North Dakota State Water Commission
900 EAST BOULEVARD AVENUE, DEPT 770 • BISMARCK, NORTH DAKOTA 58505-0850
701-328-2750 • TTY 800-366-6888 • FAX 701-328-3696 • INTERNET: http://swc.nd.gov

January 24, 2018

Mr. Ronald Beyer
Planner/Project Manager
U.S. Army Corps of Engineers
Omaha District Planning Branch
1616 Capitol Avenue
Omaha, NE 68102

RE: Mercer County Section 22- Knife River Alternative Analysis Report

Dear Mr. Beyer:

An error was found in the Knife River Hydraulic Report, dated October 2017. On page 3, the report states that the channel roughness coefficient was updated to 0.035, but should state that the roughness coefficient for the channel is 0.041. This error does not change any of the outputs from the hydraulic model, as the channel roughness coefficient was always set at 0.041. Please do not hesitate to contact myself at 701-328-2762 or ckorkowski@nd.gov with any questions.

Sincerely,

Chris Korkowski, E.I.T.
Water Resource Engineer

CK:ph/1404
cc: Curtis Miller, P.E., Hydraulic Engineer, US Army Corps of Engineers

Knife River Hydraulic Report

Mercer County, North Dakota

SWC Project #1404
October 2017

North Dakota
State Water Commission

Knife River Hydraulic Model Report

Beulah, North Dakota, Mercer County

SWC Project #1404
North Dakota State Water Commission
900 East Boulevard Ave.
Bismarck, ND 58505-0850

Prepared for:
Mercer County Water Resource District

October 2017

Prepared by:

Chris Korkowski, E.I.T.
Water Resource Engineer

Under the direct supervision of:

REGISTERED PROFESSIONAL ENGINEER
LAURA C. ACKERMAN
PE-7661
DATE 10/2/2017
NORTH DAKOTA

Laura Ackerman, P.E.
Investigations Section Chief

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1. Introduction

1.1 Purpose

This report documents the creation and calibration of a hydraulic model for the Knife River at Beulah, ND. The model was created as part of a Section 22 Planning Assistance to States study agreement between the U.S. Army Corps of Engineers (Omaha District) and the Mercer County Water Resource District (District), and pursuant to an investigation agreement between the District and the North Dakota State Water Commission (SWC). The purpose of the Section 22 study is to investigate the flood risk management alternatives for the communities along the Knife River. The purpose of the hydraulic model is to analyze impacts on water surface elevations based on future management alternatives for Beulah, ND. This report includes electronic appendices A, B, C, and D, which correspond to survey data, site photography, GIS shapefiles, and the hydraulic model, respectively.

1.2 Site Location

The Knife River reach included in the hydraulic model (**Figure 1**) is located in Mercer County, near the City of Beulah, North Dakota.

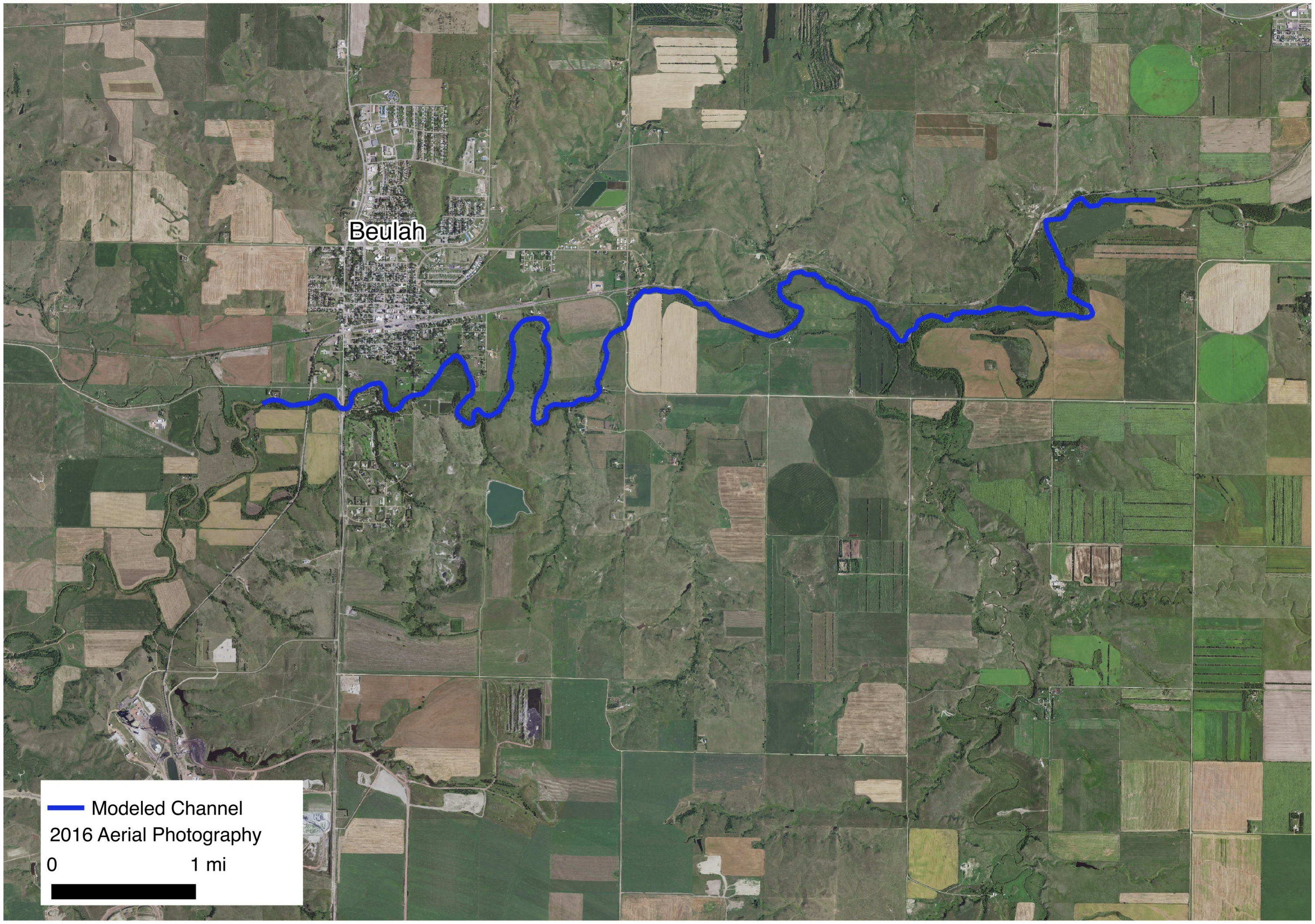

Figure 1. *Modeled Knife River reach near Beulah, ND.*

2. Hydraulic Model

2.1 Survey

The survey was conducted between 2012-2014, and included topography, bathymetry, and three crossings (railroad bridge, State Highway 49 bridge, and County Highway 20 bridge). The vertical datum for the survey was North American Vertical Datum 1988 (NAVD 88), and the horizontal datum was North American Datum 1983 (NAD 83) in projection North Dakota South (ft). Cross sections were created using Light Detection and Ranging Data (LiDAR NAVD88) and surveyed structure data. The LiDAR data was collected as part of a collaborative effort between the United States Army Corps of Engineers (St. Louis District), the SWC, the United States Fish and Wildlife Service (USFWS), and the Natural Resources Conservation Service (NRCS). The LiDAR data has a vertical datum of NAVD 88 and its horizontal projection was converted to NAD 83 in North Dakota South (ft).

