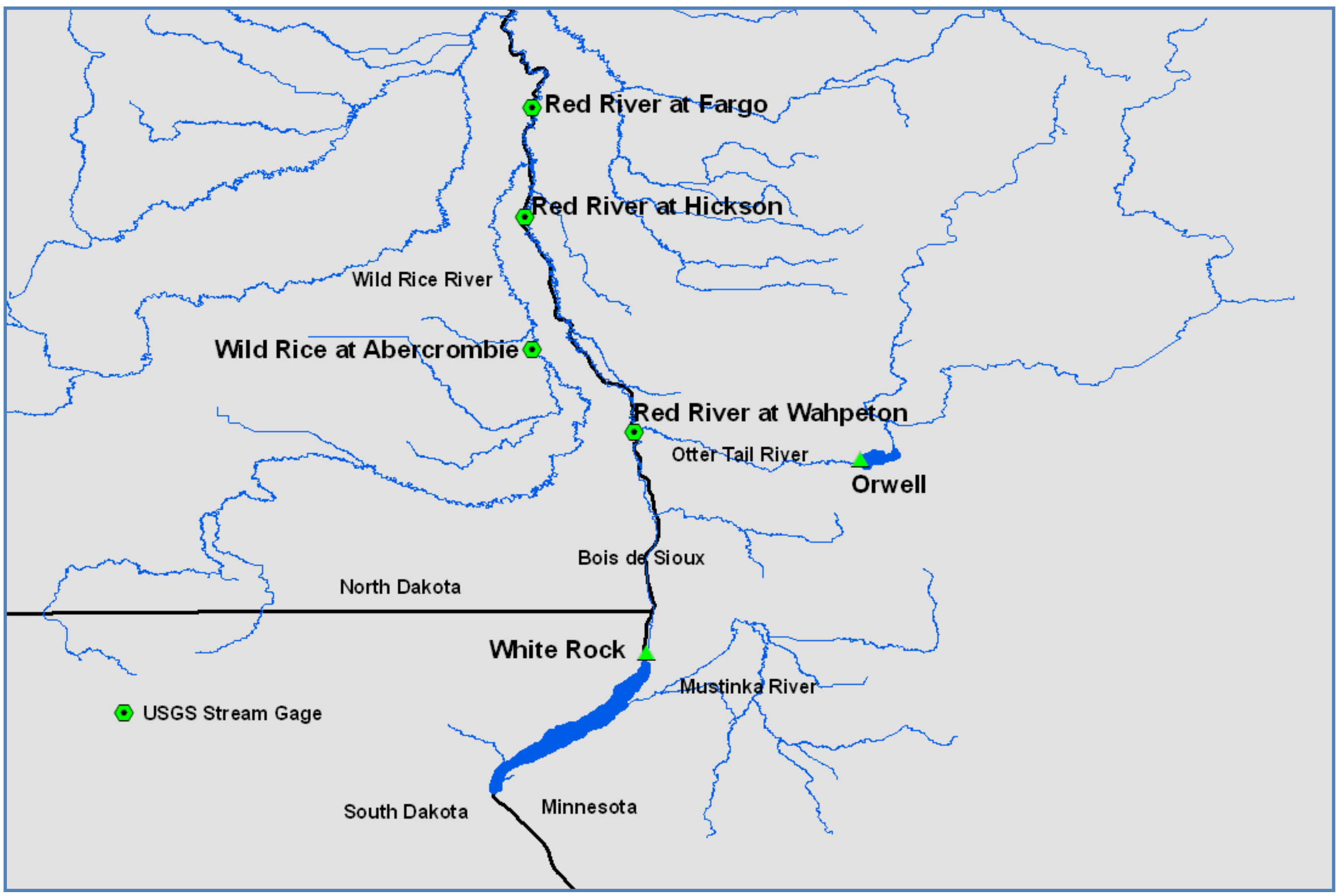
The Use of Synthetic Floods for Defining the Regulated Flow-Frequency & Volume Duration Frequency Curves for the Red River at Hickson, North Dakota



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1. Objective

The objective of this study is to develop the hydrology needed as input to the unsteady water surface profile model (HEC-RAS) for the Red of the North through the city of Hickson, North Dakota. The unsteady flow model requires balanced hydrographs for the 10%, 2%, 1%, 0.5% and 0.2% events.

It is equally important to develop synthetic hydrograph inputs to the Unsteady HEC-RAS model which reflect a statistically defined volume and peak at Hickson, North Dakota. Consequently, the synthetic event hydrographs used to assess the Fargo-Moorhead project have been developed to represent the 0.2, 0.5, 1, 2 and 10% flood peaks at Hickson, North Dakota as defined by the Hickson annual instantaneous flow-frequency curve. In addition to representing peak flows at each respective recurrence interval, the hydrographs were also developed to represent the 0.2, 0.5, 1, 2 and 10% volumes from the 3, 7, 15, and 30-day volume frequency curves at Hickson, North Dakota.

The Unsteady RAS model is being used to assess the impact that the proposed Fargo Moorhead Flood Control project will have on flood stages throughout the Red River Basin for the duration of a given flood event. The proposed Flood Control Diversion will impact the entire flood hydrograph and not just the flood peak.

Modeling extreme events like the 1%, 0.5% and 0.2% hydrograph for the with and without project condition in HEC-RAS allows modelers to gain a deeper understanding of how the diversion project will impact flood stages, hydrograph timing, tributary interactions, breakout flows, and floodplain storage throughout the Red River Basin. Modeling the entire flood hydrograph ensures that the basin-wide project impact (upstream and downstream of Fargo, North Dakota) is accurately assessed. An additional component of the Fargo Moorhead Flood Control project is man-made off channel storage. Modeling extreme events like the 1%, 0.5% and 0.2% hydrograph enables modelers assess the sizing, operation and placement of off channel storage.

The Hickson hydrology study reach extends from the White Rock Dam on the Bois de Sioux River and Orwell Dam on the Otter Tail River to Hickson, North Dakota on the Red River of the North. Due to the effects of upstream regulation, analytical techniques cannot be applied to develop balanced hydrographs at Hickson, North Dakota. Instead a graphical approach must be adopted. Because statistical means cannot be used to develop hydrographs greater in magnitude than those observed historically, synthetic, balanced hydrographs are generated to be representative of extreme event magnitudes. These synthetic events are developed using volume frequency analysis, a HEC-ResSIM model and an Unsteady HEC-RAS Model.

2. Background

Upstream of Hickson, North Dakota, the Red River of the North is formed by the confluence of the Bois de Sioux River and the Otter Tail River within the communities of Wahpeton, North Dakota and Breckenridge, Minnesota. The two reservoirs in the study area are: the Lake Traverse Reservoir Project on the Bois de Sioux River and Orwell Reservoir on the Otter Tail River. The total drainage areas upstream of the flood control reservoirs are 1,160 square miles above White Rock Dam, and 1,730 square miles above Orwell Dam. The Lake Traverse Project went into operation in water year 1942. Orwell Dam went into operation in water year 1953.

3. Available Observed Streamflow Data

As displayed in **Appendix A**, the U.S Geological Survey (USGS) maintains several continuous streamflow recording gages within the study area. Available streamflow data is listed in **Table 1**.

Table 1. Available USGS Streamflow Data

Available USGS Streamflow Data				
Station Number	Station Name	Period of Record	Drainage Area (sq. miles)	Notes
0505000	Bois de Sioux River near White Rock, SD	Oct. 1941 - Current year	1,160	Backwater effected by the Rabbit River, Regulated
05051300	Bois de Sioux River near Doran, MN	Oct. 1989 - Current year	1,880	Regulated
05046000	Otter Tail River Below Orwell Dam near Fergus Falls, MN	Oct. 1930 – Current year	1,730[1]	Pre-1953 published as "below Pelican River"
05046502	Otter Tail River at 11th St in Breckenridge, MN	Sept. 2001- June 2003, March to May 2011	unavailable	Fair Data Quality, Regulated, sporadic data
05046475	Otter Tail River Diversion at Breckenridge, MN	June 2005-Current year	not applicable	Periods of Flow Only, Regulated
05051500	Red River of the North at Wahpeton, ND	May 1942-Oct. 1942, March 1942-Current year	3,880[2]	Since 2005 provisional data/real time does not include diverted flow, regulated
0505152130	Red River of the North at Enloe, ND	Oct. 2009 - Current year	unavailable	Regulated, Seasonal
05051522	Red River of the North at Hickson, ND	Oct. 1975- Current year	4,170[3]	Regulated

[1]USGS published Drainage area 1,740 sq mi – updated drainage area from Red River Study Phase I Project
[2]USGS published Drainage area of 4,010 sq mi- error on USGS website
[3]USGS published Drainage area of 4,300 sq mi- error on USGS website

3.1. USGS Gage 0505000 Bois de Sioux River near White Rock, South Dakota

The continuous streamflow gage for the Bois de Sioux River near White Rock Dam is located 300 ft downstream from White Rock Dam, four miles south of the White Rock, South Dakota and five miles northwest of Wheaton, MN. The total drainage area regulated by White Rock Dam is 1,160 sq miles. Flows are regulated by the Lake Traverse Project. At times, outflow measurements are effected by backwater from the Rabbit River. The period of record at the gage is from water year 1942 (when the dam began operating for flood control) to the current year. The largest recorded instantaneous peak discharge was 8,750 cfs on April 20, 1997, with the highest recorded instantaneous peak stage of 16.90 feet occurring on the same day.

3.2. USGS Gage 05051300 Bois de Sioux River near Doran, Minnesota

The continuous streamflow recording station for the Bois de Sioux River near Doran, Minnesota is located 6.3 miles downstream of the Rabbit River's confluence with the Bois de Sioux River and approximately 10 miles upstream of the Otter Tail River's confluence with the Bois de Sioux River. The Doran gage is located upstream of the County Ditch No. 55 and State Highway 127 breakout flow area. The largest recorded instantaneous peak discharge at Doran, Minnesota was 12,300 cfs on April 16, 1997, with the highest recorded instantaneous peak stage of 24.42 feet occurring on the same day. The total drainage area at the gage is 1,880 square miles. There is 720 square miles of incremental drainage area between White Rock Dam and Doran, Minnesota.

3.3. USGS 05046000 Otter Tail River below Orwell Dam, near Fergus Falls, Minnesota

The continuous streamflow gage for the Otter Tail River below Orwell Dam is located 0.7 miles downstream from Orwell Dam and eight miles southwest of Fergus Falls, Minnesota. The total drainage area upstream of Orwell Dam is 1,730 square miles. The period record at the gage is from October 1930 to the current year. Flows began being regulated by Orwell Dam in March 1953.

Prior to October 1952, data was published as Otter Tail River below Pelican River. In 1953, the gage was relocated to a site 6.1 miles upstream to its current location. The largest recorded instantaneous peak discharge (since Orwell Dam began operating in March 1953) was 2,040 cfs on May 29, 2001, with the highest recorded instantaneous peak stage of 5.46 feet occurring on the same day.

3.4. USGS gage 05056502 Otter Tail River at 11th Street in Breckenridge, Minnesota

USGS gage 05056502 is located on the Otter Tail River just upstream of the Otter Tail River Diversion on the downstream side of the 11th Street Bridge in Breckenridge, Minnesota. The gage has a limited period of record from September 2001 to June 2003 and from March to May 2011. The gage was installed to carry out water quality analysis. Consequently, the record is only of “fair” data quality. Flow data collected at this site was not adopted for this study and was only used for verify the distribution of local flow between the Otter Tail River and the Bois de Sioux River.

3.5. USGS Gage 05051500 Red River of the North at Wahpeton, North Dakota

The continuous streamflow recording station for the Red River of the North at Wahpeton, ND (USGS gage 05051500) is located at river mile 548.6, 800 feet downstream from the confluence of the Bois de Sioux River and the Otter Tail River (see **Appendix A**). The Wahpeton gage is located upstream of where flows from the Otter Tail River Diversion project reach the Red River of the North.

Flows observed at the USGS gage at Wahpeton have historically been affected by breakout flows from the Bois De Sioux River. Discharges measured at Wahpeton, North Dakota are regulated by Orwell Reservoir, the Otter Tail River Diversion and the Lake Traverse Project.

Since June 2005, Otter Tail River flows are partially diverted around Breckenridge, Minnesota. The diverted flows are measured at streamflow station 05046475, Otter Tail River Diversion at Breckenridge, Minnesota. The USGS publishes a flow record for USGS gage 05051500 representative of the measured flows at Wahpeton, North Dakota. This flow record is referred to as "Red River Only." The USGS also publishes a daily, historic, combined flow record that is representative of flows from the Red River of the North plus diverted flows. Real time data and Instantaneous annual peak flow data published at Wahpeton, North Dakota is representative of "Red River Only" flows.

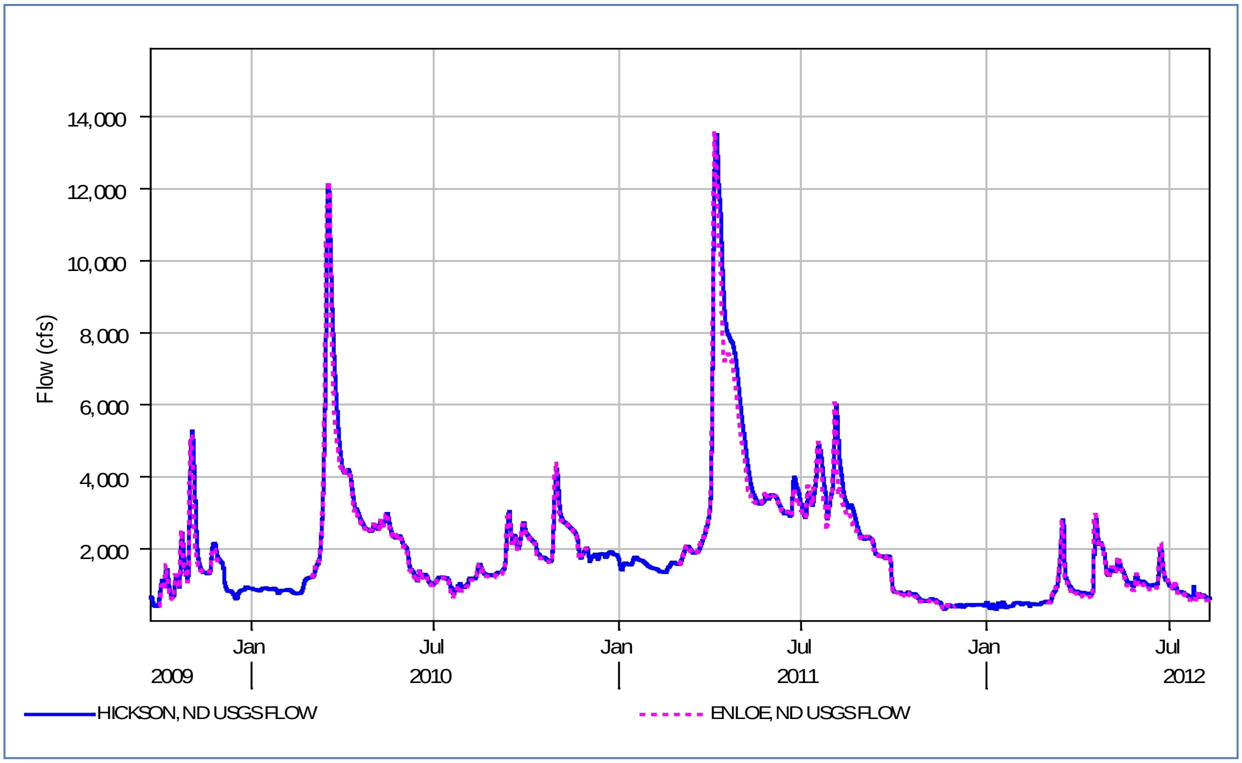
3.6. USGS 05046475 Otter Tail River Diversion at Breckenridge, Minnesota

This streamflow gage is reflective of the flows that are diverted from the Otter Tail River around Breckenridge, Minnesota, before re-entering the Red River of the North downstream of Breckenridge/Wahpeton. The gage is located at State Highway 210, on the north side of Breckenridge, Minnesota. The period of record at this site is June 2005 to the current year. Discharge is only reported during periods of flow. The highest recorded instantaneous peak discharge through the diversion was 5,400 cfs on March 24, 2009, with the highest recorded instantaneous peak stage of 20.32 feet occurring on the same day.

