Knife River Hydrology Report

SWC Project #1404
North Dakota State Water Commission
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Prepared for:
Mercer County Water Resource District

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1. Introduction

1.1 Purpose

This report has been prepared for the purpose of documenting the creation and calibration of a hydrology model for the Knife River Basin. The model was constructed under an investigation agreement between the North Dakota State Water Commission (NDSWC) and the Mercer County Water Resource District (MCWRD). This effort was part of a Section 22 study agreement between the MCWRD and the Omaha District Army Corp of Engineers. The purpose of the Section 22 agreement is to investigate flood risk management alternatives for the communities along the Knife River and its tributaries in Mercer County.

1.2 Site Location

The Knife River Basin is located in west-central North Dakota within Mercer, Oliver, Morton, Dunn, Stark, and Billings Counties (Figure 1). The Knife River outlets to the Missouri River near Stanton, North Dakota and drains an area of approximately 2,514 square miles.

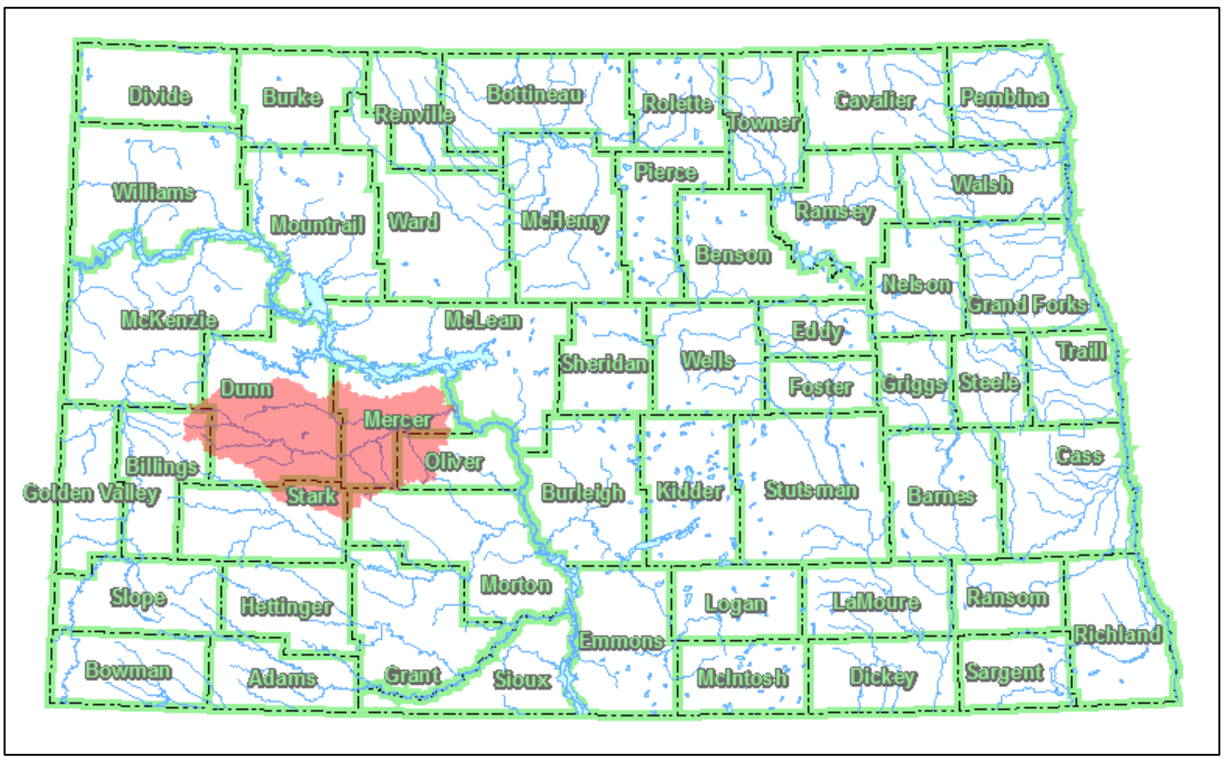

Figure 1: Location of the Knife River Basin in North Dakota.

2. Hydrology Model

The U.S. Army Corps of Engineers' Hydrologic Engineering Center Hydrologic Modeling System (version 3.5) was used to model the hydrology of the Knife River Basin. Spatial analysis and the calculation of some hydrology model parameters were performed using ArcMap (versions 9.3 and 10) and Quantum GIS (version 1.8.0).

2.1 Basin Model

2.1.1 Sub-basins

Terrain preprocessing was performed using the Spatial Analyst tools in ArcMap on a 10-meter resolution digital elevation model from the National Elevation Dataset (NED). The NED was utilized as it is currently the best available information, LiDAR is currently being collected for Mercer County and will be available in 2017.

The basin was divided into 23 sub-basins, as shown in Figure 2. The drainage area for each sub-basin is provided in Table 1. For the purposes of calibration, junctions were placed in the model at the locations of the four United States Geological Survey (USGS) streamflow gages in the Knife River Basin (Manning-06339100, Golden Valley-06339500, and Hazen-06340500) and Spring Creek Basin (Zap-06340000).

2.1.2 Transform Method

The SCS unit hydrograph model was selected as the transform method for rainfall events. The time of concentration (TOC) was calculated using a travel time tool in ArcMap developed by the Minnesota Department of Natural Resources Waters Division. The tool uses a gridded version of the Manning's equation to calculate flow velocities in the drainage basin. The final result is a grid representing time for water in each cell in the basin to travel to the outlet for the entire basin. The zonal statistics tool in ArcMap was used to calculate the maximum and minimum travel times for each sub-basin. A more detailed discussion on the travel time tool is provided in Appendix A. Land classification and wetland data were required for use of the travel time tool. Land classification data were obtained from the National Land Cover Database 2006 (NLCD, 2006). Wetland data were acquired from U.S. Fish and Wildlife Service's National Wetland Inventory. The calculated lag time values for each sub-basin were obtained by multiplying the TOC by a factor of 0.6 and are provided in Table 1.

The Clark unit hydrograph method was selected as the transform method for snowmelt events. The TOC from the rainfall events was used as a starting point for the TOC in the snowmelt events. The storage coefficient was utilized to simulate the steep peaks of snowmelt events in the basin. The initial value for the storage coefficient was estimated by multiplying the TOC by a factor of 0.6. Storage coefficients were adjusted during calibration and verified using the R/(R+TOC) relationship.

2.1.3 Loss Method

The Green-Ampt loss model was used as the loss method in the hydrology model. The input parameters required for Green-Ampt are the initial water content, saturated water content, wetting front suction, hydraulic conductivity, and percent impervious. Soil data was obtained from the Soil Survey Geographic (SSURGO) Database and the NLCD2006 was used to determine percent impervious land cover.

Soil porosity was utilized in the model as an estimate for saturated water content. Wetting front suction was calculated using an empirical equation, which required estimating the soil porosity, percent sand, and percent clay. Soil porosity, percent sand, percent clay, and hydraulic conductivity were obtained directly from the SSURGO database. The SSURGO data were used in an algorithm developed by the NDSWC that calculates the average Green-Ampt parameters for each sub-basin at a depth of 6 inches. A more detailed discussion on the Green-Ampt algorithm is provided in Appendix B. The initial moisture content was estimated through calibration for each storm and is provided below in the calibration section. The calculated Green and Ampt parameters are provided in Table 1.

2.1.4 Baseflow Method

The recession baseflow method was selected to model baseflows in the Knife River. Initial discharge was estimated from baseflows indicated on the river gages and is provided below in the calibration section. The recession constant and flow ratio to peak were determined to be 0.9 and 0.04, respectively, through calibration for all sub-basins.

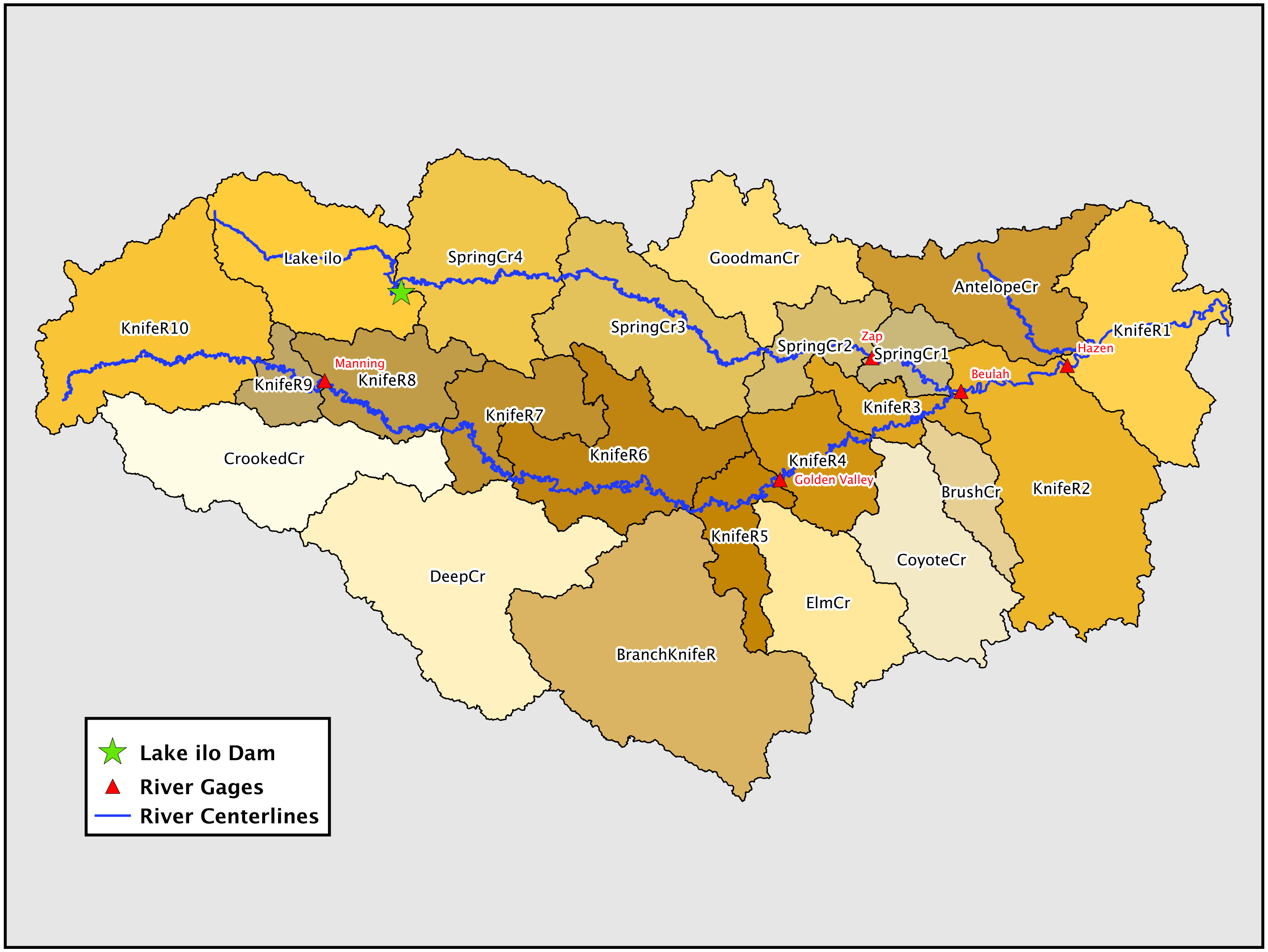

Figure 2: Sub-basins of the Knife River Basin used in the hydrology model.

Table 1: Calculated drainage area, transform, and loss parameters for each sub-basin.

	Drainage Area (square miles)	Porosity	Hydraulic Conductivity in/hr (low)	Hydraulic Conductivity in/hr (mean)	Hydraulic Conductivity in/hr (high)	Wetting Front Suction (in)	% Impervious	TOC (hr)	Lag Time (min)
AntelopeCr	109.44	0.45	0.17	1.21	10.71	21.25	1.04*	35.37	1273.37
BranchKnifeR	248.48	0.45	0.19	1.12	8.33	21.53	0.40	42.89	1544.07
BrushCr	36.01	0.45	0.30	1.53	11.01	21.13	0.42	28.92	1041.08
CoyoteCr	106.45	0.45	0.22	1.17	8.17	21.34	0.25	40.17	1446.22
CrookedCr	141.54	0.44	0.26	1.27	8.07	22.08	0.24	46.41	1670.88
DeepCr	215.55	0.45	0.20	1.07	7.78	21.39	0.27	35.94	1293.88
ElmCr	101.17	0.44	0.16	0.98	6.71	22.12	0.19	33.64	1210.98
GoodmanCr	101.52	0.45	0.24	1.32	9.64	21.03	0.23	29.19	1050.79
KnifeR1	140.72	0.45	0.51	3.72	27.64	21.27	0.32	30.57	1100.57
KnifeR10	176.96	0.45	0.30	1.38	8.60	21.79	0.22	33.63	1210.84
KnifeR2	201.57	0.45	0.38	1.84	11.85	21.44	0.46	37.89	1364.11
KnifeR3	38.92	0.44	0.26	1.67	10.84	22.05	0.64	24.29	874.38
KnifeR4	64.63	0.44	0.19	1.34	9.11	22.27	0.13	20.56	740.15
KnifeR5	49.95	0.45	0.11	0.79	5.62	21.56	0.23	25.98	935.24
KnifeR6	122.33	0.45	0.22	1.24	9.35	21.59	0.20	35.22	1267.87
KnifeR7	67.87	0.45	0.26	1.32	9.67	21.59	0.22	31.70	1141.05
KnifeR8	73.72	0.45	0.25	1.33	9.37	21.66	0.25	25.41	914.85
KnifeR9	27.90	0.44	0.39	1.68	9.56	21.97	0.26	17.03	612.92
LakeIlo	126.85	0.44	0.43	1.87	11.22	22.07	0.38	28.67	1031.96
SpringCr1	33.34	0.44	0.24	1.50	10.07	22.39	0.42	21.81	785.09
SpringCr2	50.64	0.44	0.41	2.28	14.97	21.84	0.41	29.56	1064.26
SpringCr3	132.39	0.45	0.34	1.62	11.19	21.49	0.33	33.28	1198.01
SpringCr4	145.76	0.45	0.48	2.03	12.50	21.53	0.24	35.84	1290.39

*This subbasin includes the city of Hazen

2.1.5 Reservoirs

Lake Ilo Dam is located in Section 27, Township 145 North, Range 94 West, Dunn County on Spring Creek, a tributary of the Knife River (Figure 2). This was the only dam included in the hydrology model. Table 2 provides elevation, area, storage, and discharge data for the dam (North Dakota State Water Commission, 1980).

Table 2: Elevation-Area-Storage-Discharge data for Lake Ilo Dam

Elevation (ft-NAVD88)	Area (acres)	Storage (acre-feet)	Principal Spillway Discharge (cfs)	Emergency Spillway Discharge (cfs)	Total Discharge (cfs)
2177.5	0	0	0	0	0
2179.5	29	29	0	0	0
2181.5	76	134	0	0	0
2183.5	143	353	0	0	0
2185.5	304	800	0	0	0
2187.5	497	1601	0	0	0
2189.5	815	2927	0	0	0
2191.5	940	4464	0	0	0
2192.0	1000	5000	0	0	0
2192.5	1047	5656	263	0	263
2194.5	1267	7965	1447	0	1447
2196.5	1487	10719	4000	0	4000
2198.5	1707	13913	7000	632	7632
2200.5	1927	17548	11000	3421	14421
2202.5	2147	21622	15526	7158	22684
2204.5	2367	26136	20280	11460	31740

2.2 Routing

The Muskingum-Cunge method was used for routing flows through the model reaches. Figure 3 illustrates the location of the reaches in the hydrology model and Table 3 provides the length, slope, and Manning's roughness for each reach. The length and slope for each reach was calculated from the NED, and Manning's roughness was determined through calibration. The eight-point shape was utilized as the cross-section type. Cross-section data for Spring Cr Reaches 3 and 4 were obtained from *Flood Hazard Analyses Spring Creek in Dunn and Mercer Counties* (U.S. Department of Agriculture, 1982). Cross-section data for Knife River Reaches 1A, 1B, 2, 3A, 3B, 4, 5A, 5B and for Spring Cr Reaches 1 and 2 were acquired from *Knife River Flood Hazard Analyses, Mercer County, North Dakota* (U.S. Department of Agriculture, 1977). Cross-section data for the remaining Knife River Reaches 6, 7, 8, and 9 were obtained from the NED, however, the channel portion of these cross-sections were estimated from field observations. The modifications to the cross-sections were based on on-site observations and pictures taken of the river channel on May 2, 2012.

Table 3: River reach parameters used in the hydrology model.

Reach	Upstream Elevation (ft-NAVD88)	Downstream Elevation (ft-NAVD88)	Length (ft)	Slope (ft/ft)	Channel Manning's n	Floodplain Manning's n
Knife River 1A	1711.4	1669.6	119633.2	0.00035	0.038	0.06
Knife River 1B	1721.1	1711.4	20019.5	0.00048	0.038	0.06
Knife River 2	1781.1	1721.1	81174.4	0.00074	0.038	0.06
Knife River 3A	1787.0	1781.1	37487.9	0.00015	0.038	0.06
Knife River 3B	1811.2	1787.0	46880.4	0.00052	0.038	0.06
Knife River 4	1861.3	1811.2	107134.0	0.00047	0.038	0.06
Knife River 5A	1881.3	1861.3	28140.0	0.00071	0.038	0.06
Knife River 5B	1900.3	1881.3	66805.0	0.00028	0.038	0.06
Knife River 6	2021.3	1900.3	202919.7	0.00060	0.038	0.06
Knife River 7	2080.4	2021.3	100938.8	0.00059	0.035	0.06
Knife River 8	2165.7	2080.4	145233.7	0.00059	0.035	0.06
Knife River 9	2242.4	2165.7	77240.6	0.00099	0.035	0.06
Spring Creek 1	1840.9	1781.1	79543.6	0.00075	0.035	0.06
Spring Creek 2	1894.4	1840.9	87470.3	0.00061	0.035	0.06
Spring Creek 3	2074.6	1894.4	216407.2	0.00083	0.035	0.06
Spring Creek 4	2193.2	2074.6	144284.1	0.00082	0.035	0.06

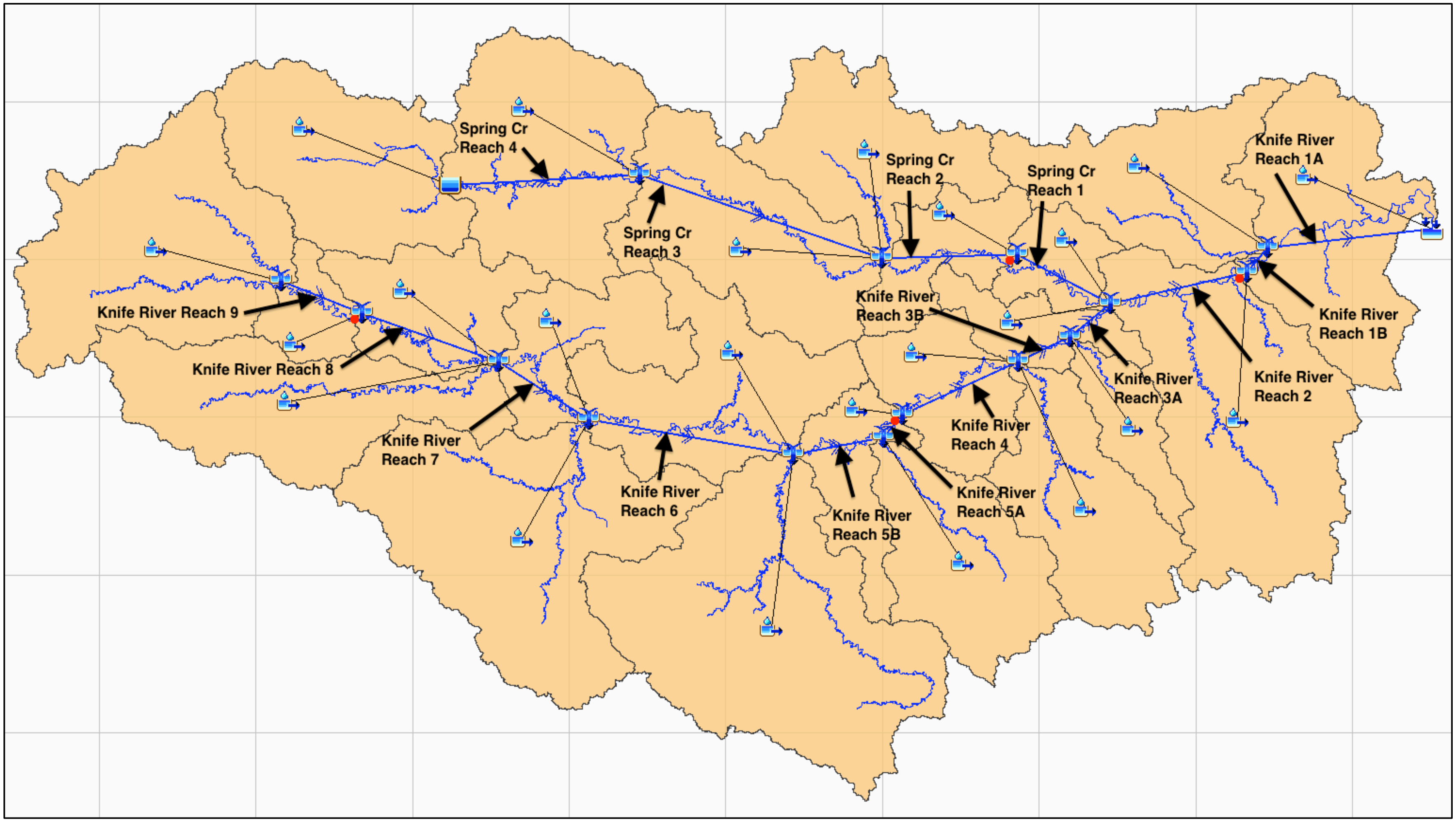

Figure 3: Layout of river reaches used in the hydrology model.