2.2 Model Setup

The U.S. Army Corps of Engineers' Hydrologic Engineering Center River Analysis System (HEC-RAS) (version 5.0.3) was used to model the hydraulics of the Knife River near Beulah. Quantum GIS (version 2.2.0) was used to cut cross-sections from the collected survey data and the LiDAR. The LiDAR makes up the majority of the overbanks of the cross sections and the survey data was used to capture the channel. The cross-sections were then transferred to ArcMap (version 10.1) where HEC-GEORAS was used to convert the cross sections and reaches into HEC-RAS format to be imported into HEC-RAS. **Figure 2** is the cross-section layout for the hydraulic model.

2.3 Roughness Coefficients (Manning's "n")

The roughness coefficients for this model were based on field reconnaissance, photos of the area, and existing studies. The initial roughness coefficients were originally 0.055 in each overbank and 0.045 in the channel. These values were later changed to replicate the existing ground and reproduce water surface elevations from observed events. Horizontally varied Manning's "n" values were added to areas with changes in land use. The updated values changed to 0.035 in the channel and between 0.055 to 0.12 in the overbanks.

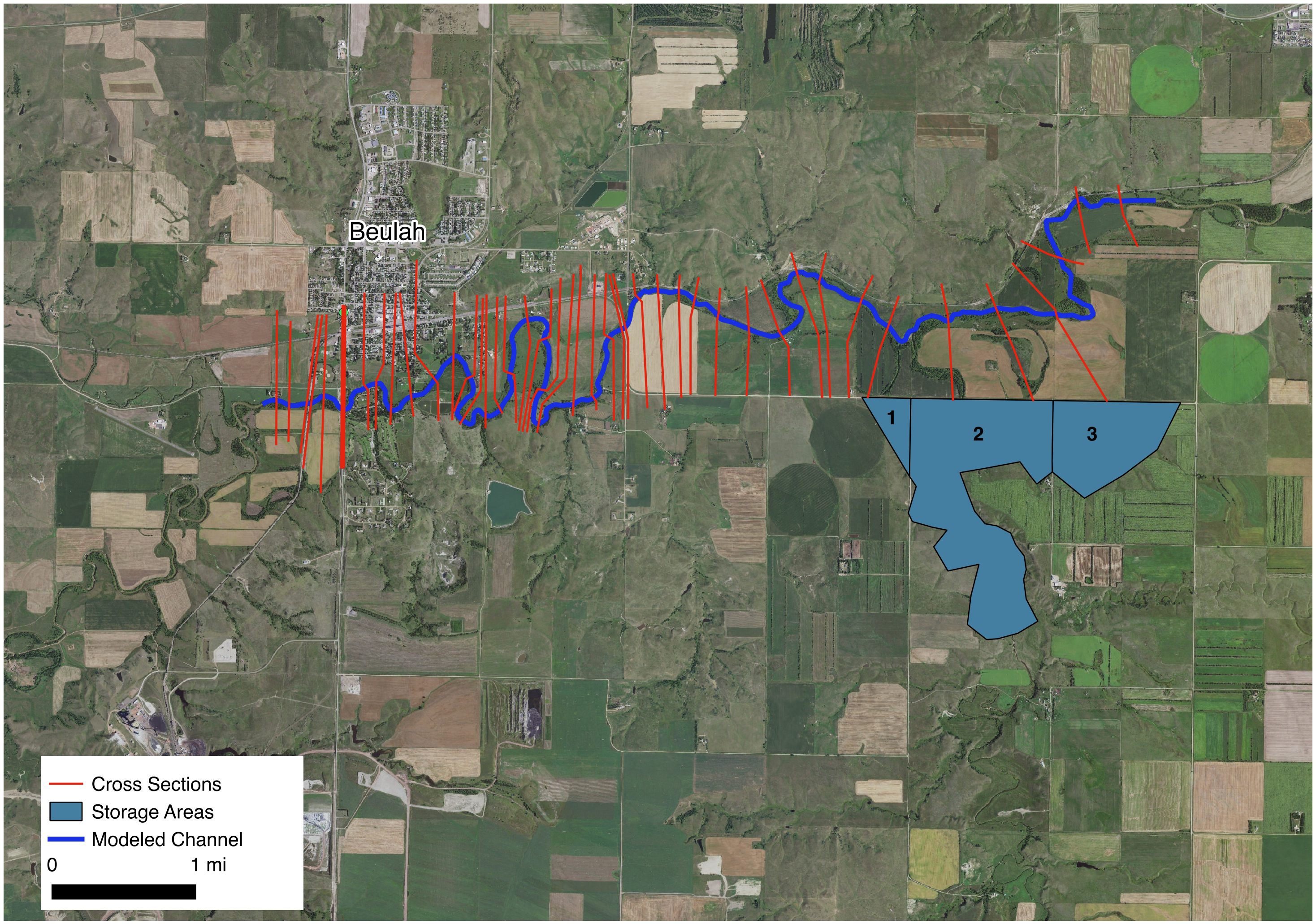

Figure 2. *Cross sections created for the Knife River model near Beulah, ND.*

3. Model Calibration

The HEC-RAS model was calibrated to a 2014 rainfall event and verified to the 2009 snowmelt event. The 2012-2014 surveys included one high-water mark measurement for the 2009 event and four high-water marks for the 2014 event. The 2014 event was chosen to calibrate the model based on high-water mark data collected by the SWC and the presence of the USGS stream gage.

The USGS stream gage was installed after the 2009 event. Known inflows for the model could not be verified, and the hydrologic model developed by the SWC was used to provide inflows for the hydraulic model. For this reason, the 2009 event was only used to verify the model.

3.1 Boundary Conditions

The steady flow boundary conditions used for the hydraulic model were discharge at the most upstream cross section and normal depth at the downstream cross section of the model. The slope used for computing normal depth was 0.0005 ft/ft. This slope was obtained from survey data and is approximately equal to the overall bed slope of the modeled river reach.

The unsteady flow boundary conditions used for this hydraulic model were a flow hydrograph at the most upstream cross section and normal depth at the most downstream cross section. The time step chosen for running unsteady flow was 6 minutes.

The inflow hydrograph for the 2009 unsteady model was produced from the HEC-HMS model developed by the SWC. A modeled hydrograph was used because the USGS gage was not present at Beulah in 2009.

The inflow hydrograph for the 2014 rainfall event was from the USGS stream gage at Beulah (gage number 06340010).

3.2 2014 Rainfall Event.

In August 2014, an intense rainstorm occurred in the Knife River Basin, producing depths of up to 2 inches in less than three hours, resulting in bank full flow conditions through Beulah. This presented the opportunity to verify channel roughness conditions based on real-time observations.

The calibration of the August 2014 rainfall event was primarily useful in capturing the Knife River’s in-bank characteristics. The 2014 rainfall event produced bank full discharges throughout the Knife River. A survey of the high-water marks was conducted by the SWC in order to calibrate the event using the USGS stream gage placed in Beulah in 2010. **Figure 3** displays the locations of the high-water marks collected by the SWC for the August 2014 rainfall event.

