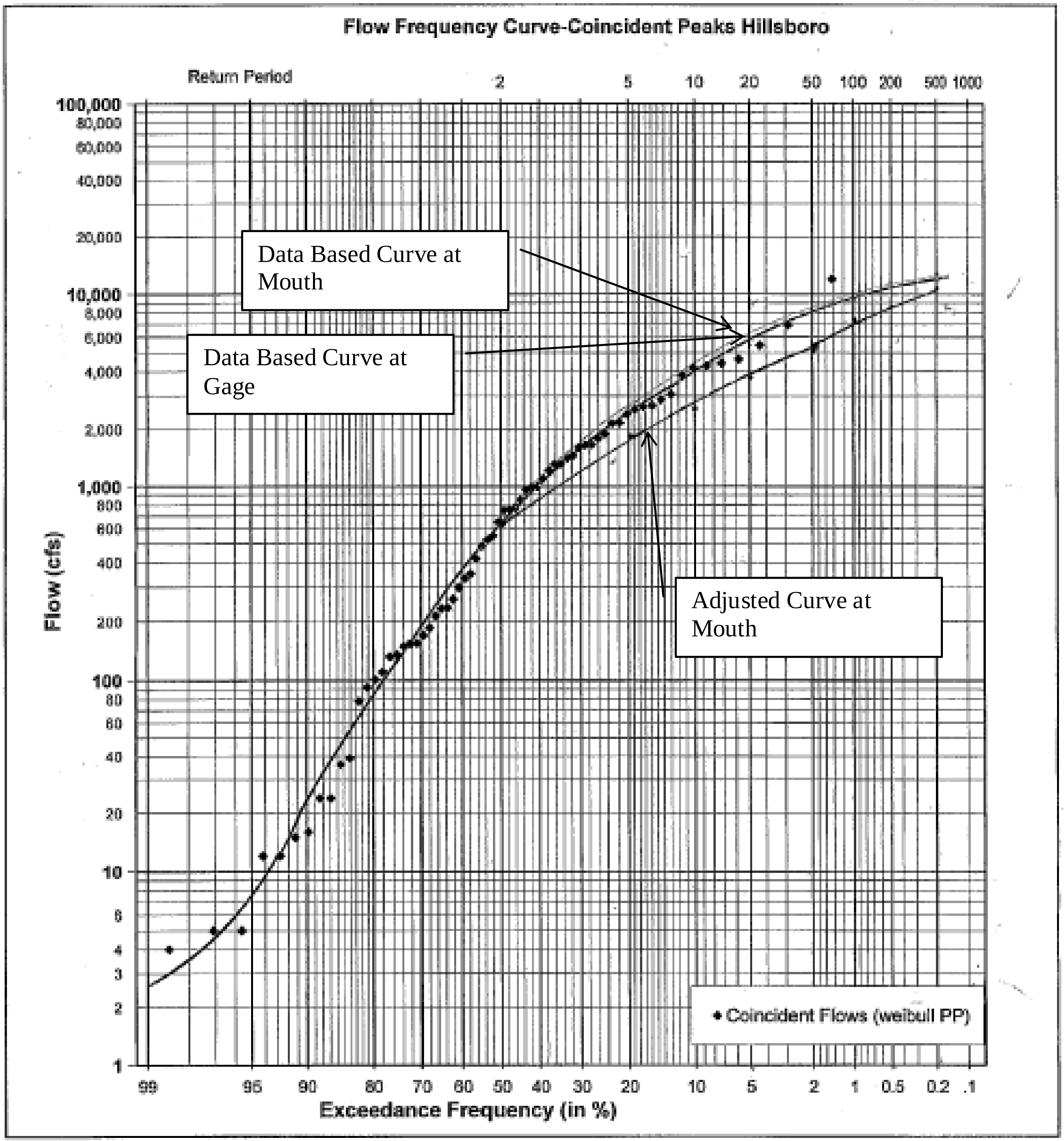
Pencil Line = Graphical Flow Frequency Curve

Figure 5- Graphical Coincident Flow-Frequency Curve at Crookston, MN



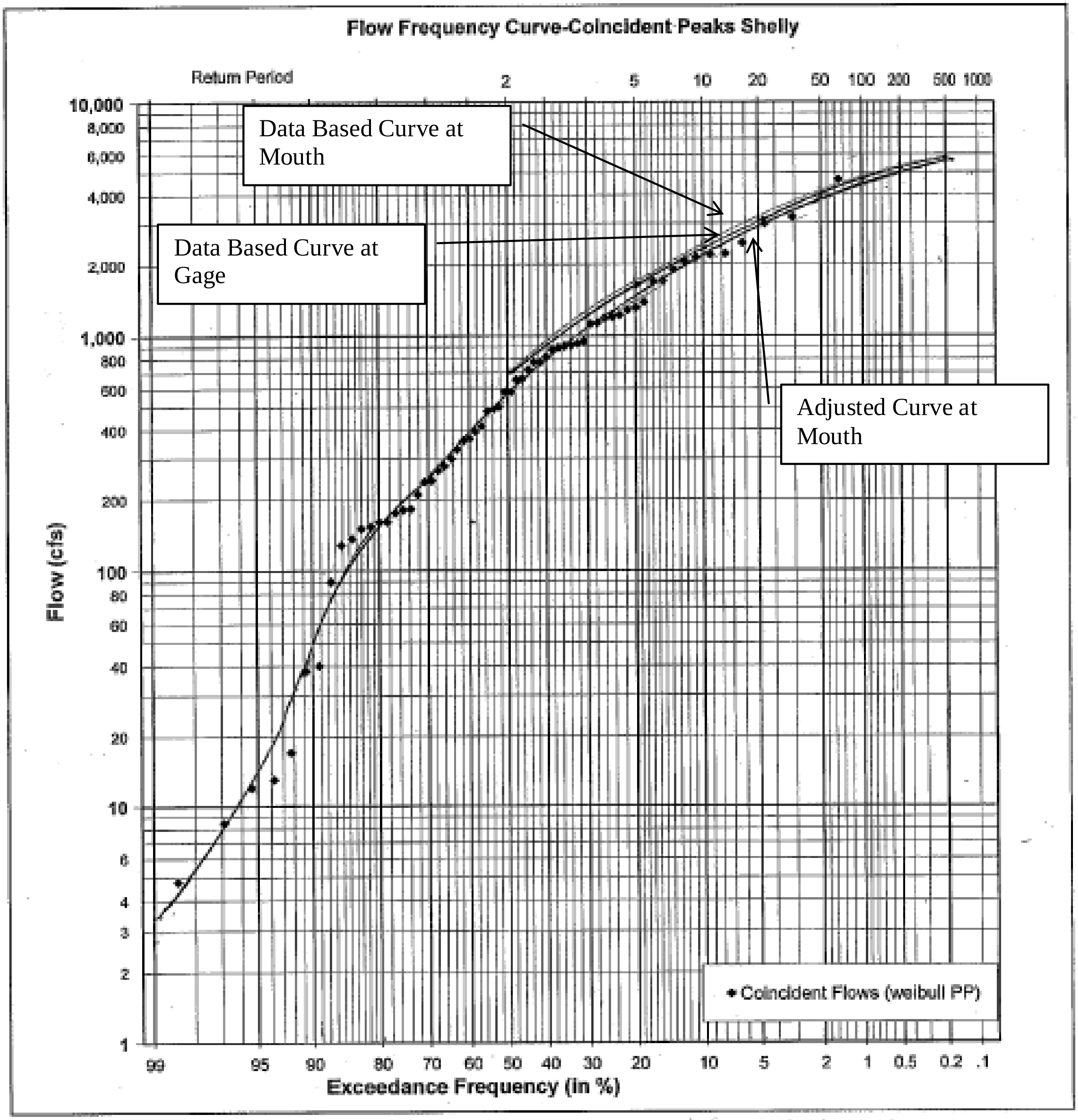
Pencil Line = Graphical Flow Frequency Curve

Figure 6. Adjusted Flow Frequency Curve- Mouth of Goose River- WET Analysis (1942-2009)



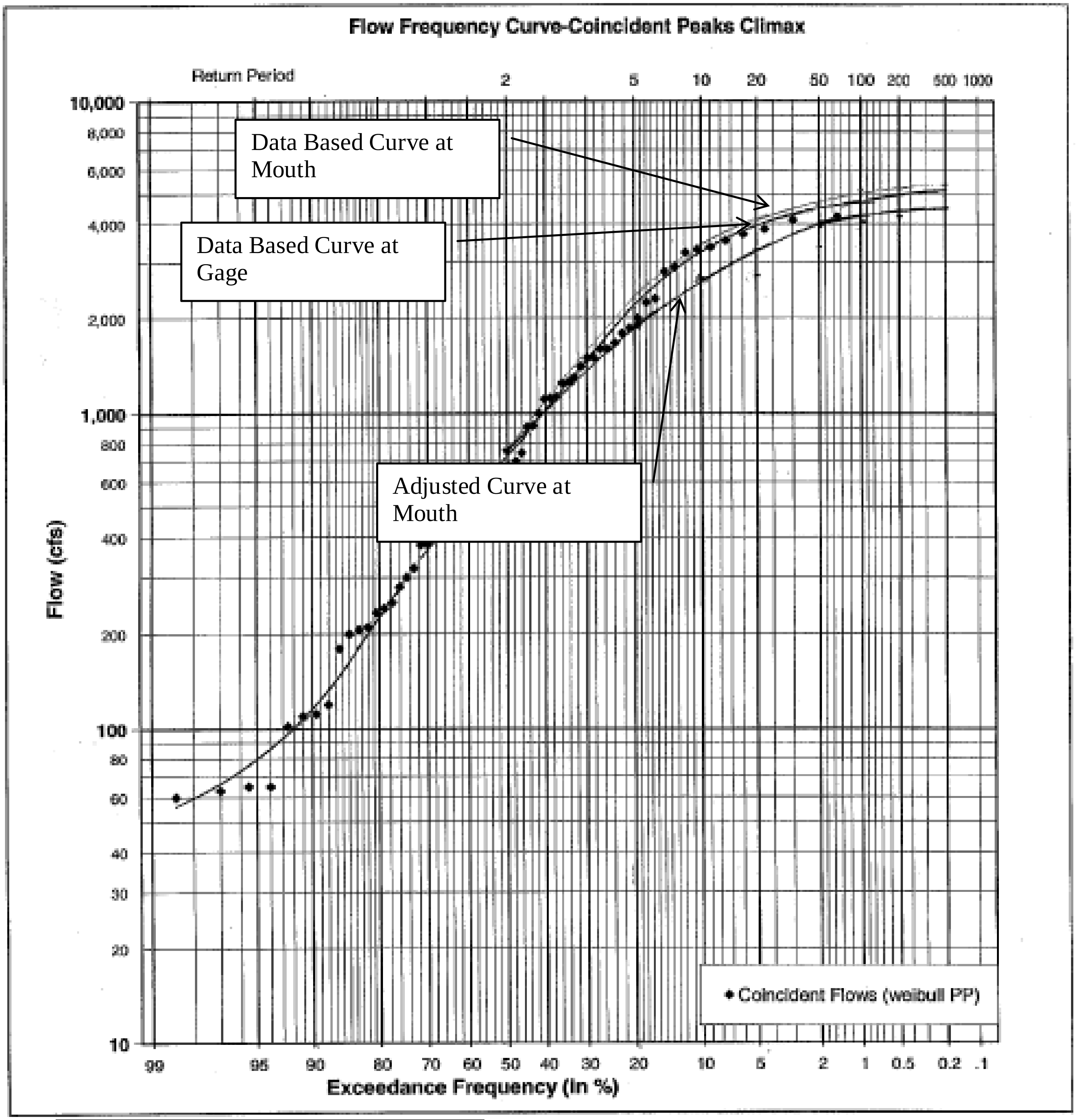
Pencil Line = Graphical Flow Frequency Curve

Figure 7. Adjusted Flow Frequency Curve- Mouth Marsh River- WET Analysis (1944-2009)