3.7. USGS gage 0505152130 Red River of the North at Enloe, North Dakota

In October 2009, a seasonally reporting USGS streamflow gage (0505152130) was installed along the mainstem of the Red River at Enloe, North Dakota (see **Appendix A**). Flows measured at Enloe are regulated by Orwell Reservoir and the Lake Traverse Project. The USGS's StreamStats program was used to approximate the drainage area at Enloe, North Dakota. As can be seen in **Figure 1**, due to the small amount of incremental drainage area between Enloe and Hickson, the flows observed at these locations are almost equivalent.

Figure 3-1. Comparison Observed data at Enloe, ND and Hickson, ND



3.8. USGS gage 05051522 Red River of the North at Hickson, North Dakota

As can be seen from **Appendix A**, the USGS gage at Hickson, North Dakota (05051522) is located six miles upstream of the confluence of the Wild Rice River (North Dakota) with the Red River of the North. The station has a relatively short record from 1976 to present. The flood of record occurred in 2009 on March 26th with an annual instantaneous peak flow of 23,700 cfs. Flows observed at the USGS gage at Hickson have historically been affected by breakout flows from the Bois De Sioux River and regulation by Orwell Dam and White Rock Dam. Unsteady HEC-RAS modeling of extreme events (greater than the 2% event) has demonstrated that there is the potential for significant breakout flows to occur from the Wild Rice River near Abercrombie, North Dakota to reach the Red River of the North between Enloe and Hickson.

4. Drainage Area Analysis

Total drainage areas used as part of analysis are displayed in **Appendix B** and **Table 2**. Drainage area values were determined using USGS data, the Red River Diversion Project Feasibility and Environmental Impact Statement Analysis (FEIS), the Red River Study Phase I and the USGS Minnesota StreamStats tool. This investigation indicates that some of the published USGS values for total drainage area along the mainstem of the Red River of the North are too high.

The USGS publishes a total drainage area of 1,160 square miles at the USGS gage located on the Bois de Sioux River just downstream of White Rock Dam, South Dakota. This drainage area was verified using the Minnesota StreamStats tool. The USGS publishes a total drainage area of 1,880 square miles at the USGS gage located on the Bois de Sioux River near Doran, Minnesota. This drainage area was verified using the Minnesota StreamStats tool. As part of the Red River Diversion Project FEIS report the total drainage area associated with the Bois de Sioux River upstream of the Otter Tail River was published as 1,970 square miles. This drainage area was verified using the Minnesota StreamStats Tool. Because the drainage areas published by the USGS, the values adopted for the Red River Diversion Project FEIS, and the drainage areas determined using Minnesota StreamStats are consistent, the Red River Phase I results were not consulted for the Bois de Sioux River.

There is an inconsistency between the drainage areas being published by the USGS at the two USGS gages near Orwell Reservoir. The USGS currently publishes a total drainage area of 1,830 square miles for gage site 05045950 Orwell Lake near Fergus Falls, Minnesota and a total drainage area of 1,740 square miles for gage site 05046000 Otter Tail River below Orwell Dam (0.7 miles downstream of Orwell Dam). As part of the Red River Diversion Project Feasibility Study Report a total drainage area of 1,830 square miles was adopted for Orwell Dam. Both Minnesota StreamStats and the Red River Study Phase I analysis were consulted to remediate this discrepancy. StreamStats identifies a total drainage area of 1,725 square miles above Orwell Dam. Red River Study Phase I results indicate a total drainage area of 1,728 square miles above Orwell Dam. The total drainage area of 1,830 square miles at Orwell Dam does not appear to be correct.

The digital elevation model (DEM) used to carry out the drainage area analysis as part of the Red River Study Phase I was a 5-meter DEM based on LiDAR data, while Minnesota StreamStats and the USGS typically use lower resolution DEMs to delineate drainage areas. Consequently, the output from the Red River Phase I analysis will be used to define the drainage area along the Otter Tail River. Red River Phase I results indicate that the total drainage above Orwell Dam is approximately 1,730 square miles and that the total drainage area between the dam and the Otter Tail River's confluence with the Red River of the North is 180 square miles. Red River Phase I results for the drainage area between Orwell Dam and the Otter Tail River's confluence with the Red River of the North were also verified using the Minnesota StreamStats Tool.

The USGS currently assigns a total drainage area of 4,010 square miles to the USGS gage at Wahpeton, North Dakota. Wahpeton, North Dakota is just downstream of the confluence of the Otter Tail River with the Bois de Sioux River. If the verified total drainage areas associated with the Otter Tail River (1,910 square miles) and the Bois de Sioux River (1,970 square miles) are combined the drainage area at Wahpeton, North Dakota should be approximately 3,880 square miles. This drainage area was verified using the Minnesota StreamStats tool. The adopted total drainage areas for the USGS gages at Enloe, ND and Hickson, ND (shown in the schematic in **Appendix B** and in Table 1), were verified using Minnesota StreamStats. The 130 sq. mi. reduction between the adopted and published drainage area at Wahpeton is also present at Hickson.

Table 2. Local Total Drainage area distribution – Wahpeton, ND to Hickson, ND

Total Drainage Area – Red River of the North		
Site	**Total Adopted D.A (sq mi)**	**Source**
USGS gage Bois de Sioux River near White Rock, SD	1,160	USGS
Bois De Sioux Incremental Local D.A	720	
USGS gage near Doran, MN	1,880	USGS
Bois De Sioux Incremental Local D.A	90	
Total Drainage Area Bois de Sioux River	1,970	Minnesota StreamStats/FMMFS *[FMMFS D.A: 1,967 sq mi]*
USGS gage Otter Tail River Below Orwell Dam near Fergus Falls, MN	1,730	USGS/Red River Phase I Study *[USGS: 1,740 sq mi]*
Otter Tail Incremental Local D.A	180	
Total Drainage Area Otter Tail River	1,910	Minnesota StreamStats/Red River Phase I *[RRN Study D.A: 180 sq mi total drainage area; 160 contributing drainage area]*
USGS gage Red River at Wahpeton, ND	3,880	Minnesota StreamStats *[USGS D.A: 4,010 sq mi total drainage area]*
Red River Incremental Local D.A	260	
USGS gage Red River at Enloe, ND	4,140	Minnesota StreamStats
Red River Incremental Local D.A	30	
USGS gage Red River at Hickson, ND	4,170	Minnesota StreamStats *[USGS D.A: 4,300 sq mi total drainage area]*

D.A = Drainage Area, RRN = Red River of the North, FMMFS = Fargo-Moorhead Metro Flood Risk Management Project Feasibility Study

The total drainage areas at the USGS gage sites listed in **Table 2** are used to determine the local incremental drainage areas contributing to the Red River of the North/Bois de Sioux River between gage sites. It is important to accurately characterize the incremental local drainage areas between gage sites within the study area because drainage area ratios are applied to distribute local flows.

5. Record Extension- Red River at Doran, MN

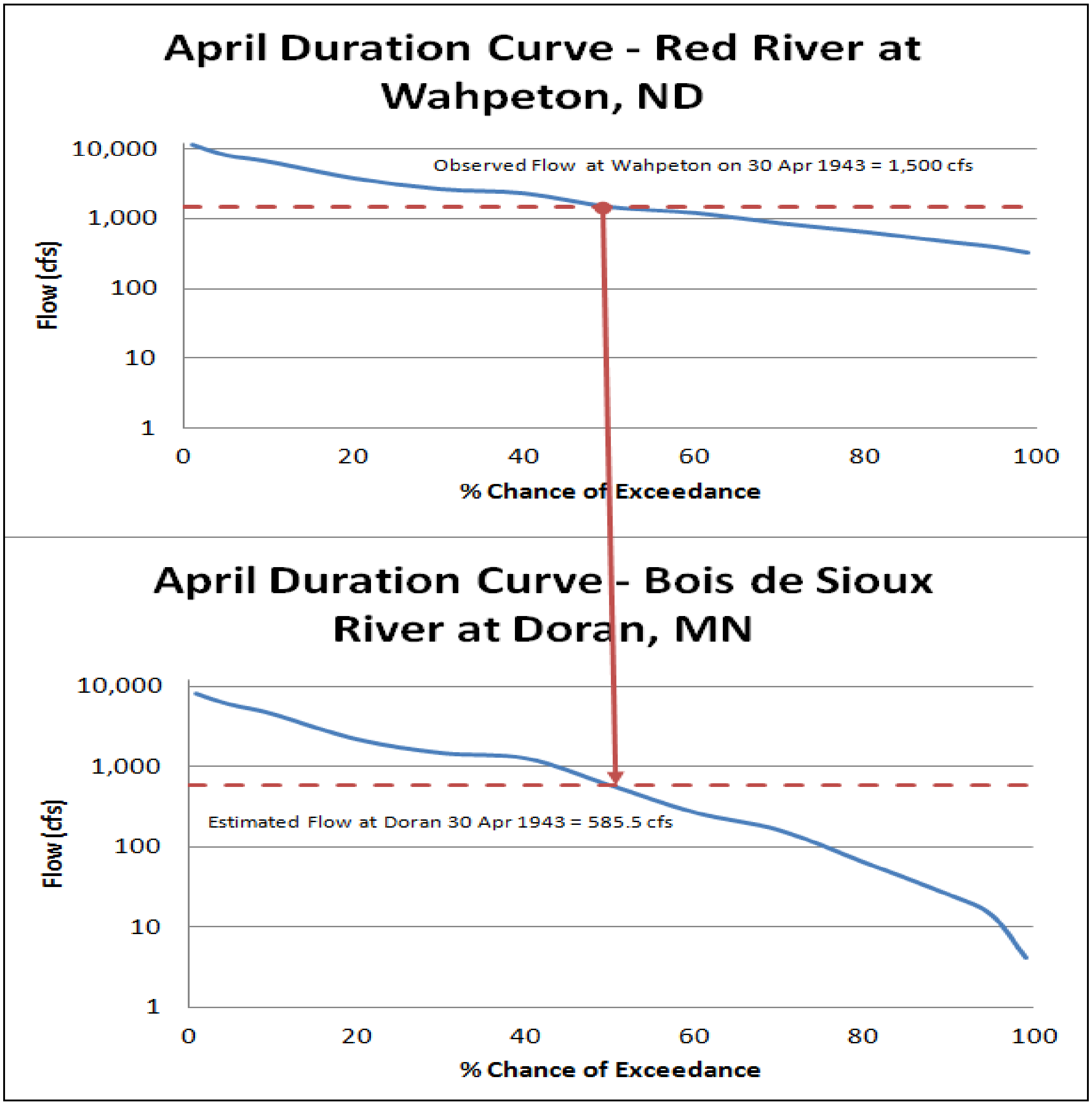
The period of record for analysis is 1942-2009. The daily streamflow record at Doran, Minnesota only starts in water year 1990. To help define the local flow contribution along the mainstem of the Bois de Sioux, an approximation of the daily flow record at Doran, Minnesota was made between 1942 and 1989. The daily streamflow record at Doran, Minnesota is back extended using a flow duration curve algorithm using the long-term station at Wahpeton, North Dakota. The daily flow record at White Rock Dam, North Dakota was also considered for extension, but the gage site at Wahpeton, North Dakota had a stronger linear correlation to flows observed at Doran, Minnesota.

Although there is a strong correlation between the magnitude of the annual instantaneous peaks observed at the USGS gage at Wahpeton, North Dakota and the USGS gage at Doran, Minnesota, the relationship between the daily flow magnitudes at these two sites varies considerably. This variation is caused by the regulated flow contributions from the Otter Tail River. The Otter Tail River reaches its confluence with the Bois de Sioux River between Doran, Minnesota and Wahpeton, North Dakota. The flow duration curve algorithm was applied, instead of a linear regression based technique such as Maintenance of Variance Equations (MOVE.1) or a general relations based record extension technique. The flow duration curve based algorithm was selected because it can capture a non-linear relationship between the flows observed at two sites.

5.1. Summary of Flow Duration Algorithm Record Extension Technique

Researchers D.A Hughes and V. Smakhtin (1996) found that flow time series can be patched or extended using a spatial interpolation approach based on flow duration curves. As is demonstrated by the example displayed in **Figure 2**, this technique uses the 1-day flow duration curves for each month of the year. The technique is based upon the assumption that flows occurring simultaneously at sites in reasonably close proximity to each other have similar flow duration percentages.

Figure 5-1. Flow-Duration Based Algorithm applied to estimate flows at Doran, MN



An estimate of the streamflow on any day at the short term gage site is made by identifying the percentage point position on the duration curve table of the streamflows on the same day at the long term station and reading off the flow value for the equivalent percentage point from the short term destination site's duration curve.

5.2. Evaluation of Estimated Streamflows

Between 1990 and the current year the Doran and Wahpeton gages are both recording daily flow measurements. The observed record at Doran is compared to the record at Doran estimated for the concurrent period using the flow duration curve algorithm. The Nash-Sutcliffe coefficient (N-S) was calculated to assess the predictive power of the flow duration curve algorithm for several years of the concurrent record (1993, 1995, 1997, 2002, 2005, 2007, 2009, and 2011). The N-S coefficient can range from negative infinity to one. The closer the N-S efficiency coefficient is to 1, the better the match to modeled discharge data. An efficiency coefficient lower than zero indicates that using the average value associated with the observed data series would be a better predicator than the modeled data. The average N-S coefficient was found to be equivalent to 0.90 which is close to one (significant higher than zero), indicating that the flow duration curve algorithm can be used to approximate the flow record at Doran, Minnesota. A comparison of estimated flows at Doran, Minnesota and USGS observed flows are shown in **Plate I**.