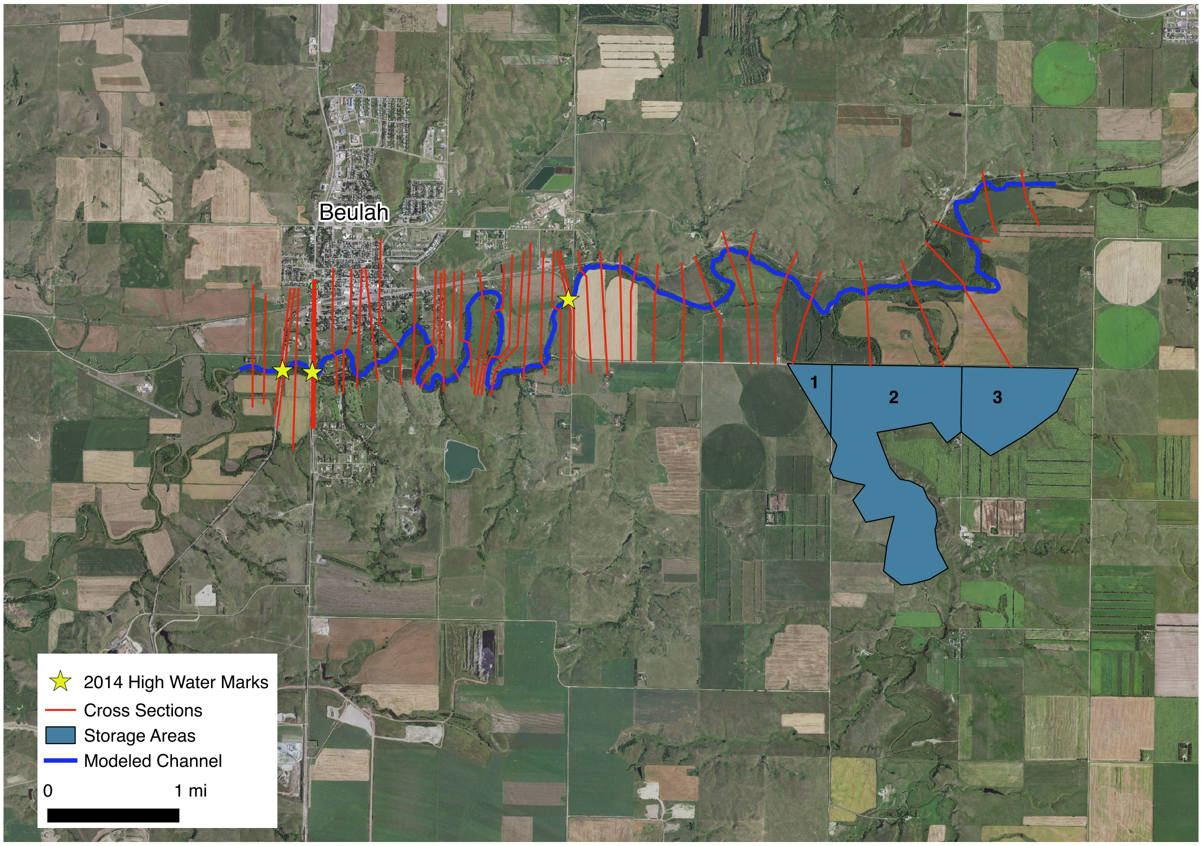

Figure 3. *2014 high-water marks in Beulah, ND.*

The 2014 rainfall event was calibrated to the surveyed high-water marks and to the USGS stream gage. **Table 1** is a comparison of the modeled water surfaces to the surveyed high-water marks and the USGS stream gage, and **Figure 4** shows the computed water surface profile.

Table 1*. 2014 water surface comparison (29577.74 is the USGS stream gage).*

Station	High-Water Mark (ft)	Modeled Maximum Water Surface (ft)	Difference (in)
30508.8	1772.25	1771.69	-6.72
29647.74	1771.24	1771.23	-0.12
29577.74	1771.07	1771.21	1.68
4297.71	1757.74	1758.15	4.92

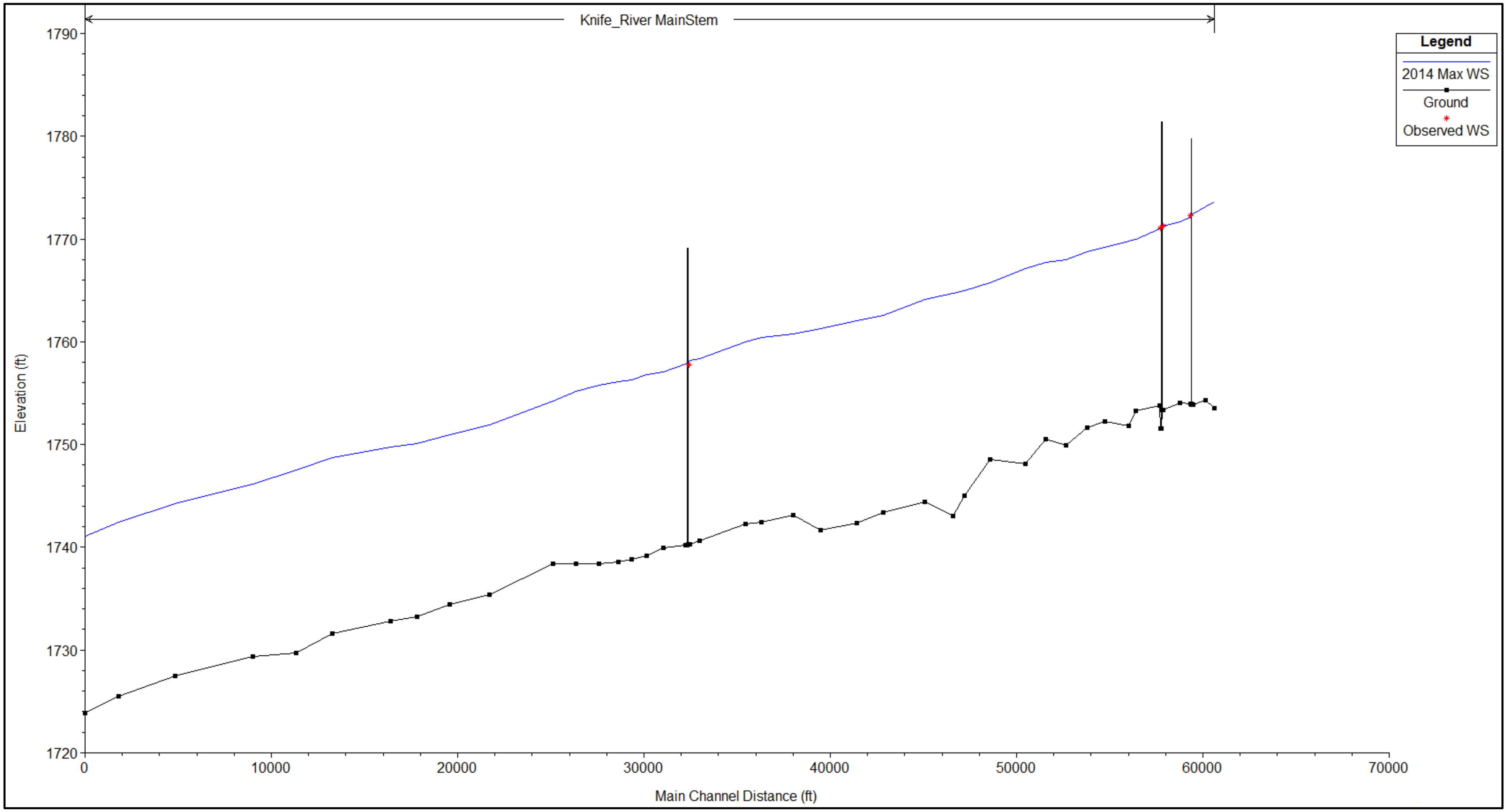

Figure 4. *2014 rainfall event, maximum water surface profile.*

The stage at the USGS stream gage was also compared to the water surface produced by the HEC-RAS model. The recorded USGS stage was converted from NGVD 29 to NAVD 88 in order to properly compare the modeled and recorded stage. The modeled water surface is very similar to the 2014 rainfall event (see **Figure 5**). The two water surfaces seem to diverge as the water surface returns to lower flow conditions. This divergence in stage is due to the control weir on the USGS gage. This structure submerges at moderate flows and was not included in the model. The divergence of water surfaces at low flows did not affect the model's ability to match high flow flood events.