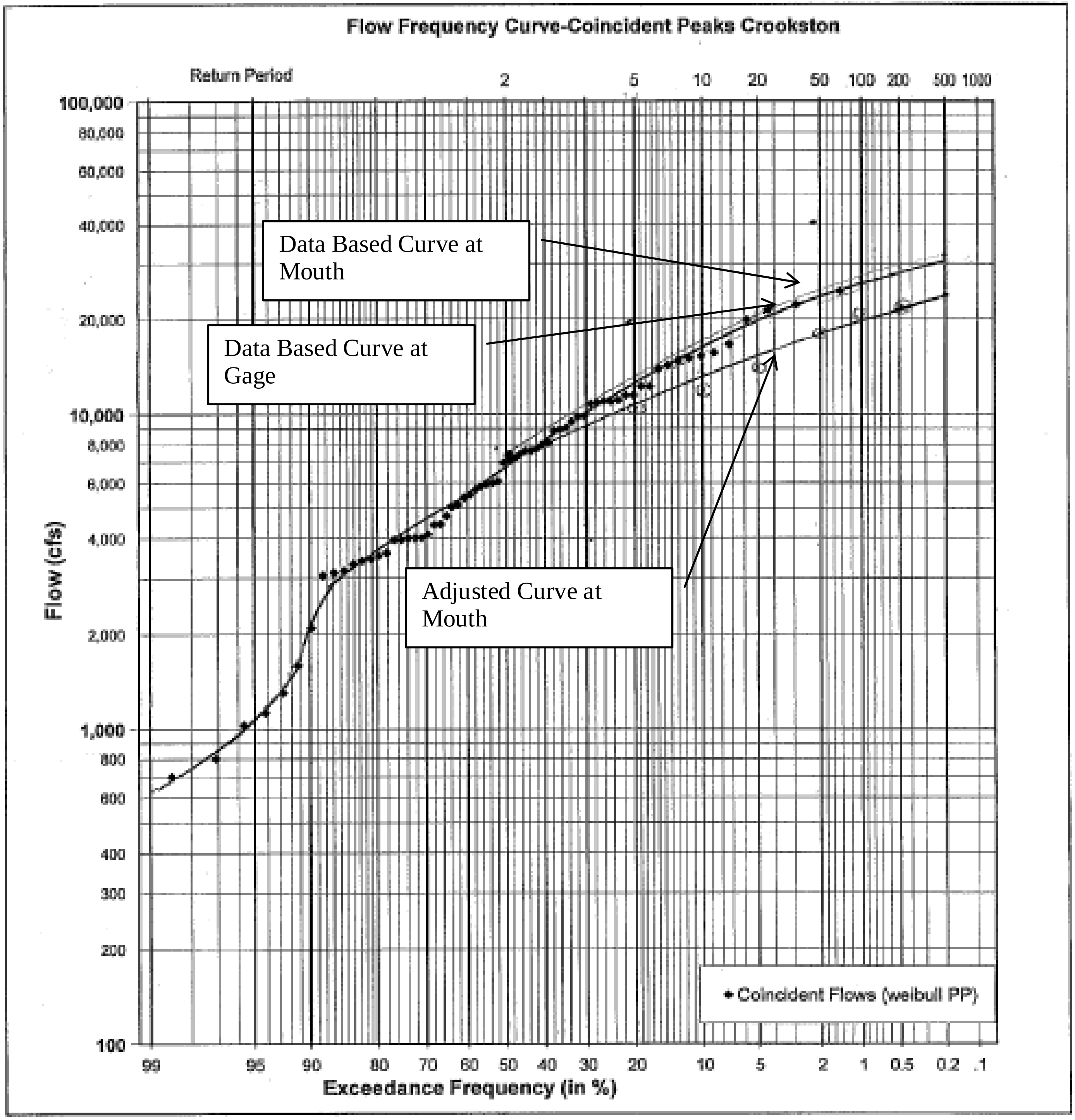
Pencil Line = Graphical Flow Frequency Curve

Figure 8-Adjusted Flow Frequency Curve- Mouth Sand Hill River Wet Analysis (1944-2009)



Pencil Line = Graphical Flow Frequency Curve

Figure 9. Adjusted Flow Frequency Curve- Mouth Red Lake River Wet Analysis (1942-2009)



Pencil Line = Graphical Flow Frequency Curve

Figure 10. Comparison between Observed and Routed Flow at Thompson, MN

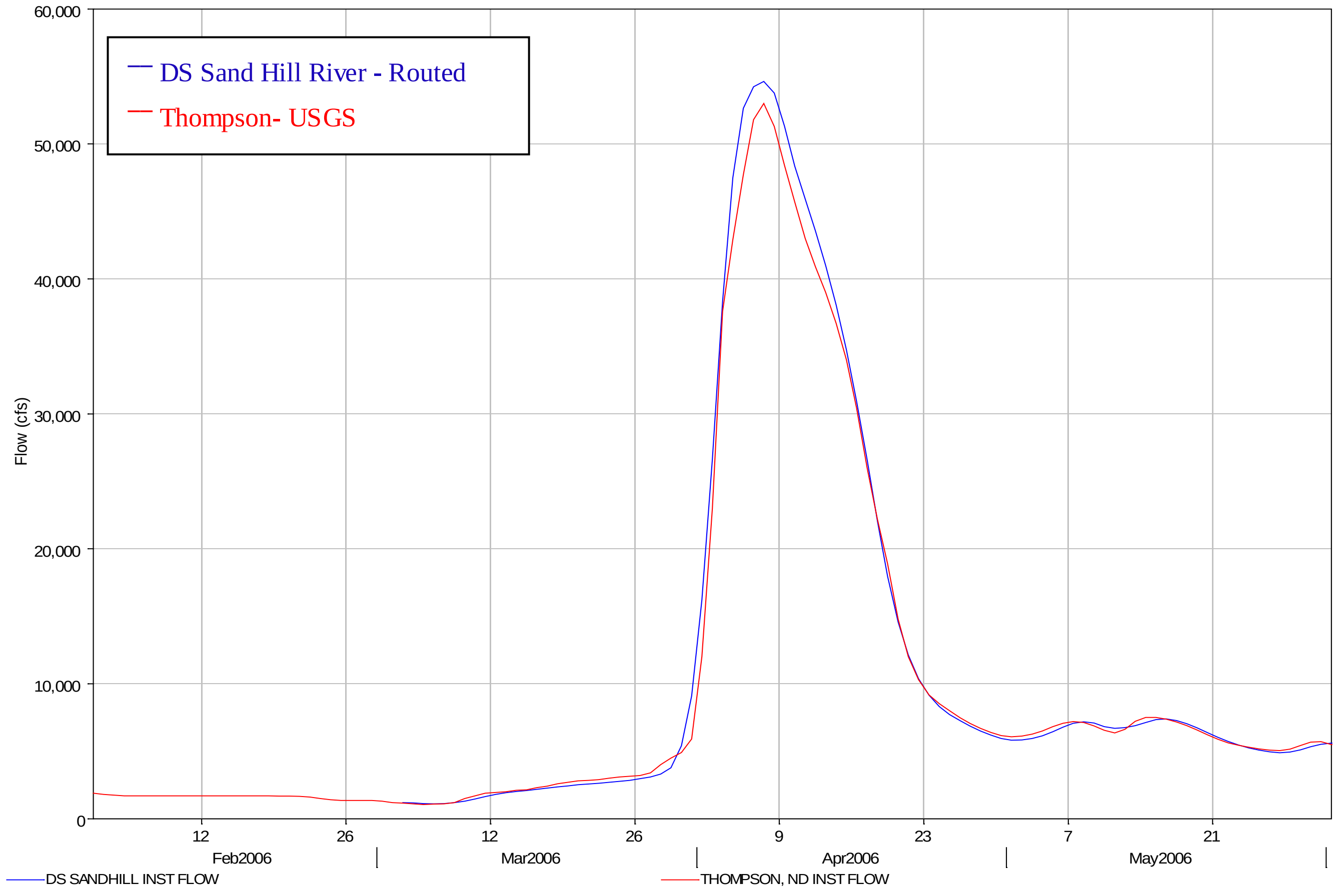


Figure 11. Comparison of Gaged based flow between Grand Forks and Thompson

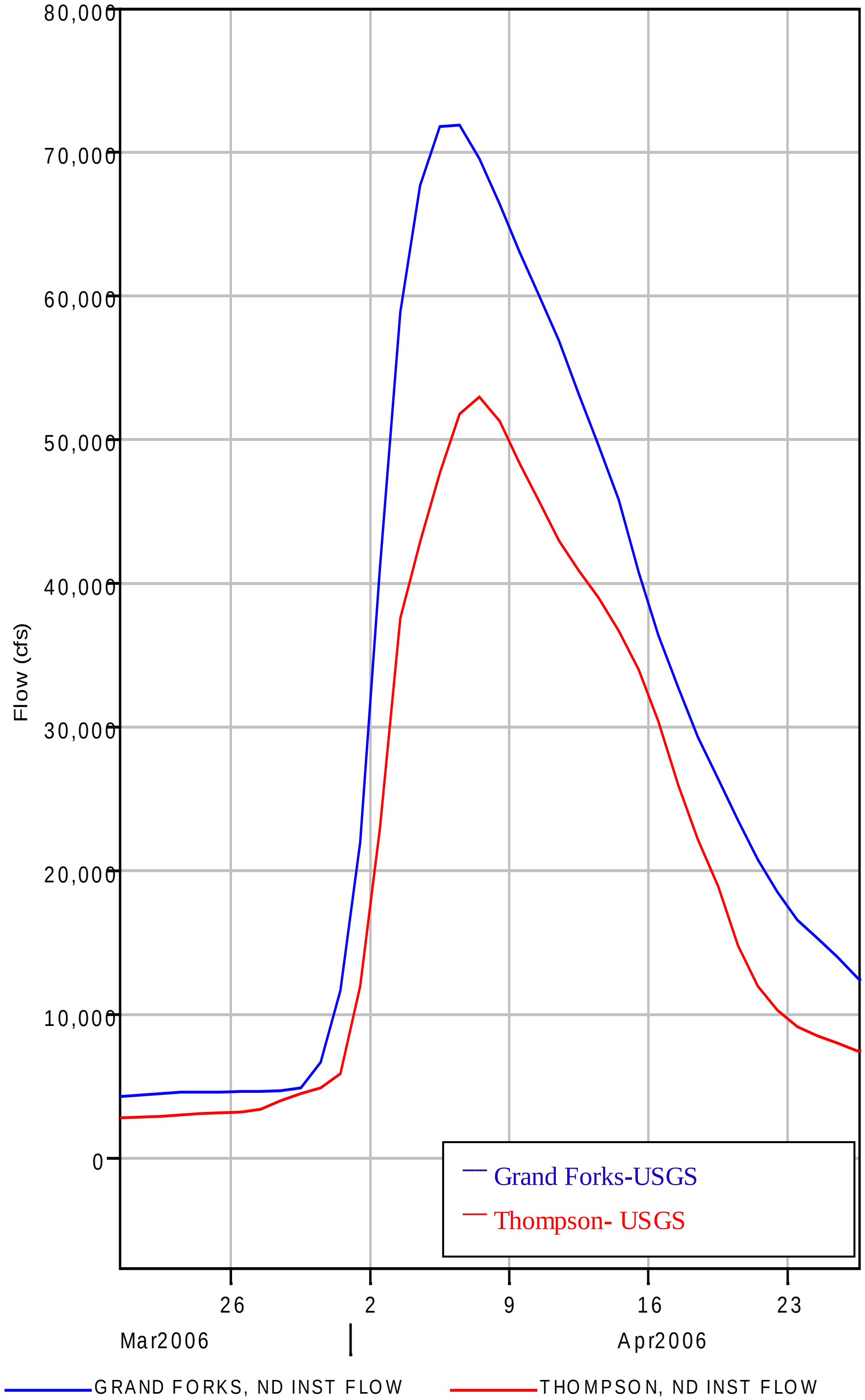


Figure 12. Routed Hydrograph and USGS gaged Hydrograph at Grand Forks

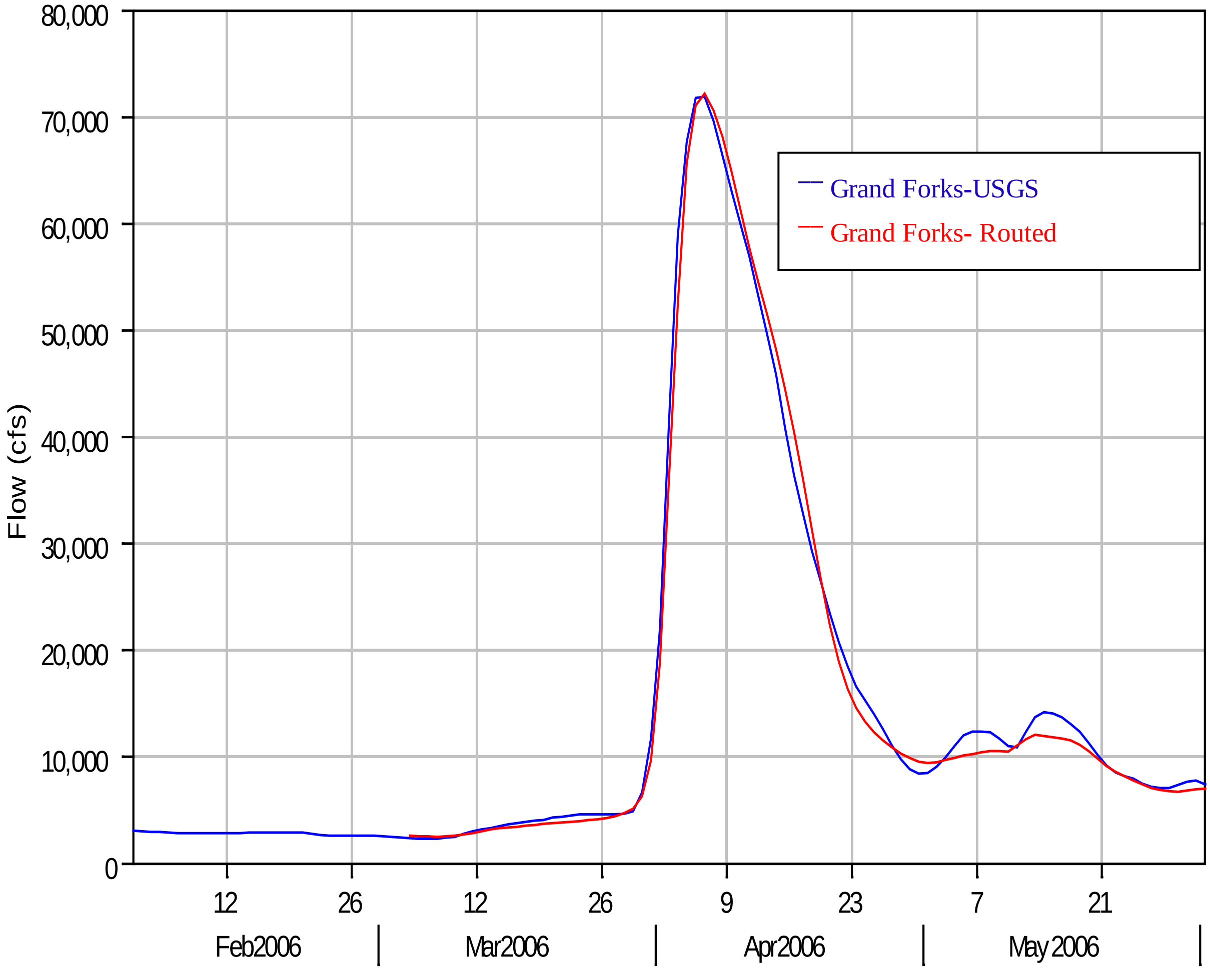


Figure 13. Timing Comparison between Routed Flows US Red Lake River and observed flows at Thompson