3. Calibration and Verification

Two rainfall events and one snowmelt event were added to the model for calibration. The 2002 and 2005 rainfall events were added to the model to calibrate wide spread rainfall across the entire Knife River Basin. The 2009 snowmelt event was modeled due to its significance as one of the largest and most documented storm on record. A large rainfall event in 1966 was added to the model for verification.

All model parameters were the same for both the 2002 and 2005 storms, except for initial discharge and initial moisture content. The computed peak flows and volumes for both storms at Golden Valley, Zap, and Hazen gages were no more than ±5.4% different than observed peak flows and volumes. The initial content during the 2002 storm varied from 0.18 to 0.20 for all sub-basins with the exception of the two sub-basins upstream of the Manning gage, KnifeR9 and KnifeR10, which had initial content values of 0.34 to 0.37, respectively. The initial content during the 2005 storm ranged from 0.35 to 0.41. Most of the sub-basin's initial content varied from 0.38 to 0.41, while the two sub-basins upstream of Manning were set at 0.35.

Model parameters changed when calibrating the 2009 snowmelt event. The timing used for the 2002 and 2005 storms did not peak fast enough to replicate the 2009 melt. The transform method was changed to the Clark unit hydrograph method in order to use storage coefficients to match observed hydrographs.

3.1 Meteorological Models – (Rainfall Events)

Two storms were chosen for calibration, one in 2002, one in 2005. Another storm in 1966 was added to the model for verification. Rainfall was estimated using hourly Quantitative Precipitation Estimate (QPE) rasters by the NOAA River Forecast Centers (RFC). Hourly precipitation grids for each storm were downloaded from NOAA's National Weather Service website (NOAA, 2016). Zonal statistics were performed on each hourly grid to determine the average rainfall per hour for each sub-basin. The average rainfall per hour values were compiled into hyetographs for each sub-basin. Table 4 provides the total rainfall simulated in the model per sub-basin for both storms. Multisensor Precipitation Estimator (MPE) data were used for the 2005 storm. MPE data combines rainfall measurements from rain gages, rainfall estimates from Next Generation Weather Radar (NEXRAD), and Geostationary Operational Environmental Satellite (GOES) products (Wang, X. et al., 2007). Since MPE data were not available for the 2002 storm, Stage III precipitation data were utilized. Stage III precipitation data consists of NEXRAD rainfall estimates that have been calibrated with rain gage measurements (Wang, X. et al., 2007).

The 1966 precipitation event was modeled using an isohyet map from the USGS paper "Summary of Floods in the United States During 1966" in Appendix B. The map document was geo-referenced. The isohyets were digitized and the values of total precipitation were then interpolated. The final step was to create the hyetograph for each sub-basin during the 1966 precipitation event. Zonal statistics was performed to produce a mean two-hour precipitation value for each sub-basin.

Table 4: Total rainfall simulated per sub-basin for 2002, 2005, and 1966 storms.

Sub-basin	2002 Storm (in)	2005 Storm (in)	1966 Storm (in)
AntelopeCr	4.15	2.54	4.00
BranchKnifeR	2.46	2.87	2.80
BrushCr	2.92	1.82	3.94
CoyoteCr	2.57	2.02	4.76
CrookedCr	3.46	2.15	0.00
DeepCr	3.55	2.79	0.00
ElmCr	2.52	2.37	3.32
GoodmanCr	3.77	2.9	0.00
KnifeR1	3.5	2.3	5.50
KnifeR10	1.8	1.55	0.00
KnifeR2	3.16	1.84	5.80
KnifeR3	3.35	2.16	2.20
KnifeR4	2.81	2.18	2.36
KnifeR5	2.77	2.69	2.38
KnifeR6	3.73	2.42	0.00
KnifeR7	3.53	2.23	0.00
KnifeR8	3.49	1.95	0.00
KnifeR9	3.42	2.17	0.00
LakeIlo	3.22	1.94	0.00
SpringCr1	3.68	2.16	2.00
SpringCr2	3.5	2.33	0.00
SpringCr3	3.93	2.57	0.00
SpringCr4	3.69	2.74	0.00

3.2 Meteorological Models – (Snowmelt Events)

A snowmelt event was modeled because over half of the annual peaks occurred in March and were most likely caused by snowmelt. The March 1997 and March 2009 snowmelt events were suggested for calibration and validation of the snowmelt modeling. Only the March 2009 snowmelt event was modeled due to the lack of snow water equivalent and snow depth data available for the basin in 1997.

The degree-day method was chosen to model the snowmelt event at Hazen. The degree-day method required obtaining snow water equivalence, average daily temperature, and snow depth for the Knife River Basin. The data obtained to compute the degree-day method is located in Appendix C.

Snow water equivalence (SWE) data was obtained from the National Operational Hydrologic Remote Sensing Center (NOHRSC) website. The SWE data was obtained as daily raster data, which were analyzed by using zonal statistics to obtain the mean SWE for each sub-basin over each day. Each sub-basin's daily SWE was then averaged to obtain the SWE for the Knife River Basin each day from March 15th 2009 to April 20th 2009.

The daily average temperature for the Knife River Basin was obtained from the North Dakota Agricultural Weather Network (NDAWN) data service. The average, high, and low daily temperatures were collected at Hazen. The temperatures obtained for Hazen were used for the entire Knife River Basin from March 15 to April 20, 2009.

The daily snow depths for the Knife River Basin were obtained from the NOHRSC interactive snow map service. The depths were read each day at noon and were estimated. This was done from March 15 to April 20, 2009.

After the SWE, temperature, and snow depth were collected the degree-day method was used to obtain an averaged hyetograph for the Knife River Basin. The recorded hydrograph began to rise on March 21st and peaked on March 23rd. The modeled hydrograph began to rise on March 20th and peaked on March 22nd. Previous calibration gave confidence in the model's routing and time of concentration. The apparent delayed response in the observed hydrograph needed some other explanation. NOHRSC shows that the total SWE still decreases even though the runoff did not get to the river. The temperatures at the time of the additional peak support the conclusion that melting did occur and then refroze, and did not contribute to the flow in the river. Therefore, the snowmelt was shifted from March 16th and 17th to the 20th and 21st. This adjustment produced peaks similar to the 2009 snow melt events. Table 5 provides the adjusted hyetograph for the Knife River Basin.

Table 5: Degree-day hyetograph for the Knife River Basin for the March and April 2009 snowmelt event.

Date	Total Precipitation (in)
3/15/09	0
3/16/09	0
3/17/09	0
3/18/09	0
3/19/09	0
3/20/09	1.14
3/21/09	0.95
3/22/09	0.97
3/23/09	0.14
3/24/09	0
3/25/09	0
3/26/09	0
3/27/09	0
3/28/09	0
3/29/09	0
3/30/09	0
3/31/09	0
4/1/09	0
4/2/09	0
4/3/09	0
4/4/09	0
4/5/09	0
4/6/09	0
4/7/09	0.05
4/8/09	0.05
4/9/09	0
4/10/09	0.17
4/11/09	0.66
4/12/09	0.52
4/13/09	0.20
4/14/09	0
4/15/09	0
4/16/09	0
4/17/09	0
4/18/09	0
4/19/09	0
4/20/09	0

3.3 2002 Precipitation Event

During the 2002 storm, most of the rainfall occurred early on June 9th for about five hours, followed by another three-hour rain shower about twenty-four hours later. During the five days prior to the main rain event on June 9th, the entire Knife River Basin had received an average rainfall amount of approximately 0.1 inches. This amount of precipitation corresponds to antecedent moisture I condition, or dry soil conditions, for the entire basin prior to the main rain event (U.S Department of Agriculture, Hydrology Manual for North Dakota).

Rainfall was simulated from June 7th to June 20th for the 2002 storm. The following figures illustrate the observed hydrograph compared to the computed hydrograph for the Manning, Golden Valley, Zap and Hazen gages. Immediately following each hydrograph is a table comparing observed and computed peak flow, timing of peak flow, and volume at that gage. The calibrated transform, loss, and baseflow parameters are shown in Table 6. The routing parameters were the same as shown in Table 3.

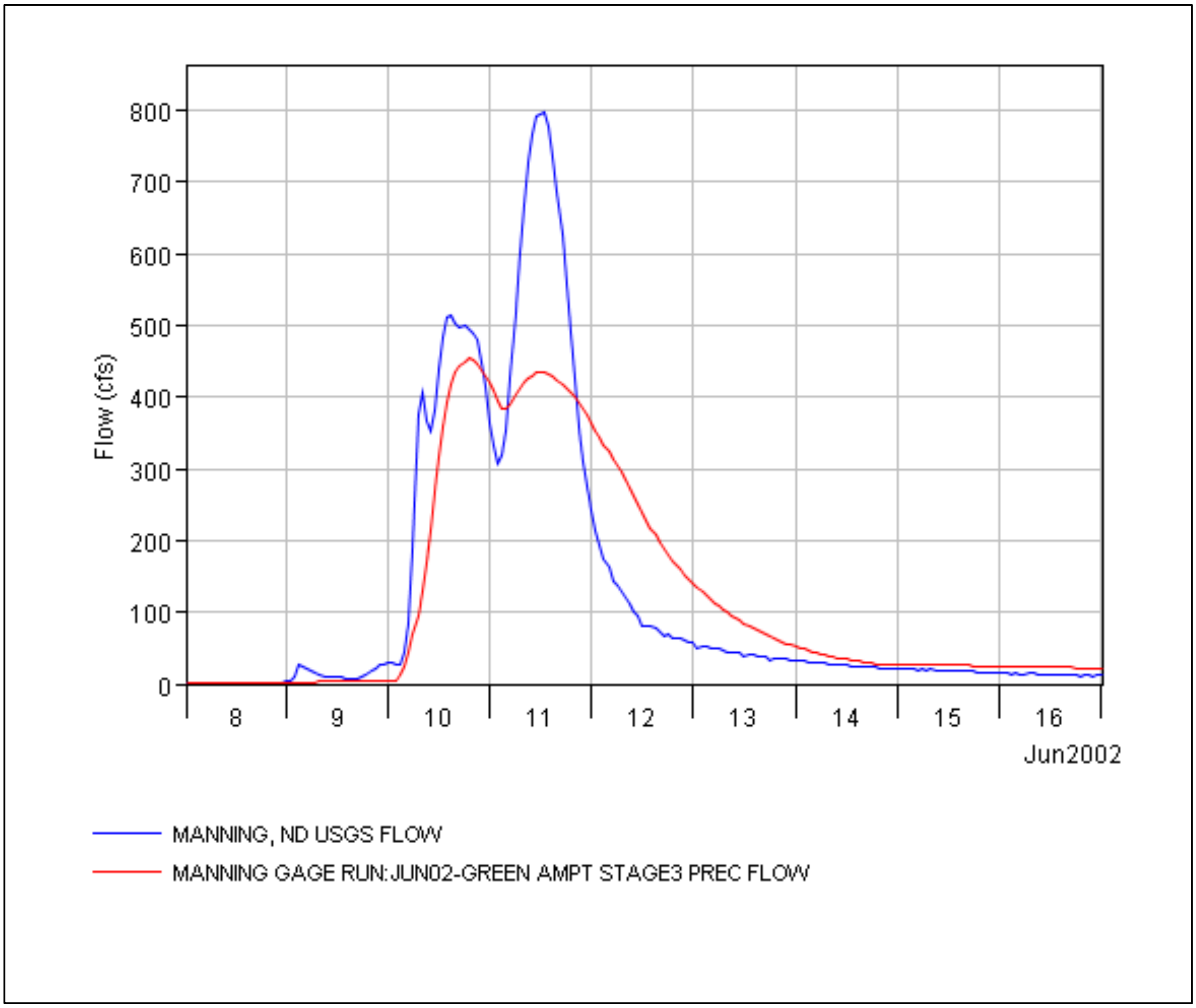

Figure 4: Manning gage 2002 storm. (The red line is the computed flow hydrograph at the Manning gage. The blue line is the observed flow at the gage.)

	Observed	Modeled	% Difference
Peak Outflow (cfs)	798	454	-43.2
Date/Time of Peak	11Jun2002, 13:00	10Jun2002, 19:00	
Volume (acre-feet)	2,267	2,308	1.7

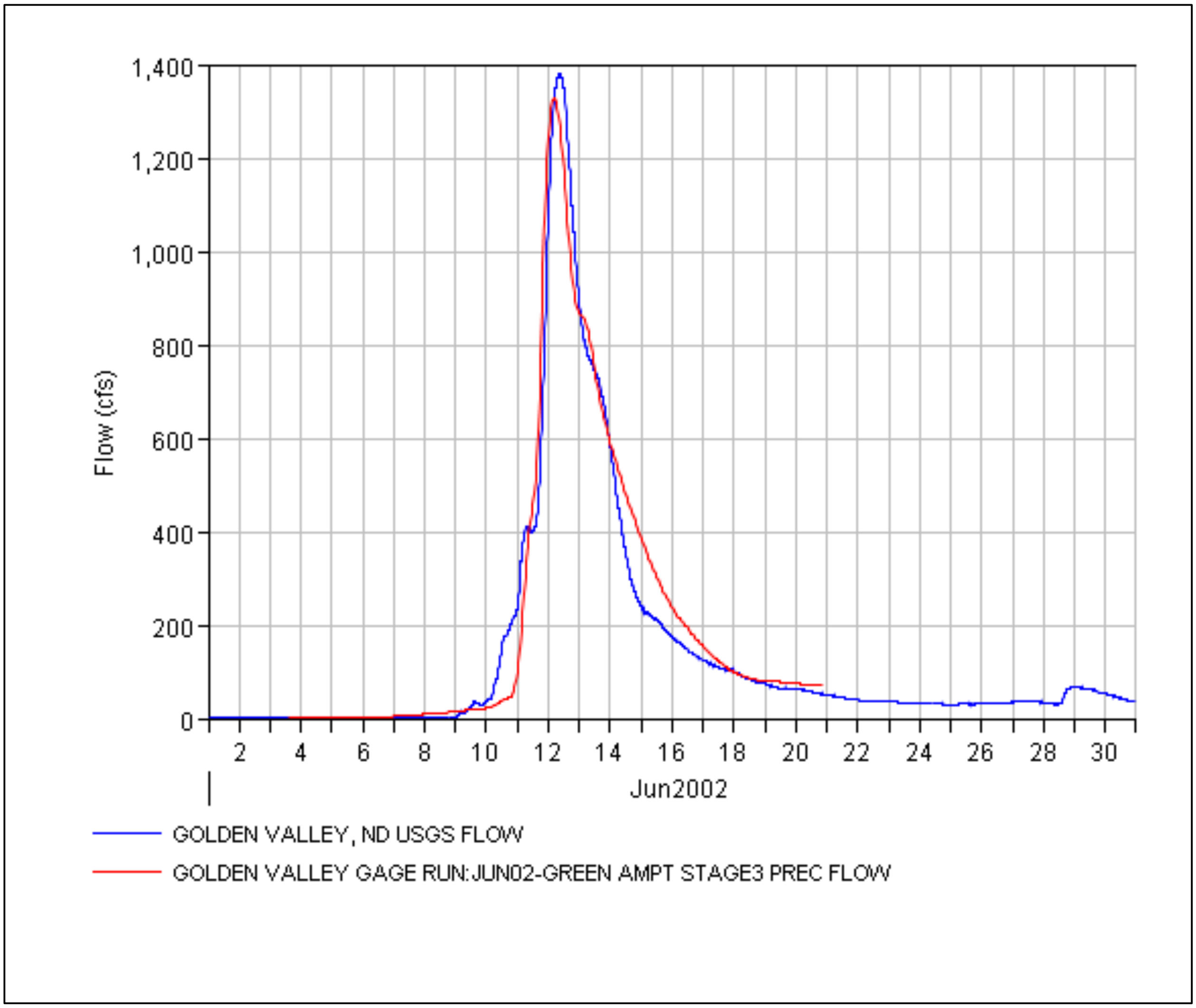

Figure 5: Golden Valley gage 2002 storm. (The red line is the computed flow hydrograph at the Golden Valley. The blue line is the observed flow at the gage.)

	Observed	Modeled	% Difference
Peak Outflow (cfs)	1,380	1,324	-4.1
Date/Time of Peak	12Jun2002, 08:00	12Jun2002, 04:00	
Volume (acre-feet)	7,241	7501	3.6

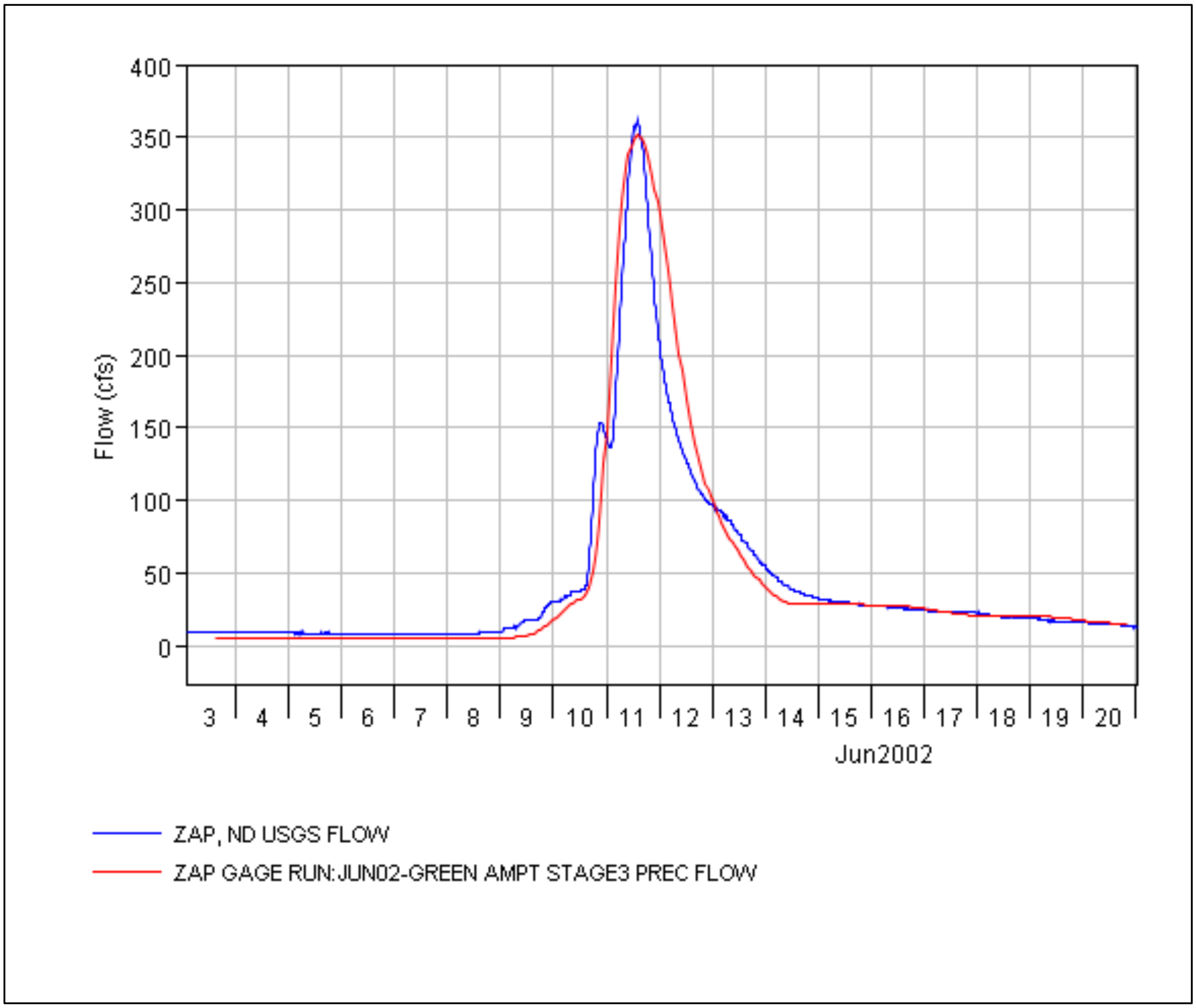

Figure 6: Zap gage 2002 storm. (The red line is the computed flow hydrograph at the Zap gage. The blue line is the observed flow at the gage.)