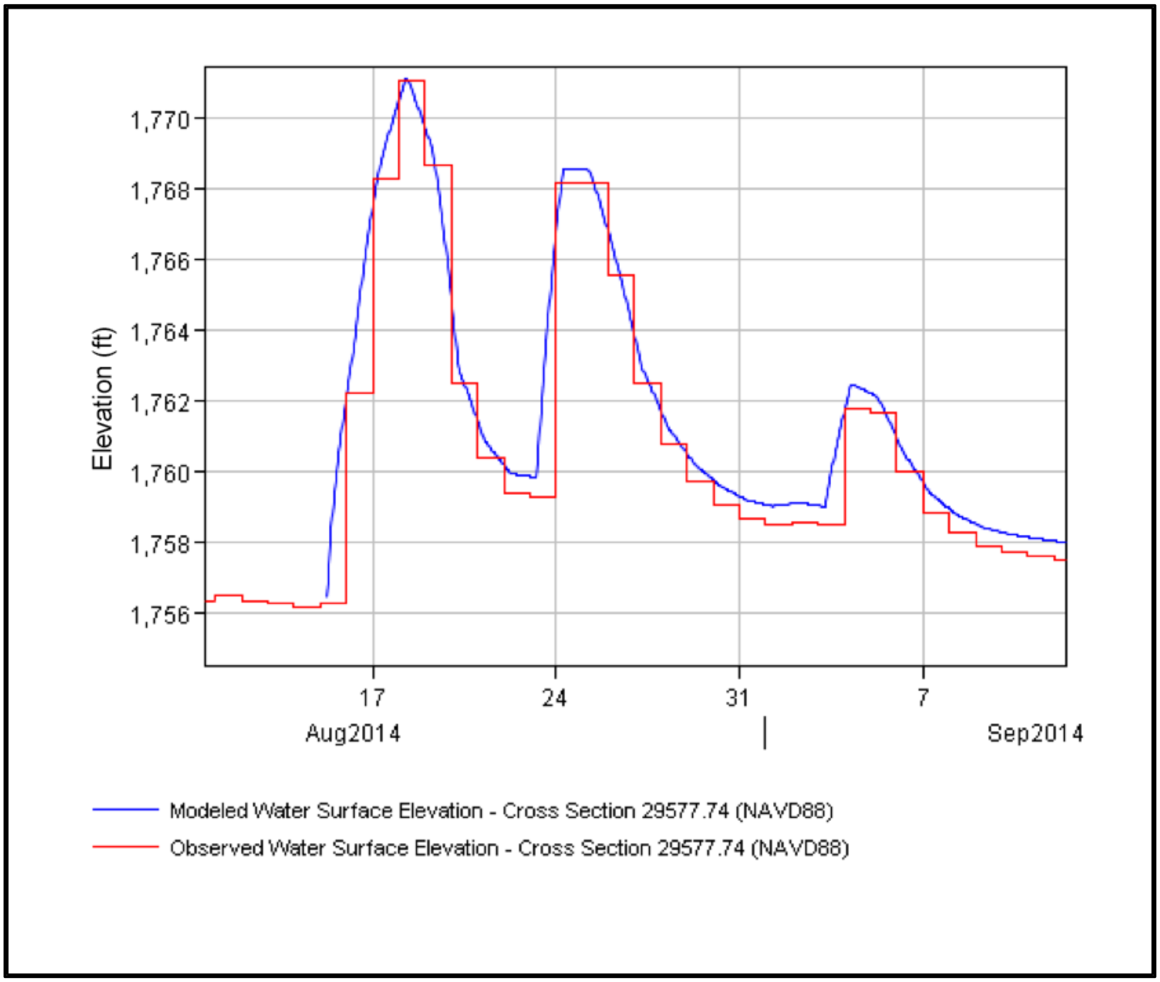

Figure 5. *2014 USGS stream gage elevation compared to modeled water surface.*

3.3 2009 Snowmelt Event

The 2009 snowmelt event was one of the largest floods on record for the Knife River. However, the resulting 2009 flood at Beulah was not well documented. Thus, the USGS stream gage at Beulah was installed after the 2009 event.

The 2009 high-water mark was located in Beulah Park on the south side of the Knife River between cross section 27853.36 and 28260.15 on the right overbank. The high-water mark was located at a restroom at an approximate elevation of 1777.97 ft (NAVD 88) and was used to calibrate overbanks of the model. **Figure 6** shows the known high-water mark for the 2009 snowmelt event in Beulah, ND.

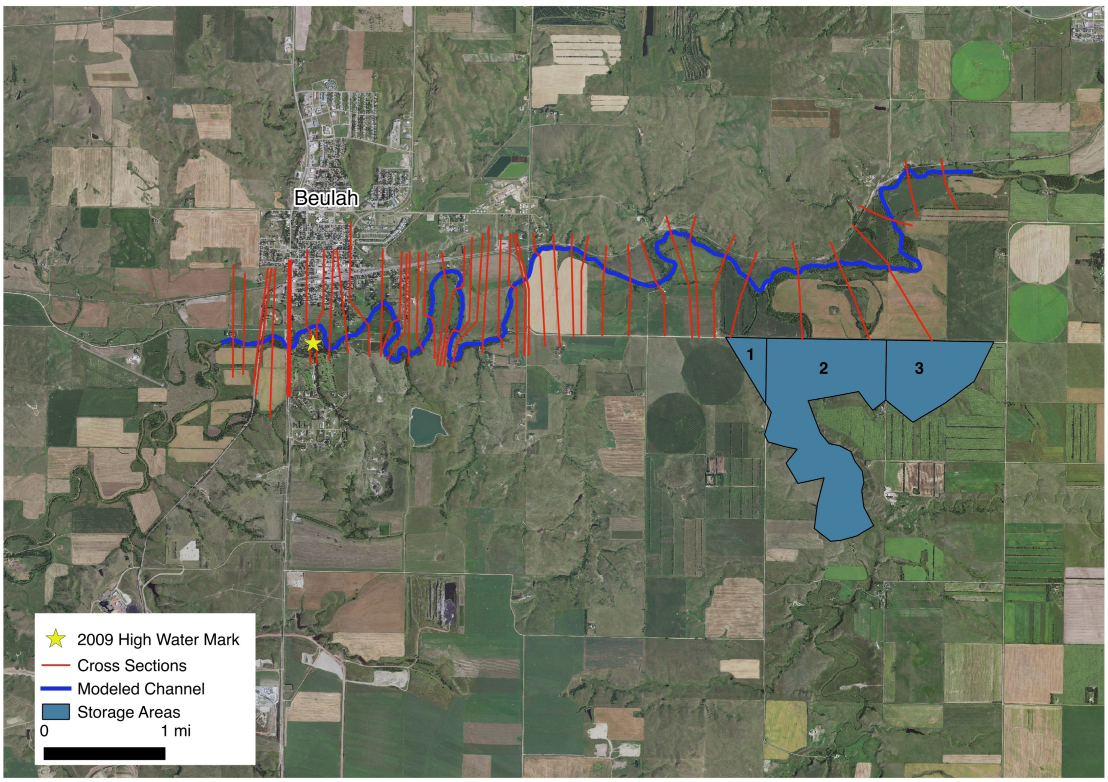

Figure 6. *2009 high-water mark in Beulah, ND (Elevation 1777.97).*

Photographs of the 2009 flood were used to determine approximate water surface elevations throughout town. These photos, along with approximate water elevations, and a brief description are located in the HEC-RAS model under the associated cross sections. **Figure 7** shows an example of one of these photos.

After calibration of the 2014 event captured the in-channel characteristics, the 2009 event was used to calibrate the overbanks of the model. Overbank calibration consisted, primarily, of adjusting roughness coefficients to replicate conditions in both overbanks and channel to produce the observed water surface elevations. Ineffective flow limits were used as secondary calibration adjustments. These limits replicate static, slow moving, or impeded water throughout the model reach.

The ineffective flow limits were also placed along the bridge abutments to replicate contraction and expansion through the bridges. Contraction and expansion coefficients were increased on the railroad bridge and State Highway 49 bridge to model the constriction of flow in the region. All bridges used the energy equation for low flows and pressure and weir flow for high flows.