6. Record Extension – Red River at Hickson, North Dakota

The period of record for analysis is 1942-2009. Because the daily streamflow record at Hickson begins in 1976, an approximation of the record is made from 1942 through 1975. The daily streamflow record at Hickson is back-extended using the Maintenance of Variance Extension (MOVE.1) Type One technique. Because no significant tributaries reach their confluence with the Red River between Wahpeton and Hickson and because there are no regulatory structures between Wahpeton and Hickson it is appropriate to apply MOVE.1. The flow duration algorithm could also be applied, but in comparison to a MOVE.1 analysis applying the flow duration algorithm is more tedious. Additionally, MOVE.1 is a more widely used technique in water resources planning. Both the streamflow record at Fargo, North Dakota and the record observed at Wahpeton, North Dakota was considered to extend the record at Hickson. Using linear regression it was determined that peak flows and average semi-monthly flows at Wahpeton are more strongly correlated to flows at Hickson, than the flows observed at Fargo, North Dakota.

6.1. Summary of MOVE.1 Technique

The purpose of a MOVE.1 analysis is to fill in flows for an extended period in order to produce a nearly unbiased estimate of mean and variance. It is used primarily for water resources planning and management models, as well as for reservoir design and operation. Unlike a simple linear regression, MOVE.1 captures the variance in the flows recorded at the two sites being compared. Consequently, MOVE.1 can be applied to two mainstem locations, while simple linear regression cannot. MOVE.1 was first described by Hirsch in 1982. The MOVE.1 equation is defined as **Equation 1** below.

EQUATION 1: $\hat{Y} = m(y_1) + \frac{Sy}{Sx}[\hat{X}_T - m(x_1)]$

$\hat{Y}$= Flow at Partial Stations

$m(y_1)$ = Mean Partial Station
sy = standard deviation partial gage station
sx= standard deviation index station
$\hat{X}_T$= Observed Flow at index station
$m(x_1)$= Mean Index Station.

MOVE.1 was carried out to extend the daily streamflow record at Hickson using the statistics associated with the daily records, semi-monthly records and annual peak records at Hickson and Wahpeton. When compared to observed flows at Hickson, semi-monthly statistics provided the best estimate of daily flows at Hickson, North Dakota.

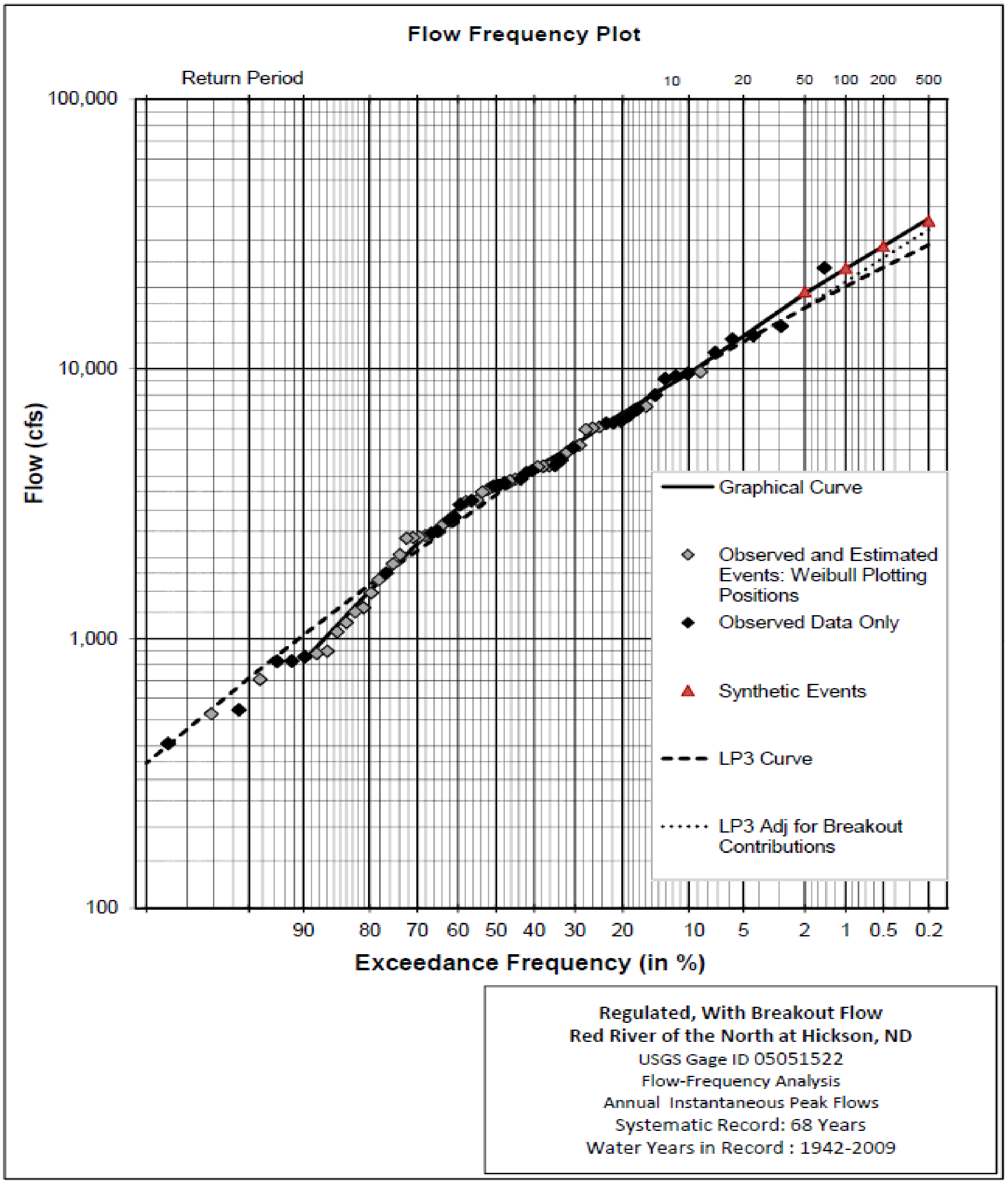
6.2. Evaluation of Estimated Streamflows

Between 1976 and the current year daily streamflow readings are available at both the Hickson and Wahpeton gages. The observed record at Hickson is compared to the concurrent, estimated record at Hickson determined using MOVE.1. The Nash-Sutcliffe coefficient (N-S) was calculated to assess the predictive power of the MOVE.1 equation for several years of the concurrent record (1982, 1991, 1997, 2001, 2003, 2007, 2009 and 2011). The N-S coefficient can range from negative infinity to one. Essentially, the closer the N-S efficiency coefficient is to 1, the better the match to modeled approximated discharge data. An efficiency coefficient lower than zero indicates that using the average value associated with the observed data series would be a better predicator than the modeled data. The average N-S coefficient was found to be equivalent to 0.85 which is close to one (significant higher than zero), indicating that MOVE.1 can be used to approximate the flow record at Hickson, North Dakota.

A comparison of estimated flows at Hickson, North Dakota and USGS observed flows are shown in **Plate II**. It is challenging to approximate long periods of flow data for a wide range events when there is no gaged data available. The results generated using a record extension technique will never match an observed record perfectly. As can be seen from **Plate II**, the MOVE.1 extension technique is able to replicate moderate flow magnitudes at Hickson, North Dakota, but tends to underestimate peak flows at Hickson, North Dakota that exceed 10,000 cfs.

To generate a peak flow at Hickson, North Dakota of 10, 000 cfs the coincident peak at Wahpeton, North Dakota would have to be at least 7,000 cfs. There are very few observed events with discharges above 7,000 cfs at Wahpeton, North Dakota. Pre-1975 the only events that could potentially generate a 10,000 cfs peak at Hickson would be the 1969 event and the 1952 event. The rest of the events have peaks at Wahpeton of substantially less than 7,000 cfs. Admittedly, the assumed peak magnitudes estimated for the 1969 and 1952 events at Hickson, North Dakota might be a bit low because it is difficult to make blanket approximations of streamflow data when a gaged record does not exist. Because the majority of the major flood events that have occurred in the Red River Basin, have happened since 1975, the shape of the upper end of the flow-frequency curve at Hickson, North Dakota is not significantly influenced by the approximated pre-1975 data points (see Figure 6-1).

Figure 6-1. Flow-frequency curve at Hickson, North Dakota Observed vs Adopted plotting positions



Because observed streamflow data is used for the majority of the years of analysis and because for the more moderate events the MOVE.1 approach does a very reasonable job of approximating daily flow data the MOVE.1 technique fulfils the objectives of this analysis.

7. Hydrologic Routing Model

The portion of the Red River Basin between White Rock, South Dakota and Hickson, North Dakota consists of the Bois de Sioux River, the Otter Tail River and a portion of the Red River of the North.

7.1. River Reach Routing

The Bois de Sioux River between White Rock, South Dakota and the confluence of the Otter Tail River with the Bois de Sioux River was broken up into two routing reaches:

- Bois de Sioux River Reach 1 (BDS_R1): White Rock Dam to Doran, MN
- Bois de Sioux River Reach 2 (BDS_R2): Doran, MN to just upstream of the Otter Tail River's confluence with the Bois de Sioux

The Otter Tail River was broken up into three routing reaches between Orwell Dam and the Otter Tail River Diversion (OT_R1, OT_R2, and OT_R3).

The Red River of the North between Wahpeton and Hickson was broken up into two routing reaches:

- Red River of the North Reach 1 (RRN_R1): Wahpeton, ND (downstream of Diversion) to Enloe, ND
- Red River of the North Reach 2 (RRN_R2): Enloe, ND to Hickson, ND

A schematic of the adopted routing reaches is displayed in **Appendix C**.

According to Table 9-3 in EM 1110-2-1417, when channel slopes are less than 2 ft/mi, hydraulic routing techniques (diffusion wave and full dynamic wave) produce the best results. The HEC-ResSIM model is limited to hydrologic routing techniques. Diffusion wave and full dynamic wave routing are unavailable within HEC-ResSIM or HEC-HMS. To address this model shortcoming, modified puls routing relationships calibrated to an unsteady HEC-RAS model are adopted to route flows from White Rock, South Dakota to Hickson, North Dakota. An unsteady HEC-RAS model was used to develop baseline Modified Puls storage-discharge routing relationships. Documentation related to unsteady HEC-RAS model used to develop baseline Modified Puls relationships is included as **Appendix D**.

For flat reaches it is difficult to come up with a representative storage-discharge relationship because the dynamic properties of a flood wave create a looped relation between storage and discharge (hysteresis). The transverse water surface slope and available storage are greater during the rising stages of a flood wave than during the falling stages. The loop effect makes it difficult to produce a definitive storage-discharge relationship using the Unsteady RAS model. Consequently, the baseline storage discharge relationship approximated using the RAS model must be adjusted to match hydrologic routing output to HEC-RAS model output. In addition to modifying the storage-discharge relationship itself, the associated subreach parameter was adjusted until hydrologic model output matched HEC-RAS output.

Eleven test hydrographs of varying magnitude were routed through the HEC-RAS model and the hydrologic routing model to calibrate modified puls relationships. To calibrate reach routing, each individual mod puls relationship was modified until routed flow volume and peak matched HEC-RAS output within 1% and the timing of the peak matched HEC-RAS output within 12 hours. This criterion was met for the majority of flood magnitudes considered. Adopted storage discharge relationships and cumulative routing calibration results are displayed in **Plate III**. Routing calibration results are displayed in **Plate VI**.

7.2. Breakout flows: Bois de Sioux River to Wild Rice River

During high flow conditions, breakout flows occur from the Bois de Sioux River to the Wild Rice River in North Dakota. Breakout flows happen downstream of the USGS gage at Doran, Minnesota (No. 0501300) and upstream of the confluence of the Bois de Sioux River and the Otter Tail River. For flood events on the Bois de Sioux River that have a return period equal to about 5 years, flow begins to back up County Ditch No. 55 at North Dakota State Highway 127 from the Bois de Sioux River, approximately 3 miles south of the Wahpeton, North Dakota. When larger flows are observed on the Bois de Sioux River (as in 1997 and 2009), flood waters start to flow over State Highway 127 about one-half mile south of the Wahpeton airport. These breakout flows continue to the northwest, and eventually reach the Wild Rice River. The Wild Rice River joins the Red River of the North between Hickson, North Dakota and Fargo, North Dakota. A diagram displaying breakout flow locations is displayed in **Figure 3.** A table and corresponding figure displaying the adopted breakout flow relationship are displayed in **Table 3** and **Figure 4**, respectively. The breakout flow rating curve was developed using the HEC-RAS model and is dependent on flows observed at the USGS gage at Doran, Minnesota.