	Observed	Modeled	% Difference
Peak Outflow (cfs)	359	353	-1.7
Date/Time of Peak	11Jun2002, 13:00	11Jun2002, 14:00	
Volume (acre-feet)	1,485	1,551	4.4

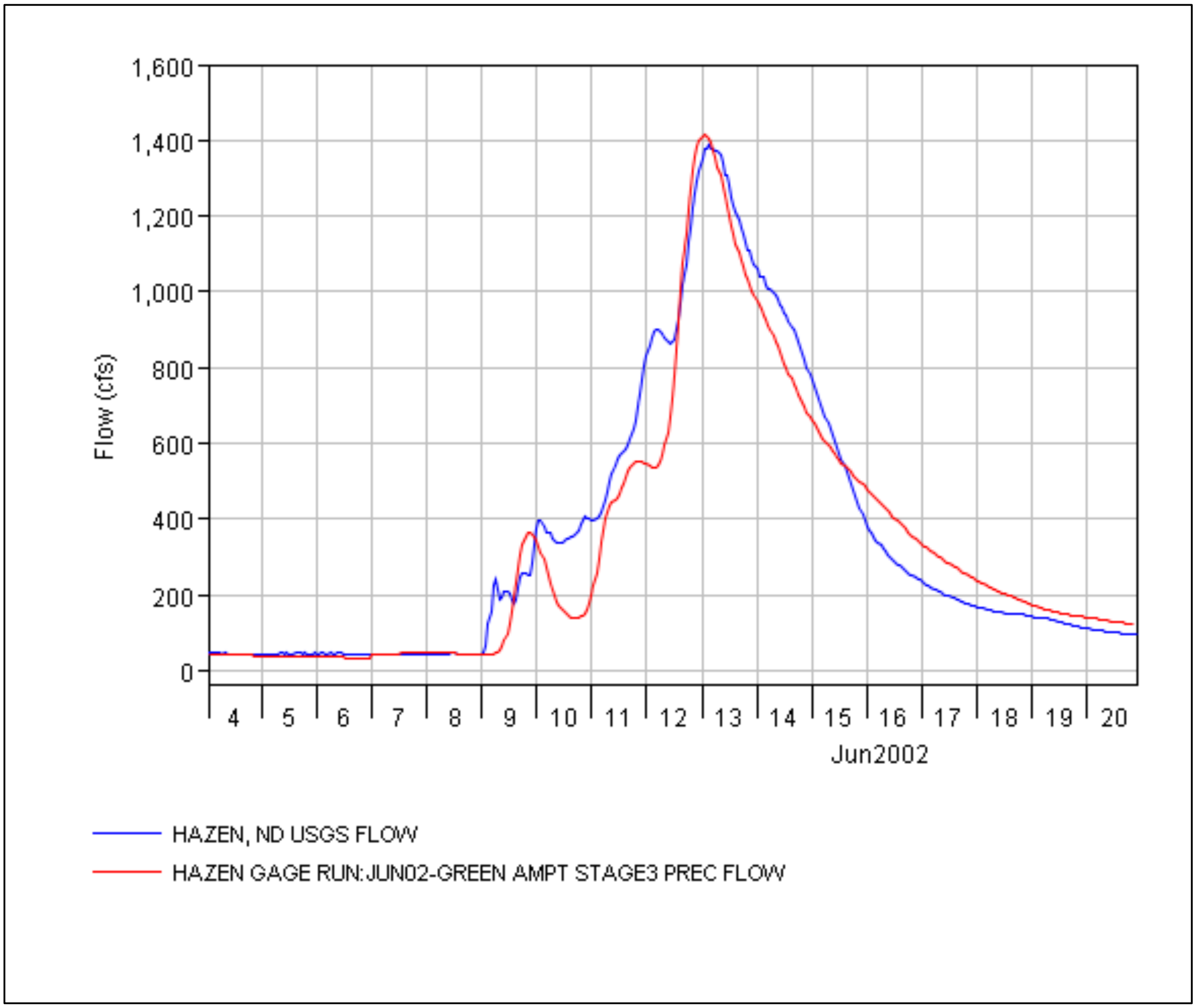

Figure 7: Hazen gage 2002 storm. (The red line is the computed flow hydrograph at the Hazen gage. The blue line is the observed flow at the gage.)

	Observed	Modeled	% Difference
Peak Outflow (cfs)	1,390	1,406	7.4
Date/Time of Peak	13Jun2002, 03:00	13Jun2002, 01:00	
Volume (acre-feet)	11,598	10,832	-6.6

Table 6: Calibrated loss, baseflow, and transform parameters for the 2002 storm.

	Losses-Green Ampt					Baseflow			Transform	
Sub-basin	**Porosity**	**Initial Content**	**Hydraulic Conductivity (in/hr)**	**Wetting Front Suction (in)**	**% Impervious**	**Initial Discharge (cfs)**	**Recession Constant**	**Ratio to Peak**	**TOC (hr)**	**Lag Time (min)**
AntelopeCr	0.45	0.200	0.17	21.25	1.04	6.00	0.90	0.04	35.37	1273.32
BranchKnifeR	0.45	0.180	0.23	21.53	0.40	0.70	0.90	0.04	51.47	1852.85
BrushCr	0.45	0.200	0.18	21.13	0.42	6.00	0.90	0.04	28.92	1041.12
CoyoteCr	0.45	0.200	0.13	21.34	0.25	6.00	0.90	0.04	40.17	1446.12
CrookedCr	0.44	0.180	0.26	22.08	0.24	0.70	0.90	0.04	46.41	1670.76
DeepCr	0.45	0.180	0.20	21.39	0.27	0.70	0.90	0.04	35.94	1293.84
ElmCr	0.44	0.180	0.16	22.12	0.19	0.70	0.90	0.04	40.37	1453.25
GoodmanCr	0.45	0.195	0.24	21.03	0.23	0.00	0.90	0.04	46.70	1681.34
KnifeR1	0.45	0.200	0.51	21.27	0.32	6.00	0.90	0.04	30.57	1100.52
KnifeR10	0.45	0.370	0.13	21.79	0.22	0.70	0.90	0.04	50.45	1816.02
KnifeR2	0.45	0.200	0.23	21.44	0.46	6.00	0.90	0.04	37.89	1364.04
KnifeR3	0.44	0.200	0.16	22.05	0.64	6.00	0.90	0.04	24.29	874.44
KnifeR4	0.44	0.200	0.11	22.27	0.13	6.00	0.90	0.04	20.56	740.16
KnifeR5	0.45	0.180	0.17	21.56	0.23	0.70	0.90	0.04	20.78	748.22
KnifeR6	0.45	0.180	0.21	21.59	0.20	0.70	0.90	0.04	42.26	1521.50
KnifeR7	0.45	0.180	0.26	21.59	0.22	0.70	0.90	0.04	31.70	1141.20
KnifeR8	0.45	0.180	0.25	21.66	0.25	0.70	0.90	0.04	25.41	914.76
KnifeR9	0.44	0.340	0.27	21.97	0.26	0.70	0.90	0.04	25.55	919.62
LakeIlo	0.44	0.195	0.43	22.07	0.38	2.00	0.90	0.04	45.87	1651.39
SpringCr1	0.44	0.200	0.15	22.39	0.42	2.00	0.90	0.04	21.81	785.16
SpringCr2	0.44	0.195	0.41	21.84	0.41	2.00	0.90	0.04	47.30	1702.66
SpringCr3	0.45	0.195	0.34	21.49	0.33	2.00	0.90	0.04	53.25	1916.93
SpringCr4	0.45	0.195	0.48	21.53	0.24	2.00	0.90	0.04	57.34	2064.38

3.4 2005 Precipitation Event

During the 2005 storm, a majority of the rainfall occurred early on June 29th. The average rainfall over the basin in the five days leading up to the main rain event was about 1.3 inches, which is just less than antecedent moisture II conditions, or average soil moisture conditions (U.S Department of Agriculture, Hydrology Manual for North Dakota). The overall lower initial content for the 2002 storm and the overall higher initial content for the 2005 storm correspond to the antecedent moisture conditions of both storms, which was expected.

Rainfall for the 2005 storm was simulated from June 27th to July 7th. Table 7 lists the calibrated transform, loss, and baseflow parameters. The routing parameters were the same as shown in Table 3. The following figures illustrate the observed hydrograph compared to the computed hydrograph for the Manning, Golden Valley, Zap and Hazen gages. Immediately following each hydrograph is a table comparing observed and computed peak flow, timing of peak flow, and volume at that gage.

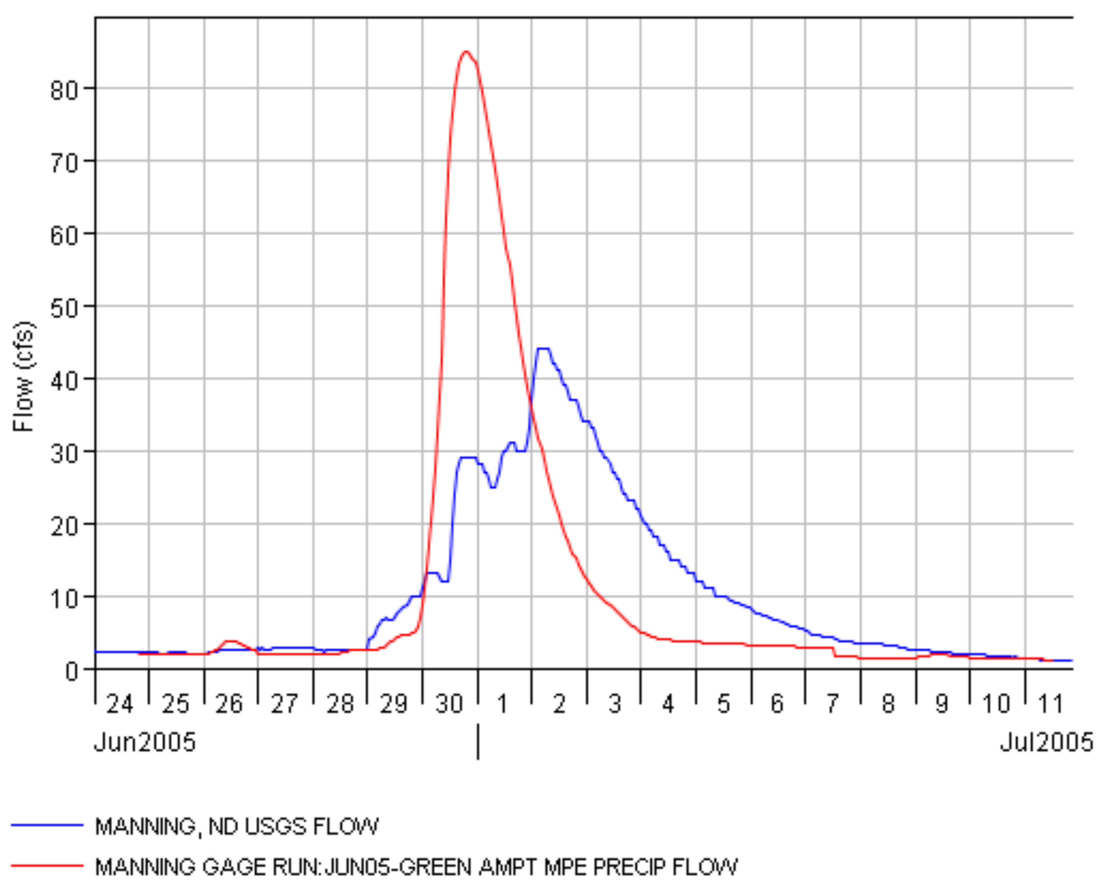

Figure 8: Manning gage 2005 storm. (The red line is the computed flow hydrograph at the Manning gage. The blue line is the observed flow at the gage.)

	Observed	Modeled	% Difference
Peak Outflow (cfs)	44	85	92.5
Date/Time of Peak	02Jul2005, 03:00	30Jun2005, 19:00	
Volume (acre-feet)	323	333	2.8

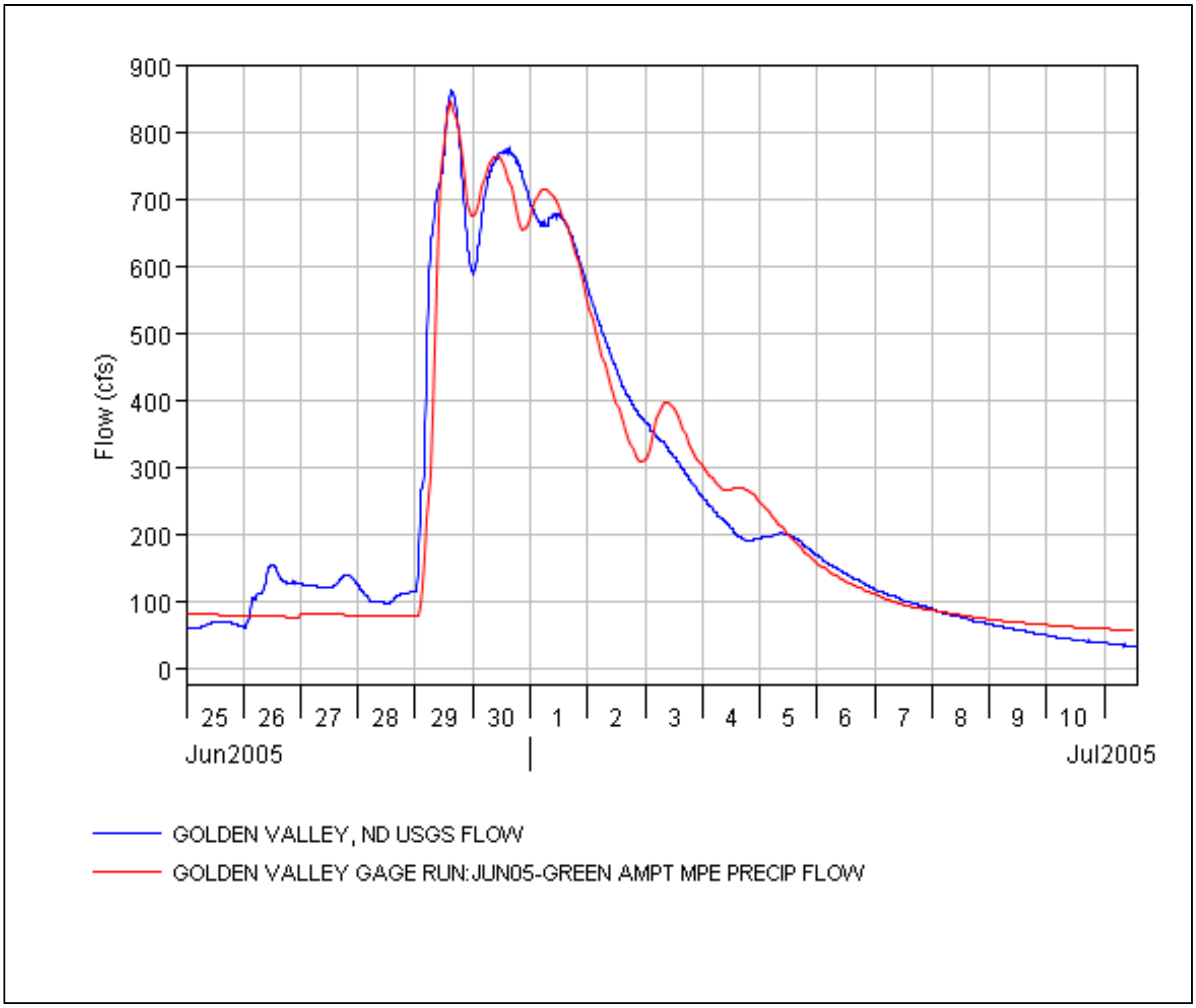

Figure 9: Golden Valley gage 2005 storm. (The red line is the computed flow hydrograph at the Golden Valley gage. The blue line is the observed flow at the gage.)

	Observed	Modeled	% Difference
Peak Outflow (cfs)	862	846	-1.86
Date/Time of Peak	29Jun2005, 15:00	29Jun2005, 15:00	
Volume (acre-feet)	7,159	6,979	-2.5

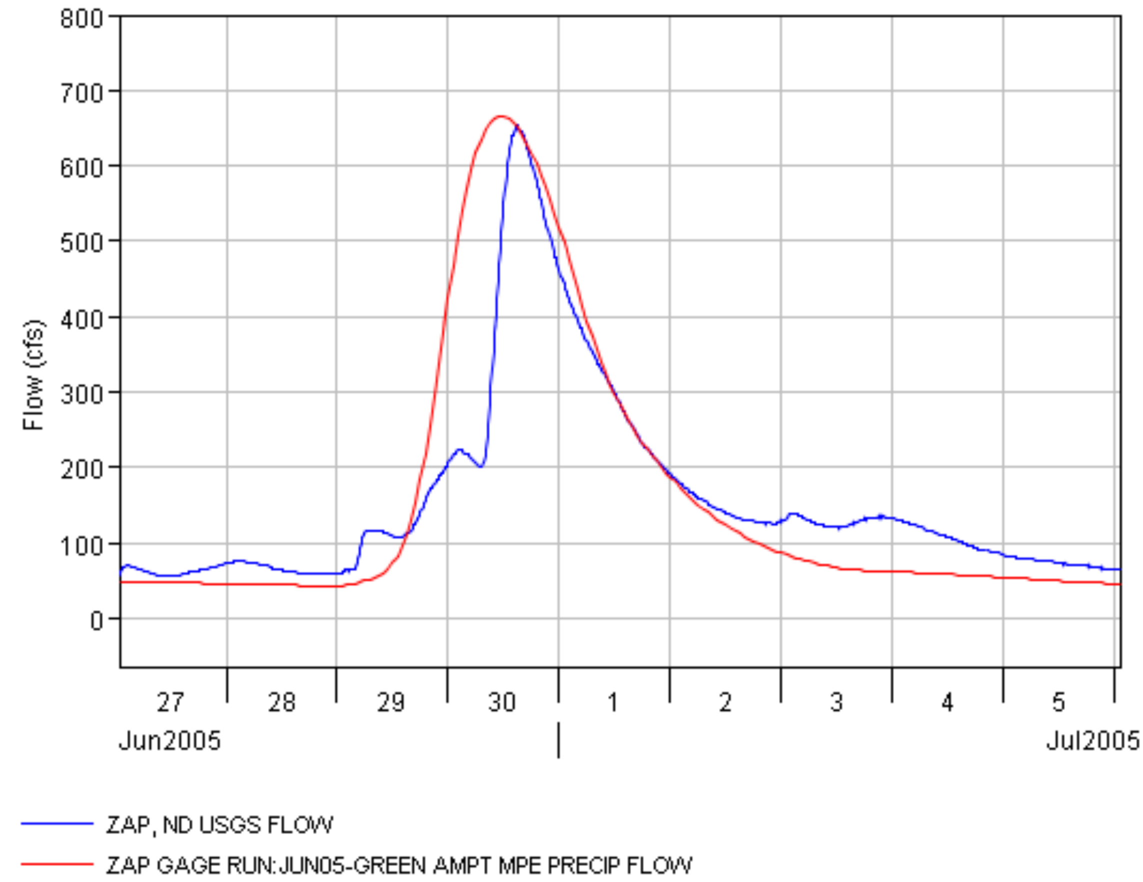

Figure 10: Zap gage 2005 storm. (The red line is the computed flow hydrograph at the Zap gage. The blue line is the observed flow at the gage.)

	Observed	**Modeled**	**% Difference**
Peak Outflow (cfs)	653	667	2.1
Date/Time of Peak	30Jun2005, 15:00	30Jun2005, 12:00	
Volume (acre-feet)	3,007	2,979	-0.9

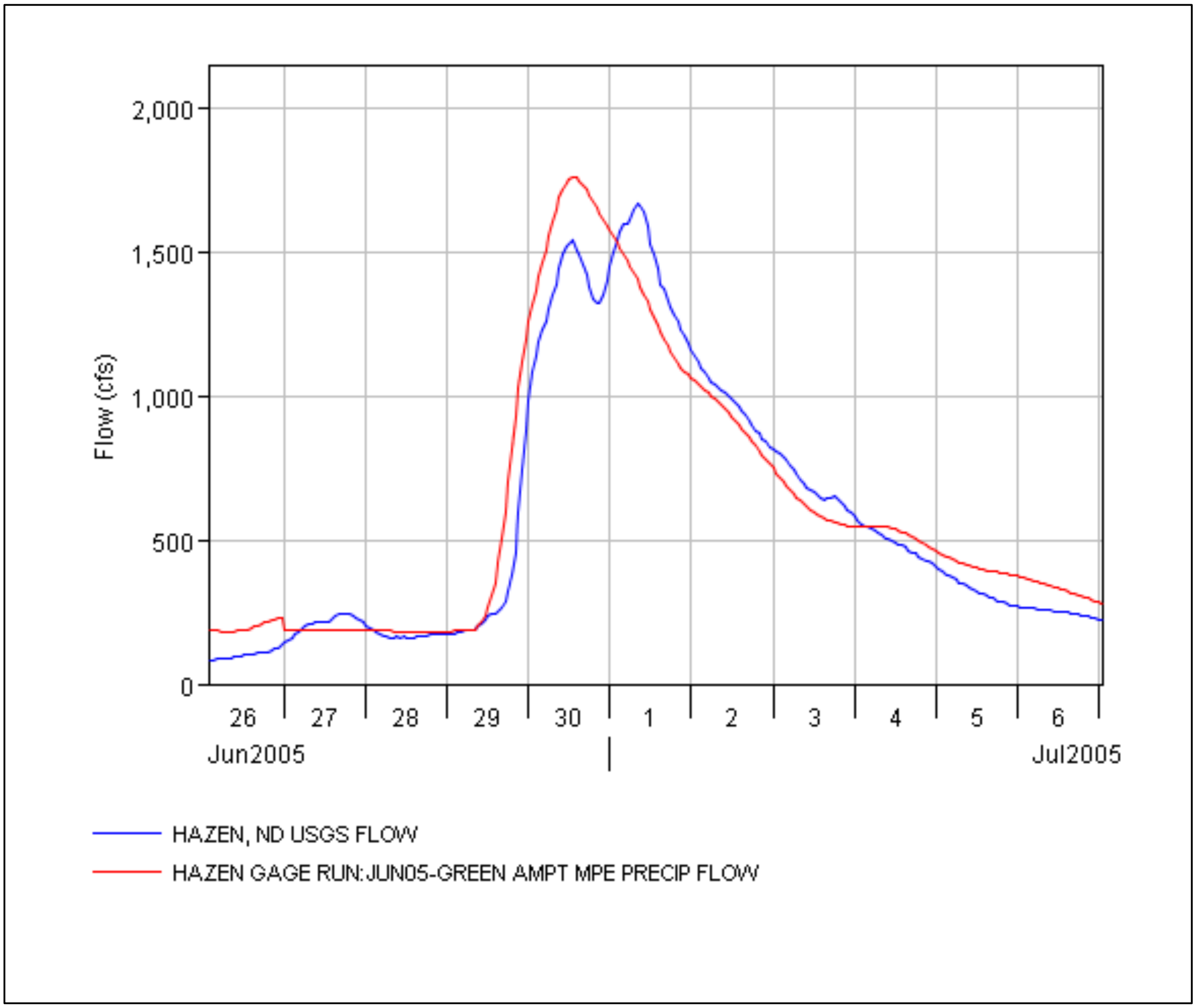

Figure 11: Hazen gage 2005 storm. (The red line is the computed flow hydrograph at the Hazen gage. The blue line is the observed flow at the gage.)

	Observed	Modeled	% Difference
Peak Outflow (cfs)	1,670	1,762	5.5
Date/Time of Peak	01Jul2005, 08:00	30Jun2005, 13:00	
Volume (acre-feet)	12,602	13,266	5.3

Table 7: Calibrated loss, baseflow, and transform parameters for the 2005 storm.