Figure 7. *2009 flood photo of state highway 49 in Beulah, ND.*

The calibrated model produced a water surface elevation at cross section 27853.36 of 1777.95 ft (NAVD 88) and energy grade line elevation of 1778.57 ft (NAVD 88). The surveyed high-water mark was 1777.97 ft (NAVD 88), which is nearly a third of an inch above the calculated water surface. After calibration of the 2009 event, the 2014 event was rerun to ensure no changes to the 2014 water surface had occurred.

Photographs of the 2009 event were also used to verify the model. These photos, attached to the HEC-RAS model, show the overbanks of the Knife River. These portions of the overbanks have little velocity when compared to the channel, so the energy grade line is better representation of local water surface elevation. The inundation area of each photograph was visually compared to the energy grade line in the corresponding cross section to verify the model. **Figure 8** is the maximum water surface profile for the 2009 snowmelt event.

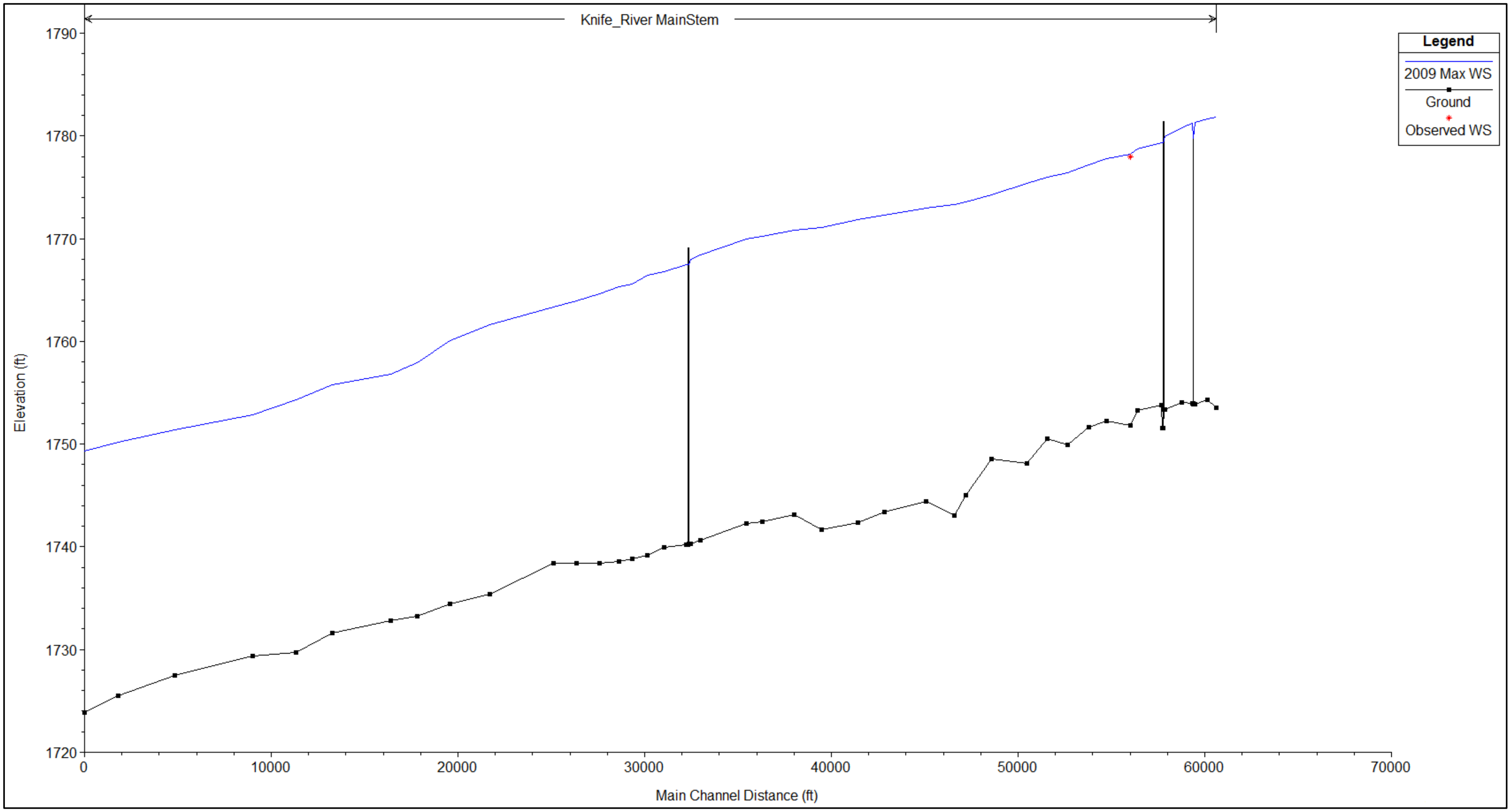

Figure 8. *2009 snowmelt event maximum water surface profile.*

The stage and flow hydrographs for cross-section 29577.74, the USGS gage location, were plotted as a reference. **Figure 9** is the stage and flow hydrographs at the USGS gage.