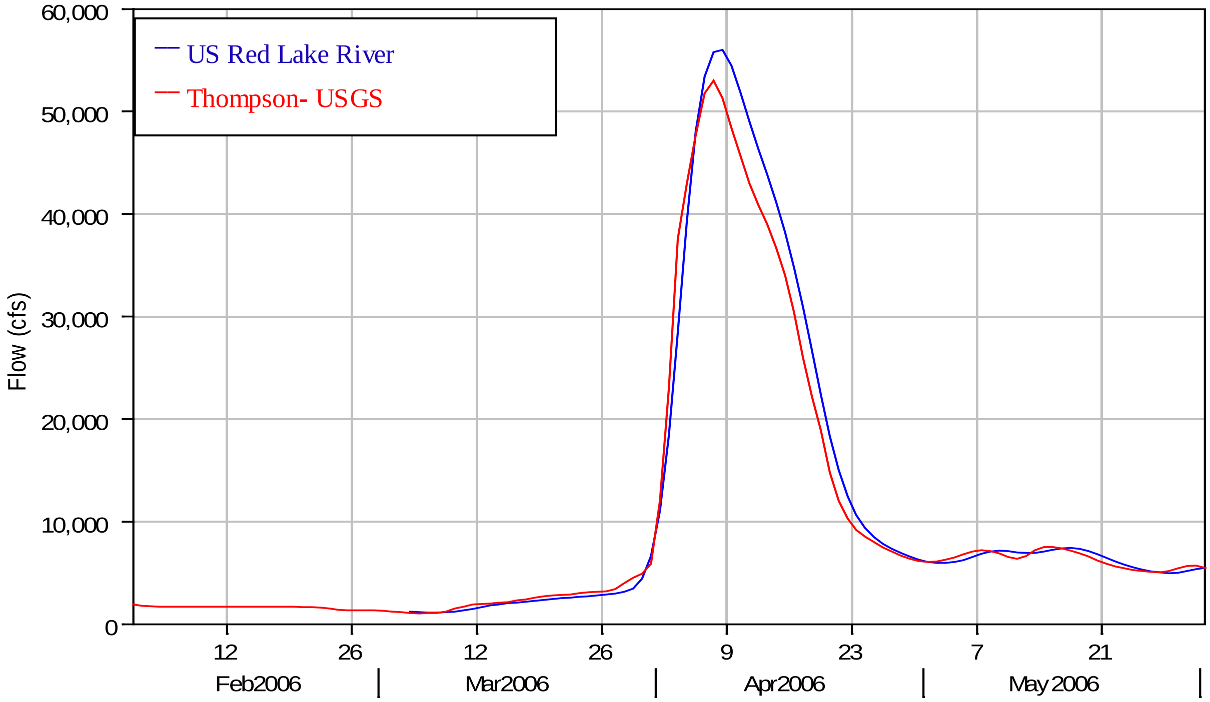


Figure 14. Adjusted Standard Deviation

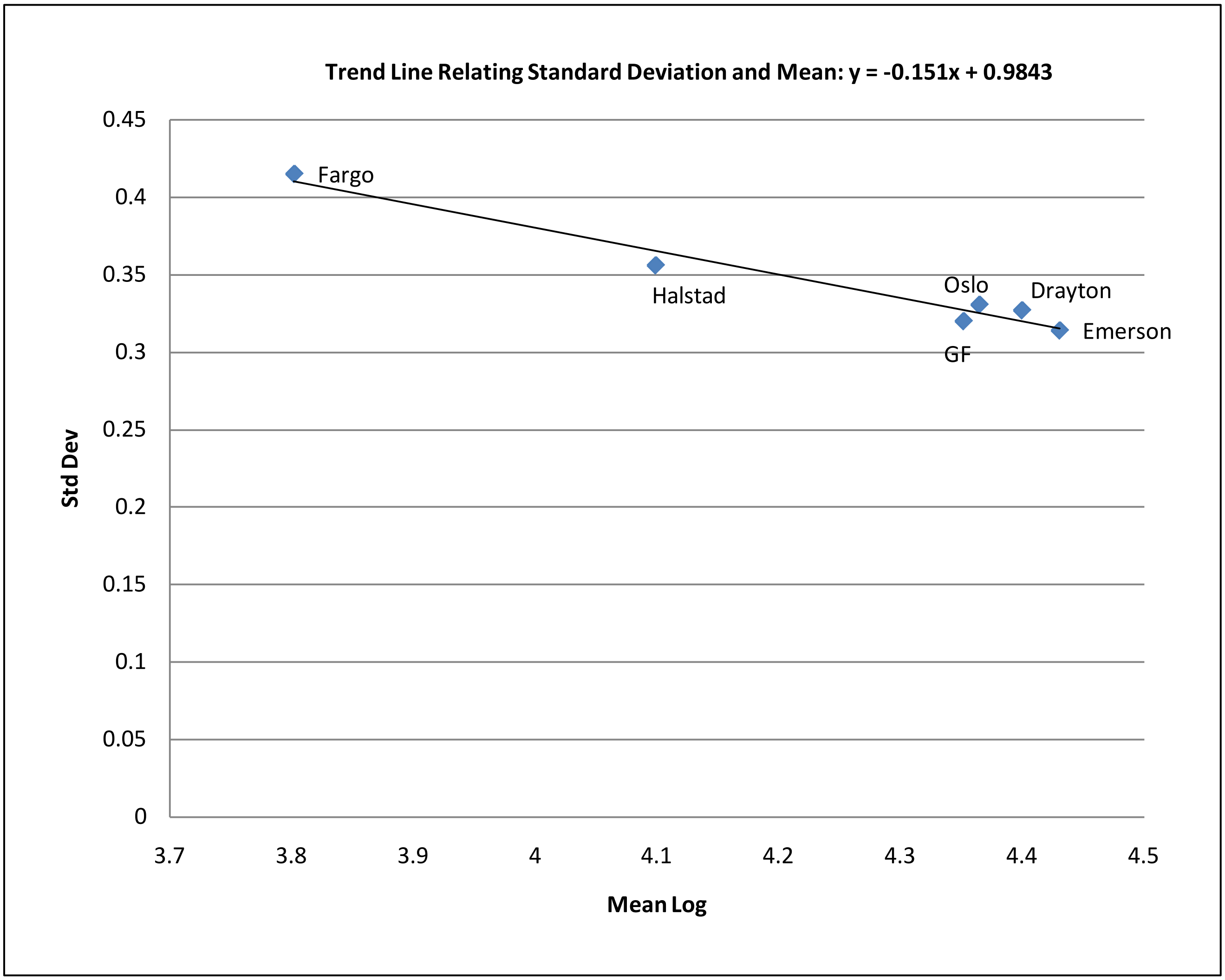


Figure 15. Adjusted Skew

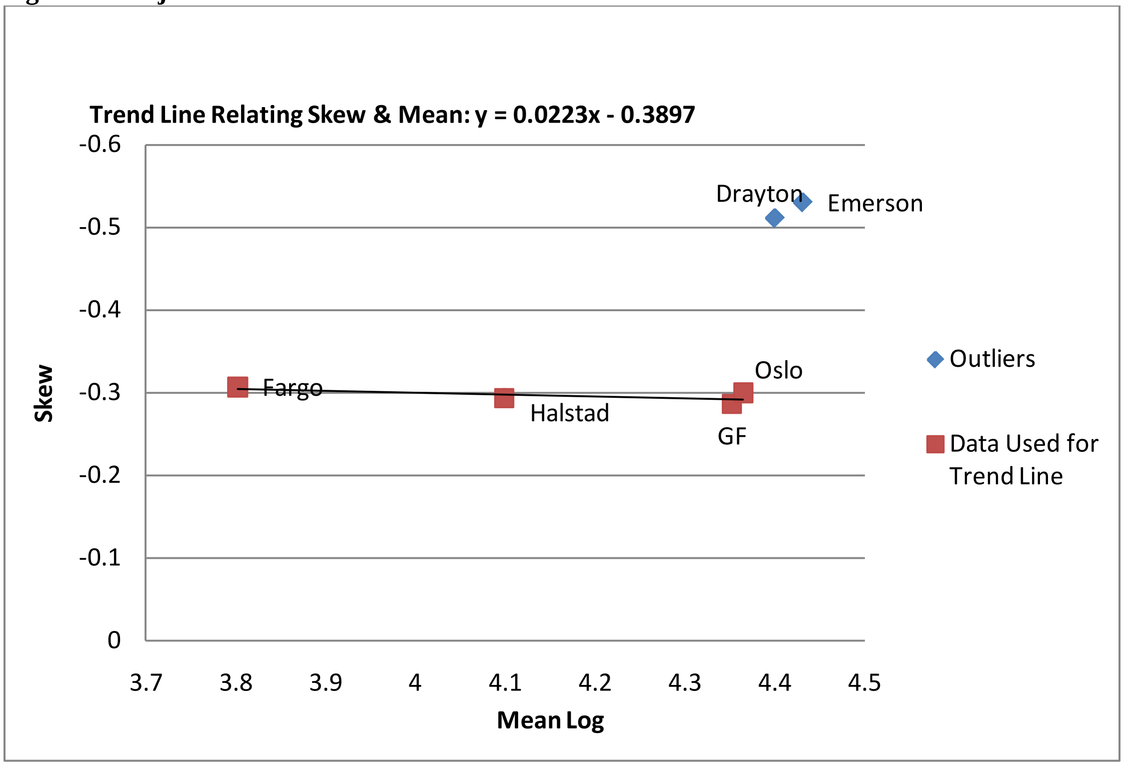


Figure 16. Nested Family of Curves on the Mainstem of the Red River of the North- WET Analysis