	Losses-Green Ampt					Baseflow			Transform	
Sub-basin	Porosity	Initial Content	Hydraulic Conductivity (in/hr)	Wetting Front Suction (in)	% Impervious	Initial Discharge (cfs)	Recession Constant	Ratio to Peak	TOC (hr)	Lag Time (min)
AntelopeCr	0.45	0.390	0.17	21.25	1.04	10	0.9	0.04	35.37	1273.32
BranchKnifeR	0.45	0.380	0.23	21.53	0.40	10	0.9	0.04	51.47	1852.85
BrushCr	0.45	0.380	0.18	21.13	0.42	10	0.9	0.04	28.92	1041.12
CoyoteCr	0.45	0.380	0.13	21.34	0.25	10	0.9	0.04	40.17	1446.12
CrookedCr	0.44	0.390	0.26	22.08	0.24	10	0.9	0.04	46.41	1670.76
DeepCr	0.45	0.390	0.20	21.39	0.27	10	0.9	0.04	35.94	1293.84
ElmCr	0.44	0.390	0.16	22.12	0.19	10	0.9	0.04	40.37	1453.25
GoodmanCr	0.45	0.410	0.24	21.03	0.23	12	0.9	0.04	46.70	1681.34
KnifeR1	0.45	0.390	0.51	21.27	0.32	10	0.9	0.04	30.57	1100.52
KnifeR10	0.45	0.350	0.13	21.79	0.22	1	0.9	0.04	50.45	1816.02
KnifeR2	0.45	0.380	0.23	21.44	0.46	10	0.9	0.04	37.89	1364.04
KnifeR3	0.44	0.380	0.16	22.05	0.64	10	0.9	0.04	24.29	874.44
KnifeR4	0.44	0.380	0.11	22.27	0.13	10	0.9	0.04	20.56	740.16
KnifeR5	0.45	0.405	0.17	21.56	0.23	10	0.9	0.04	20.78	748.22
KnifeR6	0.45	0.400	0.21	21.59	0.20	10	0.9	0.04	42.26	1521.50
KnifeR7	0.45	0.390	0.26	21.59	0.22	10	0.9	0.04	31.70	1141.20
KnifeR8	0.45	0.390	0.25	21.66	0.25	10	0.9	0.04	25.41	914.76
KnifeR9	0.44	0.350	0.27	21.97	0.26	1	0.9	0.04	25.55	919.62
LakeIlo	0.44	0.410	0.43	22.07	0.38	12	0.9	0.04	45.87	1651.39
SpringCr1	0.44	0.380	0.15	22.39	0.42	10	0.9	0.04	21.81	785.16
SpringCr2	0.44	0.410	0.41	21.84	0.41	12	0.9	0.04	47.30	1702.66
SpringCr3	0.45	0.410	0.34	21.49	0.33	12	0.9	0.04	53.25	1916.93
SpringCr4	0.45	0.410	0.48	21.53	0.24	12	0.9	0.04	57.34	2064.38

3.5 Verification Event - 1966 Precipitation Event

The 1966 storm was simulated to further verify the calibration of the hydrology model with a larger rain event than the 2002 and 2005 storms. The 1966 flood at Beulah and Hazen was caused by a 2-hour precipitation event that occurred on the lower half of the Knife River basin. The storm produced a peak flow of 35,300 cfs at the Hazen gage around June 24-25. The same basin model that was previously calibrated for the 2005 storm was used in the simulation of the 1966 storm and produced a peak flow that was 7.2% below the observed peak flow within the correct timeframe. Volume was not calibrated because the peak flow was calculated off of a point measurement.

The mean two-hour precipitation values were then converted into hourly precipitation values and placed into precipitation gages for each sub-basin. The storm was simulated in HEC-HMS using the same basin model that was previously calibrated for the June 2005 storm and produced a peak flow of 32,764 cfs at the Hazen gage on June 25 (Figure 12).

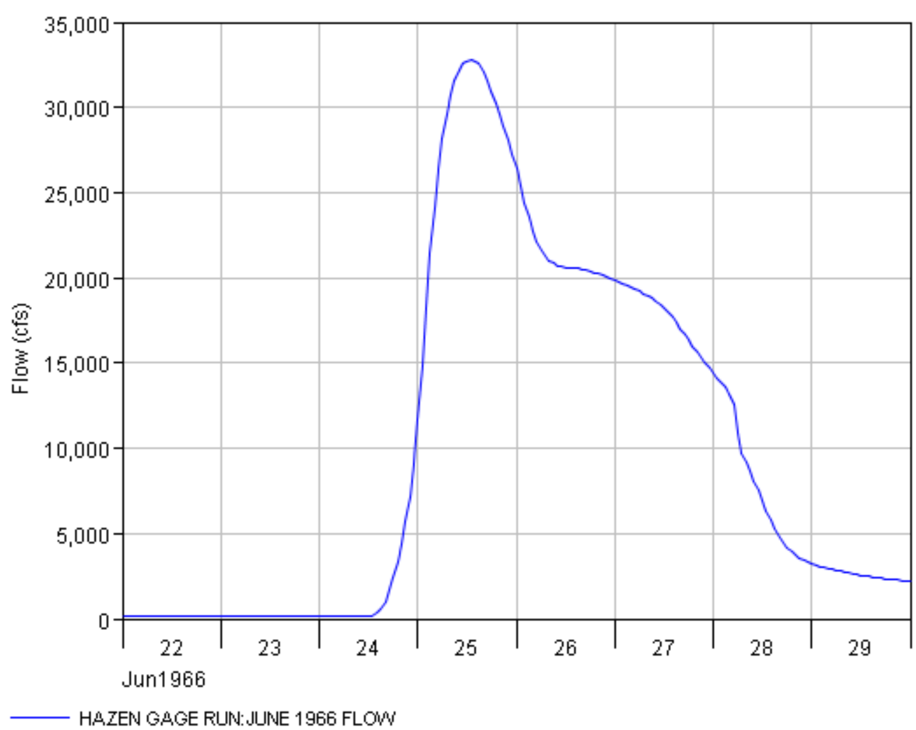

Figure 12: Computed hydrograph for 1966 storm at Hazen gage.

3.6 2009 Snowmelt Event

The 2009 March and April snowmelt event produced some of the highest recorded peak flows on record for the stream gage at Hazen. The peak flow in March 2009 according to the USGS gage data was 27,400 cfs, the second highest flow recorded at the Hazen gage. Figure 13 is the observed daily flow hydrograph for the 2009 event at the Hazen gage. The data for the Hazen gage was imported into HEC-DSS VUE from the USGS. It should be noted that the daily flow data shows a peak flow that is lower than 27,400 cfs. Instantaneous flow data or hourly data was not available for the time period of interest.

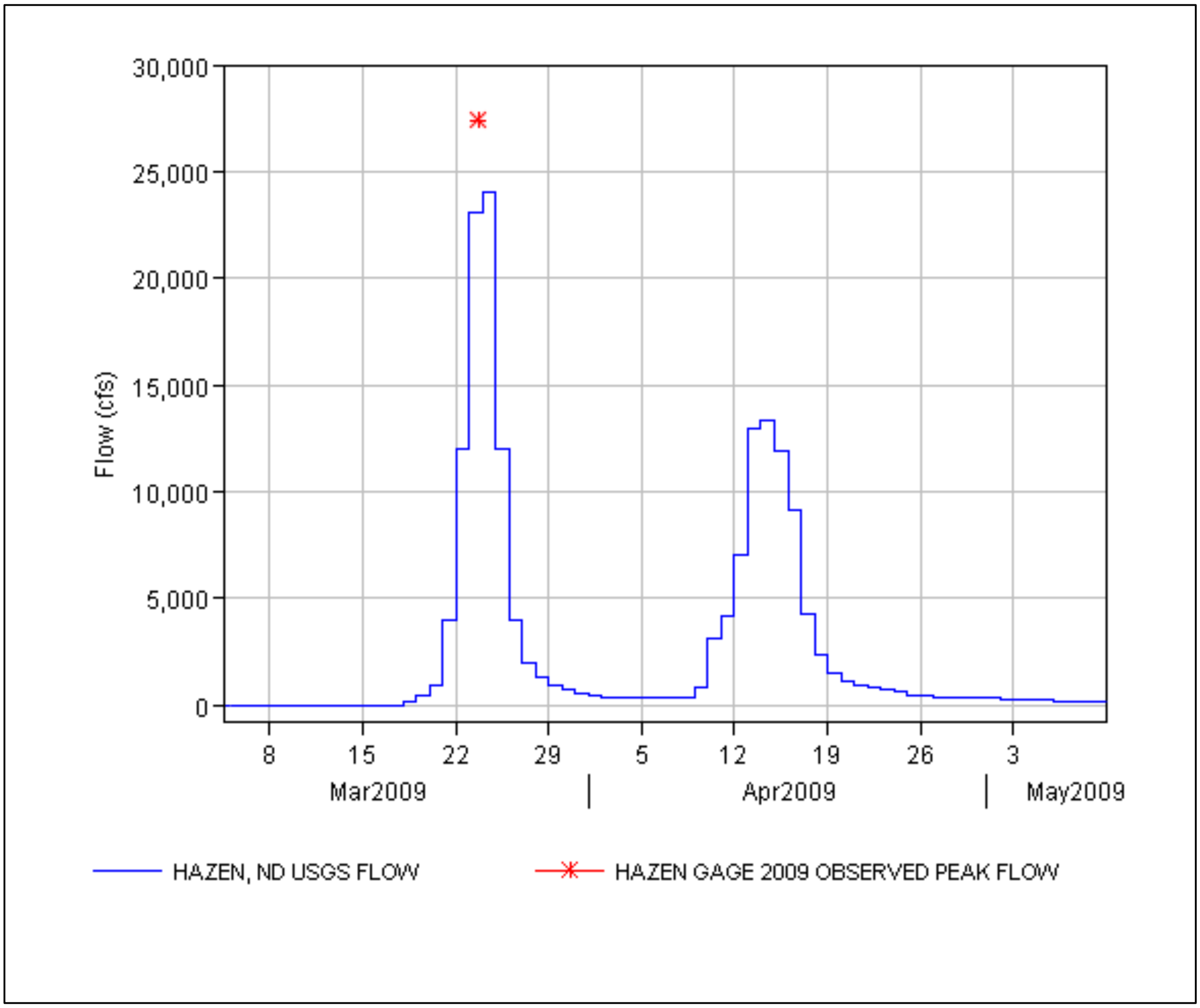

Figure 13: Observed daily flow hydrograph at Hazen from March 15 to April 20, 2009.

The hyetograph in Table 5 was then entered into precipitation gages for each sub-basin. The meteorological event was then computed in HEC-HMS from March 15 until April 20,

2009. The model initially produced significantly less stream flow at Hazen than recorded. The initial moisture content was increased to saturation and the hydraulic conductivity was adjusted to increase the direct runoff and account for the frozen ground during the snowmelt events.

During the calibration, it was noted that hydrograph shape could not be matched using the SCS unit hydrograph method. For this reason, the transform method was switched to the Clark unit hydrograph method for the snowmelt model. Travel times and storage coefficients were adjusted in order to calibrate the event. **Table 8** is the March 2009 peak calibrated parameters. After the calibration of the peak in March of 2009 was completed, both the 2002 and 2005 events were roughly calibrated using the Clark unit hydrograph method. The 2002 and 2005 event produced results similar to using the SCS unit hydrograph method.

Table 8: Calibrated loss, baseflow, and transform parameters for the March 2009 snowmelt event.

	Losses-Green Ampt					Baseflow			Transform		
Sub-basin	Porosity	Initial Content	Hydraulic Conductivity (in/hr)	Wetting Front Suction (in)	% Impervious	Initial Discharge (cfs)	Recession Constant	Ratio to Peak	TOC (hr)	Storage Coefficient (hr)	R/(R+Tc)
AntelopeCr	0.450	0.450	0.008	21.25	1.04	0	0.9	0.04	21.22	14.14	0.40
BranchKnifeR	0.450	0.450	0.027	21.53	0.40	0	0.9	0.04	22.00	6.60	0.23
BrushCr	0.450	0.450	0.008	21.13	0.42	0	0.9	0.04	17.35	11.57	0.40
CoyoteCr	0.450	0.450	0.008	21.34	0.25	0	0.9	0.04	24.10	16.06	0.40
CrookedCr	0.440	0.440	0.026	22.08	0.24	0	0.9	0.04	21.00	6.30	0.23
DeepCr	0.450	0.450	0.026	21.39	0.27	0	0.9	0.04	21.00	6.30	0.23
ElmCr	0.440	0.440	0.027	22.12	0.19	0	0.9	0.04	16.22	4.87	0.23
GoodmanCr	0.450	0.445	0.018	21.03	0.23	0	0.9	0.04	28.02	14.01	0.33
KnifeR1	0.450	0.450	0.008	21.27	0.32	0	0.9	0.04	18.34	12.23	0.40
KnifeR10	0.450	0.450	0.030	21.79	0.22	0	0.9	0.04	30.27	25.00	0.45
KnifeR2	0.450	0.450	0.008	21.44	0.46	0	0.9	0.04	22.73	22.73	0.50
KnifeR3	0.440	0.440	0.008	22.05	0.64	0	0.9	0.04	14.57	9.71	0.40
KnifeR4	0.440	0.440	0.008	22.27	0.13	0	0.9	0.04	12.34	8.22	0.40
KnifeR5	0.450	0.450	0.027	21.56	0.23	0	0.9	0.04	12.47	3.74	0.23
KnifeR6	0.450	0.450	0.027	21.59	0.20	0	0.9	0.04	17.36	5.21	0.23
KnifeR7	0.450	0.450	0.026	21.59	0.22	0	0.9	0.04	22.02	6.61	0.23
KnifeR8	0.450	0.450	0.026	21.66	0.25	0	0.9	0.04	21.25	6.38	0.23
KnifeR9	0.440	0.440	0.030	21.97	0.26	0	0.9	0.04	15.33	14.00	0.48
LakeIlo	0.440	0.435	0.018	22.07	0.38	0	0.9	0.04	27.52	13.76	0.33
SpringCr1	0.440	0.440	0.008	22.39	0.42	0	0.9	0.04	13.09	6.00	0.31
SpringCr2	0.440	0.435	0.018	21.84	0.41	0	0.9	0.04	28.38	14.19	0.33
SpringCr3	0.450	0.445	0.018	21.49	0.33	0	0.9	0.04	31.95	15.98	0.33
SpringCr4	0.450	0.445	0.018	21.53	0.24	0	0.9	0.04	34.41	17.21	0.33

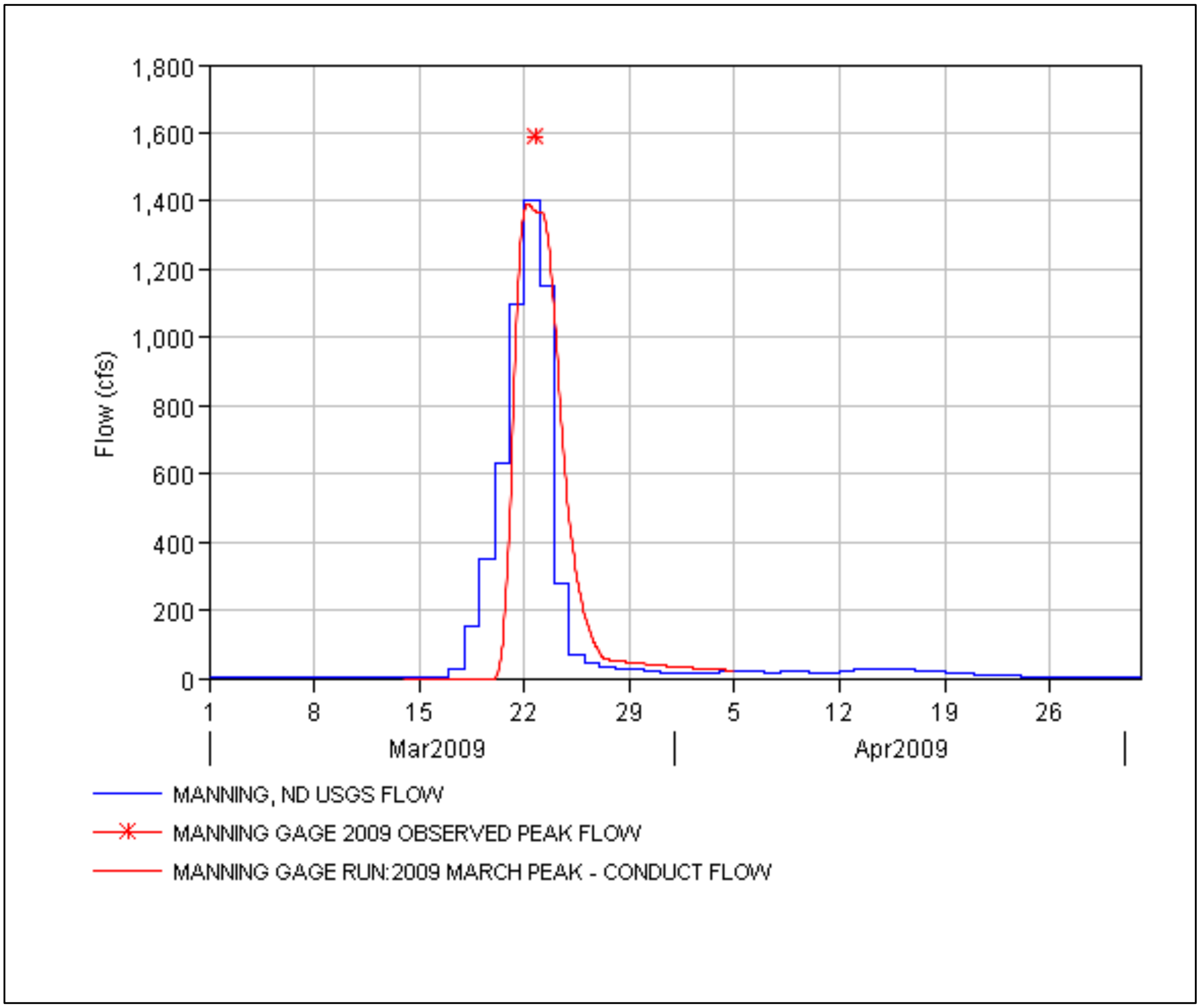

Figure 14: Computed hydrograph at Manning for March of 2009 snowmelt event compared to the observed USGS gage daily flow data (Daily observed peak of 1,400 cfs and instantaneous peak of 1,590 cfs).

	Observed Peak	Modeled Peak	% Difference
Outflow (cfs)	1,590	1,392	14.2
Date/Time of Peak	3/22/09 1:00	3/22/09 6:00	
Volume (acre-ft)	10,677	10,549	-1.20

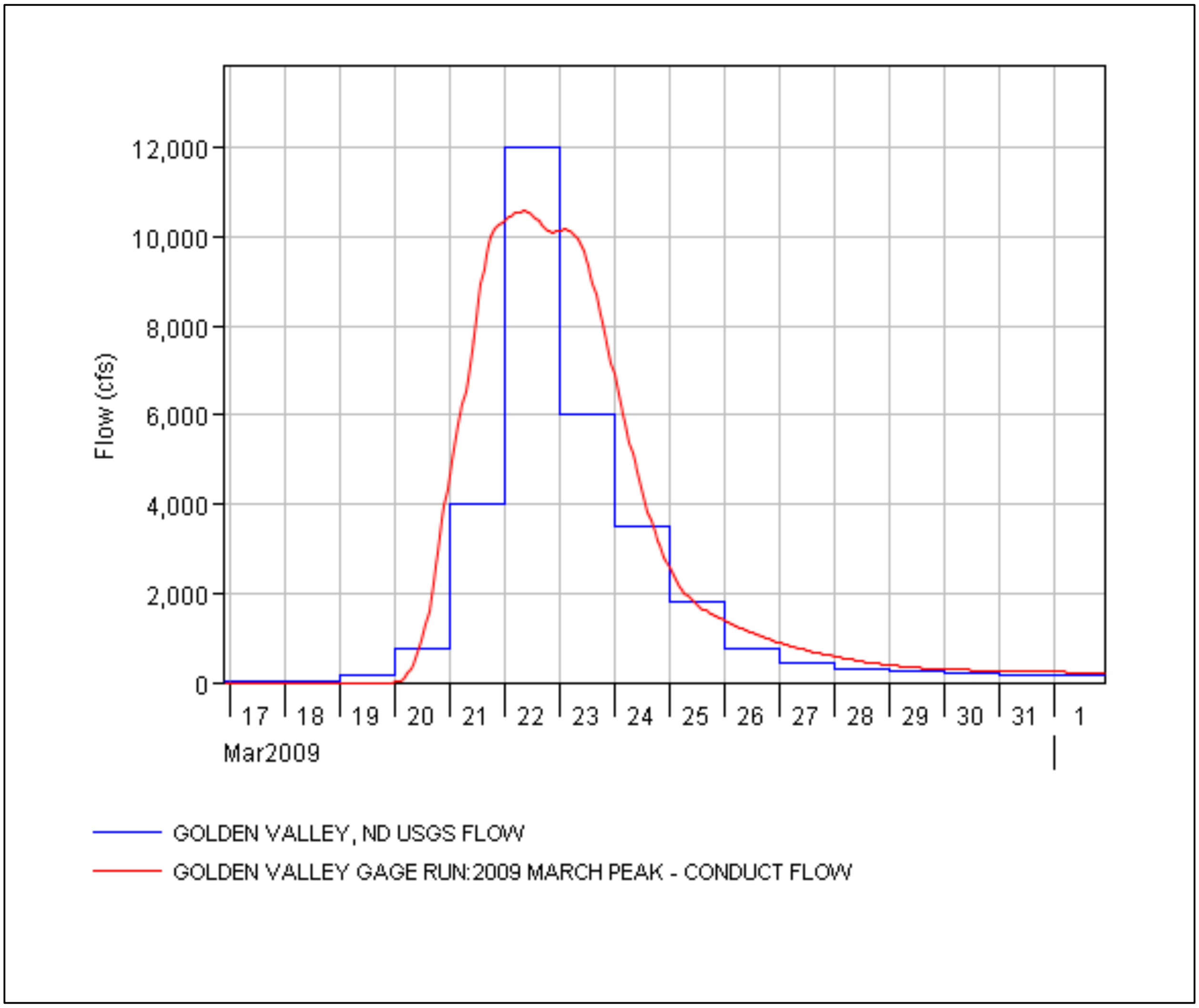

Figure 15: Computed hydrograph at Golden Valley for March of 2009 snowmelt event compared to the observed USGS gage daily flow data (Gage sensor failure, no instantaneous peak recorded).