Figure 7-1. Breakout Flows/ Backwater Effects

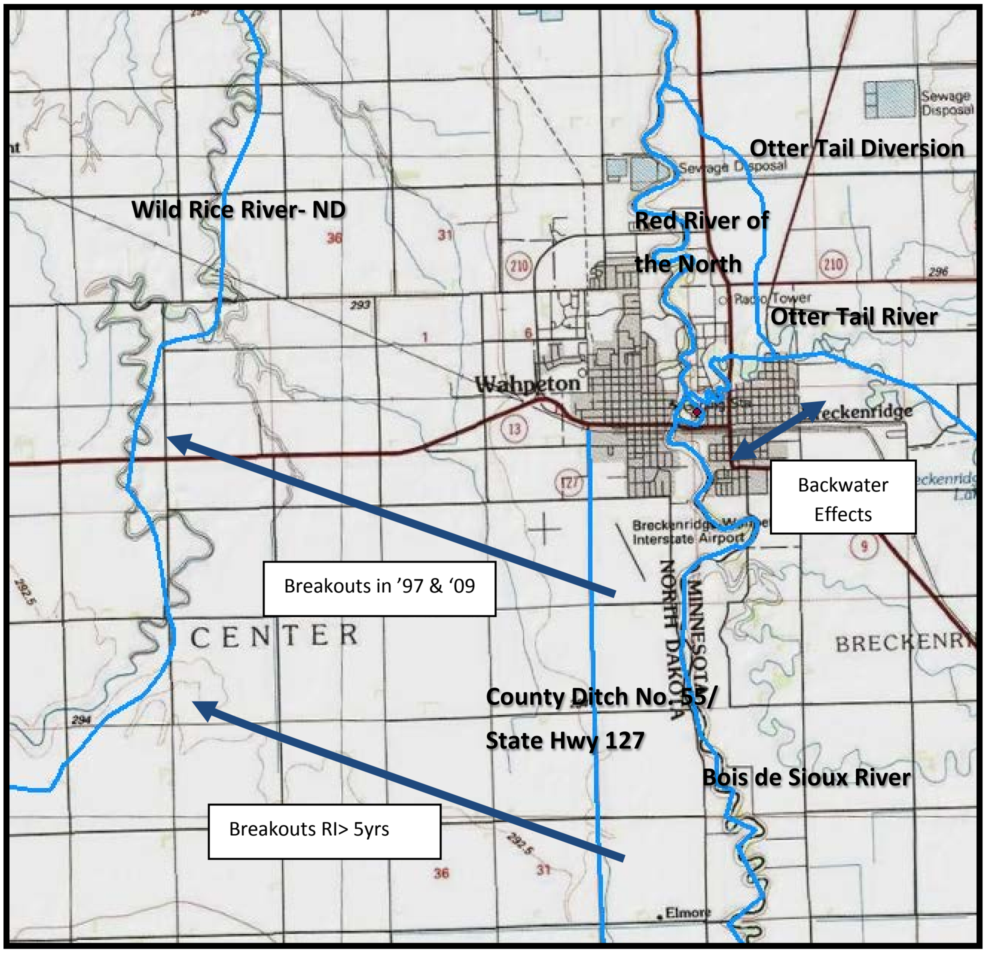
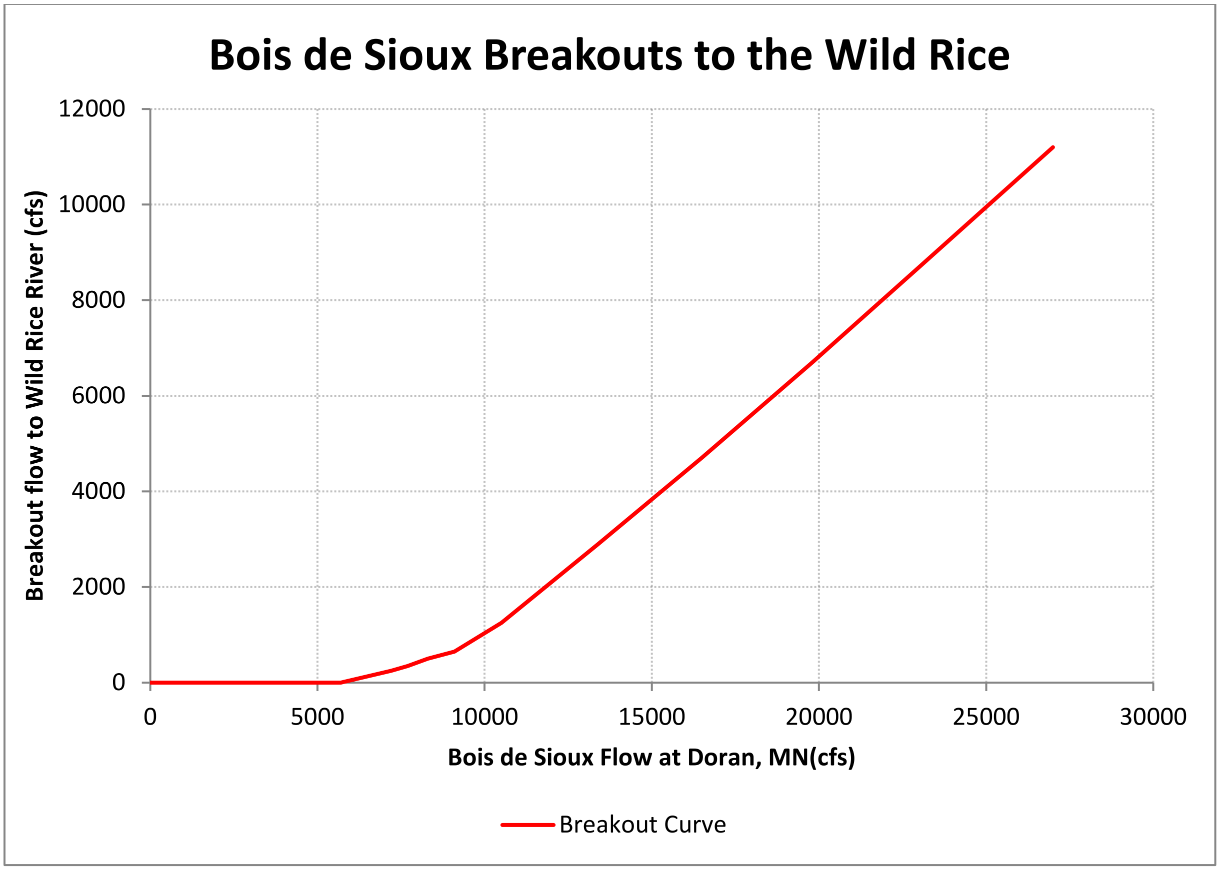


Table 3. Breakout flow relationship: Bois de Sioux River to the Wild Rice River

Adopted Breakout Flow Relationship	
Flow at USGS gage Doran (cfs)	Breakout Flow (cfs)
0	0
5,700	0
7,200	250
7,700	350
8,300	500
9,100	650
10,500	1,250
13,400	2,900
16,500	4,700
19,800	6,700
23,000	8,700
27,000	11,200

Figure 7-2. Adopted Breakout Flow Relationship- Bois de Sioux to Wild Rice River



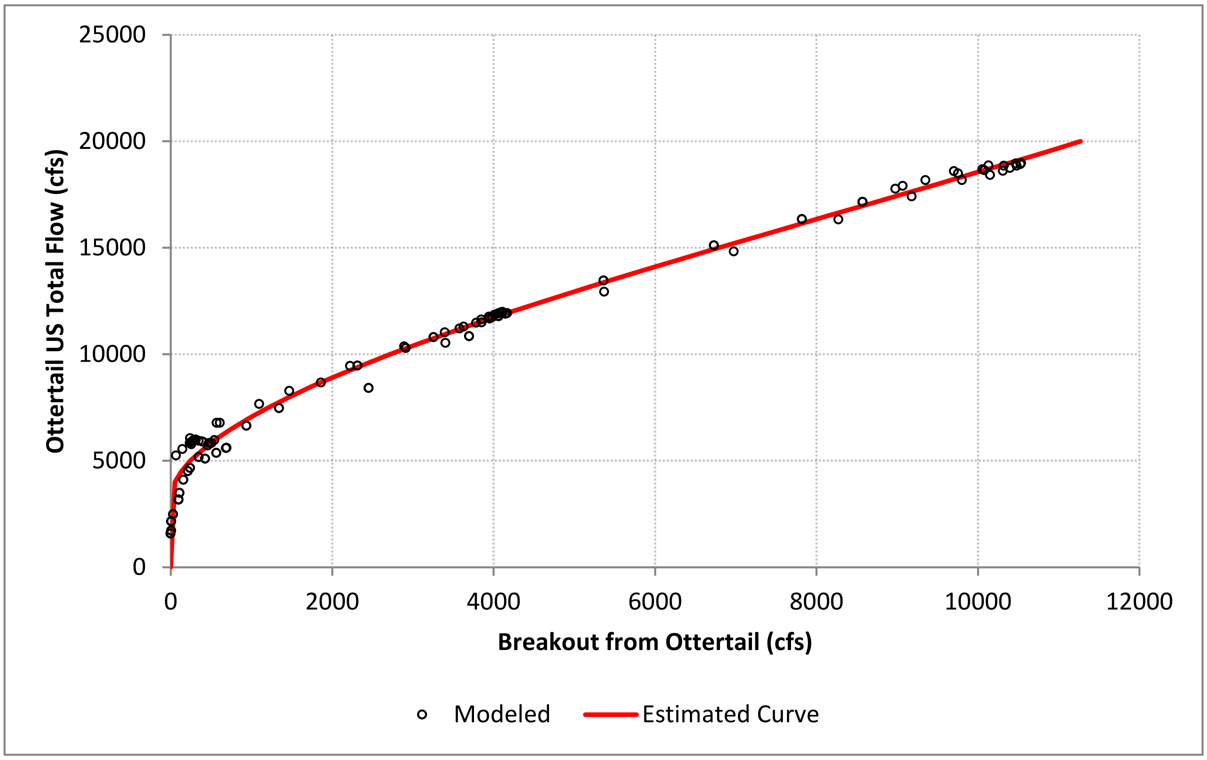
An indication of how well the breakout flow is modeled in the hydrologic routing model is displayed in **Plate V**. Breakout flows reported by the hydrologic routing model are compared to breakout flow hydrographs modeled in HEC-Unsteady RAS.

7.3. Breakout flows: Otter Tail River to Red River

The Unsteady HEC-RAS model was used to assess when breakout flows begin to occur from the Otter Tail River. Breakout flows from the Otter Tail River start becoming substantial when flows at a point approximately half-way (relative to incremental drainage area) between Orwell Dam and the Otter Tail's confluence with the Red River of the North are greater than 5,000 cfs. Historically, no substantial breakout flows have been observed from the Otter Tail River.

According to the Unsteady HEC-RAS model, a portion of these breakout flows will reconvene with the Otter Tail River further downstream with the rest entering the Bois de Sioux River basin between Doran, Minnesota and Breckenridge, Minnesota. **Figure 5** displays the relationship between flows on the Otter Tail River at the downstream end of the hydrologic routing reach immediately downstream of Orwell Dam (OT_R1 in **Appendix C**) and the estimated breakout flows.

Figure 7-3. Otter Tail River Breakout flow

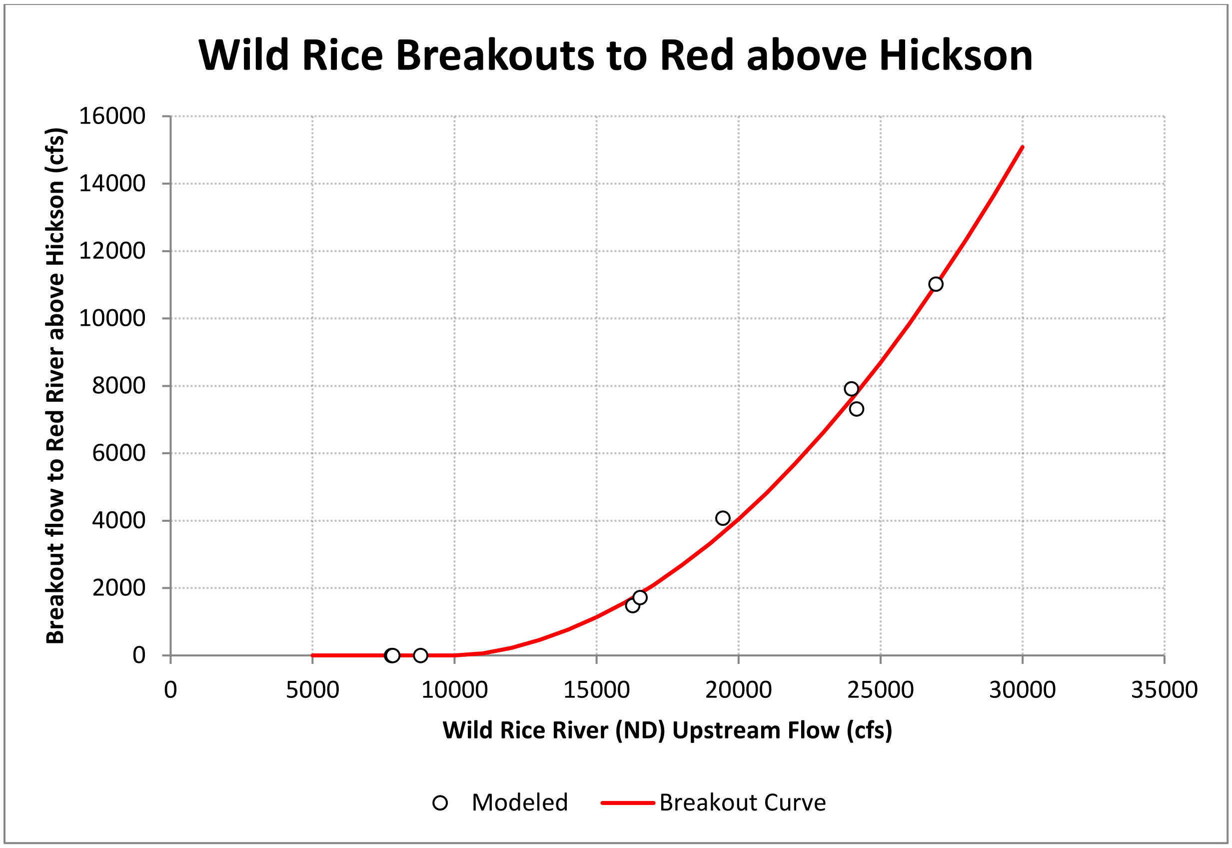


7.4. <u>Breakout flows: Wild Rice River (North Dakota) to the Red River of the North</u>

The Unsteady HEC-RAS model was used to assess when breakout flows begin to occur from the Wild Rice River (North Dakota) to the Red River of the North near Enloe and Hickson. Breakout flows from the Wild Rice River start becoming substantial when flows observed at the USGS gage near Abercrombie, North Dakota (USGS gage 05053000) exceed 14,000 cfs. Historically no significant breakout flows have been observed from the Wild Rice River (North Dakota) to the Red River of the North between Wahpeton and Hickson.

According to the Unsteady HEC-RAS model, about 50% of predicted breakout flows will reach their confluence with the Red River near Enloe, North Dakota and the remaining volume of breakout flows will converge with the Red River near Hickson, North Dakota. **Figure 6** displays the relationship between flows on the Wild Rice River at Abercrombie, North Dakota and the total flow that breaks out to the Red River of the North between Enloe and Hickson.

Figure 7-4. Wild Rice (North Dakota) breakout flow to the Red River



The relationship displayed in **Figure 6** is used to determine the corresponding breakout flow contribution from the Wild Rice River to the Red River of the North for a given event. For hydrologic modeling purposes it is assumed that fifty percent of the resulting breakout flow hydrograph reaches the Red River of the North near Enloe, North Dakota and that fifty percent of the resulting breakout flow hydrograph reaches the Red River of the North near Hickson, North Dakota.

7.5. Otter Tail Diversion

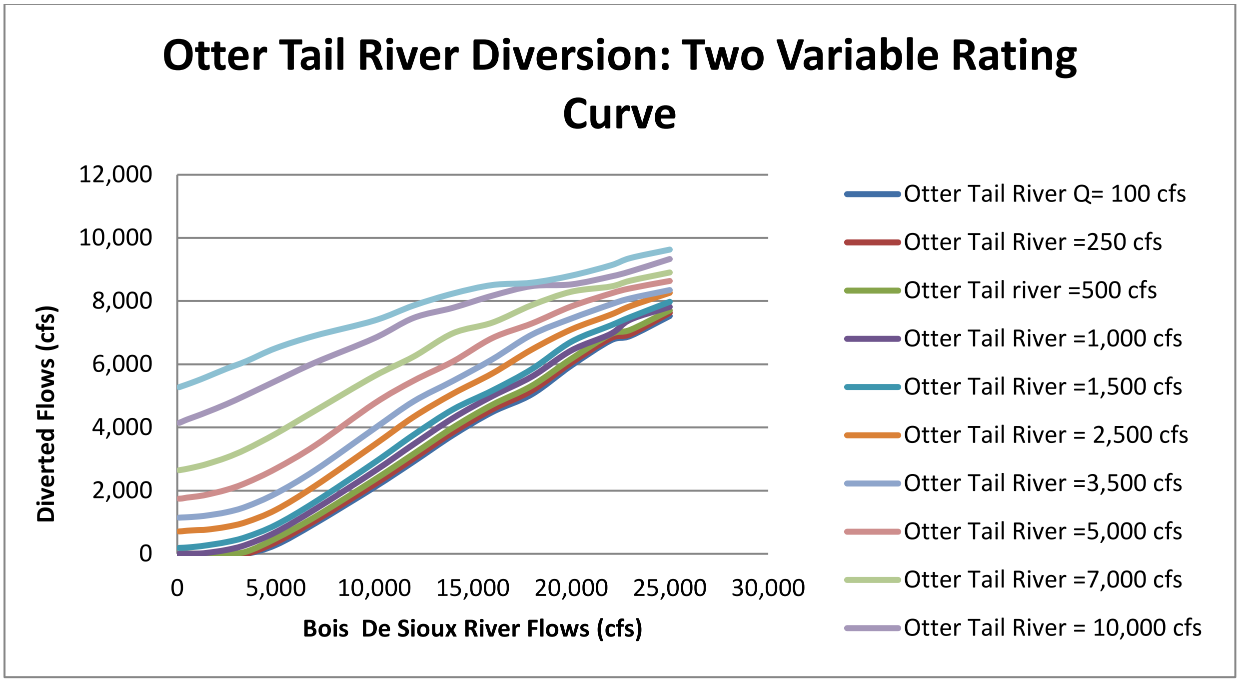
Since the inlet to the diversion is not far from the confluence of the Otter Tail and Bois de Sioux Rivers, the inflow is dependent on the flow in each tributary. This effect is enhanced by the very low channel slope between these two points. There are conditions where water can flow backwards in this reach and therefore the flow in the diversion is not solely dependent on the Otter Tail River flow, but also dependent on Bois de Sioux River flow.