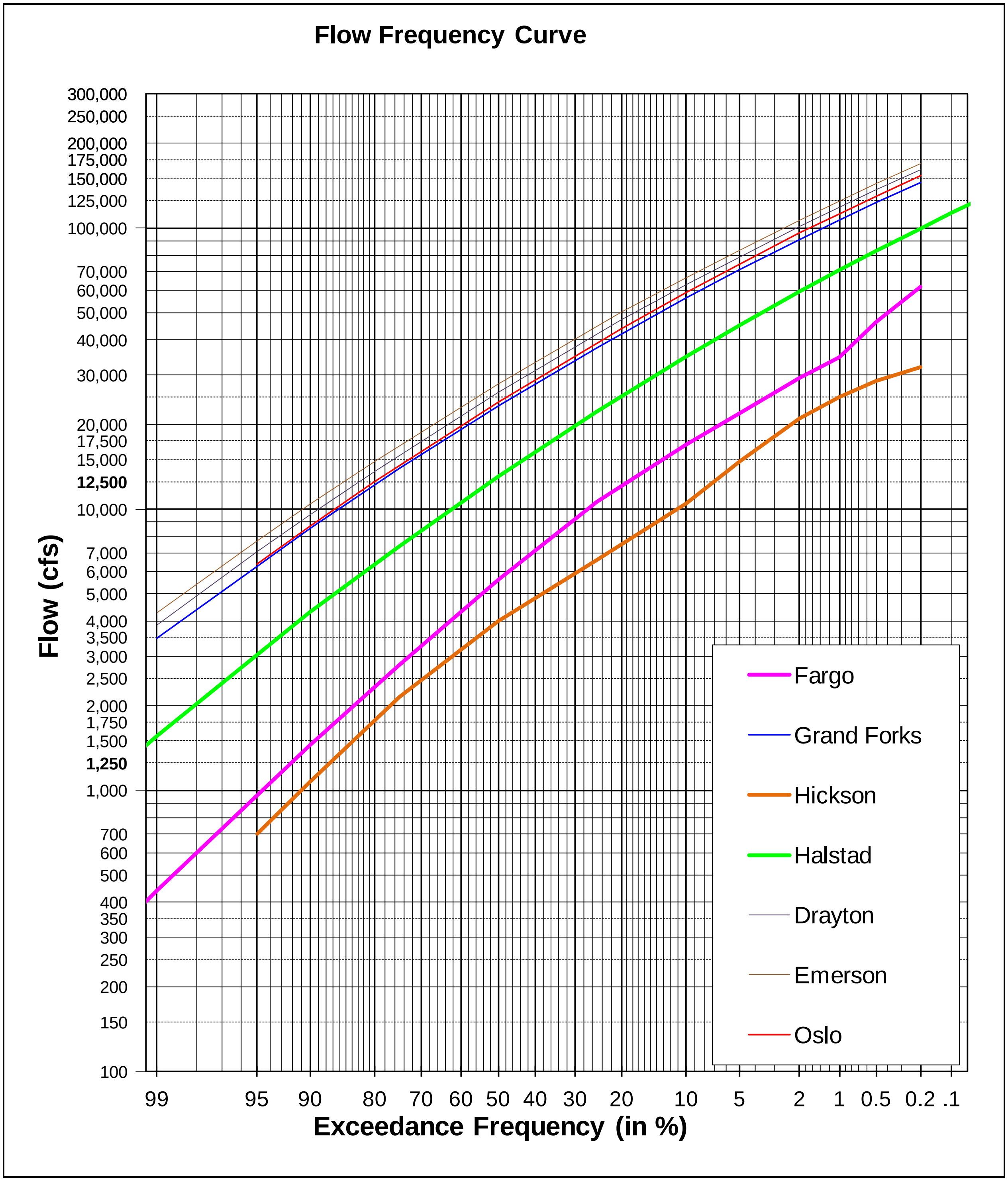


Figure 17. Schematic of Red River Reach- Grand Forks to Emerson

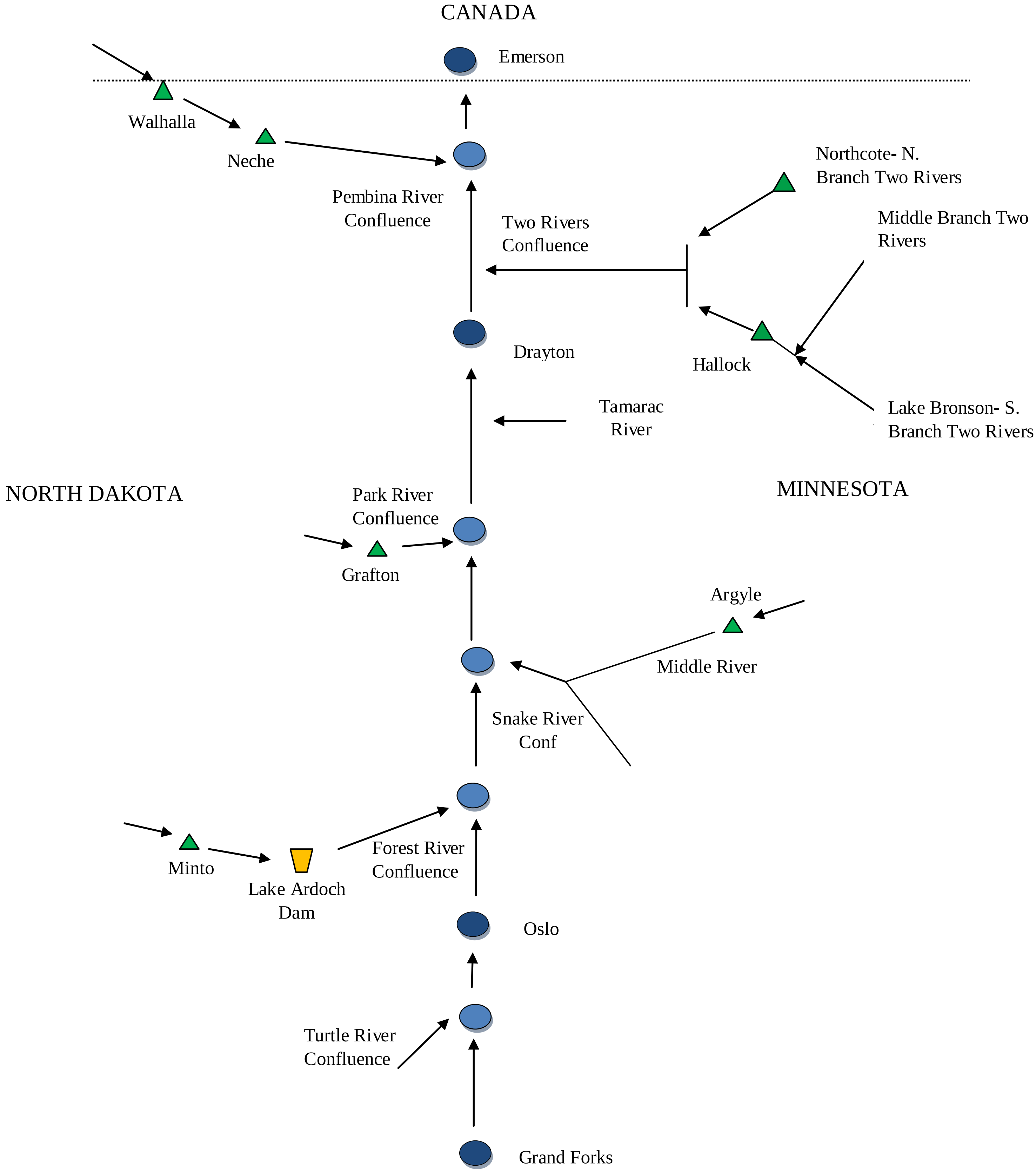


Figure 18. Red River of the North at Oslo, MN- 2006 event hydrograph- Stage

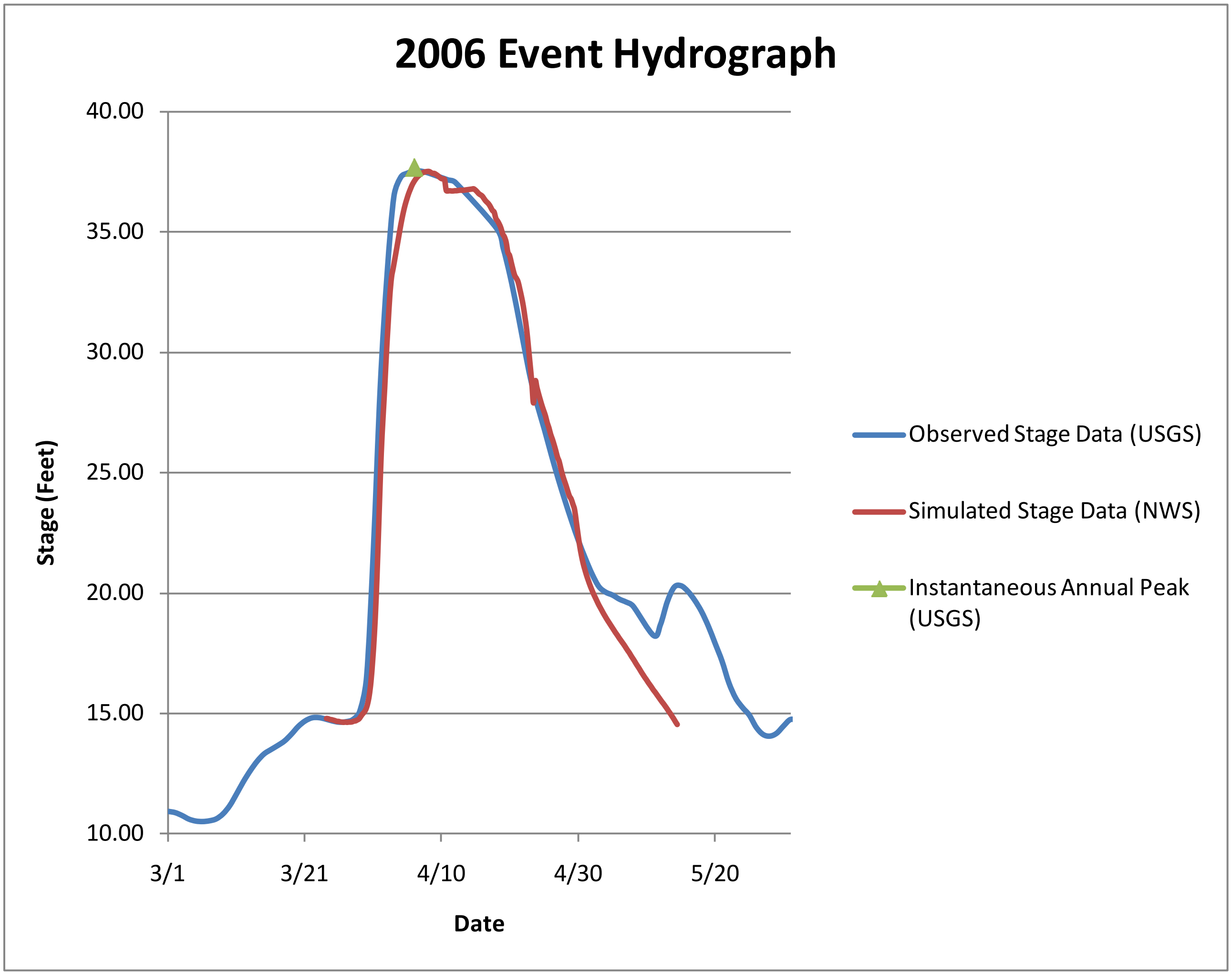


Figure 19. Red River of the North at Oslo, MN-2006 Event Hydrograph- Discharge

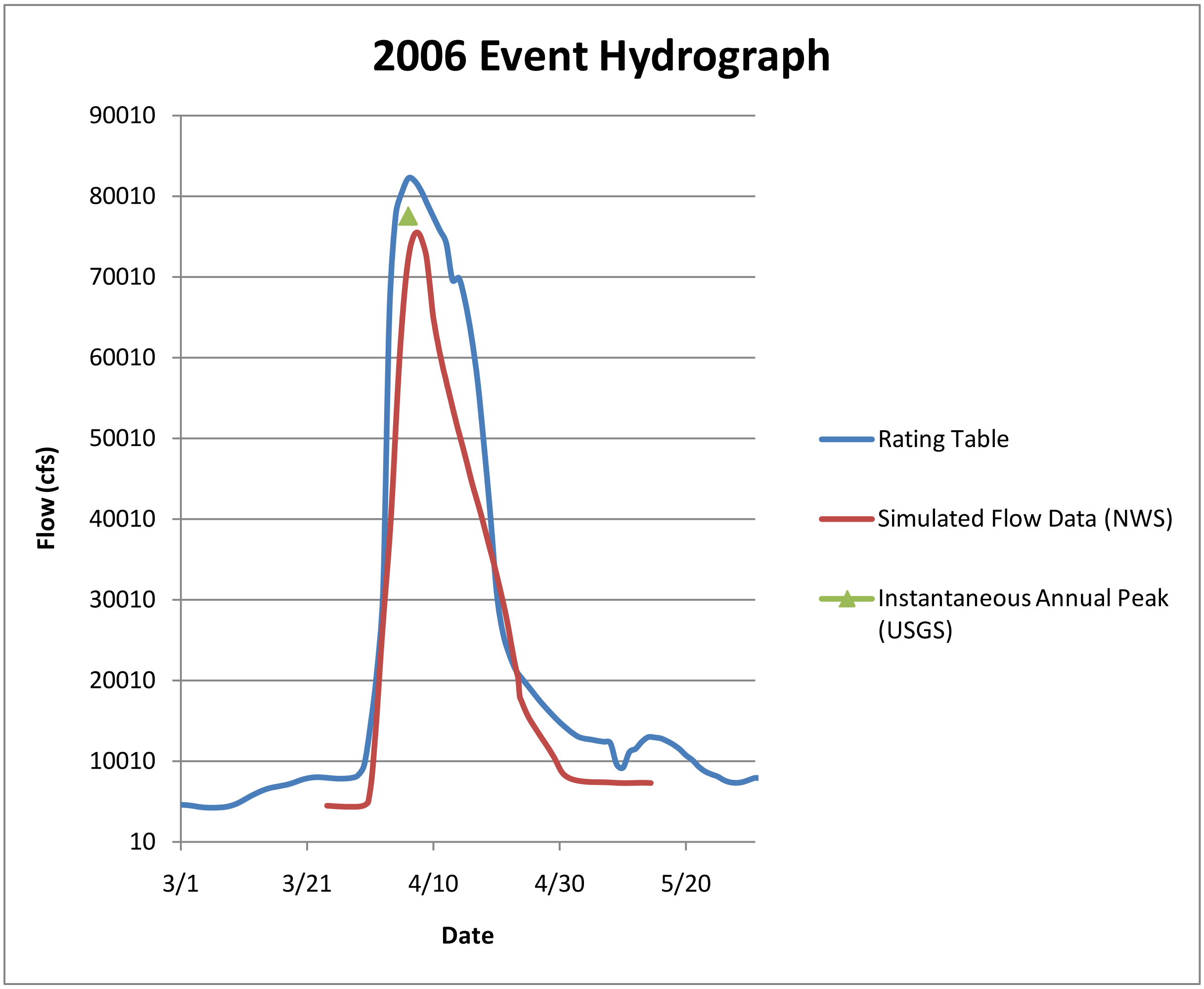


Figure 20. Available USGS Gage Data Red River Reach: Oslo- Drayton

	No Data Available
	Data Recorded

	RRN USGS GAGING STATION INFORMATION AVAILABLE FOR ANNUAL PEAKS FROM OSLO TO Drayton					