	Daily Observed	Modeled Peak	% Difference
Outflow (cfs)	12,000	10,585	-11.9
Date/Time of Peak	3/22/09 1:00	3/22/09 8:00	
Volume (acre-ft)	61,383	77,888	26.9

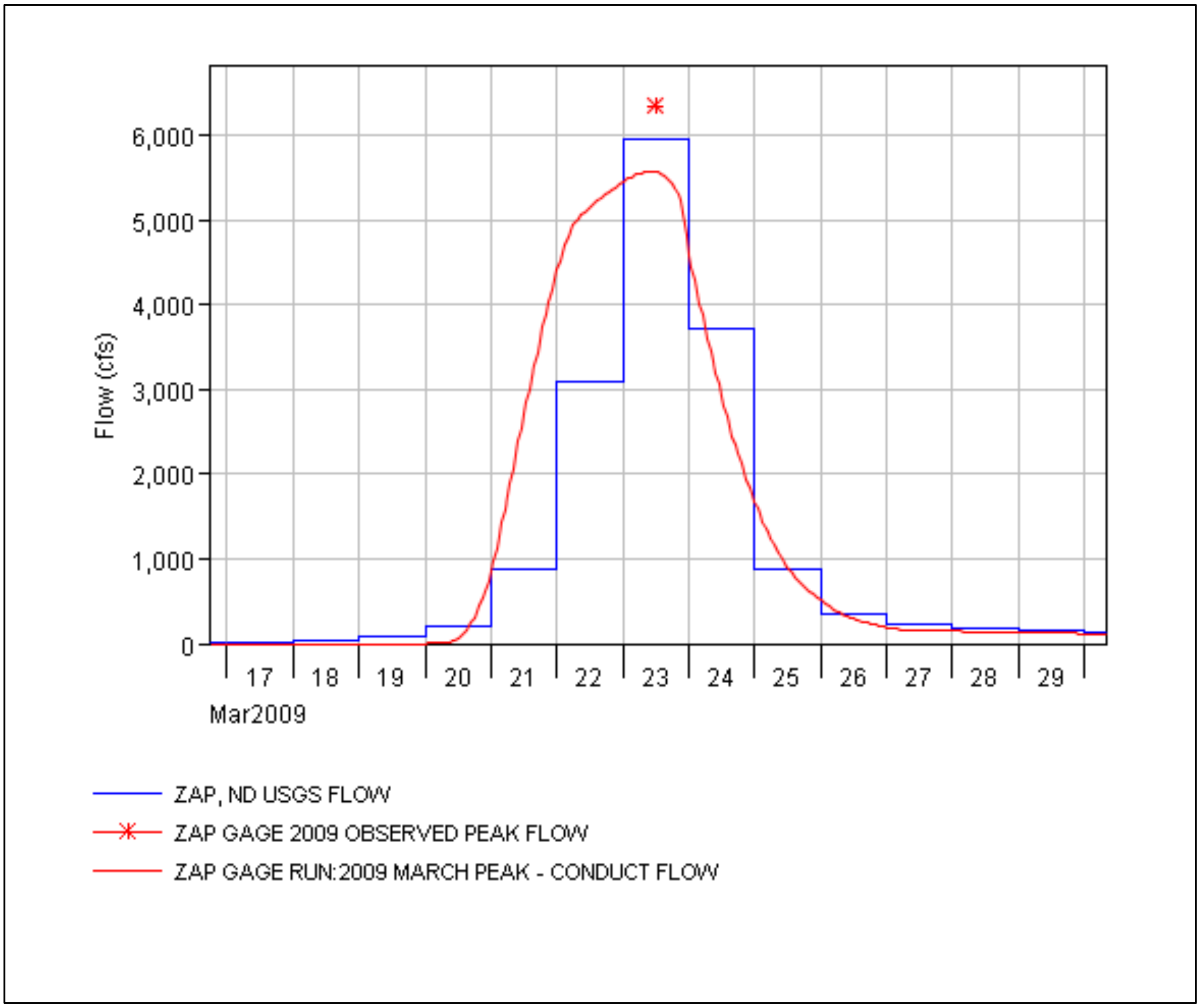

Figure 16: Computed hydrograph at Zap for March of 2009 snowmelt event compared to the observed USGS gage daily flow data (Daily observed peak of 5,940 cfs and instantaneous peak of 6,340 cfs).

	Observed Peak	Modeled Peak	% Difference
Outflow (cfs)	6,340	5,575	-12.1
Date/Time of Peak	3/23/09 1:00	3/23/09 11:00	
Volume (acre-ft)	32,443	36,876	13.7

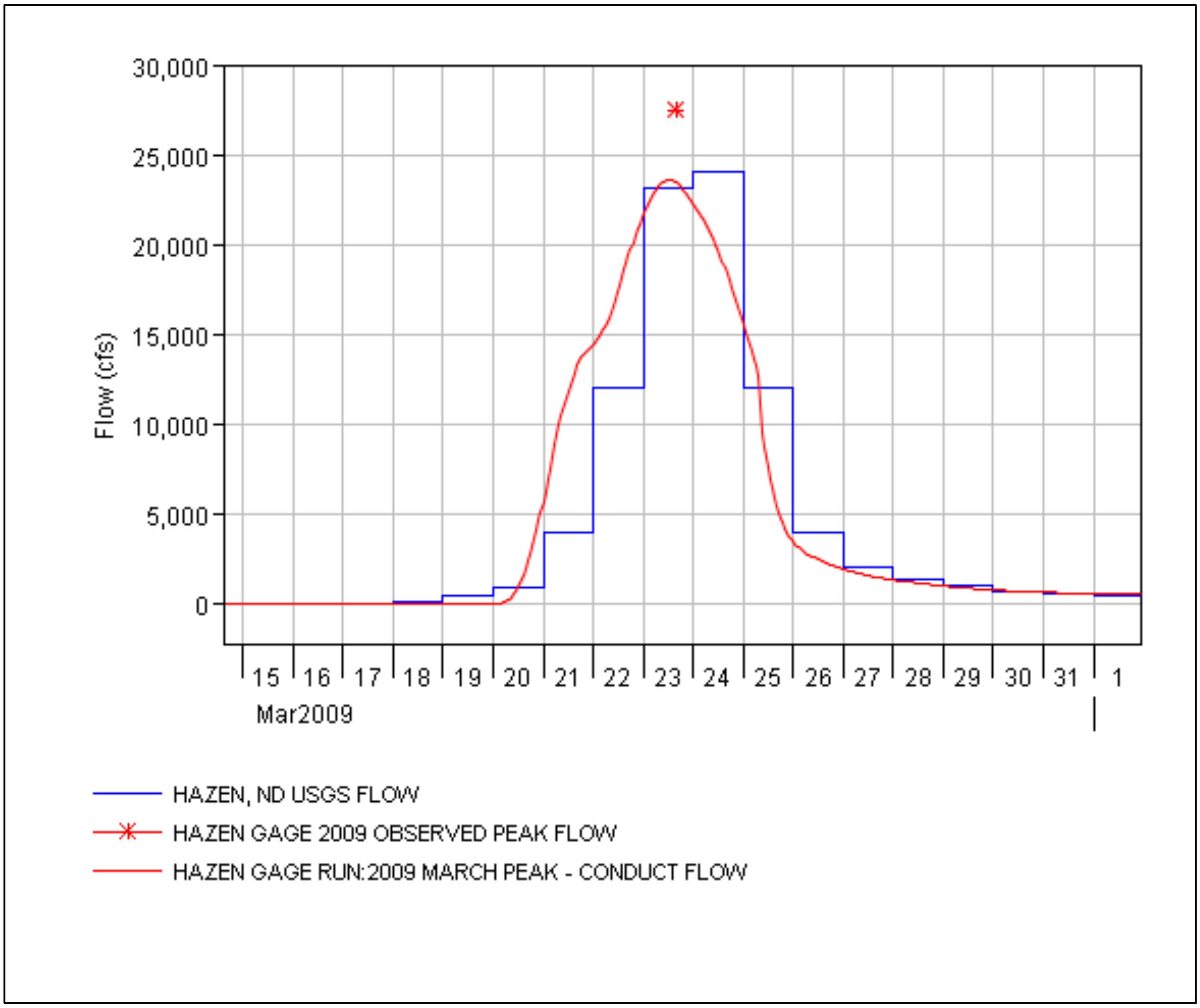

Figure 17: Computed hydrograph at Hazen for March of 2009 snowmelt event compared to the observed USGS gage daily flow data (Daily observed peak of 24,000 cfs and instantaneous peak of 27,400 cfs).

	Observed Peak	Modeled Peak	% Difference
Outflow (cfs)	27,400	24,901	-9.1
Date/Time of Peak	3/24/09 01:00	3/23/09 12:00	
Volume (acre-ft)	174,205	180,303	3.5

4. Flood Flow and Volume Frequency Analysis

Flood flow frequency analysis was based on Bulletin 17B “Guidelines for Determining Flood Flow Frequency” (1982) and was conducted with the HEC-SSP software with the gage data. HEC-SSP was used to generate a flood flow frequency curve, including a 95 percent confidence interval and a mean flow for each gage. Station skew and Weibull plotting position were used to conduct the flood flow frequency analysis.

Volume frequency analyses for each gage were also conducted in HEC-SSP. The regression analysis utilized log transform and Weibull plotting position to compute the 1-, 3-, and 7-day volumes for the volume frequency analysis. Comparing peak outflow and volumes from gage regression and simulated events provides confidence in the model. Tables 9 through 24 contain the results of the frequency analysis conducted at each gage

Table 9: Manning Gage flood flow frequency analysis mean flow, upper 95 percent confidence limit, and lower 95 percent confidence limit.

Manning Gage					
Percent Chance Exceedence	Frequency Event	Computed	Expected Probability	0.05 Confidence Limit	0.95 Confidence Limit
%	Years	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)
0.2	500	3,590	3,617	6,014	2,380
0.5	200	3,520	3,552	5,880	2,338
1	100	3,431	3,470	5,710	2,284
2	50	3,292	3,334	5,446	2,199
5	20	2,984	3,029	4,868	2,009
10	10	2,604	2,636	4,170	1,771
20	5	2,035	2,055	3,159	1,407
50	2	919	919	1,325	652
99	1	5	3	11	2

Table 10: Manning Gage flood flow frequency analysis statistics.

Manning Gage			
Log Transformation: Flow, cfs			
Mean	2.803	Historic Events	0
Standar Deviation	0.621	High Outliers	0
Station Skew	-1.630	Low Outliers	0
Regional Skew	---	Zero Events	0
Weighted Skew	---	Missing Events	0
Adopted Skew	-1.630	Systematic Events	47

Table 11: Manning Gage volume frequency analysis for 1-, 3-, and 5-day durations.

Manning Gage				
Percent Chance Exceedence	Frequency Event	1 Day Total	3 Day Total	7 Day Total
%	Years	Volume (acre-ft)	Volume (acre-ft)	Volume (acre-ft)
0.2	500	7,400	17,237	30,271
0.5	200	6,942	15,827	26,780
1	100	6,488	14,525	23,827
2	50	5,919	12,984	20,607
5	20	4,953	10,550	15,966
10	10	4,030	8,384	12,220
20	5	2,932	5,965	8,361
50	2	1,250	2,496	3,360
99	1	15	37	62

Table 12: Manning Gage volume frequency analysis statistics.

Adjusted Statistics	1 Day	3 Day	7 Day
Mean	2.688	2.524	2.302
Standard Dev.	0.571	0.562	0.559
Station Skew	-1.203	-1.073	-0.89
Adopted Skew	-1.203	-1.073	-0.89

Table 13: Golden Valley Gage flood flow frequency analysis mean flow, upper 95 percent confidence limit, and lower 95 percent confidence limit.

Golden Valley Gage					
Percent Chance Exceedence	Frequency Event	Computed	Expected Probability	0.05 Confidence Limit	0.95 Confidence Limit
%	Years	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)
0.2	500	21,160	22,331	33,356	14,737
0.5	200	18,163	19,002	28,049	12,836
1	100	15,802	16,433	23,957	11,313
2	50	13,376	13,816	19,848	9,722
5	20	10,112	10,357	14,494	7,527
10	10	7,642	7,766	10,604	5,811
20	5	5,219	5,268	6,964	4,066
50	2	2,193	2,193	2,767	1,747
99	1	70	61	110	39

Table 14: Golden Valley Gage flood flow frequency analysis statistics.

Golden Valley Gage			
Log Transformation: Flow, cfs			
Mean	3.282	Historic Events	0
Standar Deviation	0.508	High Outliers	0
Station Skew	-0.704	Low Outliers	0
Regional Skew	---	Zero Events	0
Weighted Skew	---	Missing Events	0
Adopted Skew	-0.704	Systematic Events	72

Table 15: Golden Valley Gage volume frequency analysis for 1-, 3-, and 5-day durations.

Golden Valley Gage				
Percent Chance Exceedence	Frequency Event	1 Day Total	3 Day Total	7 Day Total
%	Years	Volume (acre-ft)	Volume (acre-ft)	Volume (acre-ft)
0.2	500	29,554	79,402	153,713
0.5	200	26,646	70,703	132,540
1	100	24,113	63,330	115,712
2	50	21,267	55,244	98,287
5	20	17,010	43,503	74,628
10	10	13,420	33,894	56,537
20	5	9,552	23,814	38,682
50	2	4,169	10,229	16,217
99	1	101	262	486

Table 16: Golden Valley Gage volume frequency analysis statistics.

Adjusted Statistics	1 Day	3 Day	7 Day
Mean	3.243	3.161	3.006
Standard Dev.	0.515	0.517	0.513
Station Skew	-0.936	-0.877	-0.729
Adopted Skew	-0.936	-0.877	-0.729

Table 17: Zap Gage flood flow frequency analysis mean flow, upper 95 percent confidence limit, and lower 95 percent confidence limit.

Zap Gage					
Percent Chance Exceedence	Frequency Event	Computed	Expected Probability	0.05 Confidence Limit	0.95 Confidence Limit
%	Years	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)
0.2	500	10,338	10,784	16,046	7,281
0.5	200	9,167	9,509	14,000	6,531
1	100	8,184	8,457	12,314	5,891
2	50	7,116	7,318	10,516	5,187
5	20	5,581	5,703	8,003	4,151
10	10	4,337	4,403	6,040	3,289
20	5	3,043	3,071	4,085	2,360
50	2	1,312	1,312	1,664	1,040
99	1	36	31	57	19

Table 18: Zap Gage flood flow frequency analysis statistics.

Zap Gage			
Log Transformation: Flow, cfs			
Mean	3.046	Historic Events	0
Standard Deviation	0.511	High Outliers	0
Station Skew	-0.851	Low Outliers	0
Regional Skew	---	Zero Events	0
Weighted Skew	---	Missing Events	0
Adopted Skew	-0.851	Systematic Events	70

Table 19: Zap Gage volume frequency analysis for 1-, 3-, and 5-day durations.

Zap Gage				
Percent Chance Exceedence	Frequency Event	1 Day Total	3 Day Total	7 Day Total
%	Years	Volume (acre-ft)	Volume (acre-ft)	Volume (acre-ft)
0.2	500	20,788	57,976	98,351
0.5	200	17,787	48,117	79,515
1	100	15,420	40,737	66,043
2	50	12,993	33,497	53,337
5	20	9,734	24,291	37,872
10	10	7,281	17,730	27,313
20	5	4,896	11,652	17,852
50	2	1,977	4,610	7,207
99	1	648	1,535	2,559

Table 20: Zap Gage volume frequency analysis statistics.

Adjusted Statistics	1 Day	3 Day	7 Day
Mean	2.935	2.836	2.676
Standard Dev.	0.534	0.531	0.506
Station Skew	-0.722	-0.6	-0.468
Adopted Skew	-0.722	-0.6	-0.468

Table 21: Hazen Gage flood flow frequency analysis mean flow, upper 95 percent confidence limit, and lower 95 percent confidence limit.

Hazen Gage					
Percent Chance Exceedence	Frequency Event	Computed	Expected Probability	0.05 Confidence Limit	0.95 Confidence Limit
%	Years	Flow (cfs)	Flow (cfs)	Flow (cfs)	Flow (cfs)
0.2	500	41,359	43,691	63,657	29,255
0.5	200	34,809	36,415	52,413	25,019
1	100	29,834	31,002	44,066	21,743
2	50	24,884	25,673	35,953	18,425
5	20	18,465	18,883	25,767	14,011
10	10	13,780	13,987	18,629	10,685
20	5	9,322	9,403	12,141	7,403
50	2	3,926	3,926	4,859	3,185
99	1	149	134	226	89

Table 22: Hazen Gage flood flow frequency analysis statistics.

Hazen Gage			
Log Transformation: Flow, cfs			
Mean	3.544	Historic Events	0
Standard Deviation	0.496	High Outliers	0
Station Skew	-0.607	Low Outliers	0
Regional Skew	---	Zero Events	0
Weighted Skew	---	Missing Events	0
Adopted Skew	-0.607	Systematic Events	81

Table 23: Hazen Gage volume frequency analysis for 1-, 3-, and 5-day durations.

Hazen Gage				
Percent Chance Exceedence	Frequency Event	1 Day Total	3 Day Total	7 Day Total
%	Years	Volume (acre-ft)	Volume (acre-ft)	Volume (acre-ft)
0.2	500	67,111	193,462	345,498
0.5	200	56,983	161,258	283,576
1	100	49,183	137,155	238,377
2	50	41,327	113,490	194,966
5	20	30,984	83,280	140,951
10	10	23,315	61,596	103,170
20	5	15,912	41,281	68,544
50	2	6,783	17,159	28,395
99	1	256	655	1,195

Table 24: Hazen Gage volume frequency analysis statistics.

Adjusted Statistics	1 Day	3 Day	7 Day
Mean	3.482	3.412	3.269
Standard Dev.	0.493	0.501	0.496
Station Skew	-0.639	-0.575	-0.508
Adopted Skew	-0.639	-0.575	-0.508

5. Frequency Events

The frequency storms used in the Knife River Basin HEC-HMS model were created using NOAA Atlas 14-point precipitation data. The data collected was partial duration series data. The precipitation data for the basin were averaged to determine the mean precipitation over the entire Knife River Basin for 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year frequency events at various durations. **Table 25** is the frequency event depth duration table as entered into HEC-HMS used uniformly across each subbasin. The frequency storms were then entered with an intensity position of 50 percent, placing the largest depth in the center of the hyetograph. The larger values then are placed near the center of the hyetograph while the smallest depths were placed on the edges.

Table 25. Frequency event depth table.

Duration	2 Year	5 Year	10 Year	25 Year	50 Year	100 Year	200 Year	500 Year
	Depth, in							
1 Hour	0.97	1.29	1.55	1.98	2.30	2.75	3.32	3.84
2 Hours	1.19	1.55	1.85	2.36	2.79	3.27	3.99	4.56
3 Hours	1.30	1.70	2.01	2.55	3.01	3.51	4.32	4.86
6 Hours	1.51	1.95	2.29	2.87	3.37	3.90	4.77	5.32
12 Hours	1.75	2.23	2.62	3.24	3.75	4.30	5.07	5.71
1 Day	2.01	2.51	2.98	3.63	4.18	4.74	5.42	6.20
2 Day	2.30	2.87	3.39	4.11	4.69	5.29	5.92	6.79
4 Days	2.68	3.33	3.91	4.71	5.34	5.99	6.68	7.58
7 Days	3.14	3.85	4.48	5.32	5.96	6.66	7.41	8.32

The storms were then entered into HEC-HMS, run using the June05_GreenAmpt_MPE watershed model, and the initial moisture content of each sub-basin were raised to near saturated levels in order to be within the confidence interval of the flood flow frequency curve at the Hazen gage and match conditions that produce large flood events. The June05_GreenAmpt_MPE model is calibrated to historical events and matches well with the Golden Valley, Zap, and Hazen stream gages that provides confidence the models timing, making it ideal to model frequency events.

The 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year frequency storms were simulated and produce peak flows at Hazen that were within the 95% confidence interval of the flood flow frequency curve. Calibration resulted in increasing the initial content to near saturated levels for all sub-basins. The frequency events are run over the calibrated June 2005 model that uses similar parameters to the June 2002 model. These calibrated models work to produce timing and peaking characteristics similar to what the basin produces at Beulah and Hazen. Running the frequency storms on the June 2005 model produces similar volumes to the volume frequency analysis and peak flows within the confidence limits of the flow frequency analysis at Hazen. **Figures 19 through 21** are log probabilistic plots compared to the modeled frequency events. Although the frequency events match at Hazen, near the project's area of interest (Beulah), the frequency events varied at other stream gages. The modeled values for the lower end of the curve at Zap appeared to be lower than the gage statistics. This could be due to the operation of Lake Ilo, which does not operate for flood control or for other reasons. The Weibull plot at Zap also has discontinuities in this zone. Another station that varies from the statistical analysis is Golden Valley. Golden Valley's modeled events follow the 0.5 percent confidence limit. This was intentionally done to meet curve downstream at Hazen.

Tables 26 through 29 are flow and volume comparisons from the regression and model analysis at the gages in the Knife River Basin model. Modeled volumes were calculated using a rolling 1-, 3-, and 7-day window to compare to the regression analysis. Modeled volumes and peak flow compare well at the Hazen gage, but appear to peak too fast at the Manning and Golden Valley gage. The 7-day volume, however, compares well at the Manning and Golden Valley gage. The Zap gage volume compares well with the 3-day events which relates to historic hydrographs.

Table 26. Manning gage frequency event flow and volume comparison.