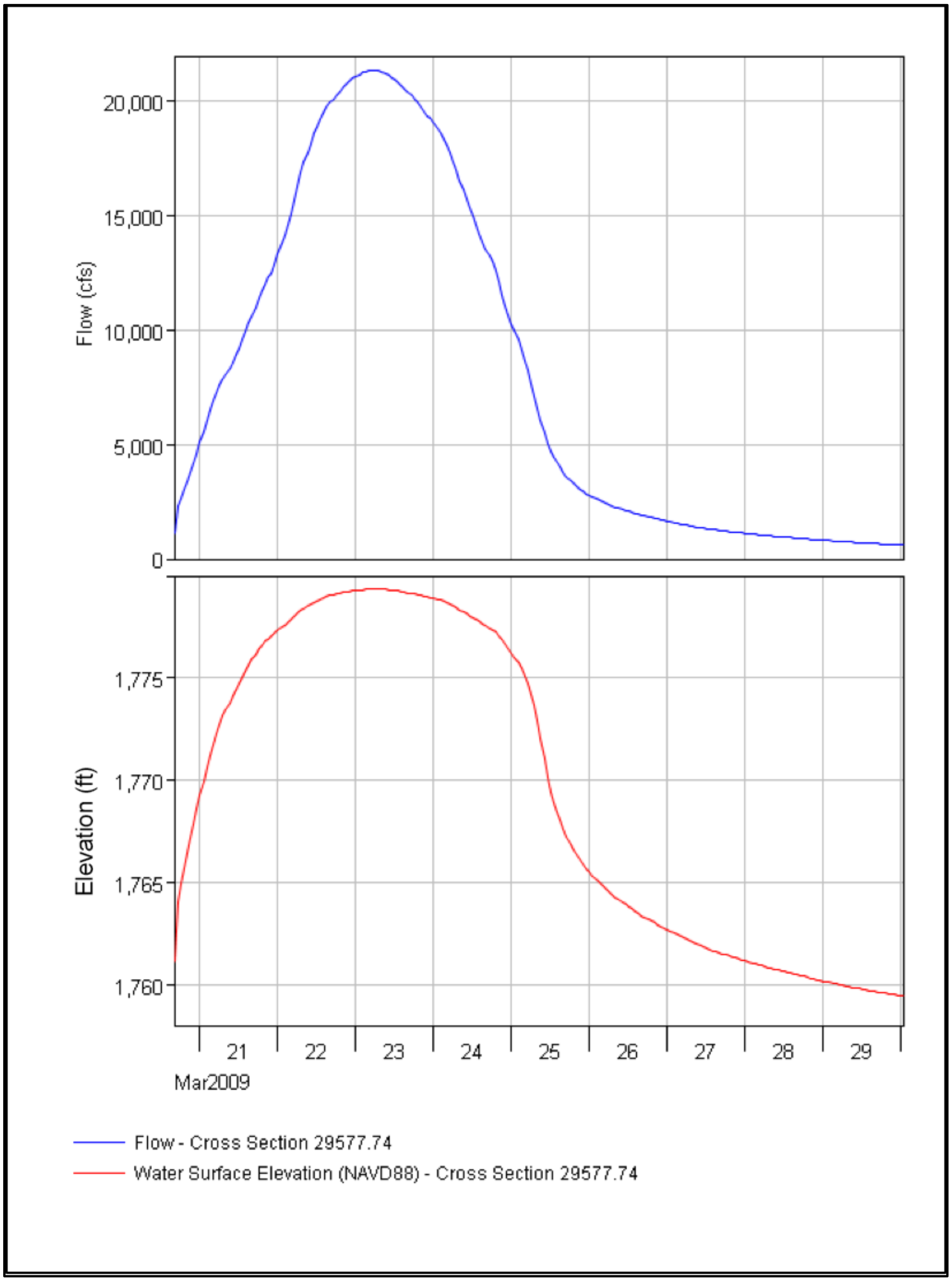

Figure 9. *2009 modeled elevation and flow hydrographs at the USGS gage.*

3.4 Sensitivity Analysis

A sensitivity analysis was conducted on parameters that were uniform between the 2009 and 2014 calibration events. Parameters analyzed included the implicit weighting factor, computation time step, and the normal depth boundary condition. The implicit weighting factor was adjusted between 0.6 to 1.0 (1.0 default) and resulted in no change in modeled water surfaces. The computation time step was adjusted between 1-minute and 12-minutes to evaluate its effect on the computation solution. A time step of 6-minutes was chosen for the model, and the variation of time steps between 1 and 12-minutes resulted in no change to the solution or model stability. A comparison of modeled solutions for adjusted time steps is shown in **Figure 10**.

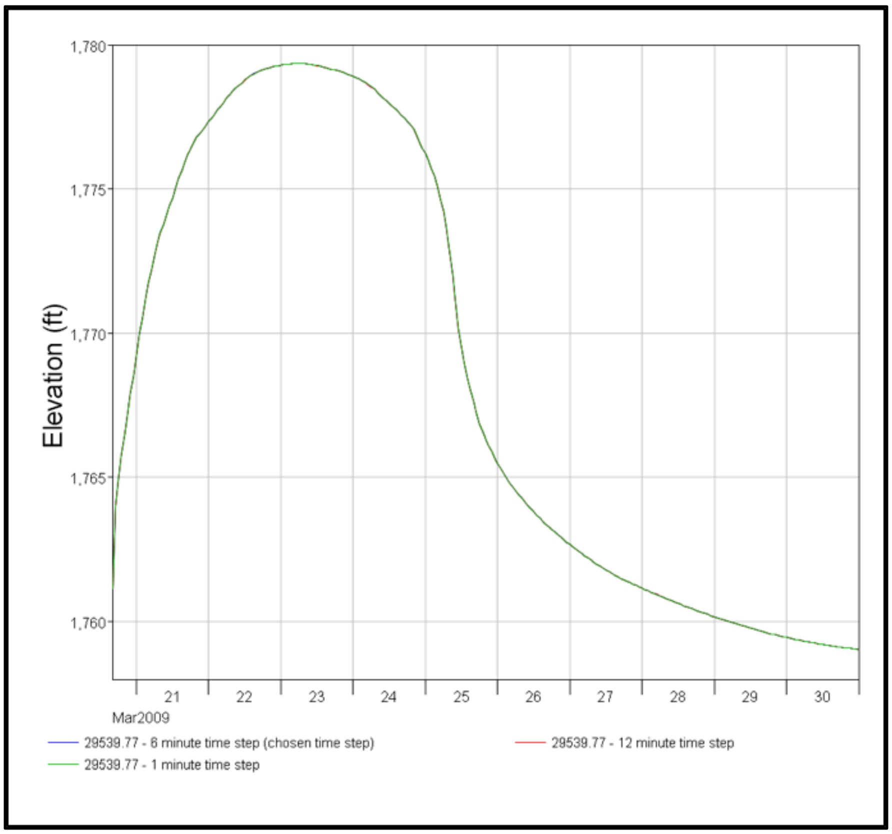

Figure 10. *Time step sensitivity analysis.*

The 2009 and 2014 events were calibrated using a normal depth slope of 0.0005. The model was extended to ensure changes to the downstream boundary condition would not affect the county road bridge, the most downstream bridge of the model. The sensitivity analysis for normal depth was conducted by comparing the calibrated normal depth of 0.0005 to 0.00025 and 0.001 and examining the water surface elevation changes along the profile. The change in normal depth slope was found to be significant on some of the cross sections added to the model, cross section 500 to the downstream boundary, but did not affect the areas of interest. This means geometric changes to the county road bridge, the most downstream area of interest, could be conducted with confidence in the solution regardless of the downstream boundary condition. **Figure 11** and **12** show the 2009 and 2014 profiles with varying normal depth boundary conditions.