	Forest River at Minto, ND	**Forest River at Fordville, ND**	**Park River at Grafton, ND**	**Snake River at Alvarado, MN**	**Middle River/ Snake River Argyle, MN**	**Snake River Warren, MN**
Station ID	5084500/ 5085000	5084000	5090000	5085900/5 086000	5087500	5085450
START YEAR			1897			
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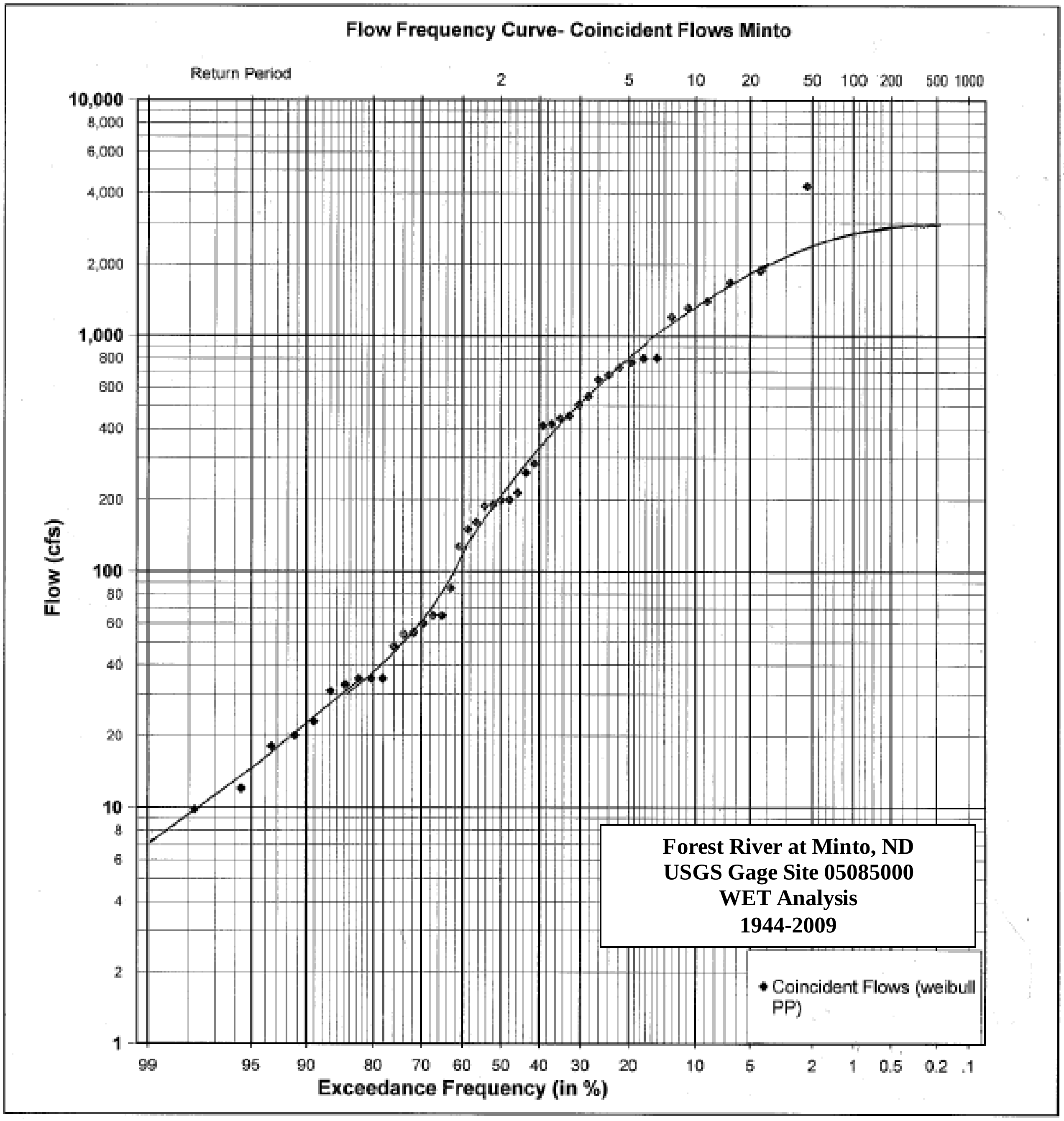
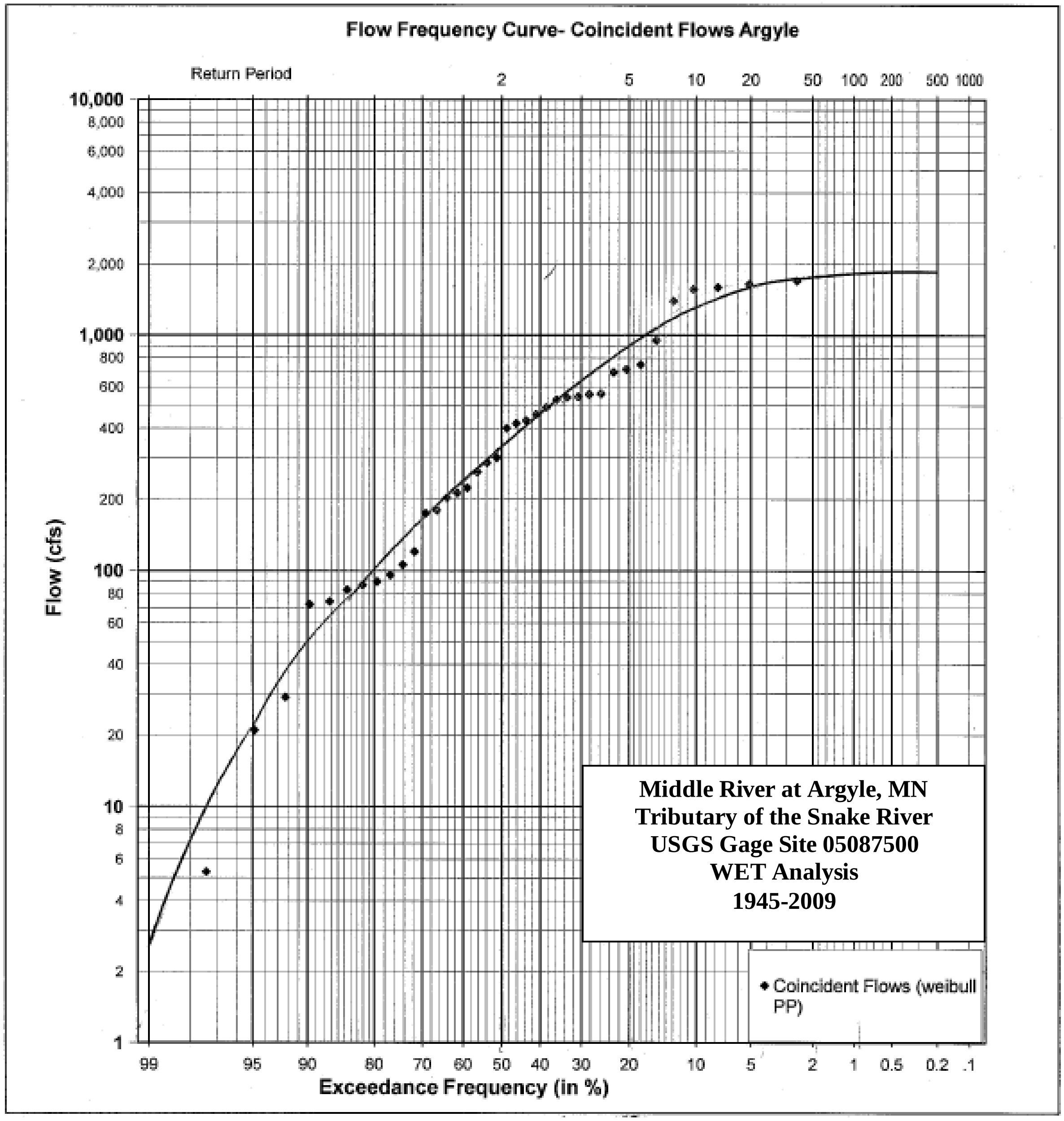
Figure 21. Coincidental Peak Flow-Frequency Curve- Forest River



Pencil Line = Graphical Flow Frequency Curve

Figure 22. Coincidental Peak Flow Frequency Curve-Argyle



Pencil Line = Graphical Flow Frequency Curve

Figure 23. Flow Drainage Area Relationship

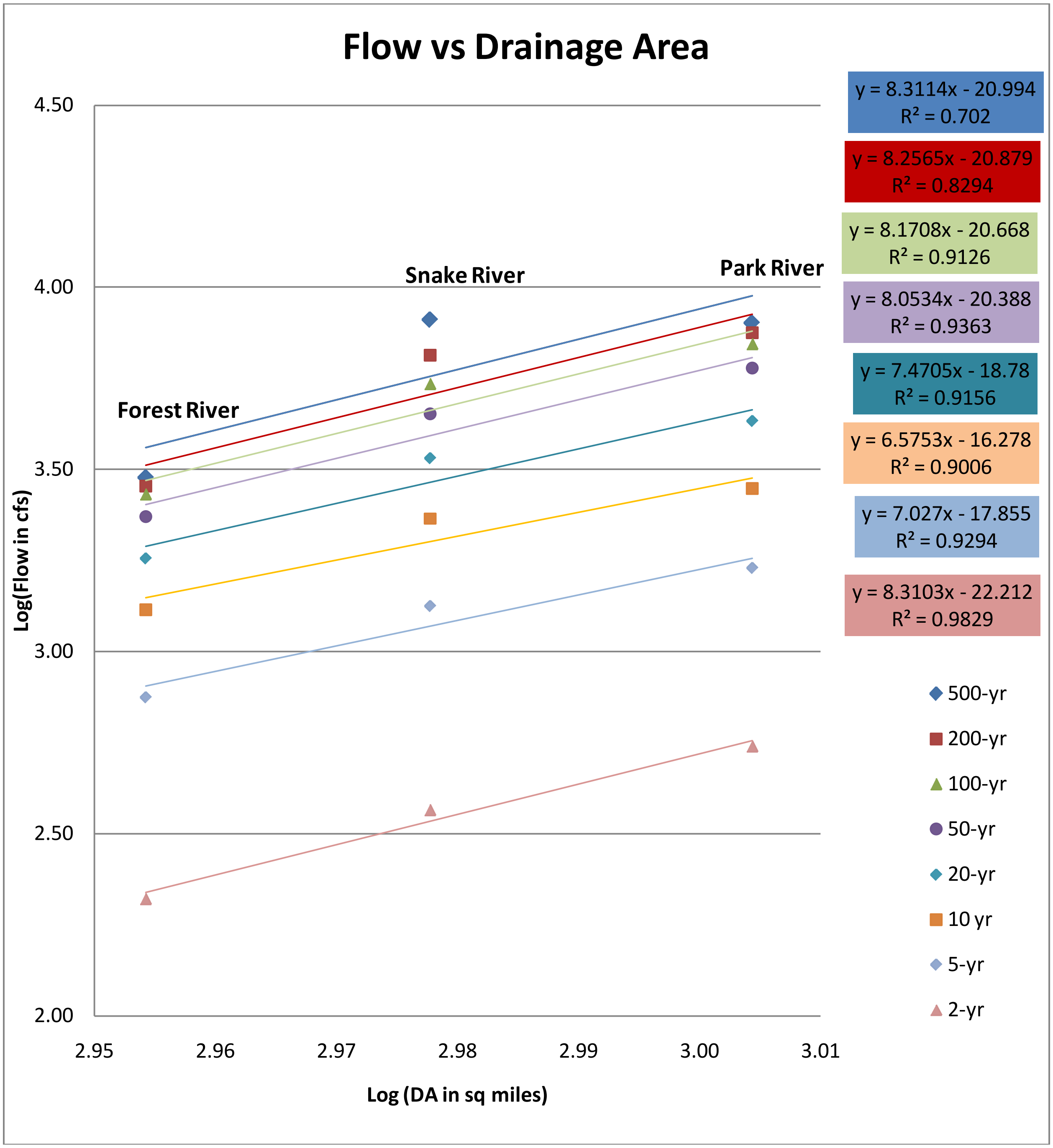
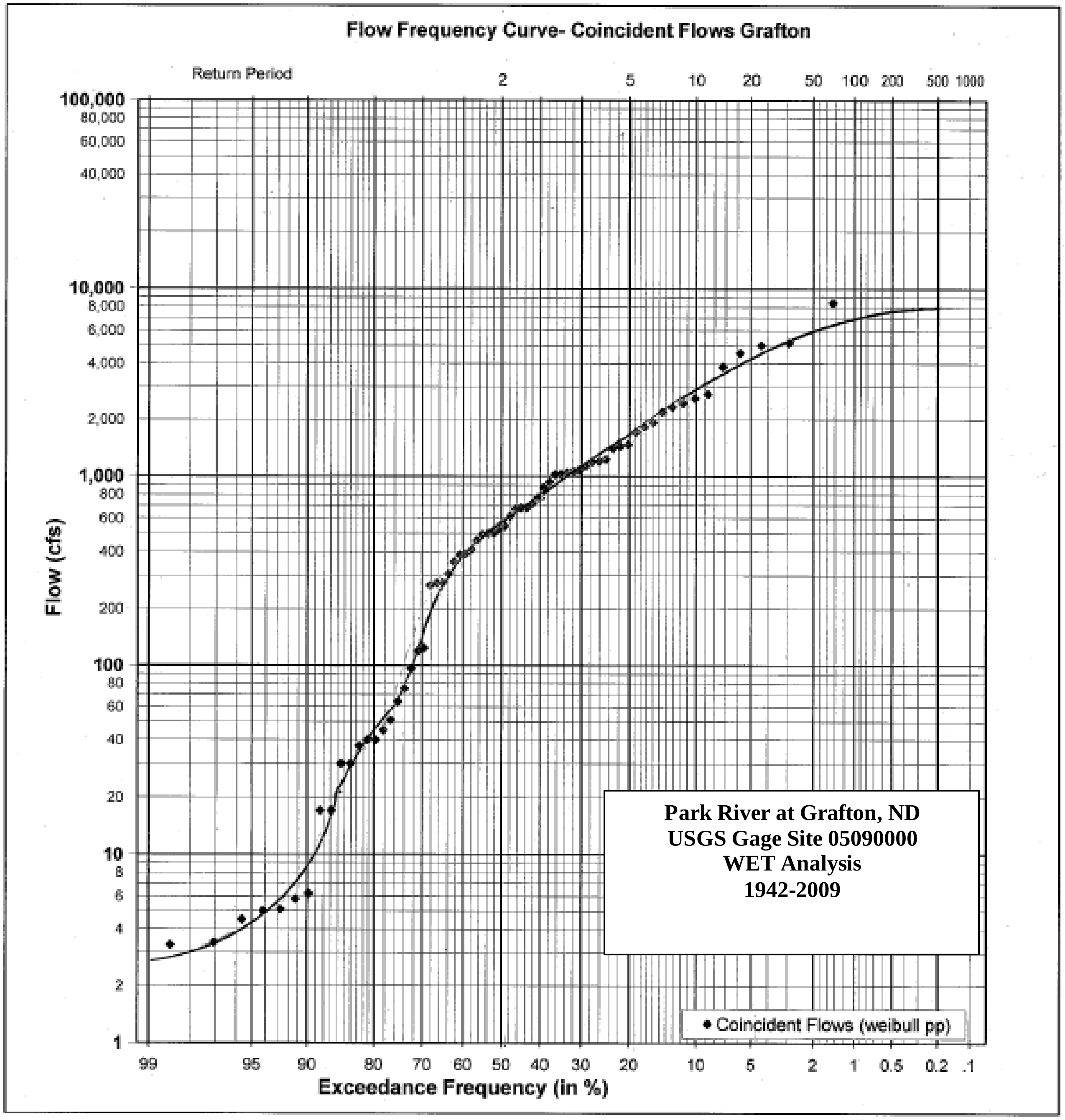