Manning Gage	0.2% Event	0.5% Event	1% Event	2% Event	4% Event	10% Event	20% Event	50% Event
Simulated Peak Flow (cfs)	9,726	8,303	6,323	5,111	3,998	2,663	1,839	889
Regression Peak Flow (cfs)	3,590	3,520	3,431	3,292	3,076	2,604	2,035	919
Percent Difference	170.92%	135.88%	84.29%	55.26%	29.97%	2.26%	-9.63%	-3.26%
Simulated 1 Day Volume (acre-ft)	18,404	15,846	12,032	9,763	7,758	5,305	3,757	1,869
Regression Analysis 1 Day Volume (acre-ft)	7,400	6,942	6,488	5,919	5,212	4,030	2,932	1,250
Percent Difference	148.70%	128.26%	85.45%	64.94%	48.85%	31.64%	28.14%	49.52%
Simulated 3 Day Volume (acre-ft)	34,143	29,386	22,313	18,089	14,349	9,781	6,921	3,399
Regression Analysis 3 Day Volume (acre-ft)	17,237	15,827	14,525	12,984	11,189	8,384	5,965	2,496
Percent Difference	98.08%	85.67%	53.62%	39.32%	28.24%	16.66%	16.03%	36.18%
Simulated 7 Day Volume (acre-ft)	38,272	32,945	25,024	20,294	16,100	10,980	7,778	3,823
Regression Analysis 7 Day Volume (acre-ft)	30,271	26,780	23,827	20,607	17,133	12,220	8,361	3,360
Percent Difference	26.43%	23.02%	5.02%	-1.52%	-6.03%	-10.15%	-6.97%	13.78%

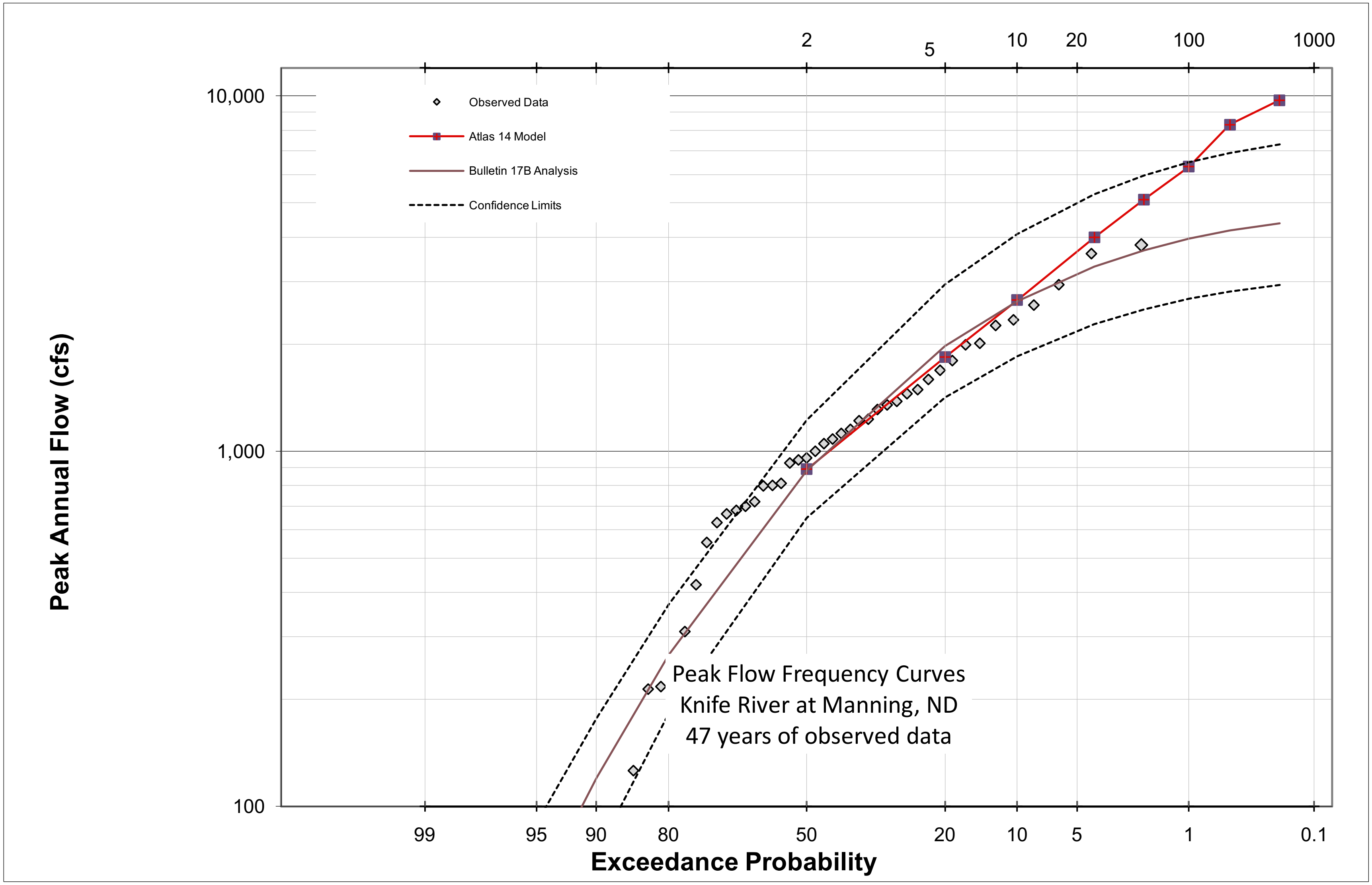

Figure 18. Manning Gage probability plot.

Table 27. Golden Valley gage frequency event flow and volume comparison.

Golden Valley Gage	0.2% Event	0.5% Event	1% Event	2% Event	4% Event	10% Event	20% Event	50% Event
Simulated Peak Flow (cfs)	40,891	34,638	25,927	21,769	15,608	9,447	6,740	2,080
Regression Peak Flow (cfs)	21,160	18,163	15,802	13,376	10,910	7,642	5,219	2,193
Percent Difference	93.25%	90.71%	64.07%	62.75%	43.06%	23.62%	29.14%	-5.15%
Simulated 1 Day Volume (acre-ft)	68,441	60,895	46,947	38,796	29,249	19,292	13,502	5,541
Regression Analysis 1 Day Volume (acre-ft)	29,554	26,646	24,113	21,267	18,099	13,420	9,552	4,169
Percent Difference	131.58%	128.53%	94.70%	82.42%	61.61%	43.76%	41.35%	32.91%
Simulated 3 Day Volume (acre-ft)	164,757	143,644	108,094	86,779	66,038	41,850	28,627	12,235
Regression Analysis 3 Day Volume (acre-ft)	79,402	70,703	63,330	55,244	46,467	33,894	23,814	10,229
Percent Difference	107.50%	103.17%	70.68%	57.08%	42.12%	23.47%	20.21%	19.61%
Simulated 7 Day Volume (acre-ft)	205,074	176,159	131,584	105,978	81,719	53,220	37,184	17,187
Regression Analysis 7 Day Volume (acre-ft)	153,713	132,540	115,712	98,287	80,429	56,537	38,682	16,217
Percent Difference	33.41%	32.91%	13.72%	7.83%	1.60%	-5.87%	-3.87%	5.98%

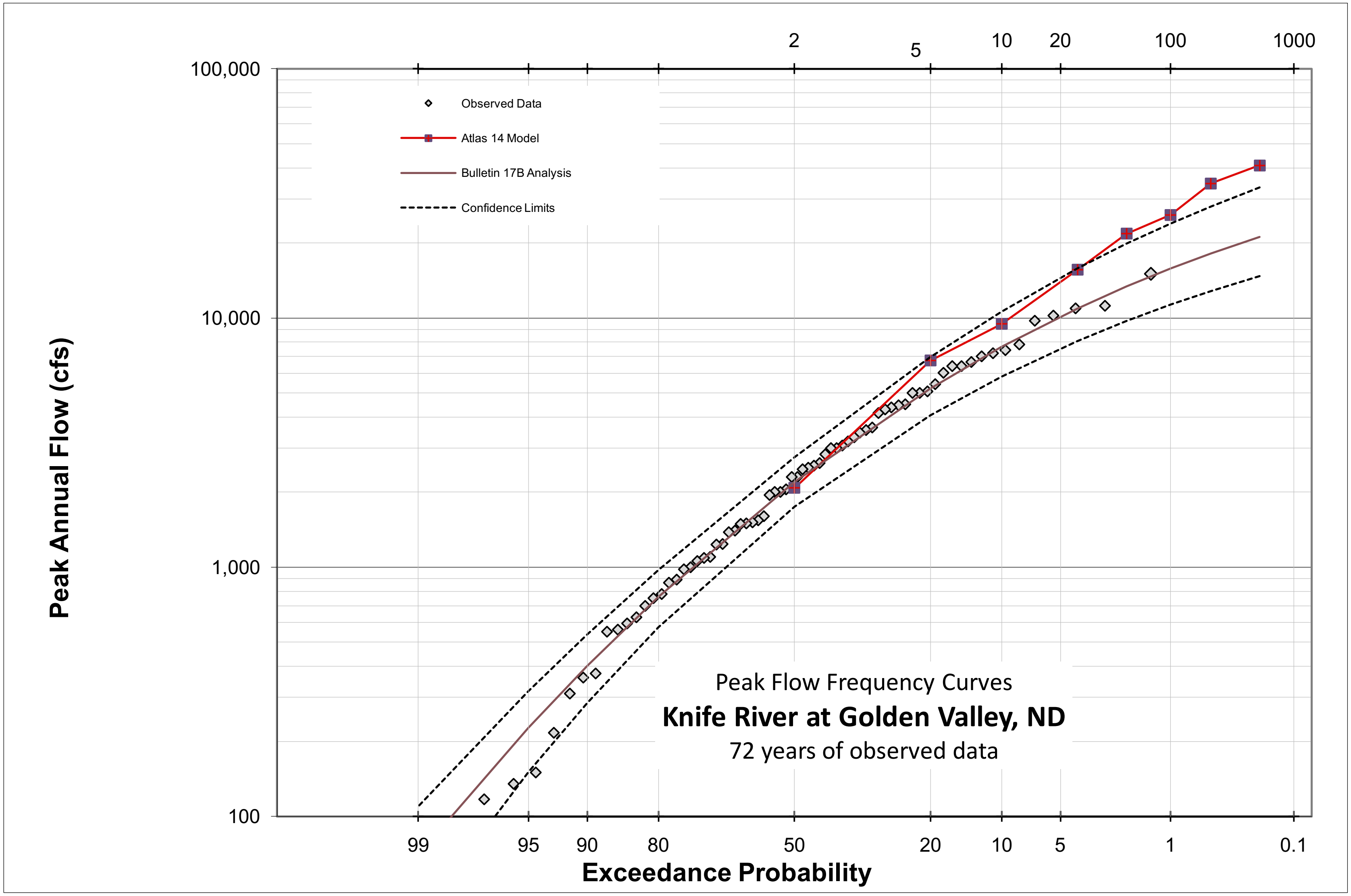

Figure 19. Golden Valley probability plot.

Table 28. Zap gage frequency event flow and volume comparison.

Zap Gage	0.2% Event	0.5% Event	1% Event	2% Event	4% Event	10% Event	20% Event	50% Event
Simulated Peak Flow (cfs)	16,333	13,652	9,751	7,658	5,634	3,801	2,532	1,133
Regression Peak Flow (cfs)	10,338	9,167	8,184	7,116	5,967	4,337	3,043	1,312
Percent Difference	57.99%	48.93%	19.15%	7.62%	-5.58%	-12.36%	-16.79%	-13.64%
Simulated 1 Day Volume (acre-ft)	26,070	21,531	15,786	11,802	9,139	5,443	3,233	904
Regression Analysis 1 Day Volume (acre-ft)	20,788	17,787	15,420	12,993	10,529	7,281	4,896	1,977
Percent Difference	25.41%	21.05%	2.37%	-9.17%	-13.20%	-25.24%	-33.97%	-54.27%
Simulated 3 Day Volume (acre-ft)	60,520	49,908	35,982	26,944	20,232	12,088	6,884	1,684
Regression Analysis 3 Day Volume (acre-ft)	57,976	48,117	40,737	33,497	26,485	17,730	11,652	4,610
Percent Difference	4.39%	3.72%	-11.67%	-19.56%	-23.61%	-31.82%	-40.92%	-63.47%
Simulated 7 Day Volume (acre-ft)	73,526	60,525	44,242	33,445	25,336	15,386	8,899	2,109
Regression Analysis 7 Day Volume (acre-ft)	98,351	79,515	66,043	53,337	41,488	27,313	17,852	7,207
Percent Difference	-25.24%	-23.88%	-33.01%	-37.29%	-38.93%	-43.67%	-50.15%	-70.74%

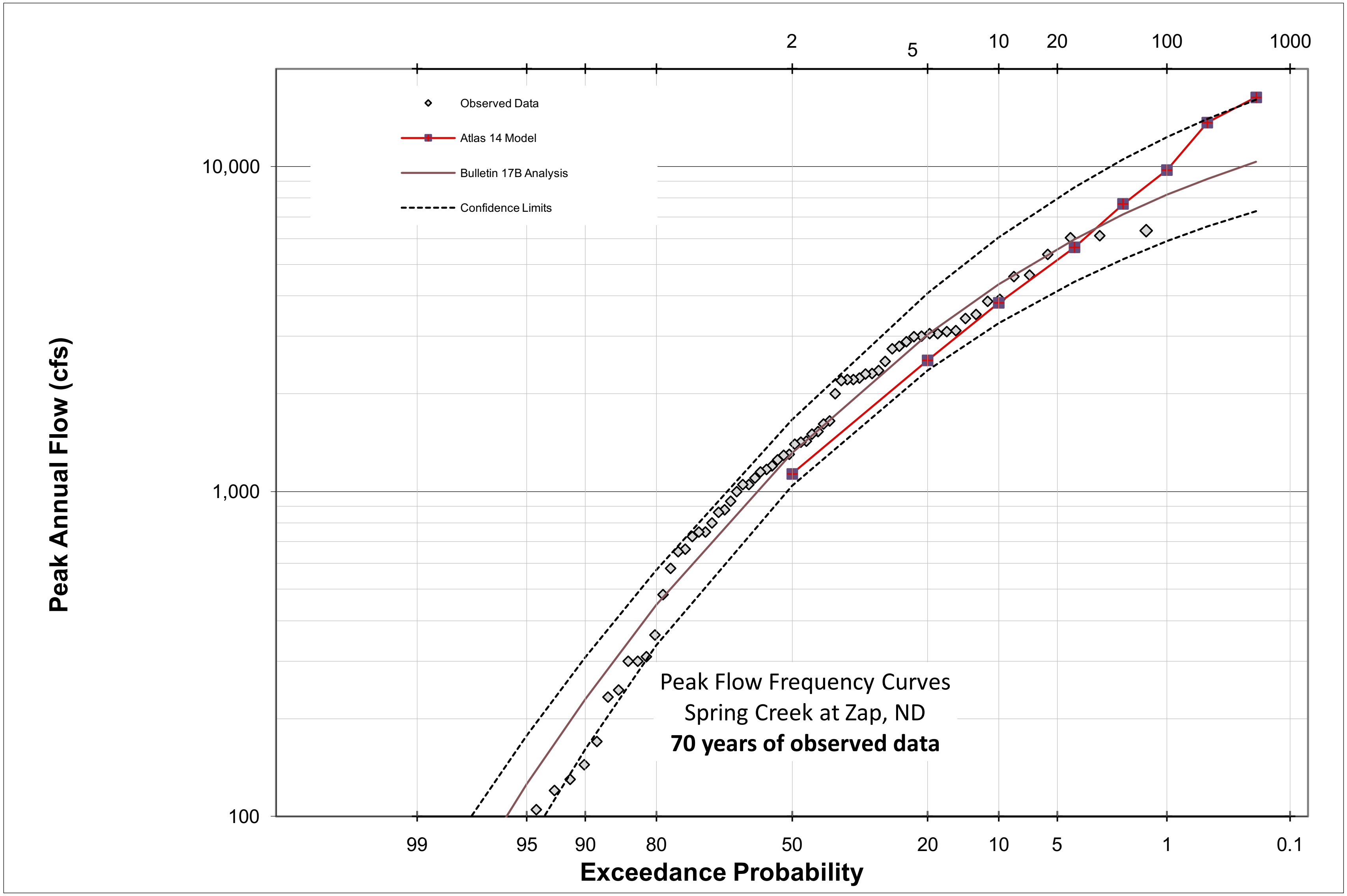

Figure 20. Zap probability plot.

Table 29. Hazen gage frequency event flow and volume comparison.

Hazen Gage	0.2% Event	0.5% Event	1% Event	2% Event	4% Event	10% Event	20% Event	50% Event
Simulated Peak Flow (cfs)	52,492	44,636	32,863	24,958	18,768	13,140	8,813	3,726
Regression Peak Flow (cfs)	41,359	34,809	29,834	24,884	20,009	13,780	9,322	3,926
Percent Difference	26.92%	28.23%	10.15%	0.30%	-6.20%	-4.64%	-5.46%	-5.09%
Simulated 1 Day Volume (acre-ft)	79,773	67,682	47,161	37,971	32,138	22,322	16,188	6,937
Regression Analysis 1 Day Volume (acre-ft)	67,111	56,983	49,183	41,327	33,489	23,315	15,912	6,783
Percent Difference	18.87%	18.78%	-4.11%	-8.12%	-4.03%	-4.26%	1.73%	2.27%
Simulated 3 Day Volume (acre-ft)	210,807	178,989	132,885	108,133	90,199	63,848	43,997	18,538
Regression Analysis 3 Day Volume (acre-ft)	193,462	161,258	137,155	113,490	90,496	61,596	41,281	17,159
Percent Difference	8.97%	11.00%	-3.11%	-4.72%	-0.33%	3.66%	6.58%	8.04%
Simulated 7 Day Volume (acre-ft)	350,931	295,579	217,026	172,864	136,599	90,069	61,435	27,489
Regression Analysis 7 Day Volume (acre-ft)	345,498	283,576	238,377	194,966	153,709	103,170	68,544	28,395
Percent Difference	1.57%	4.23%	-8.96%	-11.34%	-11.13%	-12.70%	-10.37%	-3.19%

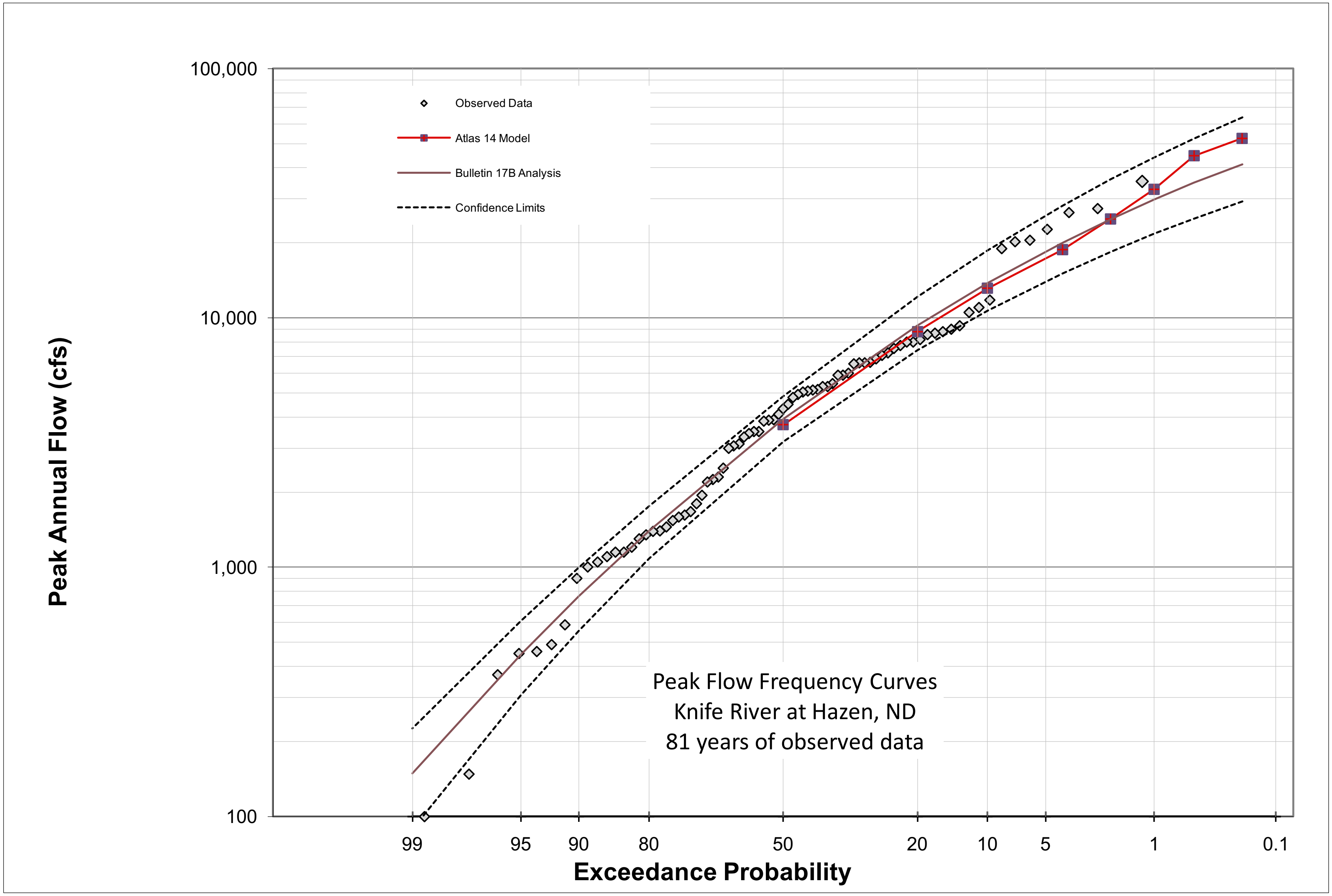

Figure 21. Hazen probability plot.

North Dakota State Water Commission

Many of the annual peak flows at Hazen are from snowmelt events. The frequency events used NOAA Atlas 14 precipitation data. Atlas 14 is composed of rainfall data, which doesn't include snowfall in its derivation. The lack of snowfall considerations may cause the frequency events computed in the hydrologic model to be lower than the gage computed frequency flows.