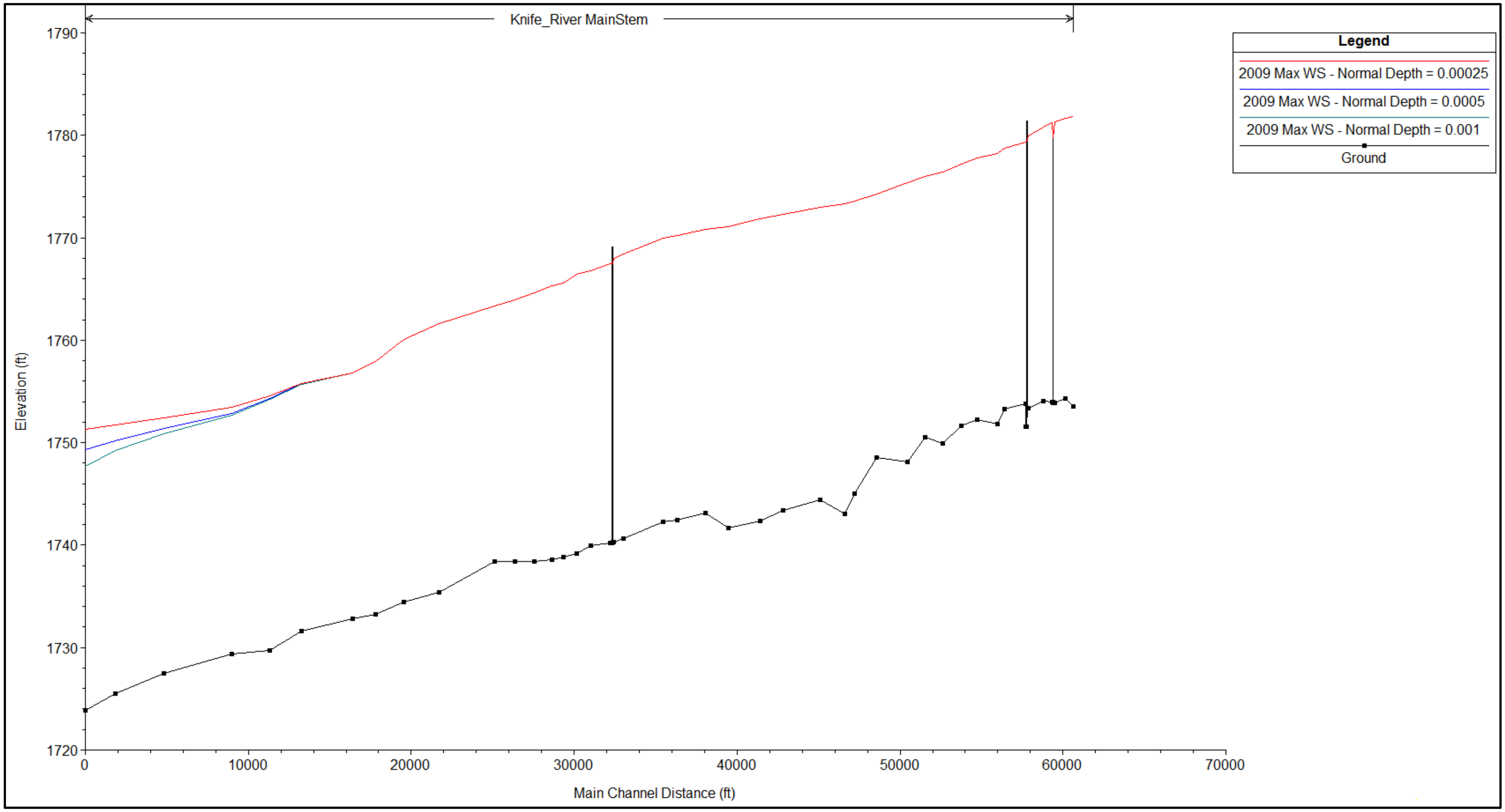

Figure 11. *2009 normal depth sensitivity.*

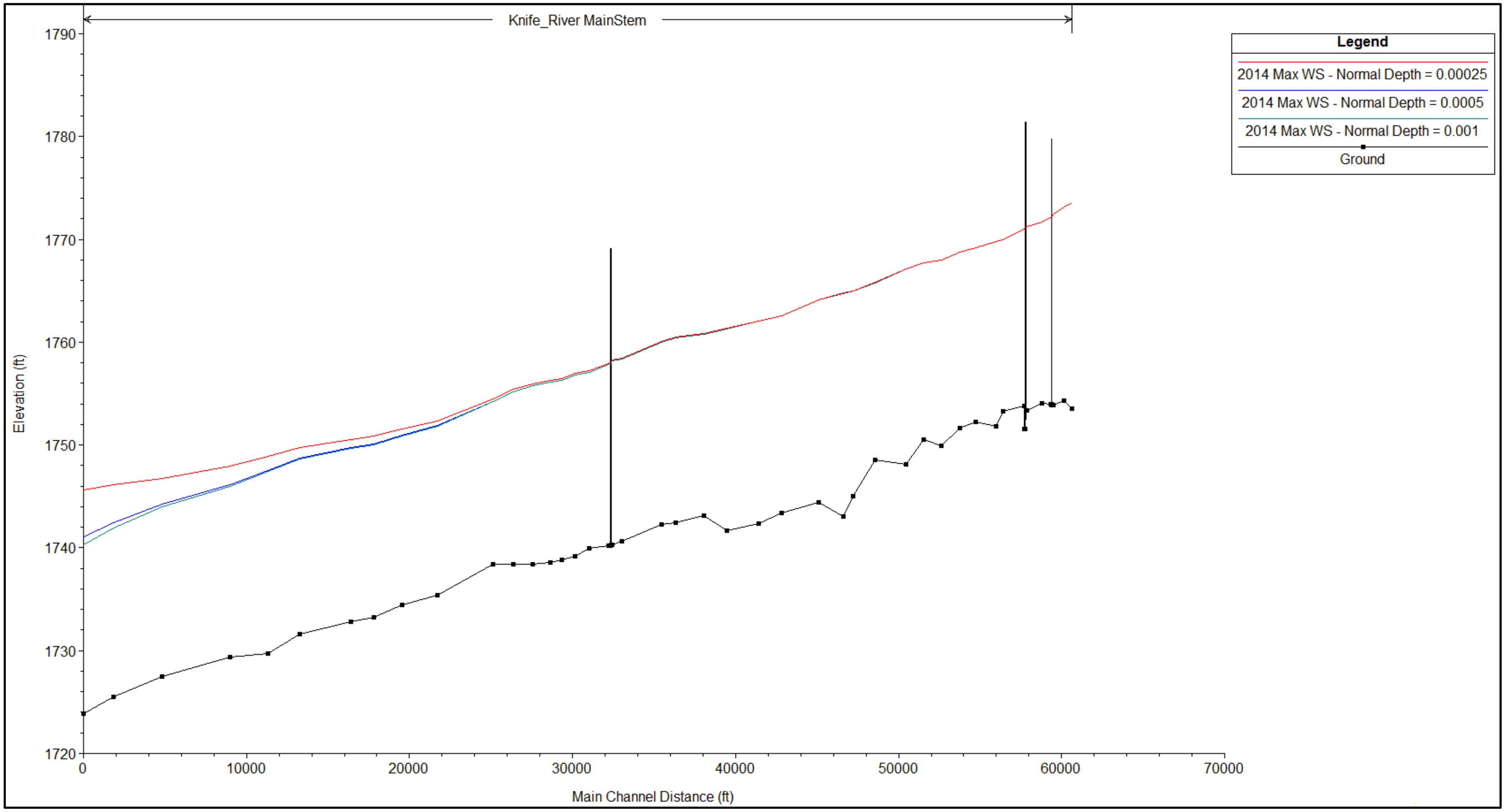

Figure 12. *2014 normal depth sensitivity.*

4. Frequency Events

Frequency events were also included in the HEC-RAS model of the Knife River at Beulah. The Frequency events modeled include the 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year events derived from the Knife River Basin HEC-HMS model. The frequency events were computed as part of the hydrologic study using NOAA Atlas 14 precipitation data because of the lack of record at Beulah's stream gage. Atlas 14 precipitation data uses only rainfall data and can under predict storm events in areas where large flows can be caused by snowmelt in combination with rainfall. The frequency flows in Table 2 were computed using Atlas 14 precipitation data using an HEC-HMS model that had been calibrated to historic events. The frequency events were then adjusted by raising initial moisture content parameters to fit within the confidence limits for volume and peak flow at the Hazen gage. **Table 2** lists the peak frequency flows from the HEC-HMS model results at the Beulah gage that were used in the HEC-RAS model.

Table 2. *Peak frequency flows and total volumes modeled at the USGS gage.*

Frequency Event	Peak Flow (cfs)	Total Volume (acre-ft)
500	52,185	367,322
200	44,357	311,941
100	32,691	232,818
50	24,948	185,071
25	18,595	141,405
10	13,034	92,054
5	8,460	63,028
2	3,151	27,604

The elevation and flow for each modeled frequency event were plotted in the Hydrologic Engineering Center's Data Storage System Visual Utility Engine (DSS-VUE) for the USGS gage at Beulah, cross section 29577.74. **Figure 13** is the DSS-VUE plot of stage at cross section 29577.74. Plotted frequency events can provide a reference of event severity according to stage. In Figure 13 it can be seen that the 200-year event jumps above the 500-year event in two locations, this is due to hydraulic effects at the Highway 49 bridge.

The maximum water surface profiles for each of the frequency events were also plotted along the Knife River's profile through Beulah. **Figure 14** depicts the frequency event profiles through the modeled reach. The drop-in water surface downstream of the county road bridge (near station 20000) is caused by a channel restriction followed by the widening on the floodplain.