Figure 24. Coincidental Flow-Frequency Analysis at Grafton



Pencil Line = Graphical Flow Frequency Curve

Figure 25. Drayton to Emerson Schematic

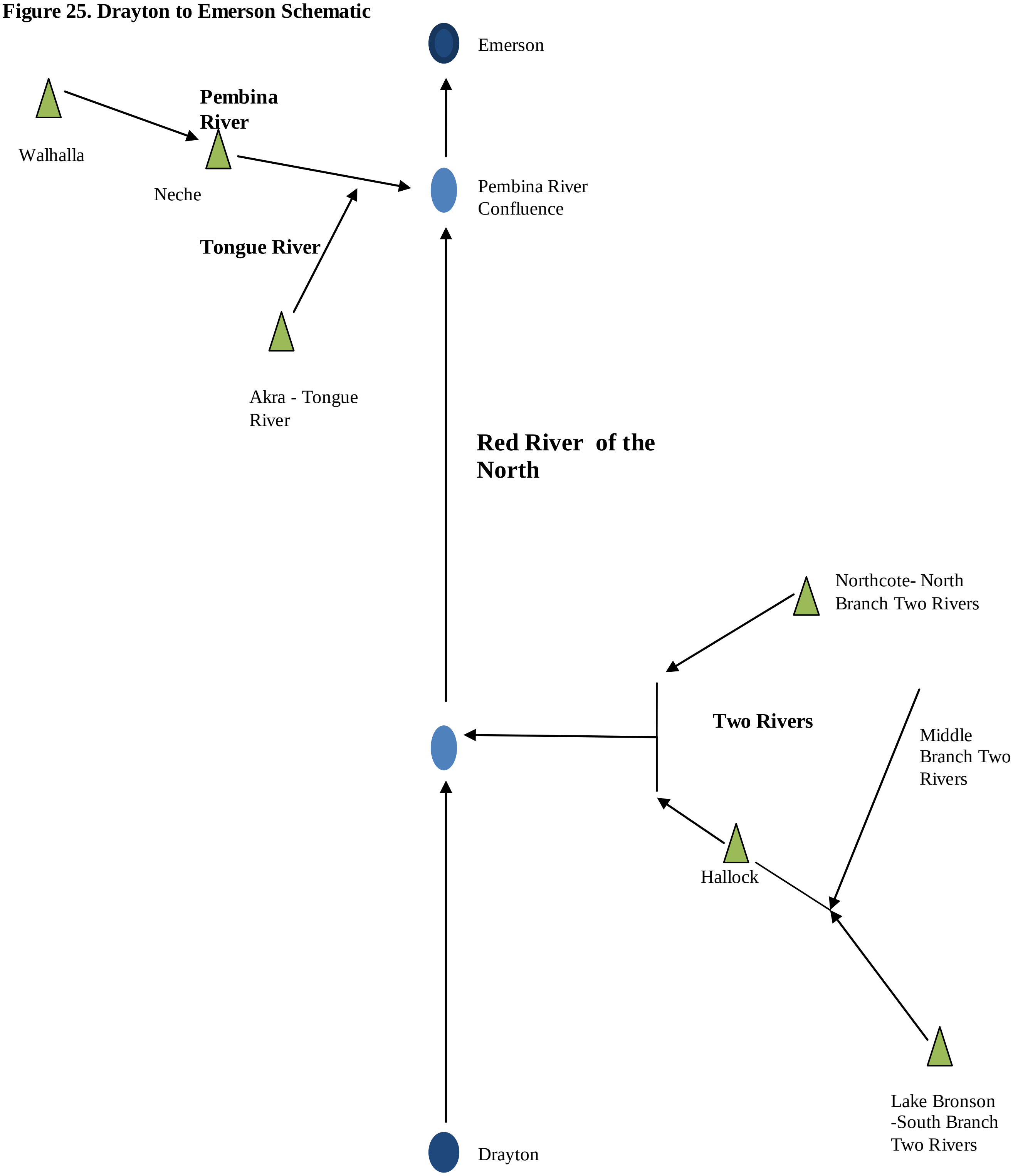


Figure 26. Red River of the North near Drayton 1979 (USGS)

Figure 27. Routed & Observed Hydrographs at Emerson

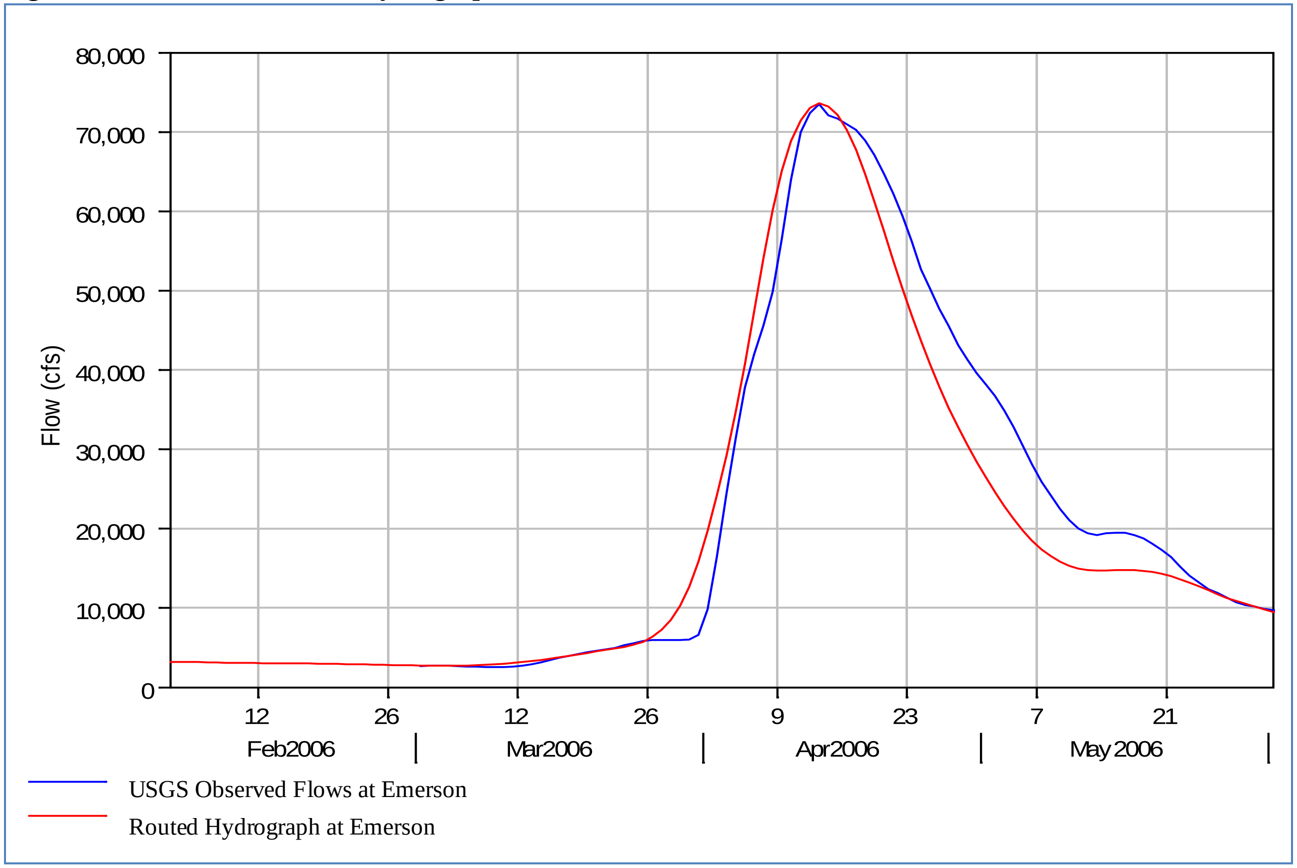


Figure 28. Two Rivers Watershed (Google Earth)

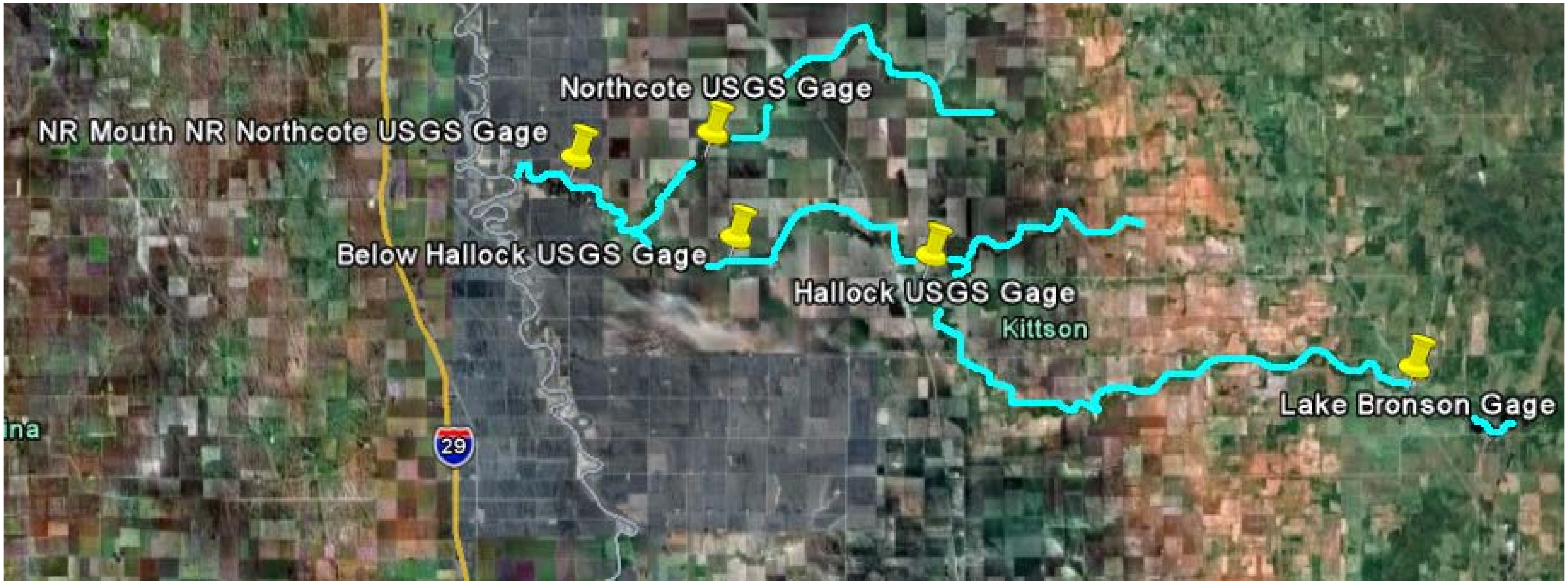


Figure 29. Linear Relationship between USGS gage at Lake Bronson and USGS gage at Hallock