Synthetic events were also compared to the March 2009 snowmelt event at Hazen. A 50-year frequency event computed from HEC-SSP at Hazen has a similar peak flow, volume, and duration as the daily data from the March 2009 event. **Figure 18** is a hydrograph comparison of the modeled 50- and 100-year modeled frequency events to the March of 2009 daily data.

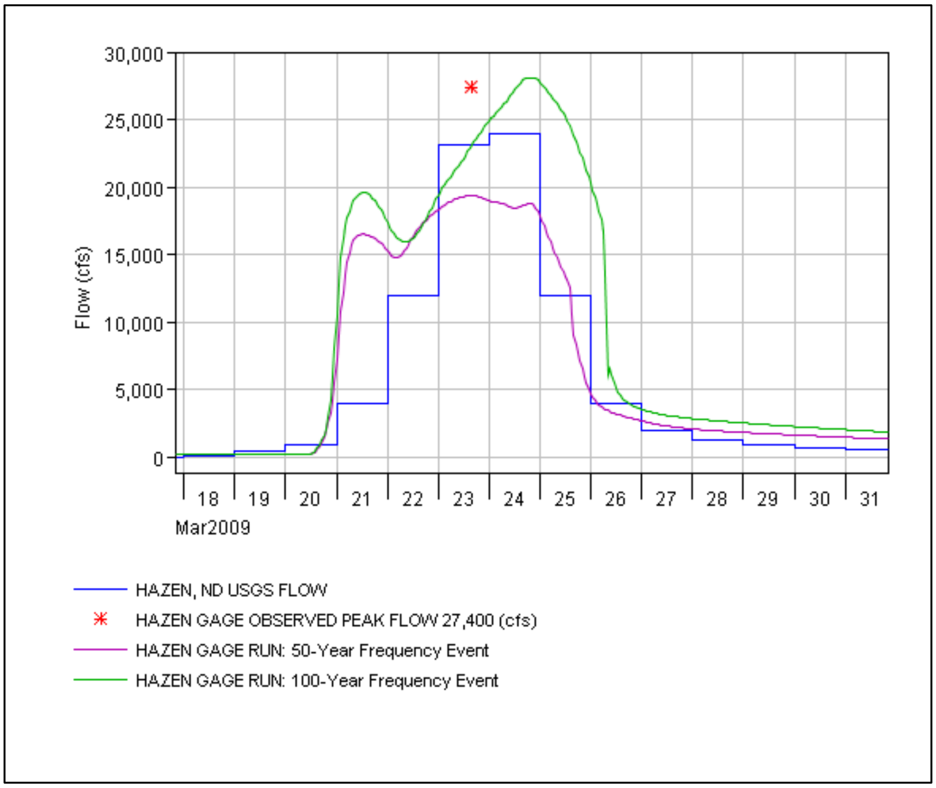

Figure 22. Frequency event comparison to the March of 2009 daily observed data.

The modeled frequency events and the March of 2009 hydrograph were then compared based on volume and peak flow at Hazen. **Table 30** is a peak flow and volume comparison for a 50- and 100-year modeled frequency events to the March of 2009 hydrograph.

Table 30. Hazen gage frequency and 2009 historic event comparison.

Hazen Gage	Volume (acre-ft)	Discharge (cfs)
March 2009 (USGS Daily Averaged Data)	170,959	24,000 (Peak of 27,400)
50-Year Frequency Event (Modeled Peak)	188,698	18,768
100- Year Frequency Event (Modeled Peak)	236,380	24,958

The daily observed data from the USGS for the peak in March of 2009 also compares well to the 50-year frequency event, as seen in Figure 20 and Table 30.

After comparing frequency events with the March 2009 snowmelt event, frequency events were compared to the August of 2014 rainfall event. **Figure 19** is a hydrograph comparison of the observed hydrograph to a 2- and 5- year frequency event.

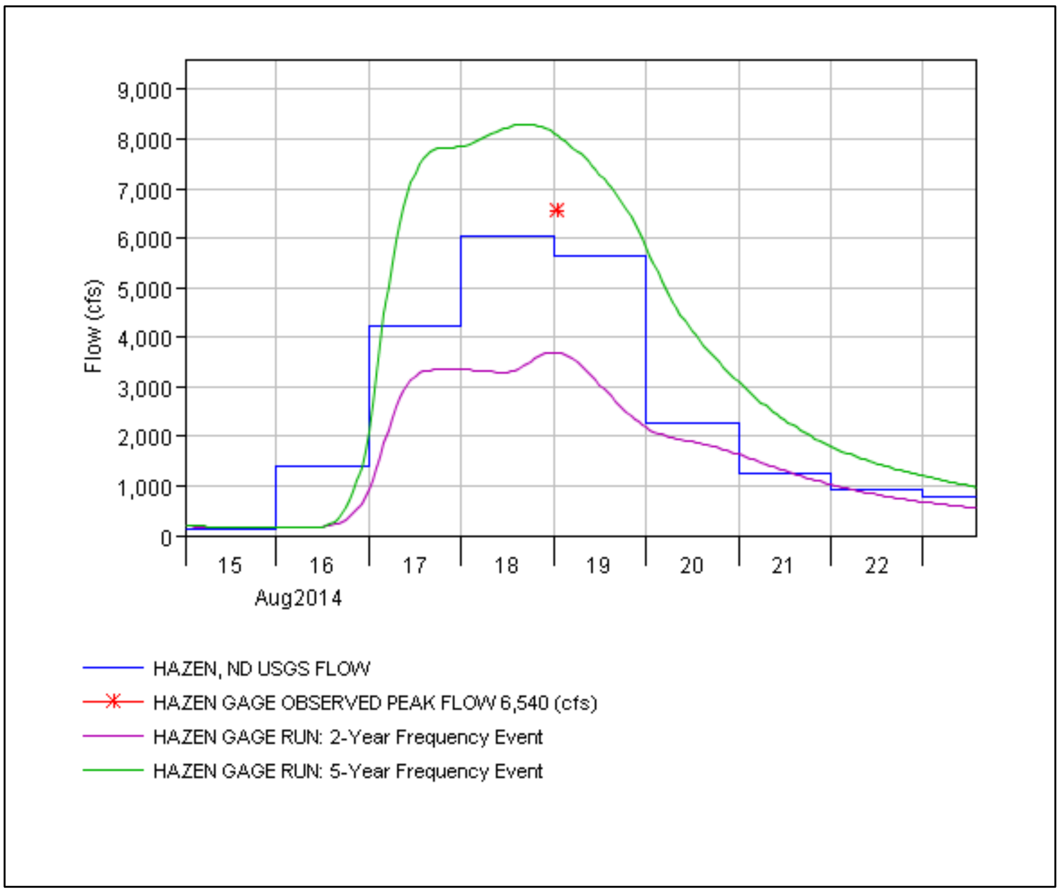

Figure 23. Frequency event comparison to the August of 2014 daily observed data.

Table 31. Frequency event comparison to the August of 2014 daily observed data.

Hazen Gage	Volume (acre-ft)	Peak Discharge (cfs)
August 2014 (USGS Daily Averaged Data)	44,916	6,030 (Peak of 6,500)
2-Year Frequency Event (Modeled Peak)	31,501	3,726
5-Year Frequency Event (Modeled Peak)	68,056	8,813

The daily observed data from the USGS for the peak in August of 2014 falls between a 2- and 5-year frequency event as seen in Figure 19 and Table 31. The shape and receding limb of the 2-year frequency event match well with the observed hydrograph.

6. Discussion

The Knife River hydrologic model was calibrated and reasonably reproduced recent flood events. Based on the calibration of the 2002 and 2005 rainfall events and verification of the 1966 rainfall event, the model provides a reasonable representation of how the basin reacts to rainfall events. The calibration of the 2009 snowmelt event provides confidence in the model's ability to reproduce the fast peaking snowmelt events that often affect this basin.

Although different transform methods were used for rainfall and snowmelt events, it was justified because of the frozen ground and the freezing and rethawing of snowmelt that occurs during a snowmelt event. The calibrated parameters for each type of event allow one to reasonably simulate observed flood events.

Synthetic events simulated by the model generally replicated statistically derived peak flows and volumes at gages for a given probability event. The modeled frequency events for Hazen and Zap stream gages compare well to the statistically derived peak flows and volumes and are within the peak flow computed confidence limits. The Manning and Golden Valley stream gages appear to compare well with 7-day volumes from the regression analysis. The frequency events at these gages appear to peak faster causing 1- and 3-day volumes and their peak flows to be higher than the gage statistics.

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Appendix F. Flood Storage Screening

As part of the study, structural flood protection was examined. Flood storage was quantified for many of the surrounding streams to identify possible mitigation efforts. The National Weather Service flood impact statement for the Hazen gage states a stage of 25-ft, which is major flood stage, or approximately 14,000 cfs is the threshold for floodwaters entering the city of Beulah upstream. The goal of this screening is to examine the potential of flood storage and reduce a 100-year frequency event to below 14,000 cfs at Beulah. This memorandum contains the findings of a coarse flood storage analysis of the Knife River basin.

Flood Storage Screening Method:

The Knife River basin has many potential flood storage sites due to the hilly terrain surrounding the river. Ravines along the Knife River may allow for water storage areas. Flood storage was analyzed using the hydrologic model created as part of the investigation. Figure 1 is the Knife River Basin as represented in the hydrologic model.

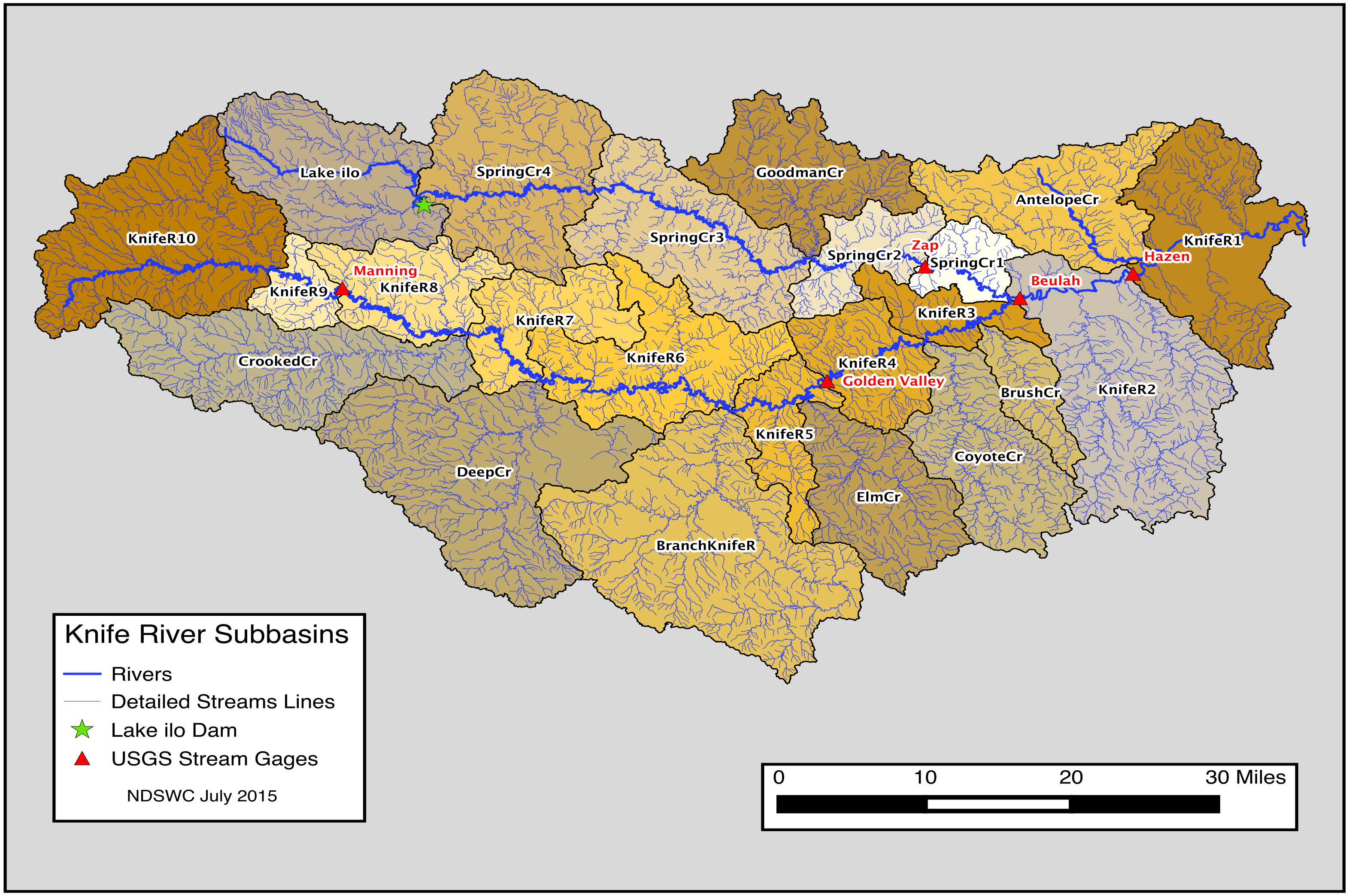

Figure 1. Knife River Basin.

Flood storage was examined using a modeled 100-year frequency event. The 100-year event was run on the existing model creating a base condition to compare each potential flood storage site. The base condition event was run over a future date to avoid confusion with historic events. Table 1 contains each subbasin's drainage area, percentage of total drainage area, peak discharge, and total runoff volume for the Knife River's base condition. Table 2 contains Beulah and Hazen gage's drainage area, peak discharge, time of peak discharge, and total runoff volume for the Knife River's base condition

Table 1. Subbasin's drainage area, percentage of total drainage area, peak discharge, and total runoff volume for the base condition.

Subbasin	Drainage Area (MI2)	Peak Discharge (CFS)	Volume (AC-FT)	Percentage of Total Drainage Area
AntelopeCr	109.44	5,125	14,555	4.35%
BranchKnifeR	248.48	6,674	25,576	9.88%
BrushCr	36.01	2,005	4,907	1.43%
CoyoteCr	106.45	4,715	14,744	4.23%
CrookedCr	141.54	3,979	14,013	5.63%
DeepCr	215.55	8,805	25,137	8.57%
ElmCr	101.17	4,006	12,584	4.02%
GoodmanCr	101.52	3,490	12,374	4.04%
KnifeR1	140.72	4,233	10,718	5.60%
KnifeR2	201.57	7,826	23,343	8.02%
KnifeR3	38.92	2,655	5,705	1.55%
KnifeR4	64.63	5,746	10,883	2.57%
KnifeR5	49.95	3,699	7,081	1.99%
KnifeR6	122.33	4,163	13,569	4.87%
KnifeR7	67.87	2,779	7,250	2.70%
KnifeR8	73.72	3,802	8,388	2.93%
KnifeR9	27.9	1,379	3,035	1.11%
KnifeR10	176.96	5,993	22,475	7.04%
LakeIlo	126.85	3,438	12,035	5.05%
SpringCr1	33.34	2,558	5,094	1.33%
SpringCr2	50.64	1,371	4,985	2.01%
SpringCr3	132.39	3,451	13,661	5.27%
SpringCr4	145.76	2,963	12,494	5.80%

Table 2. Beulah and Hazen gage's drainage area, peak discharge, time of peak discharge, and total runoff volume for the base condition.

Gage Site	Drainage Area (MI2)	Peak Discharge (CFS)	Volume (AC-FT)
Beulah Gage	2,061.98	32,691	232,818
Hazen Gage	2,263.55	32,863	255,253

Potential flood storage sites were compared to the base condition by disconnecting individual subbasins from the base condition model. Disconnecting a subbasin from the model removes the subbasin's runoff from the model. Using this method, three major assumptions were made in order to test each subbasin. The assumptions are as follows: (1) disconnecting a subbasin represents the creation of a dam capable of capturing base condition runoff; (2) each subbasin has a suitable location for a dam capable of capturing all base condition runoff; and (3) the dams created are dry dams, dams that only impound water during flood events. Using these three assumptions a coarse flood storage screening was completed.

This is a very severe standard of screening, but if under it, a site shows minimal benefits we know there is little good to be gained by installing less capable structures there. The peak flow reduction at the Beulah gage caused by subbasin disconnection is reported in Table 3. Figure 2 shows the individually screened basins from Table 3.

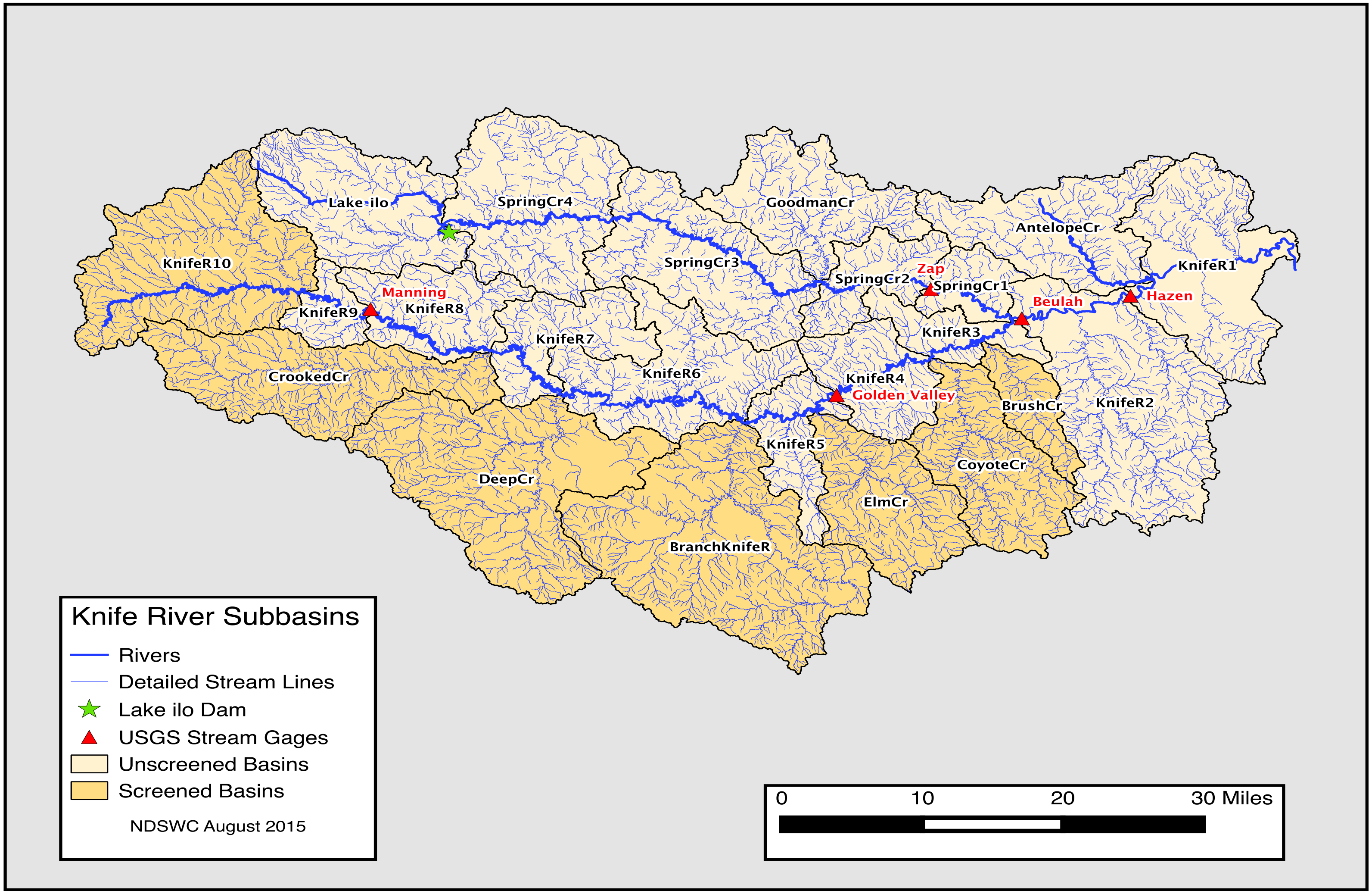

Figure 2. Knife River individually screened subbasins.

Table 3. Peak discharge reduction at Beulah gage.

Run	Peak Flow (cfs)	Reduction in Peak Flow (cfs)	Percent Reduction in Peak Flow
100YR BASELINE	32,691	-	-
100YR BRANCHKNIFER_REMOVE	27,138	5,553	16.99%
100YR BRUSHCR_REMOVE	32,605	86	0.26%
100YR COYOTECR_REMOVE	31,879	812	2.48%
100YR CROOKEDCR_REMOVE	31,564	1,127	3.45%
100YR DEEPCR_REMOVE	25,868	6,823	20.87%
100YR ELMCR_REMOVE	30,774	1,917	5.86%
100YR KNIFER10_REMOVE	32,357	334	1.02%

The coarse storage analysis of the subbasins listed in Table 3 does not provide Beulah with enough flood relief to prevent the city from flooding. The construction of dams to provide the results in Table 3 would also require large-scale land acquisition and may require displacing residents. In order to visualize the size of the dam and magnitude of inundation, the Branch Knife River subbasin was analyzed further.

The Branch Knife River subbasin was chosen for further analysis, because removing its runoff caused a large reduction on peak flow and because it had a better dam site, compared to the Deep Creek subbasin. In order to collect approximately 25,000 acre-ft of runoff (Table 1), the dam was placed at the outlet of the subbasin. GIS tools were used to develop a rating curve of basin storage versus elevation for the dam site. This was performed in Grass GIS using the National Elevation Dataset's (NED) 10-meter elevation grid. The resulting elevation that produces nearly 30,000 acre-ft of storage is 1968.6ft NAVD 88. Figure 3 is the location of the theoretical dam and its inundation footprint at the outlet of the Branch Knife River subbasin. Table 4 contains elevation, depth, inundated area, and volume information for the theoretical dam and Figure 4 shows the theoretical dam's elevation-storage curve. The created dam would be more than 1/2 mile long with a max pool elevation of 1968.6ft NAVD 88 (requiring a significantly higher dam crest) and inundates approximately 1,710 acres impacting 5 locations that contain structures.