The Otter Tail River Diversion is input into the hydrologic routing model using a two-variable rating curve. The magnitude of diverted flow is dependent on the flows measured just upstream of the diversion on the Otter Tail River, and the flows on the Bois de Sioux River just upstream of its confluence with the Otter Tail River. The two-variable, Otter Tail River diversion relationship was developed by MVP Hydraulics using HEC-RAS and is displayed in **Table 4** and **Figure 7**.

Table 4. Two-Variable Rating Curve for Otter Tail River Diversion

Bois de Sioux River Flows Just Upstream of its Confluence with the Otter Tail River (cfs)	Otter Tail River Flows Just Upstream of Otter Tail River Diversion (CFS)										
	100	**250**	**500**	**1,000**	**1,500**	**2,500**	**3,500**	**5,000**	**7,000**	**10,000**	**12,000**
100	0	0	0	0	188	709	1,145	1,745	2,647	4,146	5,276
250	0	0	0	0	191	715	1,150	1,753	2,662	4,185	5,309
500	0	0	0	0	200	731	1,157	1,780	2,691	4,252	5,363
1,000	0	0	0	5	229	750	1,178	1,818	2,760	4,365	5,478
1,500	0	0	0	30	269	765	1,213	1,872	2,842	4,485	5,602
2,500	0	0	0	124	372	854	1,317	2,026	3,046	4,739	5,860
3,500	0	1	68	286	532	1,006	1,494	2,247	3,311	5,025	6,097
5,000	280	364	486	685	912	1,391	1,909	2,694	3,801	5,470	6,510
7,000	966	1,048	1,172	1,413	1,643	2,150	2,648	3,431	4,532	6,056	6,907
10,000	2,105	2,195	2,342	2,612	2,885	3,450	3,963	4,758	5,624	6,824	7,384
12,000	2,921	3,016	3,165	3,469	3,768	4,334	4,827	5,481	6,243	7,469	7,861
14,000	3,761	3,852	4,000	4,298	4,572	5,071	5,476	6,091	6,984	7,790	8,240
16,000	4,490	4,576	4,721	4,994	5,170	5,713	6,160	6,832	7,320	8,173	8,509
18,000	5,050	5,167	5,322	5,610	5,848	6,468	6,937	7,292	7,873	8,475	8,583
20,000	5,958	6,048	6,173	6,437	6,713	7,102	7,448	7,832	8,297	8,529	8,806
22,000	6,755	6,825	6,949	6,961	7,229	7,570	7,895	8,240	8,462	8,777	9,131
23,000	6,898	6,955	7,091	7,414	7,494	7,841	8,087	8,404	8,647	8,940	9,363
25,000	7,528	7,629	7,707	7,819	7,978	8,263	8,350	8,638	8,907	9,333	9,631

Figure 7-5. Rating Table for Otter Tail River Diversion



Note: X-axis is flow on the Bois de Sioux River as observed just upstream of Wahpeton, ND, Each graph corresponds to a flow on the Otter Tail River just upstream of the Diversion, the Y-axis is the resulting flow in the Diversion.

The validity of the two variable rating curve used in the hydrologic model to route flows through the Otter Tail River diversion was verified by comparing the observed flows through the diversion (as recorded by USGS gage 050464475 Otter Tail Diversion at Breckenridge, MN) to diversion flows estimated using the two variable rating curve displayed in **Table 4** and **Figure 7**. An indication of how well the two variable rating curve represents diverted flows is displayed in **Plate V**.

8. Local Flow Analysis

8.1. <u>Upstream of Wahpeton, North Dakota</u>

Upstream of Wahpeton, North Dakota local flow hydrographs were determined by first routing flows observed at USGS gage 05050000 (White Rock Dam outflows) to Doran, Minnesota using the calibrated, hydrologic routing model. The period of record (1942-2009) holdout hydrograph was computed using the combined observed/approximated daily flow record at USGS gage 05051300 near Doran, Minnesota. The holdout hydrograph is defined as the difference hydrograph between the adopted Doran Flow record and the routed outflow hydrograph from White Rock Dam. It can be assumed that the local drainage areas between White Rock, South Dakota and Doran, Minnesota and Doran, Minnesota and the Otter Tail River's confluence with the Bois de Sioux River are hydrologically similar. The watershed drained by the Bois de Sioux

River lies within the former bed of Glacial Lake Agassiz. As a result, with the exception of the upland western portion of the watershed, the rest of the drainage area is characterized by flat, lowland glacial plain. According to the Minnesota Pollution Control Agency over 86% of the land in the Bois de Sioux Basin is used for agricultural purposes. Because the topography, climate, land use practices and soils are similar throughout the basin, the drainage area between White Rock Dam, South Dakota and Doran, Minnesota can be considered hydrologically similar to the drainage between Doran, Minnesota and Wahpeton, North Dakota. Consequently, an approximation of local flow between Doran, Minnesota and the confluence can be estimated by applying a drainage area ratio to the local flow hydrograph approximated for the drainage area between White Rock and Doran (application of general relations methodology).

Observed outflows from White Rock Dam (USGS gage 05050000) and Orwell Dam (USGS 05046000) are routed downstream using the calibrated hydrologic routing model and combined with the two local flow hydrographs approximated along the Bois de Sioux River. The computed holdout hydrograph at Wahpeton, North Dakota is representative of the total local flow contributions observed along the Otter Tail River. The holdout hydrograph is defined as the difference hydrograph between observed flows at the USGS gage at Wahpeton (05051500) and the routed hydrograph at Wahpeton. The total Otter Tail River local flow hydrograph is distributed between the three reaches along the Otter Tail by drainage area (see **Table 5**). To account for the effects of attenuation, local flow hydrographs had to be determined using an iterative process.

Table 5. Drainage Area Distribution Otter Tail River

Cross Section	Latitude	Longitude	Drainage Area (sq mi)	Percentage of Drainage Area
USGS gage 05046000 Otter Tail River near Fergus Falls, MN (XS 1)	46° 12.583	96° 11.083	1,730	
Incremental Drainage Area:			85	47%
Otter Tail River XS 2	46° 12.186	96° 19.825	1,815	
Incremental Drainage Area:			32	18%
Otter Tail River XS 3	46° 14.326	96° 28.301	1,847	
Incremental Drainage Area:			63	35%
Mouth of the Otter Tail River (XS 4)	46° 15.185	96° 35.899	1,910	

To assess how accurately local flows are being distributed between the Bois de Sioux River and the Otter Tail River, flows observed along the Otter Tail River Diversion at USGS gage 05046475 are compared to modeled diversion flows. Flows observed along the Otter Tail River Diversion are dependent on the distribution of flow between the Bois de Sioux River and the Otter Tail River and can consequently be used to gage how accurately this distribution is being represented by the approximated local flow hydrographs. Approximated flows upstream of Otter Tail River Diversion are also compared to daily flows observed at USGS gage 05046502 Otter Tail River at 11th Street in Breckenridge, Minnesota. These comparisons are displayed in **Plate VI**.

8.2. Downstream of Wahpeton, North Dakota

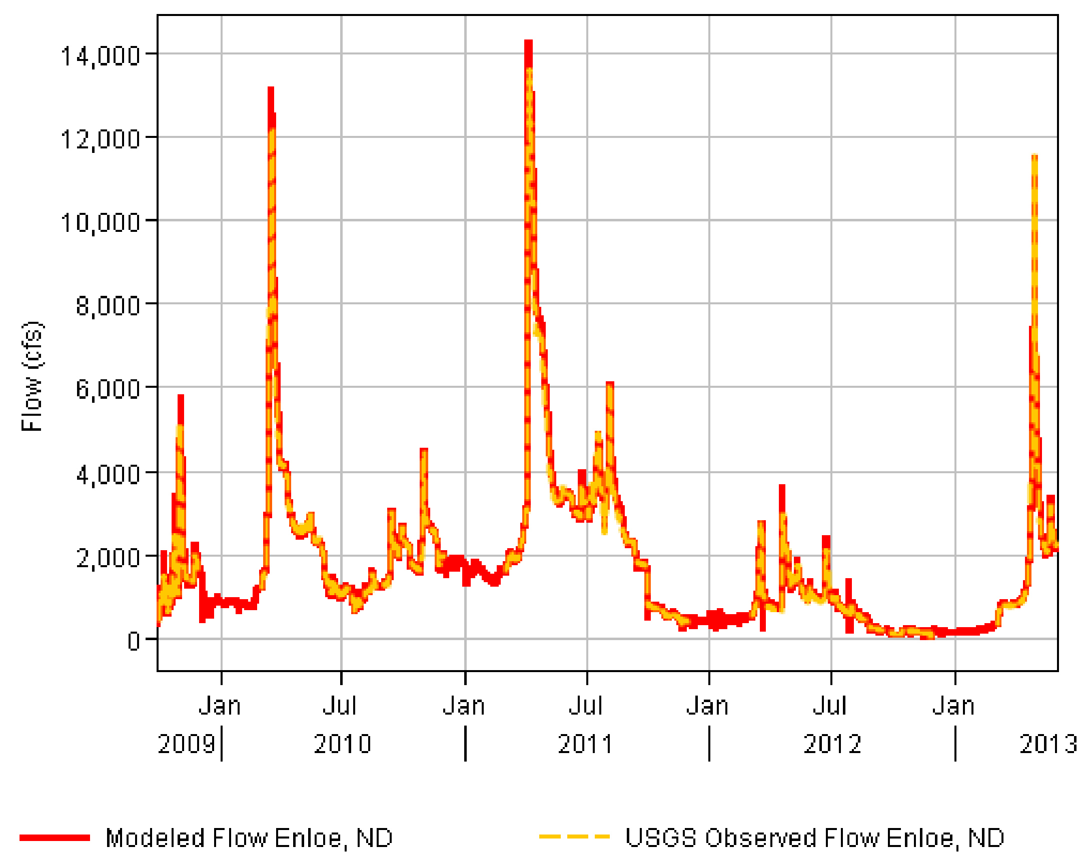
The daily, historic, combined flow record at Wahpeton, North Dakota is representative of flows recorded by the USGS gage at Wahpeton (05051500) plus diverted flows. The flow record representative of the summation of the flows observed at the Wahpeton gage site and the flows recorded within the Otter Tail River Diversion (combined flow record) is routed downstream to Hickson, North Dakota. Incremental local flows are estimated by finding the holdout hydrograph. The holdout hydrograph is determined by subtracting observed flows routed from Wahpeton, North Dakota from flows observed/approximated at the USGS gage at Hickson, North Dakota (05051522). For the portion of the period of record prior to 1976 observed data is unavailable at Hickson, North Dakota. Consequently, the estimated daily flow record at Hickson was used to determine local flows (see **Section** 6). Using a drainage area ratio (see **Table 6**) the total local flow hydrograph is distributed between the two reaches (Reach 1: Wahpeton to Enloe and Reach 2: Enloe to Hickson).

Table 6. Drainage Area Distribution Red River of the North

Gage	Drainage Area (sq mi)		Percentage of Drainage Area
USGS gage Red River at Wahpeton, ND		3,880	
Incremental Drainage Area:	260		90%
USGS gage Red River at Enloe, ND		4,140	
Incremental Drainage Area:	30		10%
USGS gage Red River at Hickson, ND		4,170	

To account for the effects of attenuation, local flow hydrographs had to be determined using an iterative process. In October 2009 the USGS installed a seasonal, recording gage at Enloe, North Dakota (0505152130). Because of the limited amount of data available at the Enloe USGS gage, it is not possible to carry out a record extension at Enloe, North Dakota. As can be seen in **Figure 8**, gaged data at Enloe was used to verify the distribution of local flow.

Figure 8-1. Observed Flows versus Estimated Flows at Enloe, ND



9. Unregulated, No Breakout Analytical Frequency Analysis

Flows observed at Wahpeton, North Dakota and Hickson, North Dakota are impacted by upstream regulation and breakout flows. Due to the effects of breakouts and regulation, flow-frequency distributions at these two sites cannot be fit using an analytical, Log Pearson Type III distribution. Instead graphical techniques must be applied to develop annual instantaneous peak flow-frequency analysis and volume frequency analysis at these two sites. To help define the portions of the graphical flow-frequency curves representing extreme events (greater in magnitude than the 2%), synthetic event hydrographs representative of the 2%, 1%, 0.5% and 0.2%, (50-year, 100-year, 200-year and 500-year) events are defined.

To define synthetic events, it is first necessary to develop annual instantaneous peak streamflow frequency analysis and volume frequency analysis representative of the unregulated, no breakout condition for Wahpeton, North Dakota and Hickson, North Dakota. By removing the impacts of regulation and breakout flows, an analytical distribution can be applied to generate a frequency analysis. The unregulated, no breakout flow daily streamflow records at Wahpeton, North Dakota and Hickson, North Dakota were generated using computed reservoir inflows to the Lake Traverse Project and Orwell Dam, estimated local flow contributions and the hydrologic routing model (with the breakout flow relationship removed). The methodology applied to generate reservoir inflow hydrographs is described in **Appendix E**. Annual maximum daily flow values were computed using HEC-DSSVUE and converted to annual instantaneous peak streamflow values using linear relationships developed using observed annual maximum daily flows and annual instantaneous peak flows at Wahpeton and Hickson.

Adopted annual instantaneous peak streamflows representative of the unregulated, no breakout condition are displayed in **Appendix F**. HEC-SSP was used to generate annual instantaneous peak flow-frequency analysis for Wahpeton and Hickson using a period of record of 1942-2009. Station skew was adopted to be consistent with the methodology applied for the Red River Diversion Project FEIS analysis. The results of the annual instantaneous peak flow-frequency analysis for the unregulated, no breakout flow condition at Wahpeton and Hickson are displayed in **Appendix F**, as well as in **Table 7** and **Table 8**, respectively.