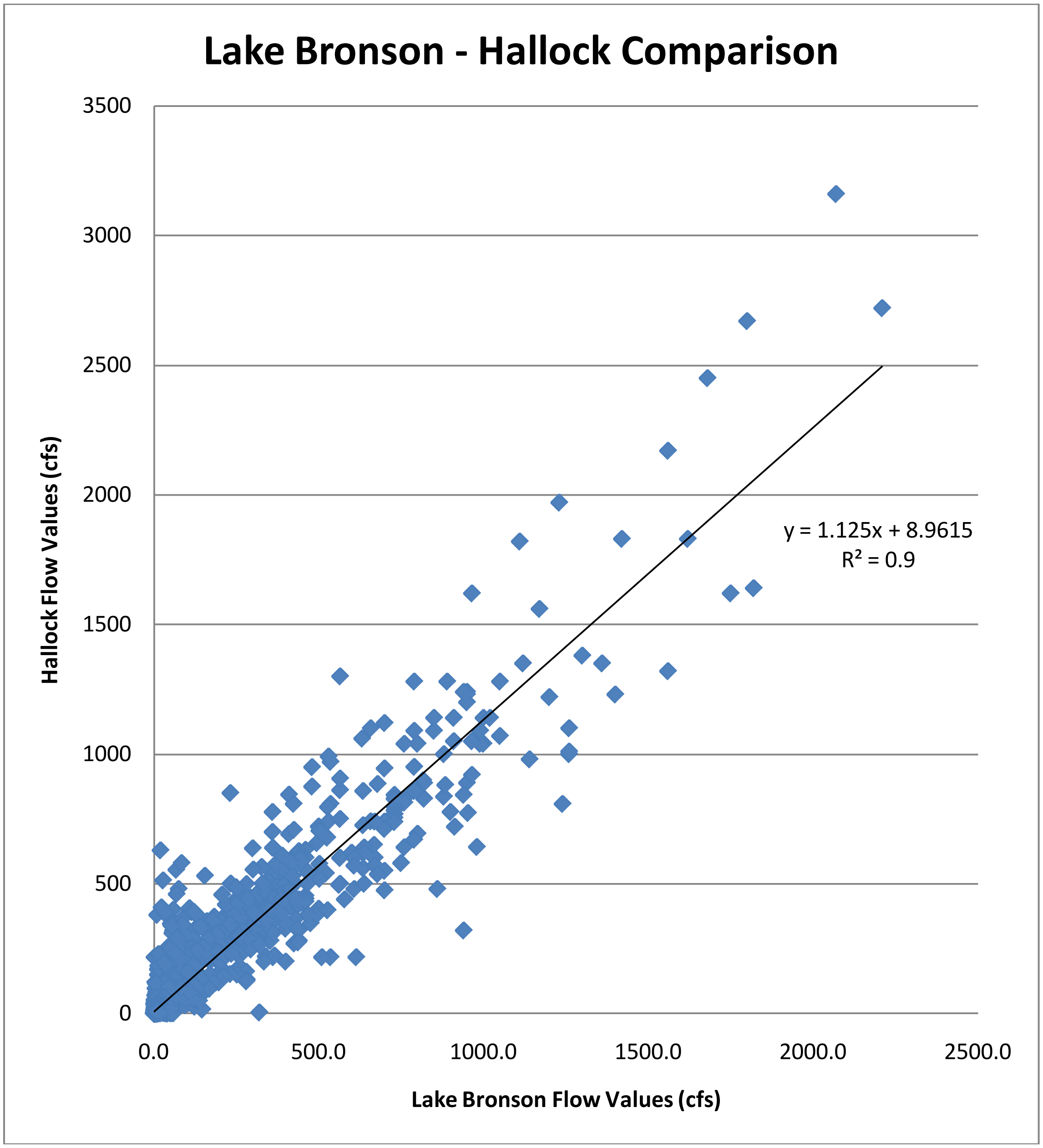
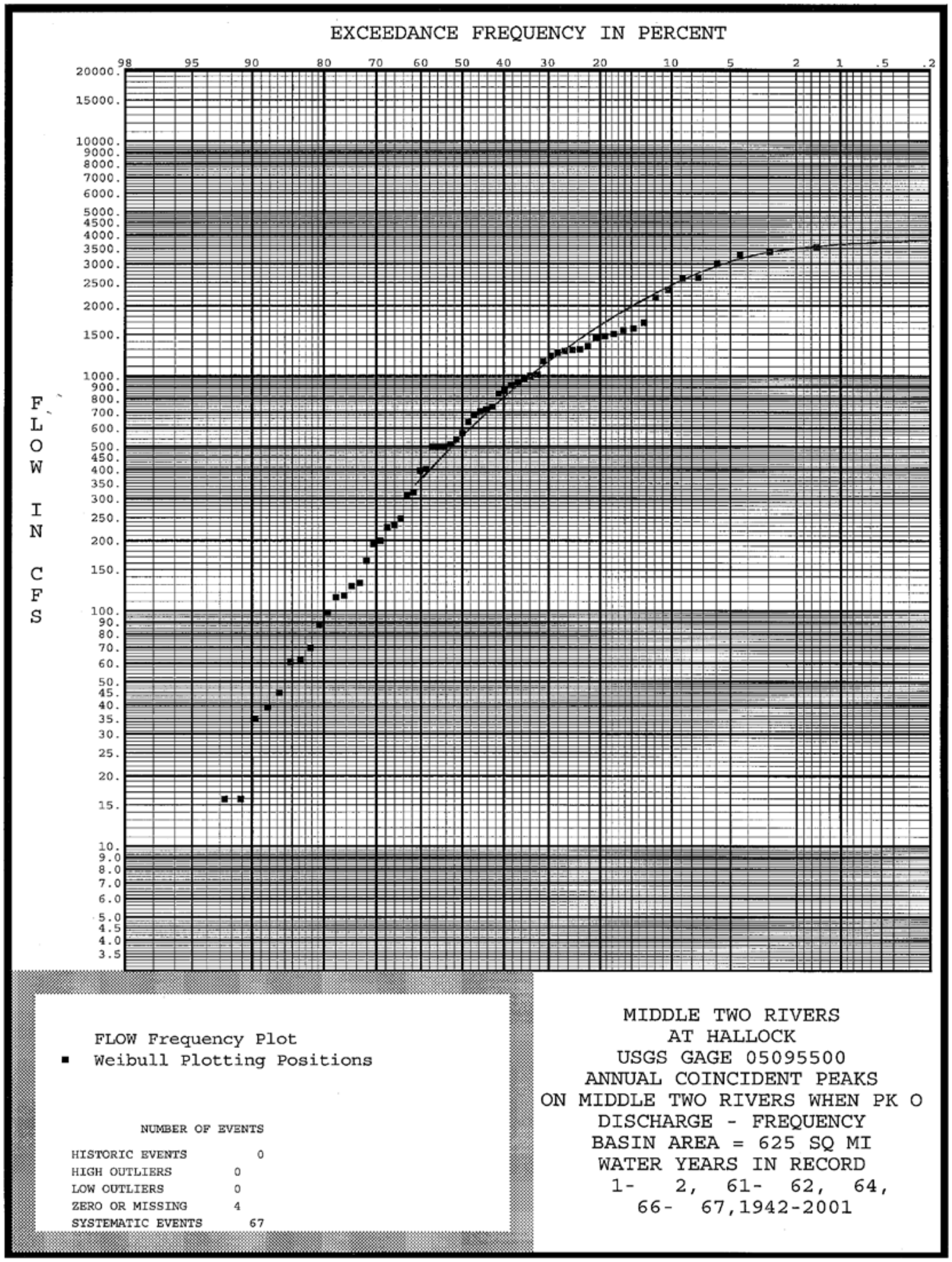


Figure 30. Two Rivers at Hallock



Pencil Line = Graphical Flow Frequency Curve

Figure 31. Pembina River

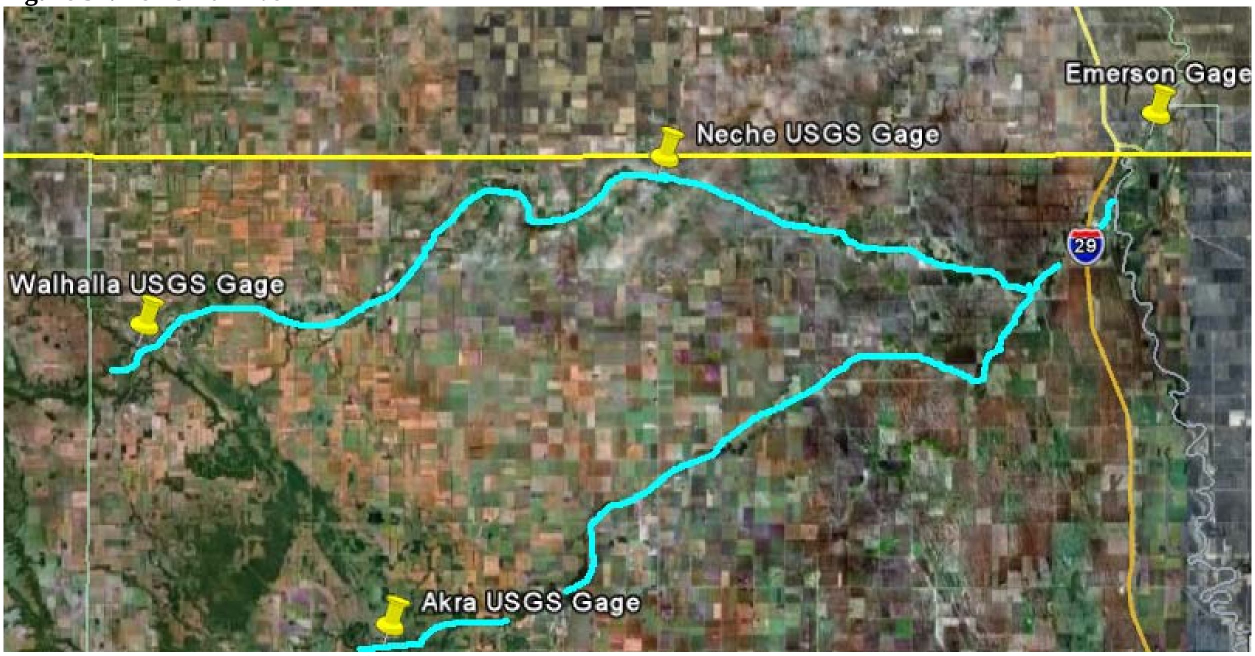


Figure 32. Floodwater spills from the Pembina River just northeast of Neche, ND. (North Dakota State Water Commission, April 21, 2009)

Figure 33. 1997 Peak Flow Distribution for Existing Conditions, Peak Flow 15, 100 cfs (Water Management Consultants).