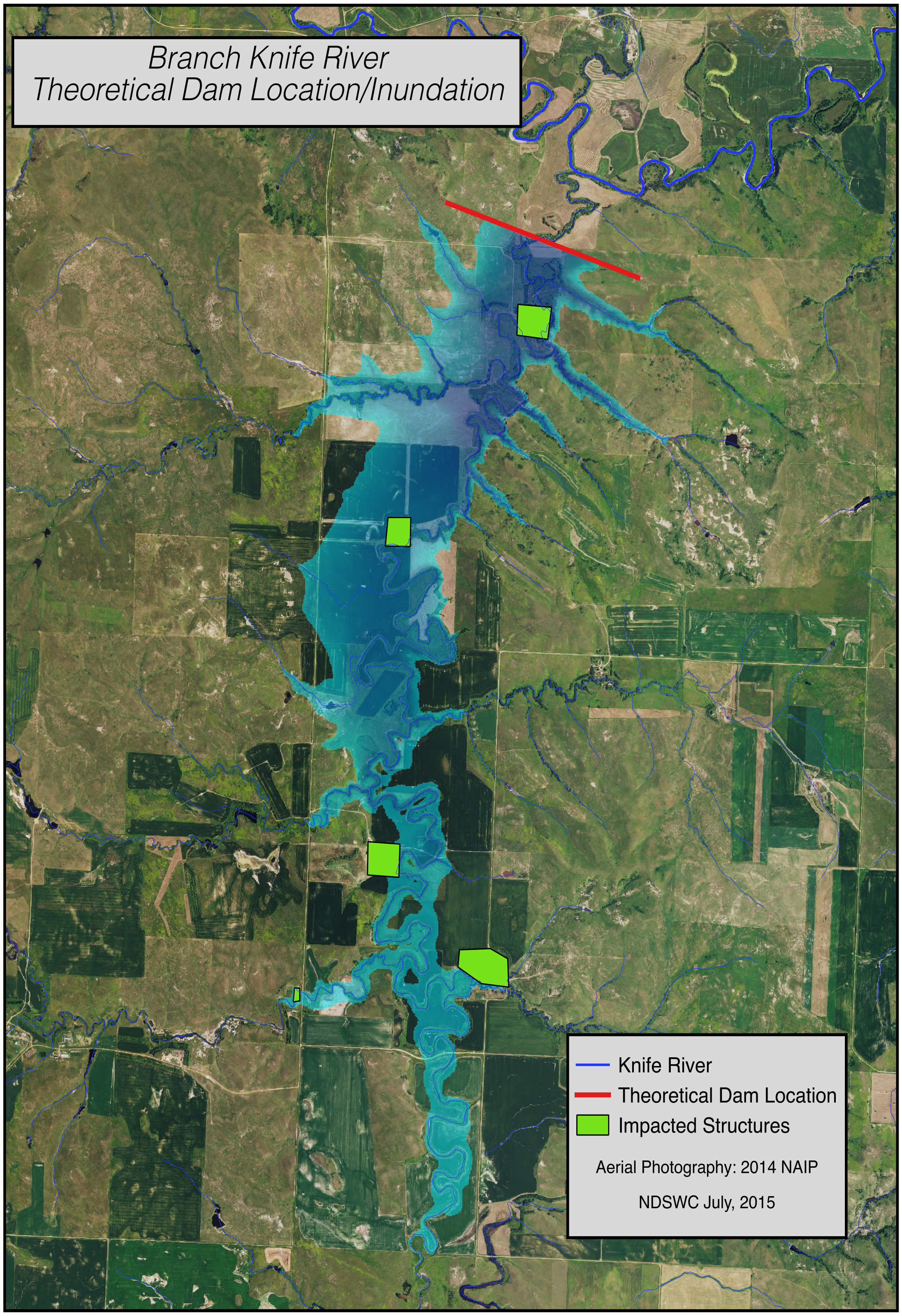

Figure 3. Theoretical dam location and inundation map for the Branch Knife River subbasin.

Table 4. Branch Knife River theoretical dam pool level, depth, inundated area, and volume table.

Level (ft)	Depth (ft)	Inundated Area (acres)	Volume (acre-ft)
1921.67	0	0	0
1929.22	8.82	209.57	1,225.17
1939.07	18.66	330.42	3,837.12
1948.91	28.50	812.36	9,698.91
1958.76	38.34	1,092.69	18,997.38
1968.60	48.19	1,710.55	32,686.97

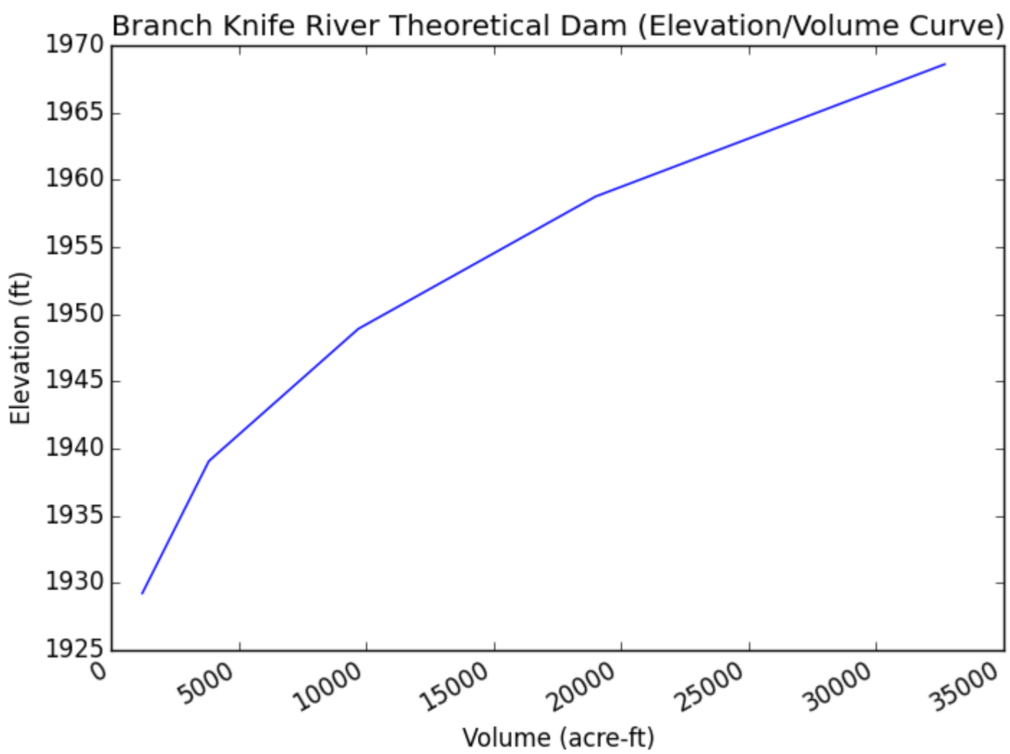

Figure 4. Branch Knife River subbasin theoretical dam (elevation/volume curve).

The final area examined for potential flood storage was the Spring Creek subbasins. Spring Creek contains 5 smaller subbasins contributing approximately 50,000 acre-ft of runoff during a 100-year frequency event at the Beulah stream gage. Removal of runoff from Spring Creek subbasins reduces the peak stream flow at Beulah by nearly 8,100 cfs (Figure 5).

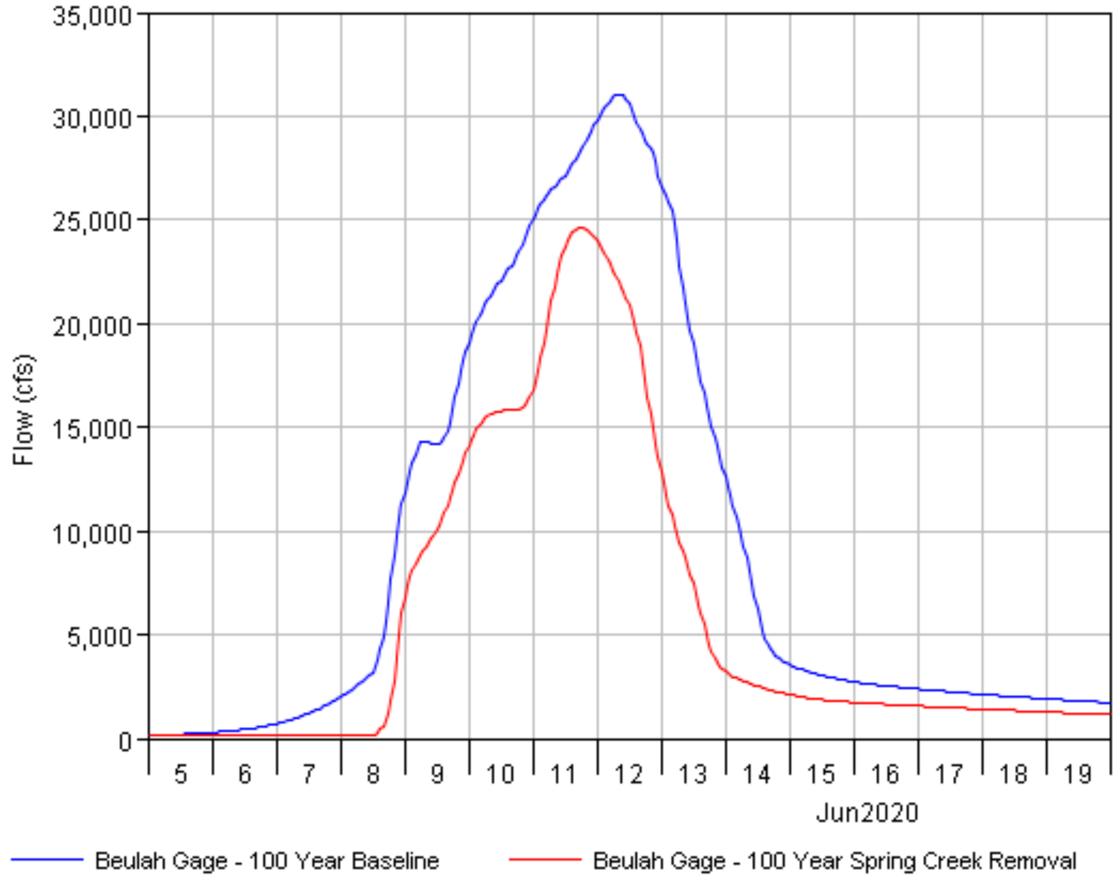

Figure 5. Hydrograph comparison at Beulah stream gage.

A theoretical dam capable of containing Spring Creek's runoff was simulated using the same GIS techniques described above. Figure 6 shows the Knife River subbasins collectively screened to simulated flood storage of the entire Spring Creek basin. The dam, as shown in Figure7, would need to have a max pool elevation of approximately 1837.5 ft NAVD88 and inundate approximately 2,300 acres, roads, and other structures.

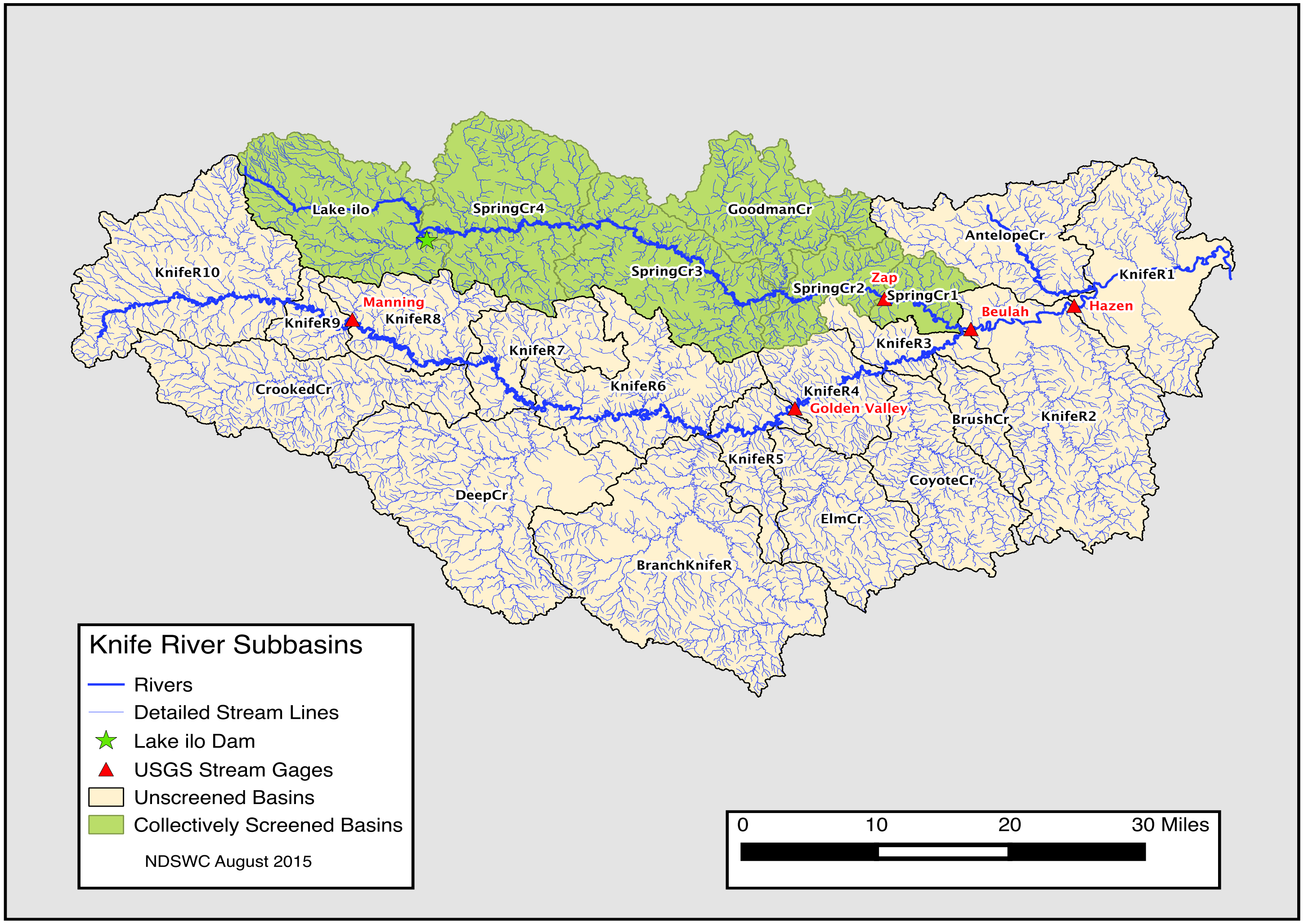

Figure 6. Knife River collectively screened subbasins.

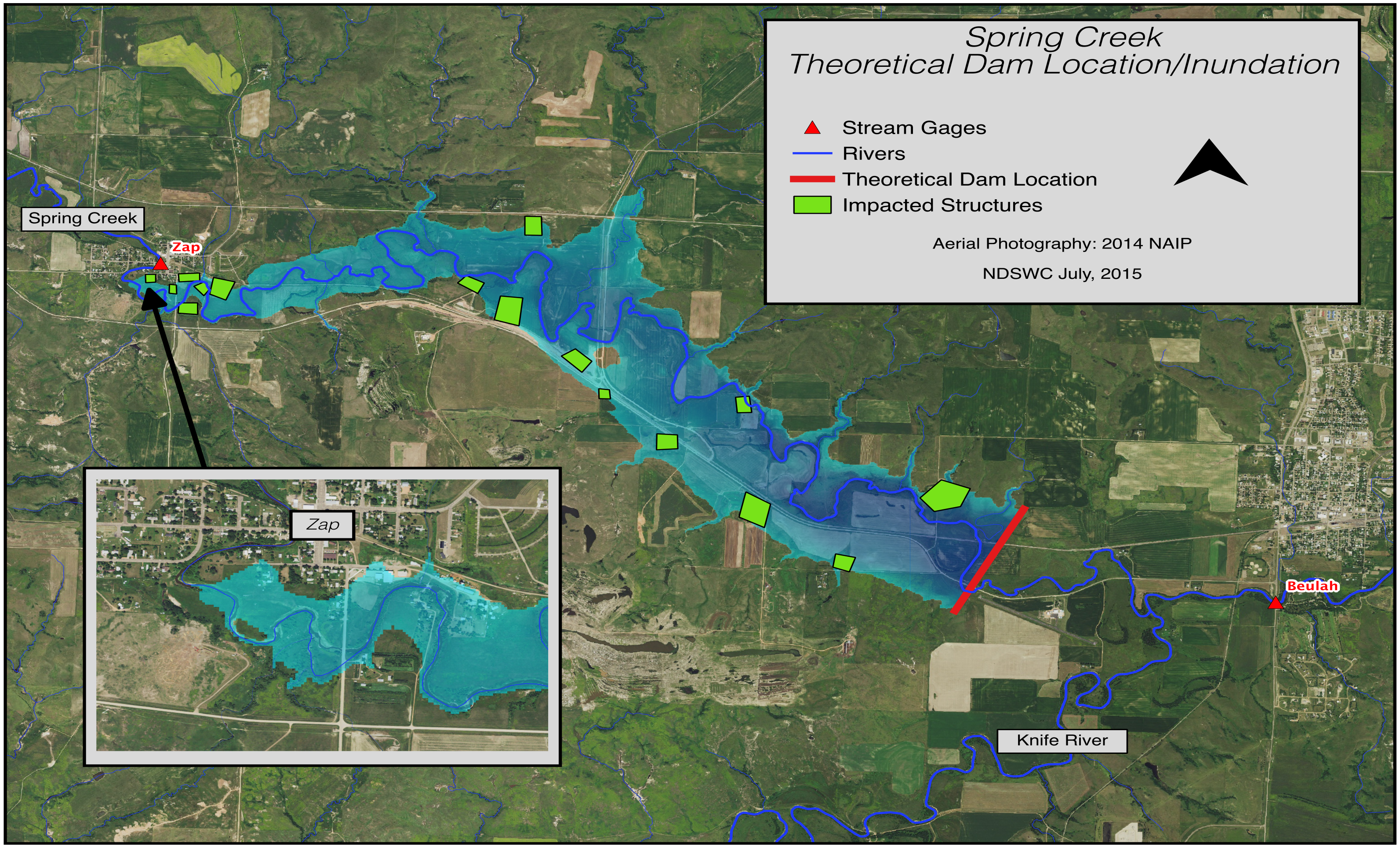

Figure 7. Theoretical dam location and inundation map of Spring Creek.

Table 5. Spring Creek theoretical dam pool level, depth, inundated area, and volume table.

Level (ft)	Depth (ft)	Inundated Area (acres)	Volume (acre-ft)
1780.24	0	0	0
1797.99	17.75	432.8	4,492.1
1807.83	27.59	992.6	11,654.9
1817.67	37.43	1,296.2	22,869.2
1827.52	47.28	1,932	38,938.5
1837.36	57.12	2,275.9	59,632.2

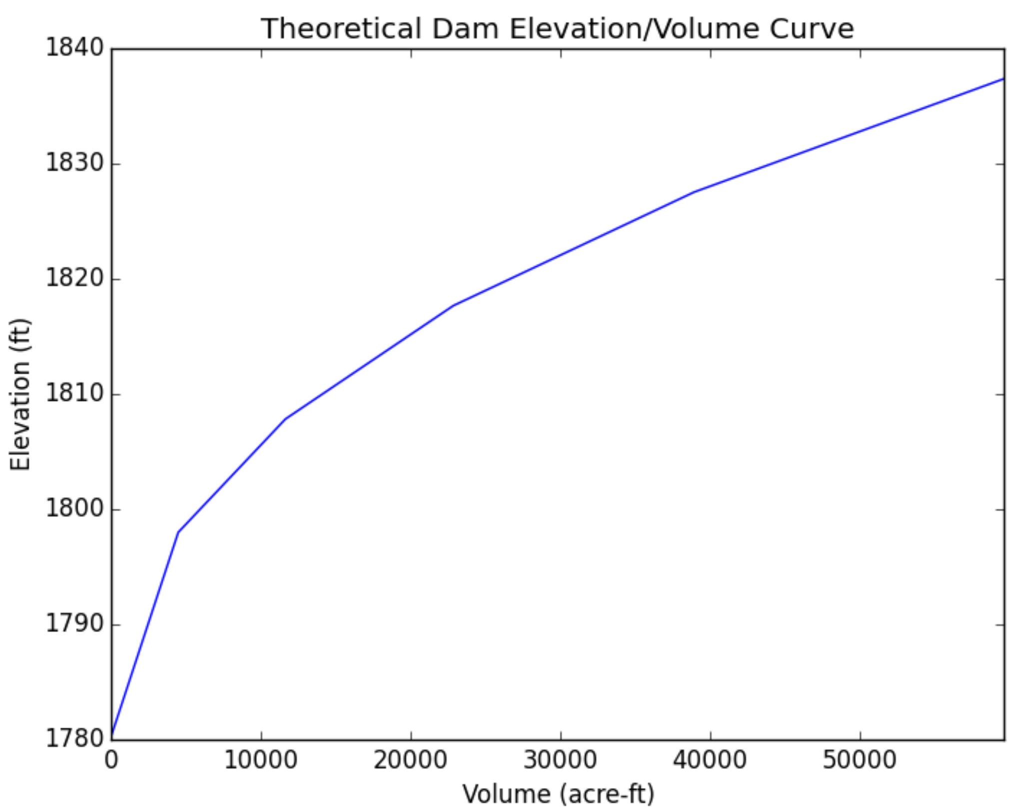

Figure 9. Spring Creek theoretical dam (elevation/volume curve).

Conclusion:

The flood storage analyzed using the methods described in this memo revealed that no individual subbasin could be modified to significantly reduce the effects of a large flood event. Reducing Beulah's stream flow below the major flood stage (14,000 cfs) would require damming multiple subbasins and inundate thousands of acres of cropland along with displacing residents. In many cases, damming of these subbasins could flood more residents than it would protect in the city of Beulah.

Reducing flooding below major flood stage would take the construction of several high hazard dams. Flood storage of this magnitude would have a significant economic impact on the region and would likely not be feasible to construct.