Table 7. Unregulated, no breakout condition at Wahpeton, ND

Frequency Curve for Natural No Breakout Condition at Wahpeton, ND			
Percent Chance of Exceedance	Annual Instantaneous Peak Flow (cfs)	Confidence Limits (cfs) 5%	95%
0.2	29,726	42,957	22,328
0.5	24,732	34,786	18,942
1.0	21,170	29,116	16,475
2.0	17,792	23,880	14,087
5.0	13,601	17,610	11,041
10.0	10,629	13,348	8,806
Summary Statistics			
Mean	3.609		
Standard Deviation	0.333		
Station Skew	-0.234		
Systematic Events	68		

Table 8. Unregulated, no breakout condition at Hickson, ND

Frequency Curve for Natural No Breakout Condition at Hickson, ND			
Percent Chance of Exceedance	Annual Instantaneous Peak Flow (cfs)	Confidence Limits (cfs) 5%	95%
0.2	35,482	52,625	26,096
0.5	29,540	42,658	22,146
1.0	25,251	35,657	19,235
2.0	21,147	29,134	16,391
5.0	16,016	21,264	12,735
10.0	12,361	15,896	10,039
Summary Statistics			
Mean	3.634		
Standard Deviation	0.369		
Station Skew	-0.331		
Systematic Events	68		

Volume frequency (flow-duration) analysis was carried out for the 1-, 3-, 7-, 15-, 30-, 60-, and 90- day volumes, using the estimated unregulated, no breakout daily flow records at Hickson and Wahpeton. HEC-SSP was used to carry out volume frequency analysis using an analytical Log Pearson Type III distribution. As discussed in EM 1110-2-1415, a necessary step in a volume frequency analysis is to make sure the analytical frequency curves are consistent for all durations. To ensure frequency curves are consistent, standard deviation and skew are smoothed to make sure the frequency curves do not cross one another. The results of the volume frequency analysis, along with adopted statistics are displayed in **Appendix F**.

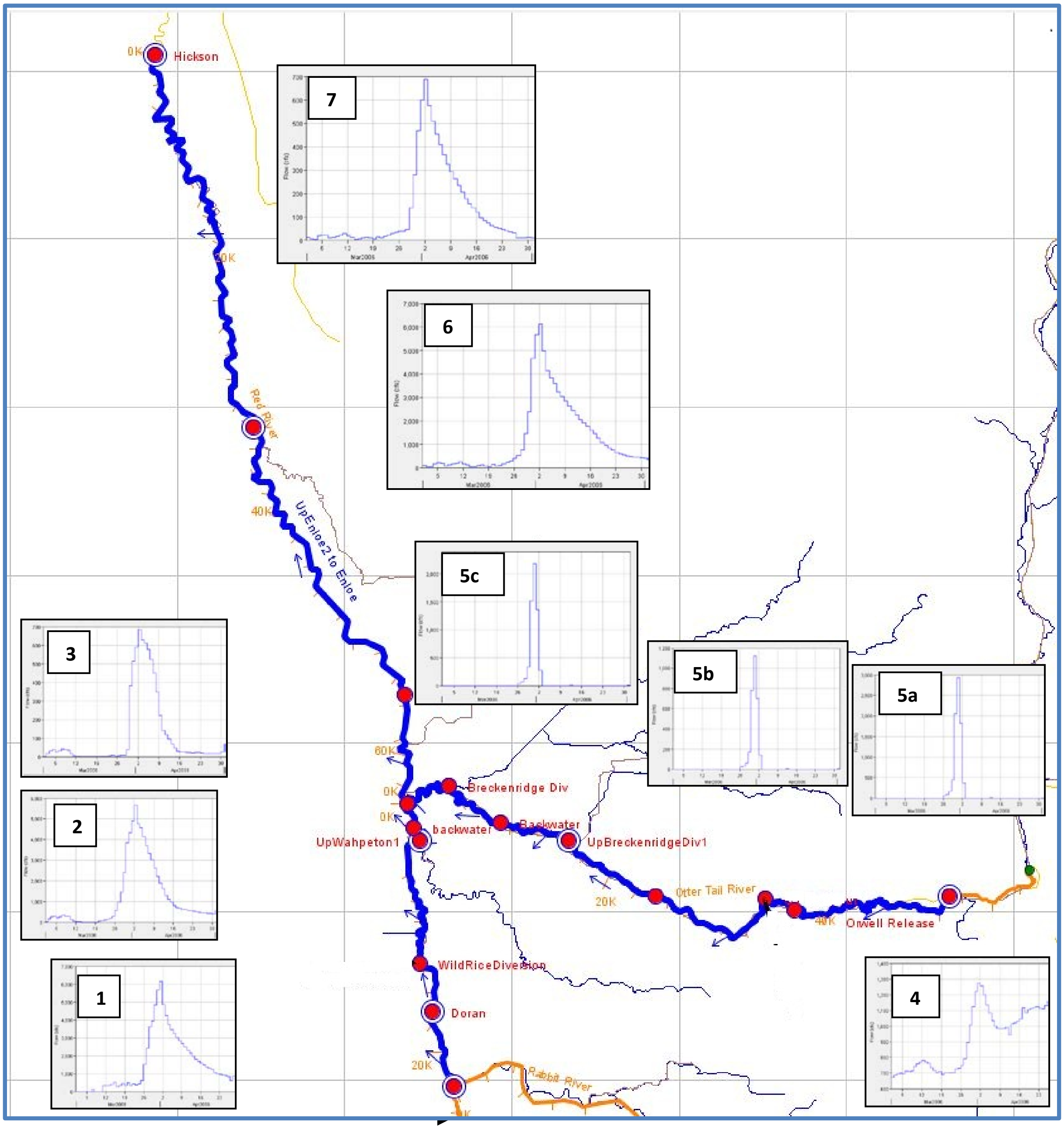
10. Synthetic Event Analysis

The synthetic flood hydrographs were developed to reproduce the 2, 1, 0.5 and 0.2 percent flows corresponding to the natural, without breakout flow volume-duration frequency curves described in the previous section of this report. As can be seen in **Figure 9**, local flow hydrographs and reservoir inflow hydrographs were inputted at the following locations:

1. Inflow to the Lake Traverse Project on the Bois de Sioux River
2. Local flow hydrograph at the USGS gage site at Doran, Minnesota on the Bois de Sioux River
3. Local flow hydrograph just upstream of Wahpeton, North Dakota on the Bois de Sioux River
4. Inflow to Orwell Reservoir on the Otter Tail River
5. Three local flow hydrographs at input points along the Otter Tail River (5a-5c in **Figure 9**)
6. Local flow hydrograph at the USGS gage site at Enloe, North Dakota on the Red River of the North
7. Local flow hydrograph at the USGS gage site at Hickson, North Dakota on the Red River of the North

Upstream reservoir inflow and local flow hydrographs were adjusted so that when routed and combined downstream they produce a balanced hydrograph at Hickson, North Dakota that replicated the volumes associated with the Annual instantaneous Peak, 3-day, 7-day, 15-day and 30-day frequency curves. A second set of reservoir inflow and local flow hydrographs were developed so that when routed and combined downstream they produce a balanced hydrograph at Wahpeton, North Dakota. For example, the 1 percent hydrograph at Hickson contains a peak flow of 25,251 cfs, a maximum average 3-day flow of 24,503 cfs, a maximum average 7-day flow of 23,064 cfs, a maximum average 15-day flow of 20,356 cfs and a maximum average 30-day flow of 14,681 cfs. A HEC-ResSIM model was used to develop the synthetic hydrographs by routing and combining the reservoir inflow and local runoff hydrographs. **Figure 9** shows the HEC-ResSIM schematic used to model the Red River of the North above Hickson without reservoirs.

Figure 10-1. HEC-ResSIM Schematic of the Input hydrographs that produce the 1-Percent Synthetic Event Hydrograph



10.1. Input Hydrographs

Input hydrographs are developed using two, recent pattern events:

- March 11 – May 1, 2006
- March 02 – May 1, 2009

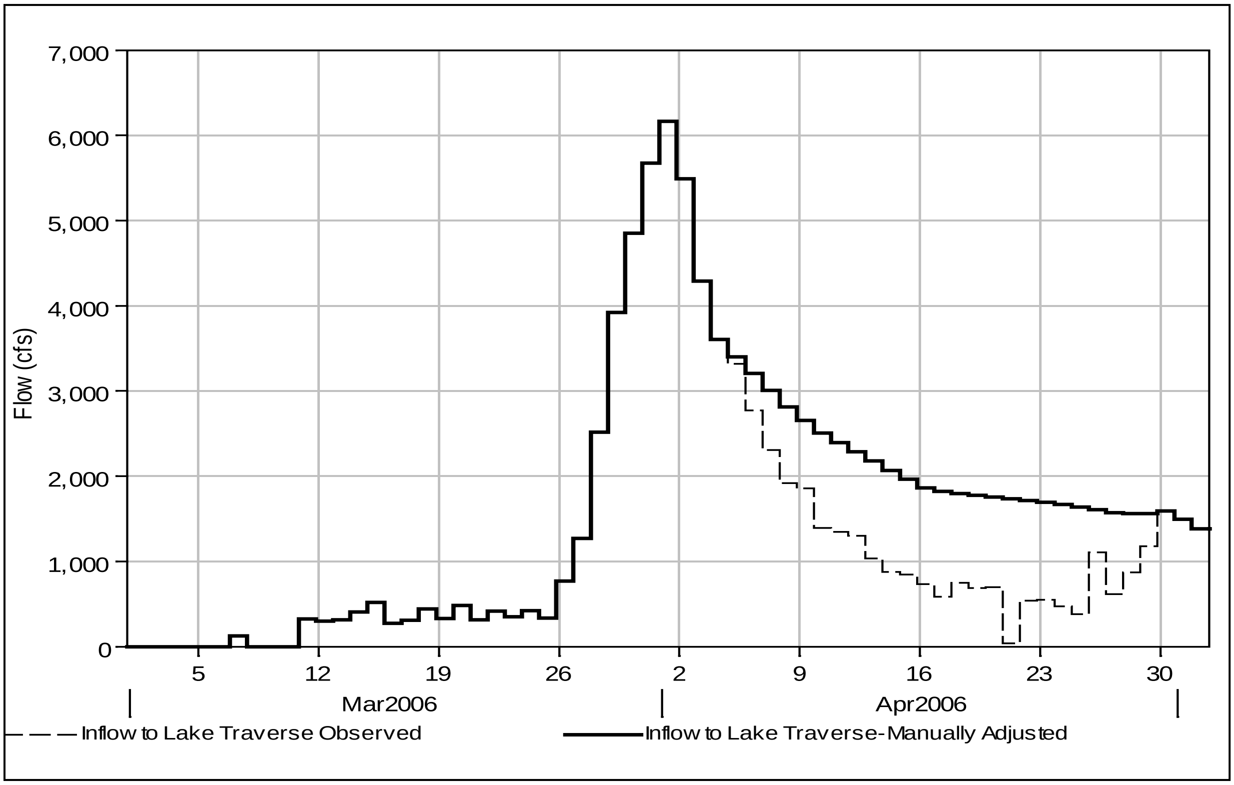
The use of these historic events provides information about the timing of the flood hydrograph. For example, a historic event provides information about how the timing of the peak flow on the Otter Tail River coincides with the timing of the peak flow on the Bois de Sioux River/Red River of the North. These flood events were chosen because they are amongst the largest in the period of record and because the 2006 and 2009 flood hydrographs have a single, well defined flood peak.

10.2. Development of Synthetic Input Hydrographs

Because local flows associated with the historic pattern events were approximated using the "holdout" method and reservoir inflows were computed using a level pool, reverse routing technique, there were initially some negative local flow and reservoir inflow values. These negative quantities were set to zero before any further modifications were made to the pattern hydrographs.

The ratio option in HEC-ResSIM was applied to increase or decrease the ordinates of all inflow and local flow hydrographs to facilitate a match between the pattern hydrographs and the flow volumes associated with the balanced hydrographs. Because the ratio option applies a uniform adjustment to all ordinates of the hydrographs, some additional manual adjustments were made to the upstream and local runoff hydrographs. HEC-DSSVUE was used to graphically adjust input hydrographs. **Figure 10** displays an example of how the inflow hydrograph to Lake Traverse was adjusted. Manual adjustments were made in conjunction with adjustments to the ratio option in HEC-ResSIM to generate balanced hydrographs representative of the 2, 1, 0.5 and 0.2 percent events at Hickson and Wahpeton.

Figure 10-2. Example of Manual Adjustments made to the Inflow Hydrograph to Lake Traverse



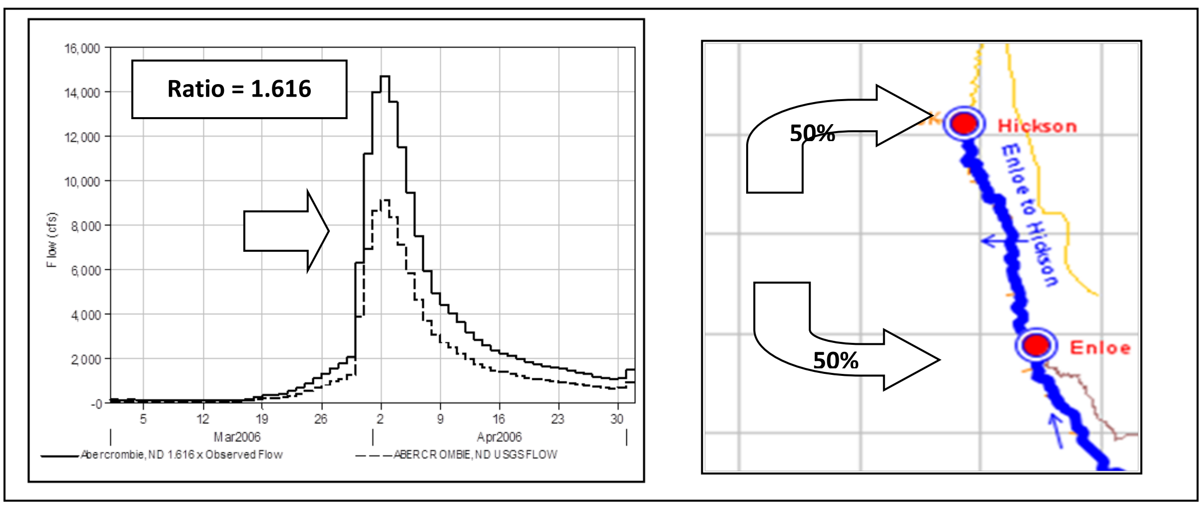
Using HEC-ResSIM to develop the synthetic hydrographs was an iterative procedure. After a flow ratio was applied to the inflow and the local runoff hydrographs, the computed flow time-series at Hickson or Wahpeton was exported from HEC-ResSIM to a spreadsheet and the 1, 3, 7, 15, and 30-day maximum average flows were computed. These outputs were then compared with the appropriate values from the natural conditions, without breakout flow volume-duration frequency curves. The ratio was then increased or decreased and further graphical adjustments were made to improve the results. An effort was made to match the maximum flow for each frequency event to within 0.1% of the annual instantaneous frequency curve magnitudes. For the maximum 3-day, 7-day, 15-day and 30-day durations, an effort was made to match the maximum average flow within 5% of the natural, no breakout flow conditions volume duration frequency curves.

10.3. Development of Synthetic Regulated, With Breakout Flow Outputs

After developing the reservoir inflow and local runoff hydrographs that generate the 2%, 1%, 0.5% and 0.2% events at Wahpeton or Hickson for the unregulated, no breakout flow condition, these hydrographs were inputted into the regulated, with breakout flow HEC-ResSIM model (. The reservoirs are operated in response to each of the synthetic events in accordance with the USACE St. Paul District Water Control Manuals for the Lake Traverse Project and Orwell Reservoir. A detailed description of the reservoir model can be found in **Appendix E**.