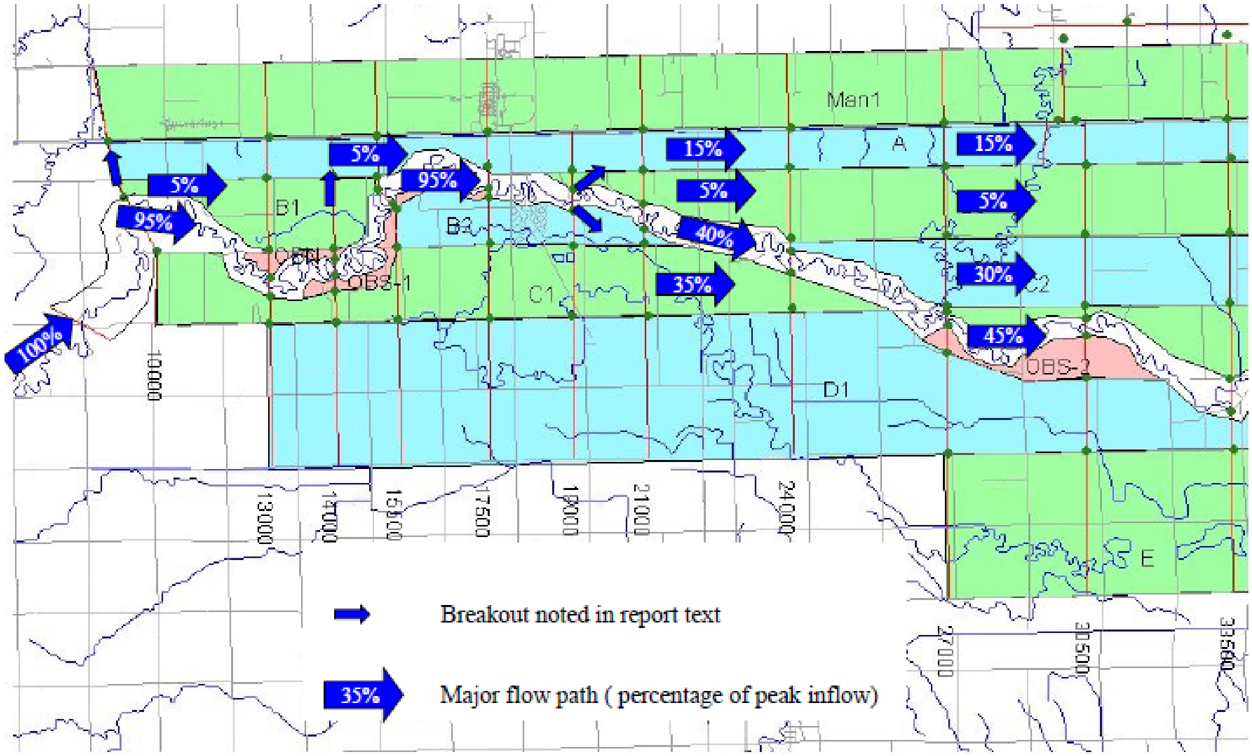


Figure 34. 1996 Peak Flow Distribution for Existing Conditions Peak Flow: 8, 500 cfs (Water Management Consultants).

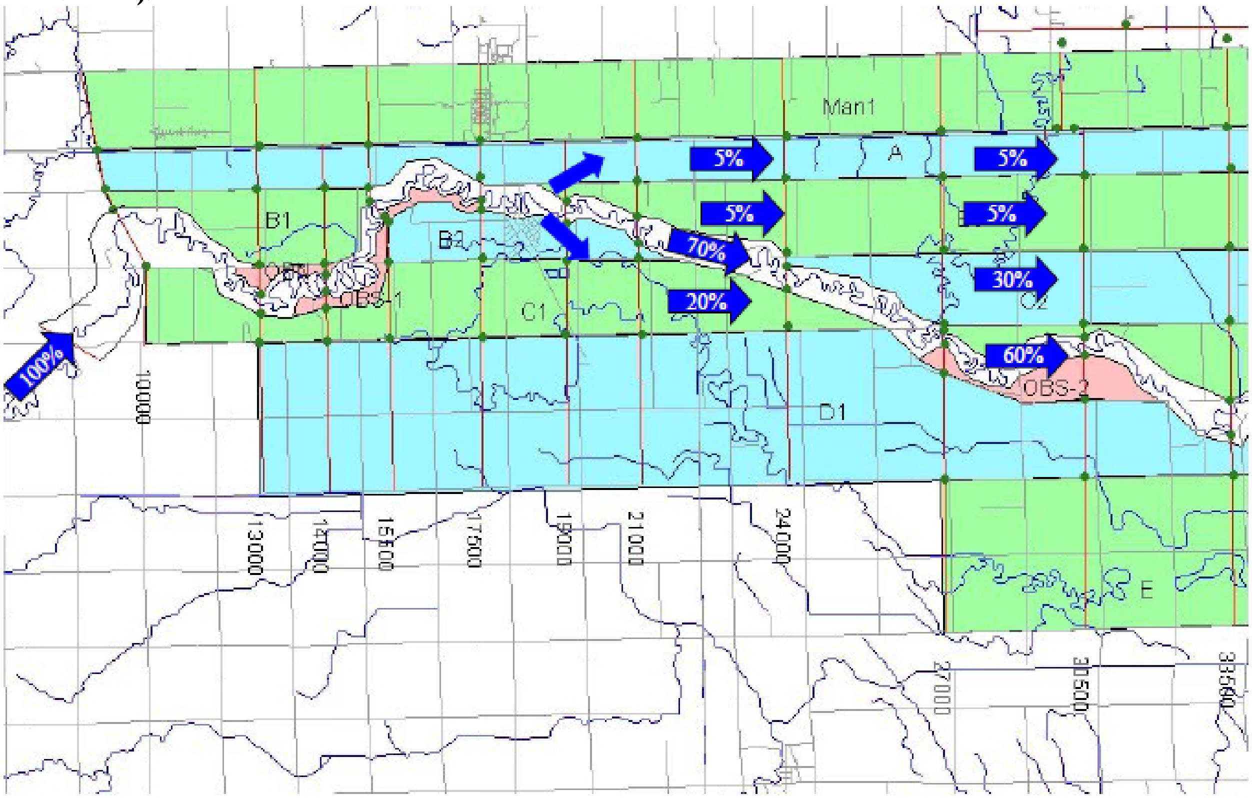


Figure 35. Breakout Flows Downstream of Neche

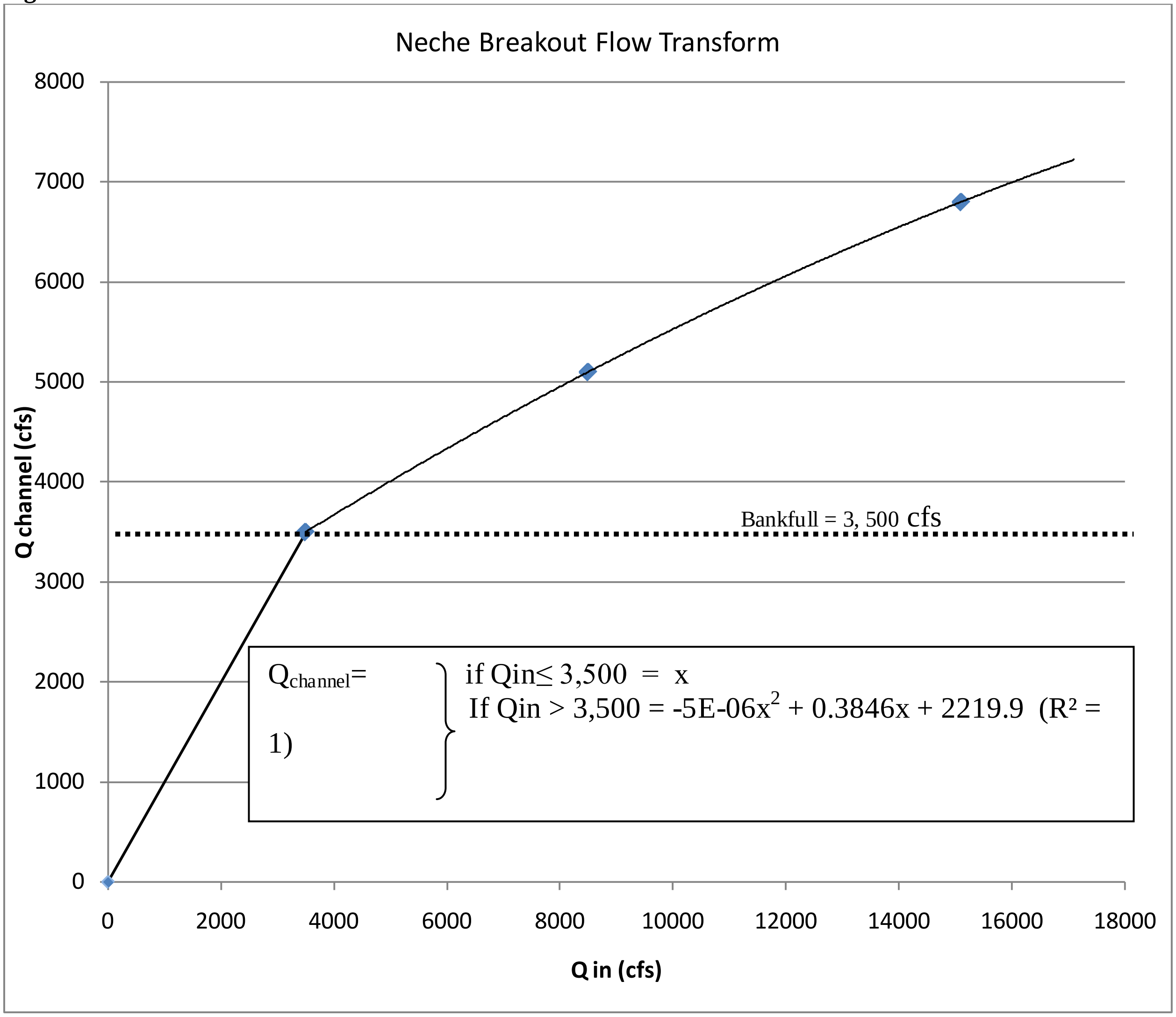
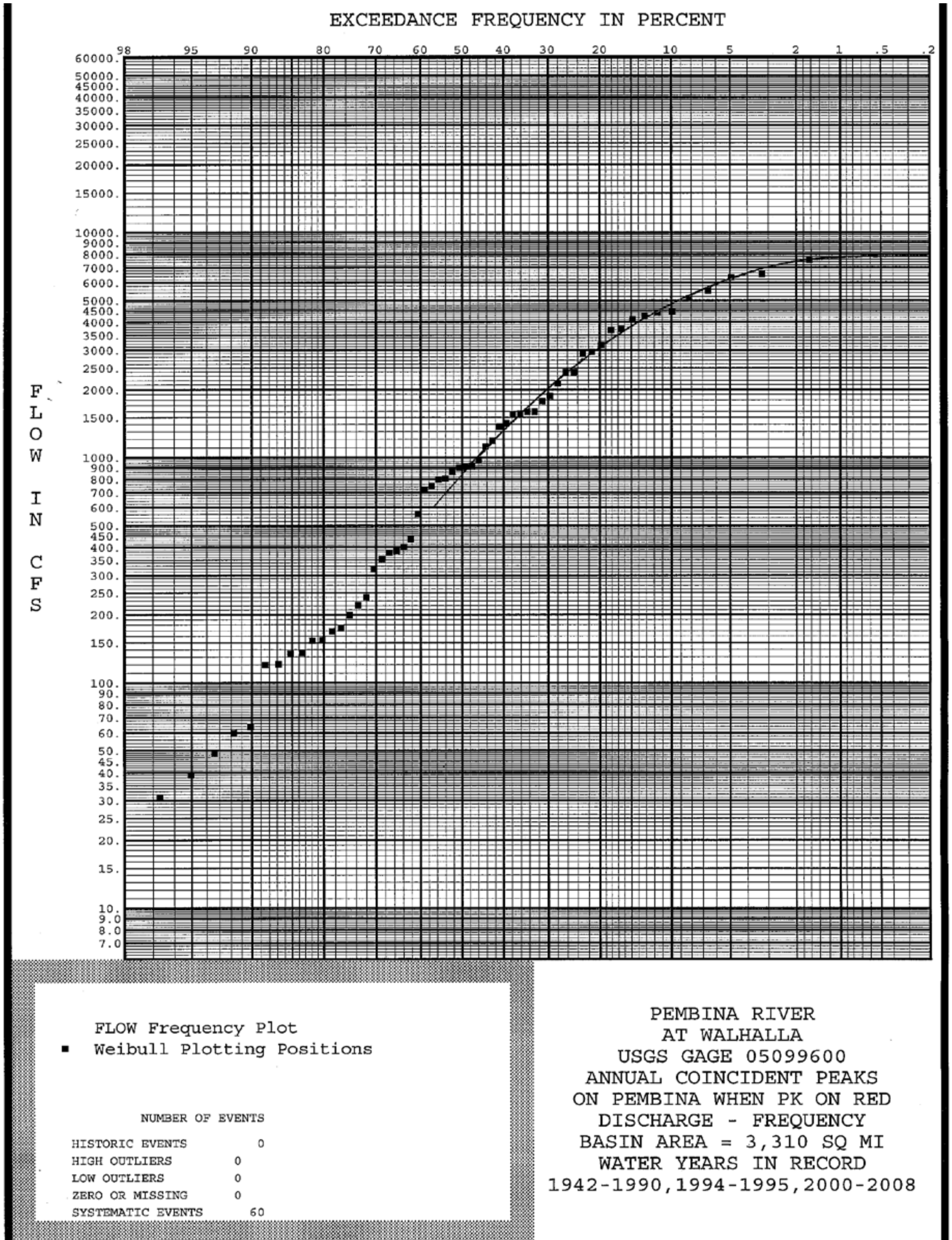


Figure 36. Two Rivers at Walhalla



Pencil Line = Graphical Flow Frequency Curve