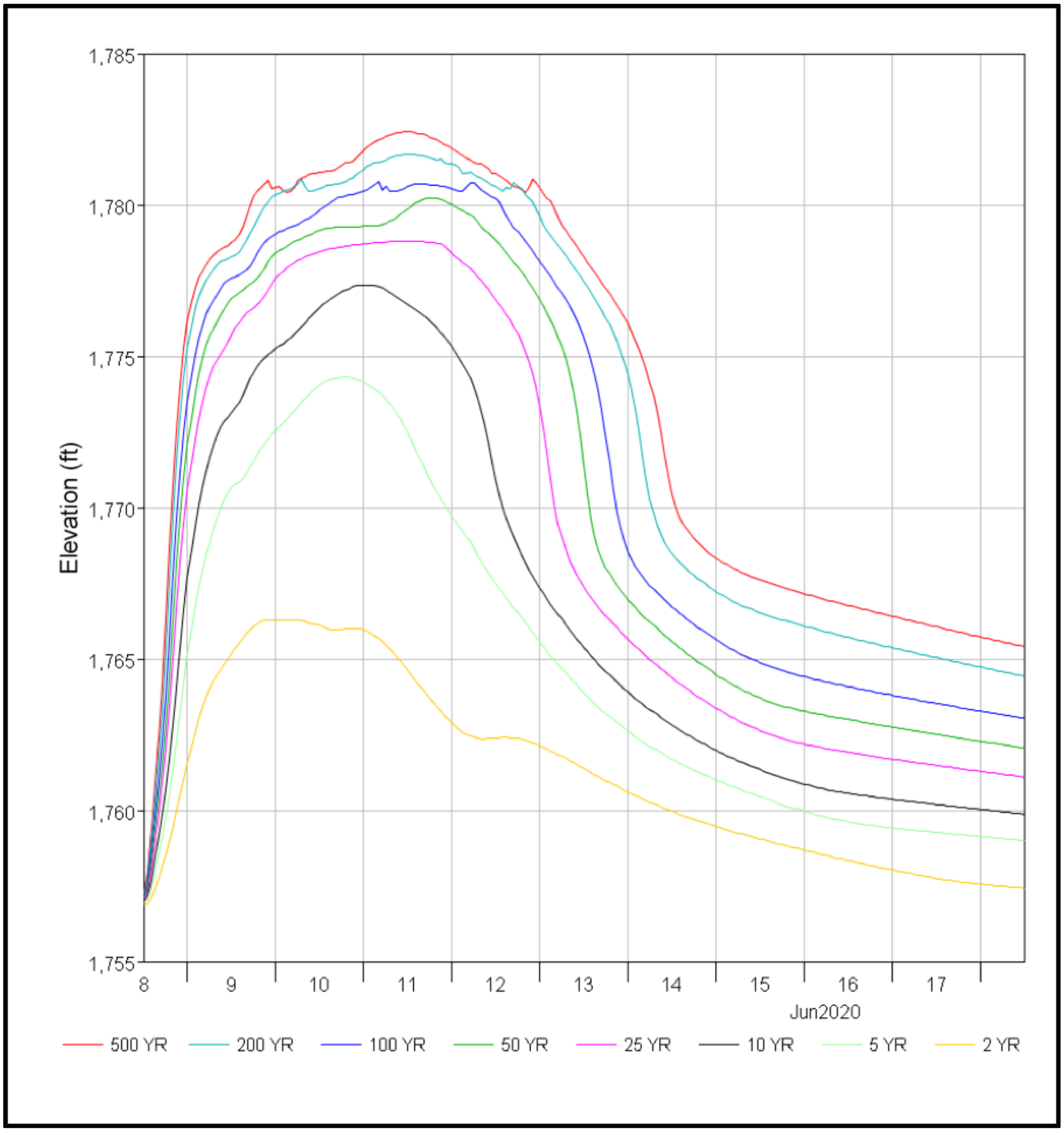

Figure 13. *Frequency events modeled elevation plotted at the Beulah USGS gage.*

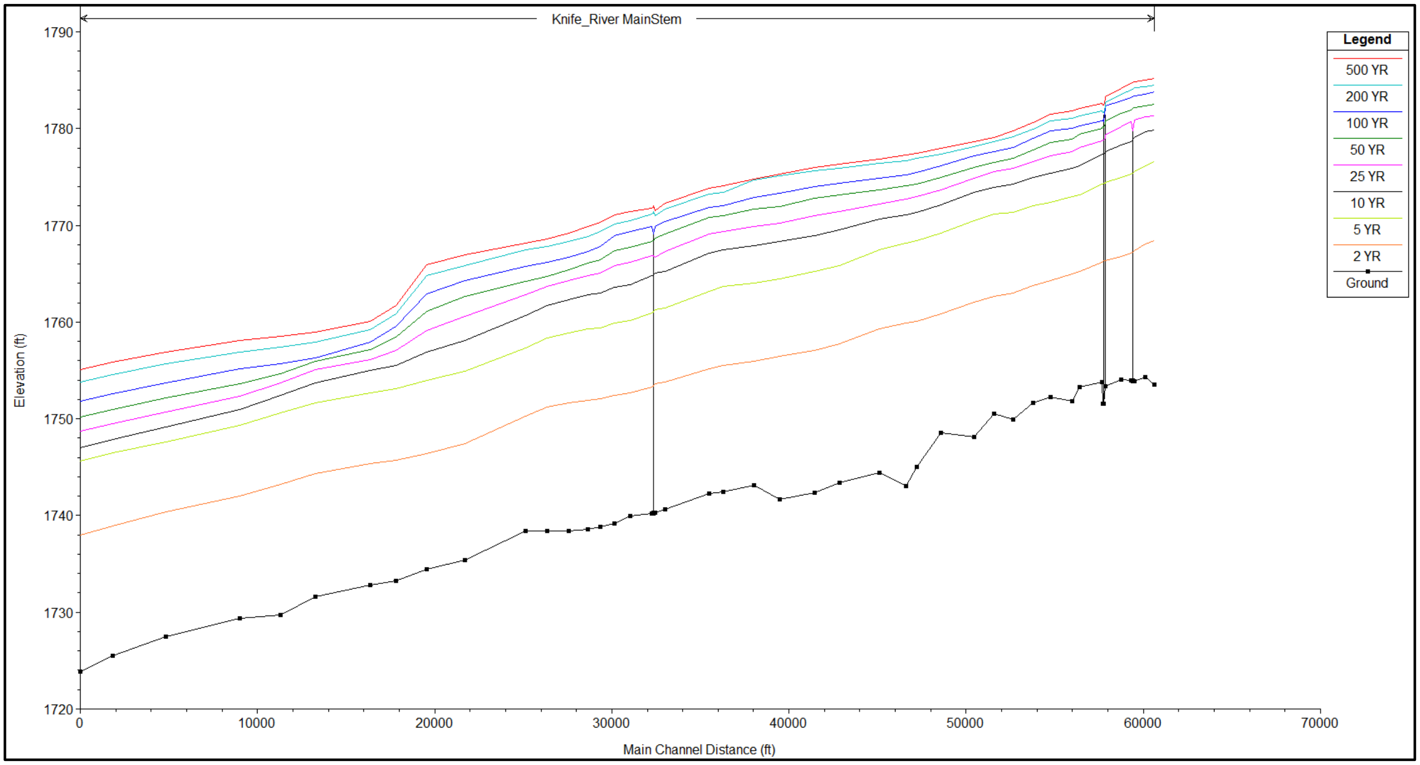

Figure 14. *Frequency events maximum water surface profile plot.*

5. Summary

An HEC-RAS model of the Knife River at Beulah was created and tested against natural (2009 and 2014) and synthetic events. After the model was calibrated to the 2009 event, all parameters were adjusted to be the same for both the 2009 and 2014 events.

The model can provide accurate large event flood analysis for Beulah, ND, as well as provide a starting point for design of flood risk management alternatives, and determine localized urban inundation areas. A future report will detail a series of flood mitigation alternatives analyzed by the model.

6. Citations

Hydrologic Engineering Center, 2013. River Analysis System HEC-RAS, User's Manual, Version 5.0.3, U.S. Army Corps of Engineers, Davis CA.

"National Weather Service - NHDS - NOAA Hydrologic Data Systems Group." National Weather Service - NHDS - NOAA Hydrologic Data Systems Group. National Weather Service. Web. 29 Jan. 2016.

"USGS 06340010 KNIFE RIVER NEAR BEULAH, ND." USGS Current Conditions for USGS 06340010 KNIFE RIVER NEAR BEULAH, ND. Web. 05 Feb. 2016.