The HEC-RAS modeling effort indicates that flow can break out from the Wild Rice River to the Red River between Wahpeton and Hickson. The observed streamflow record at the USGS gage located on the Wild Rice River near Abercrombie, North Dakota was used to estimate breakout flow contributions from the Wild Rice River to the Red River of the North between Enloe, North Dakota and Hickson, North Dakota. The same ratio applied to each of the other baseline inflow/local flow hydrographs was applied to the observed daily flow record at the USGS gage located at Abercrombie, North Dakota for each synthetic event. No graphical adjustments were made to the hydrograph shape observed at Abercrombie. After applying the ratio to the observed hydrograph at Abercrombie, HEC-DSSVUE was used to apply the rating curve displayed in **Figure 6** to determine the corresponding breakout flow contribution from the Wild Rice River to the Red River of the North for the 2%, 1%, 0.5% and 0.2% events. Fifty percent of the resulting breakout flow hydrograph is inputted at Enloe, North Dakota and fifty percent of the resulting breakout flow hydrograph was inputted at Hickson, North Dakota (**see Figure 16**).

Figure 10-1 . Computation of Breakout Flows from the Wild Rice River (ND) to the Red River



The resulting synthetic event peak magnitudes and volumes for each recurrence interval at Hickson, North Dakota are displayed in **Table 9**.

Table 9. Regulated with Breakout Flows Synthetic Events at Hickson, North Dakota

Summary Table of Synthetic Events Hickson, North Dakota

Percent Chance of Exceedance	Annual Instantaneous Peak	Max 3-day	Max 7-day	Max 15-day	Max 30-day
	Flows in CFS				
0.20	35,400	34,000	30,100	25,400	20,300
0.50	28,500	27,550	24,150	19,800	15,600
1.00	23,600	22,500	19,700	16,000	12,500
2.00	19,400	18,400	15,900	12,700	9,500

A summary of annual instantaneous peak regulated synthetic events at Wahpeton, North Dakota are displayed in **Table 10** and **Table 11**. The synthetic event magnitudes are used to augment the systematic flow record in order to aid in the definition of the upper end of the flow-frequency curve. They do not define the magnitude of the 2%-0.2% events, but help to guide the construction of the graphical flow-frequency curve.

Table 10. Regulated Synthetic Events total flow Red River- Wahpeton, ND

Synthetic Events for Wahpeton, ND Downstream of Otter Tail River Diversion	
% Chance of Exceedence	**Annual Instantaneous Peak Flow (cfs)**
2.00	15,200
1.00	18,400
0.50	21,900
0.20	26,000

Table 11. Regulated Synthetic Events at USGS gage site (excludes flow diverted via Otter Tail River Diversion Project) – Wahpeton, ND

Synthetic Events for Wahpeton, ND at USGS Gage Site	
% Chance of Exceedence	**Annual Instantaneous Peak Flow (cfs)**
2.00	10,000
1.00	12,000
0.50	14,600
0.20	18,200

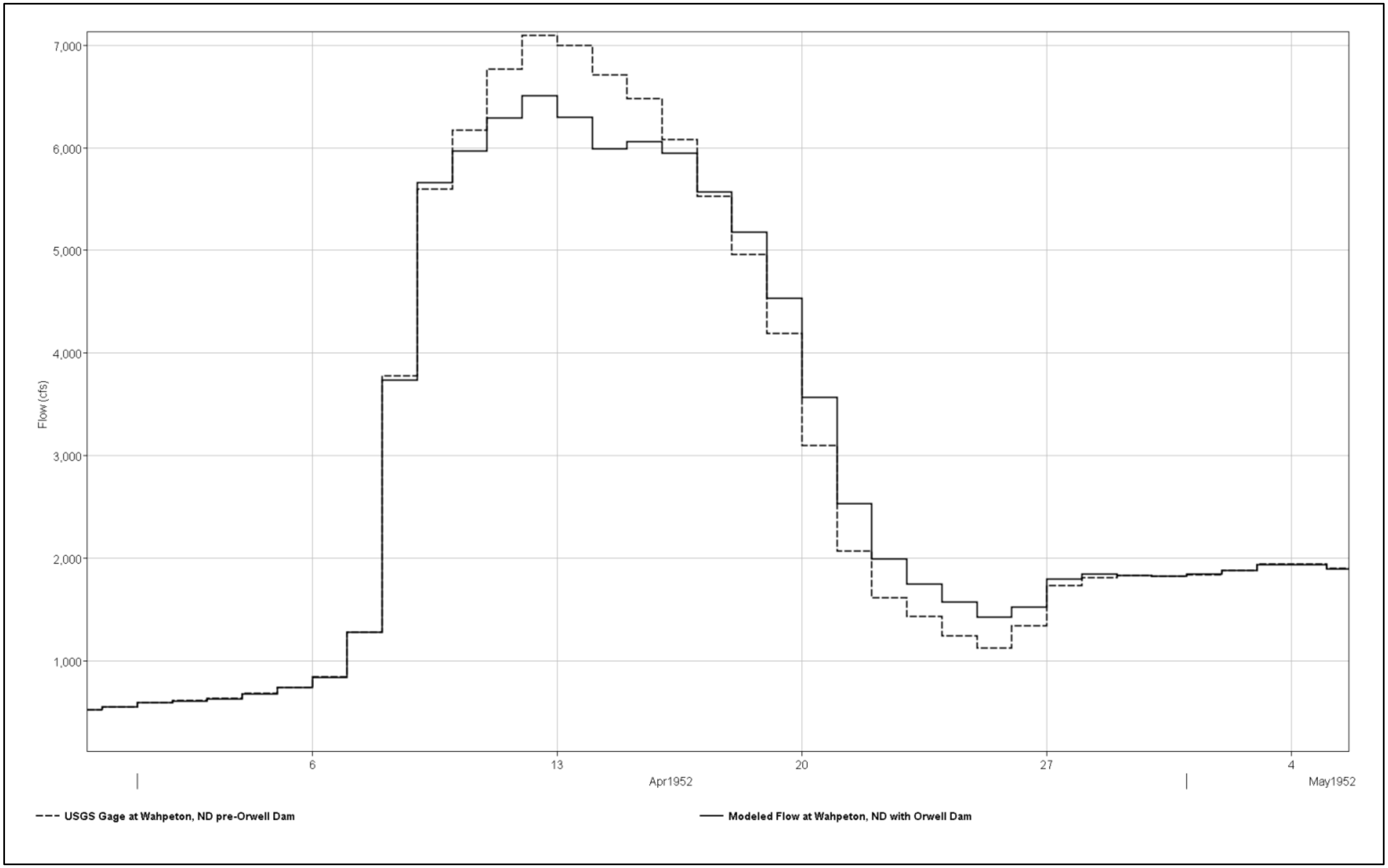
Synthetic Events are plotted along with the adopted regulated, with breakout flows flow-frequency and volume frequency curves in **Appendix G**.

11. Regulated Frequency Analysis

11.1. Historic Annual Peak Flow Record

To carry out a flow-frequency analysis it is important that the flow record being analyzed be representative of homogenous hydrologic conditions in the study area. The historic flow record is used to aid in the definition of the graphical flow frequency curve for exceedance probabilities smaller in magnitude than approximately the 2% event. Exeedence probabilities are assigned to the historic record using Weibull plotting positions. In order to be consistent with what was done for the Fargo-Moorhead Feasibility Study and Environmental Impact Statement assessment, the period of analysis adopted for this study is 1942-2009. For the period of record from 1975 to 2009, historic, annual instantaneous peak streamflow events and daily flow data measurements are published by the USGS for the Red River of the North at Hickson, North Dakota. Annual instantaneous events and the daily flow record for the portion of the period of record from 1953 to 1974 were approximated based on a MOVE.1 analysis with the USGS gage at Wahpeton, North Dakota (see **Section 6.1**). Orwell Dam was constructed in 1953; consequently, the HEC-ResSIM model had to be used to adjust daily flows and annual instantaneous peaks observed at Wahpeton and Hickson to impose Orwell Dam regulation for the period of record prior to 1953. A comparison of pre-dam observed flows and modeled flows accounting for the impacts of Orwell Dam at Wahpeton, North Dakota are displayed in **Figure** 12. Historic annual instantaneous peak flows used for flow frequency analysis at Hickson, North Dakota are displayed in **Appendix G**.

Figure 11-1. Flows at Wahpeton, North Dakota with and without Orwell Dam: Spring 1952



For the period of record from 1942 to 2009, historic annual instantaneous peak streamflow events and daily flow data measurements are published by the USGS at Wahepton, North Dakota. Discharges measured at Wahpeton, North Dakota are regulated by Orwell Reservoir, the Otter Tail River Diversion and the Lake Traverse Project. Consequently, discharges published prior to the construction of Orwell Dam (1942-1952) had to be adjusted using the HEC-ResSIM model.

In 2005 the Otter Tail River Diversion was constructed. The diverted flows are measured at streamflow station 05046475, Otter Tail River Diversion at Breckenridge, Minnesota. The USGS publishes a flow record for USGS gage 05051500 representative of the measured flows at Wahpeton, North Dakota (upstream of where the diversion reaches its confluence with the Red River of the North). This flow record is referred to as "Red River Only." Instantaneous annual peak data published at Wahpeton, North Dakota by the USGS is representative of "Red River Only" flows. The sum of the flows reported at streamflow station 05046475 and 05051500 are representative of the total flow traveling downstream from Wahepton, North Dakota towards Hickson, North Dakota. The total flow on the Red River just downstream of where the Otter Tail River Diversion reaches its confluence with the Red River of the North (just downstream of Wahpeton, North Dakota) will be referred to as "Combined Red River Flow."

The HEC-ResSIM hydrologic routing model was used to develop hydrographs for the period of record at the location just upstream of the diversion on the Otter Tail River and just upstream of the Otter Tail River's confluence with the Bois de Sioux River on the Bois de Sioux River. Using HEC DSS-VUE these hydrographs were used as inputs to the he two variable rating curve displayed in **Figure 7**. The corresponding output hydrograph is an approximation of what flows would have been through the Otter Tail River Diversion between 1942 and 2005. By subtracting the hydrograph representative of diverted flows from the observed hydrograph at the USGS gage site at Wahpeton an approximation of the flow record at Wahpeton could be made for the with diversion condition for the period of record prior to its construction (1942-2005).

Flows published by the USGS as "Red River Only" instantaneous peak flows (flows excluding flows traveling through the Otter Tail River Diversion) were adjusted to include diverted flow to develop an Annual Instantaneous Peak flow record representative of the "Combined Red River Flow" record representative of the total flow (flow at Wahpeton gage site plus diverted flow) along the Red River near Wahpeton for the post-2005 portion of the period of record. Historic annual instantaneous peak flows used to define the portion of the graphical flow-frequency curve associated with more frequent events at Wahpeton, North Dakota for both the "Red River Only" and "Combined Red River Flow" conditions are displayed in **Appendix G**.

11.2. Regulated, With Breakout Flows Flow Frequency Curves

Due to the effects of breakouts and regulation, flow-frequency distributions at Wahpeton, North Dakota and Hickson, North Dakota cannot be fit using an analytical, Log Pearson Type III distribution. Instead graphical techniques must be applied to develop annual instantaneous peak flow-frequency analysis and volume frequency analysis at these two sites. The synthetic events developed in **Section 10** are used to define the flow-frequency curves for extreme events (greater in magnitude than the 2% event).

To develop graphical annual instantaneous peak stream flow frequency curves at Wahpeton and Hickson, HEC-SSP was used to define the Weibull plotting positions associated with each of the historic, annual instantaneous peak flows displayed in **Appendix G**. The historic data was plotted in Microsoft Excel using the computed plotting positions, along with the synthetic events plotted at their associated recurrence interval. Similarly, HEC-SSP was used to define Weibull plotting positions for the daily, historic record to develop volume-frequency analysis at Hickson, North Dakota. Using Microsoft Excel, the average of the maximum three days, seven days, fifteen days, and thirty days of flow associated with each synthetic event hydrograph were plotted alongside the historic plotting positions generated in HEC-SSP. Flow-frequency curves were developed graphically to fit both the historic plotting positions and the synthetic event magnitudes. The adopted regulated, with breakouts annual instantaneous peak flow-frequency curves for Hickson, North Dakota and Wahpeton, North Dakota are displayed in **Table 12** . The adopted regulated, with breakouts volume frequency curves for Hickson, North Dakota are displayed in **Table 13**. Regulated flow frequency curves are displayed in **Appendix G**.

Table 12. Regulated, With Breakout Flow Annual Instantaneous Frequency Curves

Annual Instantaneous Peak Flow-Frequency Curves for Regulated, With Breakout Flow Condition			
Percent Chance of Exceedance	Red River of the North at Wahpeton, ND Upstream of Otter Tail River Diversion (Red Only)	Red River of the North at Wahpeton, ND Downstream of Otter Tail River Diversion (Combined)	Red River of the North at Hickson, ND
Flow in cfs			
0.2	17,200	25,500	36,000
0.5	13,800	20,900	28,500
1.0	11,400	17,500	23,500
2.0	9,500	14,400	19,000
5.0	7,500	10,500	13,200
10.0	6,500	8,200	9,600
20.0	5,000	6,000	6,850

Table 13. Regulated, With Breakout Flow Volume Frequency Curves – Hickson, North Dakota

Volume Frequency Curves for Regulated, With Breakout Flow Condition at Hickson, North Dakota					
Percent Chance of Exceedance	Annual Instantaneous Peak Flow-Frequency Curve	Maximum 3-Day Average	Maximum 7-Day Average	Maximum 15-Day Average	Maximum 30-Day Average
Flow in cfs					
0.2	36,000	34,500	30,500	25,300	20,200
0.5	28,500	27,600	24,000	19,700	15,400
1.0	23,500	22,000	19,400	15,900	12,400
2.0	19,000	17,800	15,500	12,500	9,500
5.0	13,200	12,200	10,700	8,600	6,400
10.0	9,600	9,000	8,100	6,300	4,700
20.0	6,850	6,400	5,700	4,350	3,400

11.3. Impacts of Wild Rice River Contributions on Hickson Analysis

The regulated, with breakout flow frequency curve at Hickson, North Dakota is slightly higher than the unregulated, without breakout flow frequency curve at Hickson, North Dakota. Due to contributions from breakouts from the Wild Rice River near Abercrombie, North Dakota, substantial flow is being added to the Red River of the North above Hickson. The final plot in **Appendix G** displays a comparison between the following plots:

- The unregulated, no breakout flow frequency curve at Hickson, North Dakota
- The regulated, with breakout flow-frequency curve at Hickson, North Dakota
- The regulated curve at Hickson, North Dakota excluding contributions from the Wild Rice River (North Dakota).

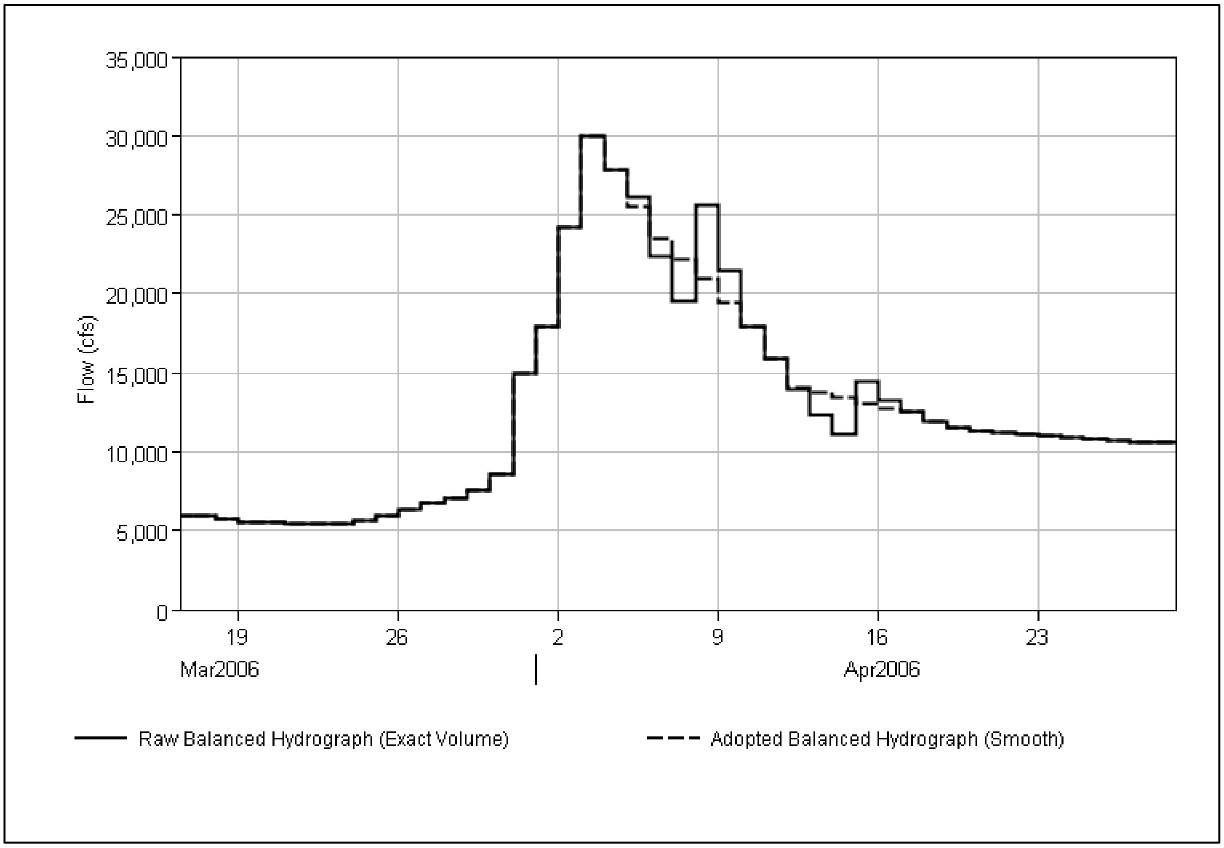
12. Balanced Hydrographs at Hickson, North Dakota

12.1. Balanced Hydrographs

Balanced hydrograph volumes are based upon the volume duration frequency curves displayed in **Appendix G** and in **Table 13**. In order to be consistent with how balanced hydrographs were generated during the FEIS phase of the Red River Diversion Project, the 2006 regulated flow hydrograph observed at Hickson, North Dakota is used as the pattern event for this analysis. A Microsoft Excel spreadsheet is used to generate balanced hydrographs by applying excel's solver capabilities. Multipliers were applied to the pattern event to minimize the difference between the balanced hydrograph volume and the volumes defined by the volume frequency analysis.

After allocating flow volumes in exact accordance with the volume frequency curves, it is necessary to smooth out the receding limb of the hydrographs by redistributing volume associated with several of the durations. Effort was made to remain within 5% of the volumes initially specified by the volume frequency analysis for each duration. An example of how the receding limb of each raw, balanced hydrograph is modified to resemble the shape of the original pattern hydrograph is displayed in **Figure 13**. The peak of each balanced hydrograph is defined by the regulated annual instantaneous peak flow frequency curve. The resulting balanced hydrographs are displayed in **Plate VI**.

Figure 12-1. Sample Balanced Hydrograph Smoothing of Receding Limb



13. Validation of Annual Instantaneous Peak Flow-Frequency Analysis

13.1. Comparison to Previous Studies

The annual instantaneous flow frequency curve and volume frequency curves for the USGS gage at Hickson, North Dakota were generated as part of the Red River Diversion Project Feasibility Study and Environmental Impact Statement (FEIS) for the period of record from 1942-2009. These values were later updated to include data from water years 2010 and 2011. The period of record for this analysis is 1942 to 2009. As can be seen from **Table 14**, this iteration of analysis produced comparable Hickson, North Dakota annual instantaneous peak flows to what was produced in support of the FEIS.

Table 14. Flow-Frequency Curve Comparison at Hickson, North Dakota

Regulated Peak Flow Frequency Curves for the Wet Period, Red River at Hickson, ND				
Exceedance Probability	Feasibility Report (1942-2009)	HEC Summer 2011 Update (1942-2011)	2015 Updated Analysis (1942-2009)	Percent Difference from Feasibility Study
10	10,500	12,000	9,600	-9%
2	19,000	22,100	19,000	0%
1	22,000	27,100	23,500	7%
0.5	28,500	31,800	28,500	0%
0.2	37,000	40,300	36,000	-3%

The volumes generated as part of this analysis are significantly greater than the volumes produced in support of the FEIS. A comparison between the FEIS 10%, 1%, and 0.2% balanced hydrograph generated using the period of record from 1942-2009 and the balanced hydrograph generated as part of this analysis is displayed in **Figure 14**, **Figure 15**, and **Figure 16**.

Figure 13-1. 10% Balanced Hydrograph Comparison

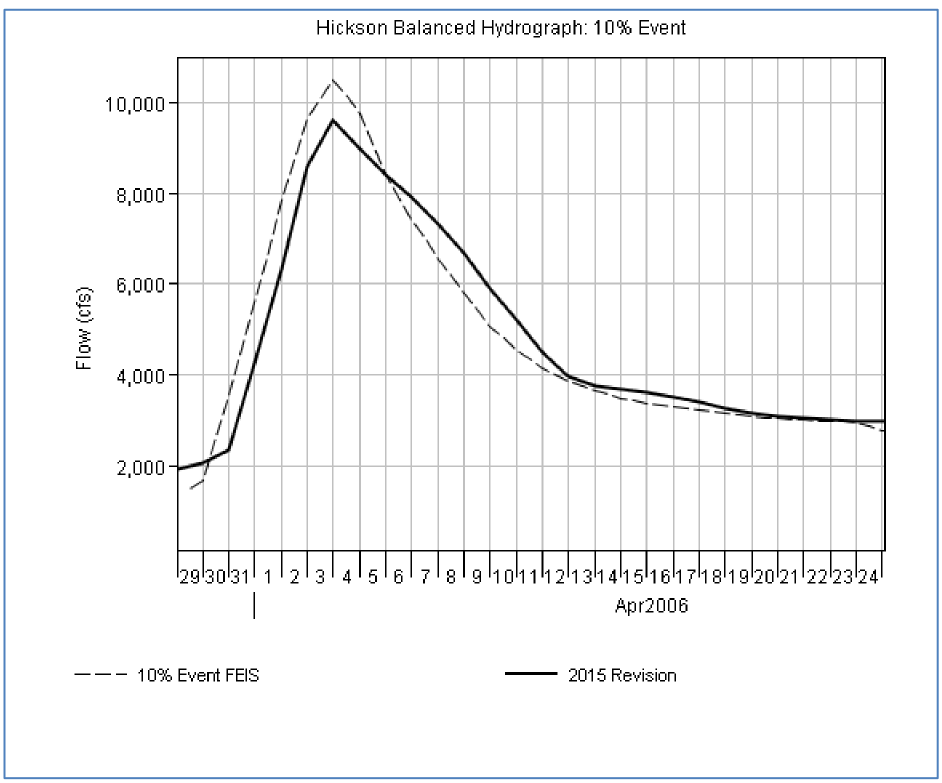


Figure 13-2. 1% Balanced Hydrograph Comparison

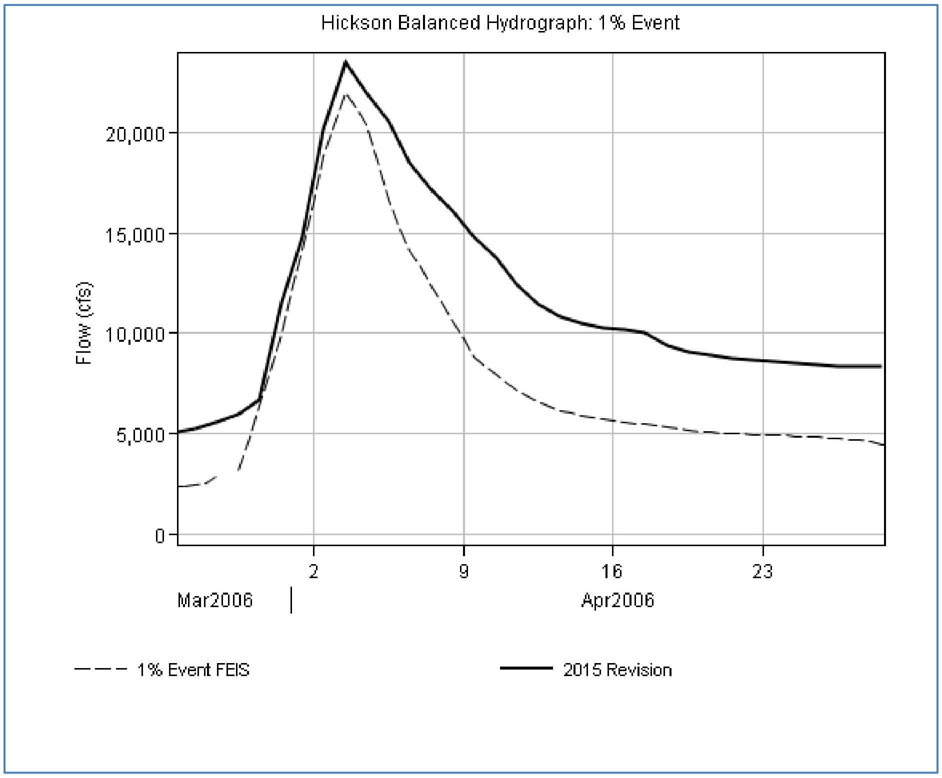
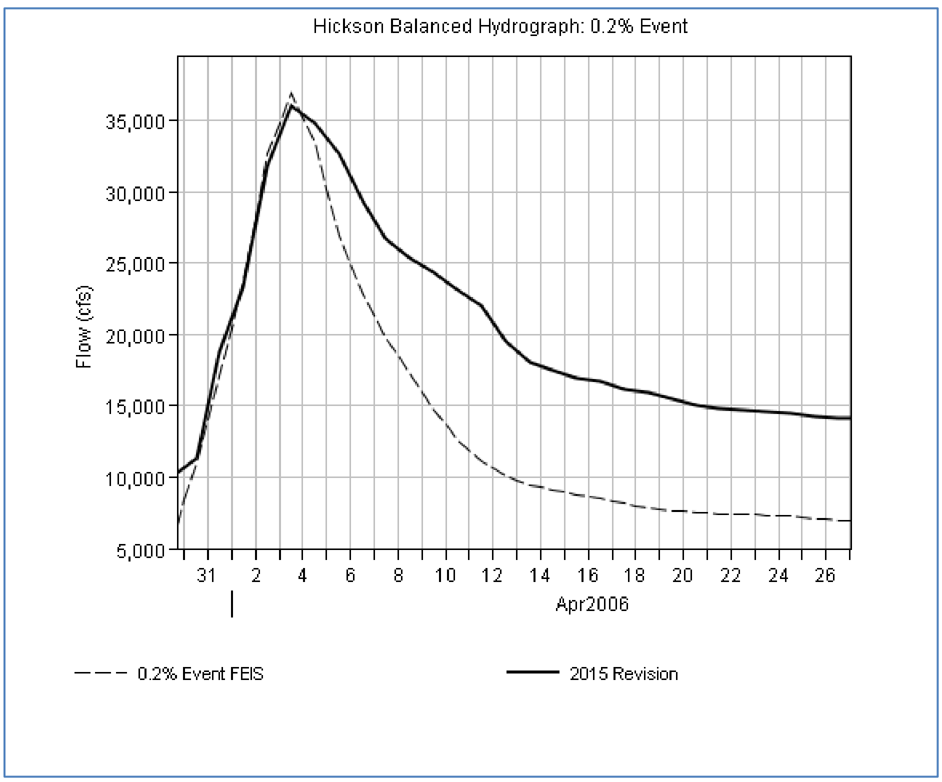


Figure 13-3. 0.2% Balanced Hydrograph Comparison



A flow-frequency curve was generated at Wahpeton, North Dakota as part of the Red River Diversion Project FEIS and as part of the Wahpeton Breckenridge Levee Safety Evaluation Report (LSER). A comparison of frequency curve results generated for this study and for the FEIS and LSER are displayed in **Table 15** and

Table 16. The frequency curve generated as part of this study is significantly higher (greater than 10%) for the 0.2% and 0.5% events than both the frequency curve generated in support of the FEIS and the LSER. The frequency curve generated in support of the FEIS was developed using a general relations based methodology. The curve generated in support of the LSER was developed using similar methods as was adopted for this study, but relied on a different distribution of local flow between the Otter Tail River and the Bois de Sioux River.

Table 15. Regulated Peak Flow Frequency Curves for the Red River at Wahpeton, North Dakota- Combined Flow

Regulated Peak Flow Frequency Curves for Red River at Wahpeton, ND: Combined Flow Red River Mainstem + Otter Tail Diversion Flow					
Percent Chance of Exceedance	Feasibility Report (Extended with Fargo, ND: 1902-2009) General Relations Based Method	Levee Safety Evaluation Report (1942-2011) General Relations Based Method	Levee Safety Evaluation Report (1942-2011) Synthetic Event Routing	2015 Updated Analysis (1942-2009) Synthetic Event Routing	Percent Difference from LSER
10	6,690		8,900	8,200	-8%
2	10,950	13,900	13,900	14,400	4%
1	13,300	15,800	16,000	17,500	9%
0.5	16,000	18,800	17,800	20,900	17%
0.2	19,600	23,100	20,000	25,500	28%

Table 16. Regulated Peak Flow Frequency Curves for the Red River at Wahpeton- Red Only

Regulated Peak Flow Frequency Curves for Red River at Wahpeton, ND: Red River Mainstem Only			
Percent Chance of Exceedance	Levee Safety Evaluation Report (1942-2011)	2015 Updated Analysis (1942-2009)	Percent Difference from LSER
10	7,000	6,500	-7%
2	9,650	9,500	-2%
1	10,800	11,400	6%
0.5	11,800	13,800	17%
0.2	12,600	17,200	37%

The flow-frequency curve at Wahpeton, North Dakota is very sensitive to how local flow is distributed between the Otter Tail River and the Bois de Sioux River. There is no continuous streamflow gage that captures the local flow that reaches the Otter Tail River downstream of Orwell Dam.

14. References

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