Pembina River Hydraulic Model Report

Pembina County, North Dakota

SWC Project #1701
October 2015

North Dakota
State Water Commission

Cover photograph: Looking upstream the Pembina River at confluence of the Pembina and Red Rivers, Pembina, ND. (photograph by North Dakota State Water Commission, 1997)

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SWC Project #1701
North Dakota State Water Commission
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For:
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Introduction

The Pembina River is a tributary to the Red River of the North that flows through Manitoba, Canada and North Dakota (**Figure 1**). The Pembina River frequently floods areas of northern Pembina County including the rural areas near Walhalla, Neche, and Pembina, North Dakota. The North Dakota State Water Commission (SWC) and the United States Army Corps of Engineers (USACE) entered an agreement, most recently during 2010, to develop an unsteady flow model of the Red River. As part of this agreement, an unsteady flow model of the Pembina River from Walhalla to its confluence with the Red River was constructed. This report details the model development and simulated results for four flood events.

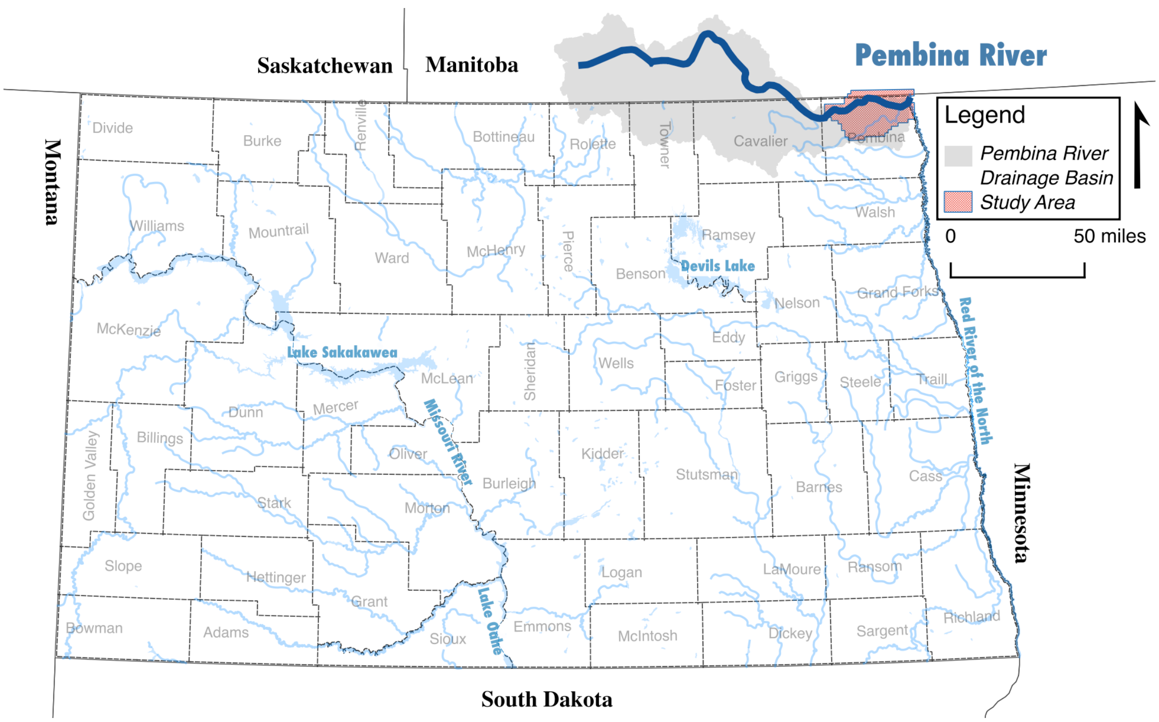

Figure 1: Project location.

A 1-dimensional (1D), unsteady flow, hydraulic model was developed using a beta version of HEC-RAS 5.0 software dated October 2014 (Hydrologic Engineering Center, 2014). This version of software was used because it has an improved, faster unsteady flow solver than the current HEC-RAS 4.2 release. The model was used to simulate the river hydraulics of the Pembina River during flood events. The model and associated geographical information system (GIS) files are included as an electronic appendix within **Appendix A**.

Purpose and Limitations

This model was constructed by the SWC as part of a larger effort to create an unsteady flow model of the Red River within the United States. This model was developed and calibrated as part of a regional study; therefore, use of this model at finer scales, such as Federal Emergency Management Agency (FEMA) floodplain studies and USACE levee certification, is not recommended without considerable refinement within the area of interest. Channel bathymetry within this model was estimated, and the focus of this model was low-frequency flood events. The model was developed to be used for long-term flood control planning within the Pembina River region, screen the effects of flood control alternatives, and provide supplemental information to flood forecasters.

Pembina River Hydraulics and Conceptual Model

This study focuses on the lower Pembina River from Walhalla, ND to its confluence with the Red River at Pembina, ND (**Figure 2**). This reach of the Pembina River lies almost entirely within the Red River Valley, which is the former bed of glacial Lake Agassiz. The Pembina River is susceptible to floods from snowmelt and rain events. These floods are often amplified by backwater effects from concurrent flooding of the Red River.

When the Pembina River upstream of Walhalla floods out of its banks, it is confined by high ground; however, within the Red River Valley, flood waters spill over the banks along flat ground resulting in many breakout flows. When breakouts occur, natural levees can form on top of the banks as the velocity of sediment laden flood waters suddenly decreases, allowing the suspended sediment to settle out.

Breakout flows escaping the river channel typically result in overland flow that is impeded or impounded by rural roads. In some instances, overland flow occurs as 2-dimensional (2D) flow, which is problematic for a 1D model. To approximate these overland flows within HEC-RAS, a series of storage areas were used (**Figure 2**). This assumption is reasonable because many of the breakouts are impounded by roads and transfer to the next section of land by overtopping the road or flowing though a culvert (**Figure 3**). Where the breakout flows reach a man-made or natural drainage, 1D river reaches were added to the model to route the breakouts back to the Pembina River.

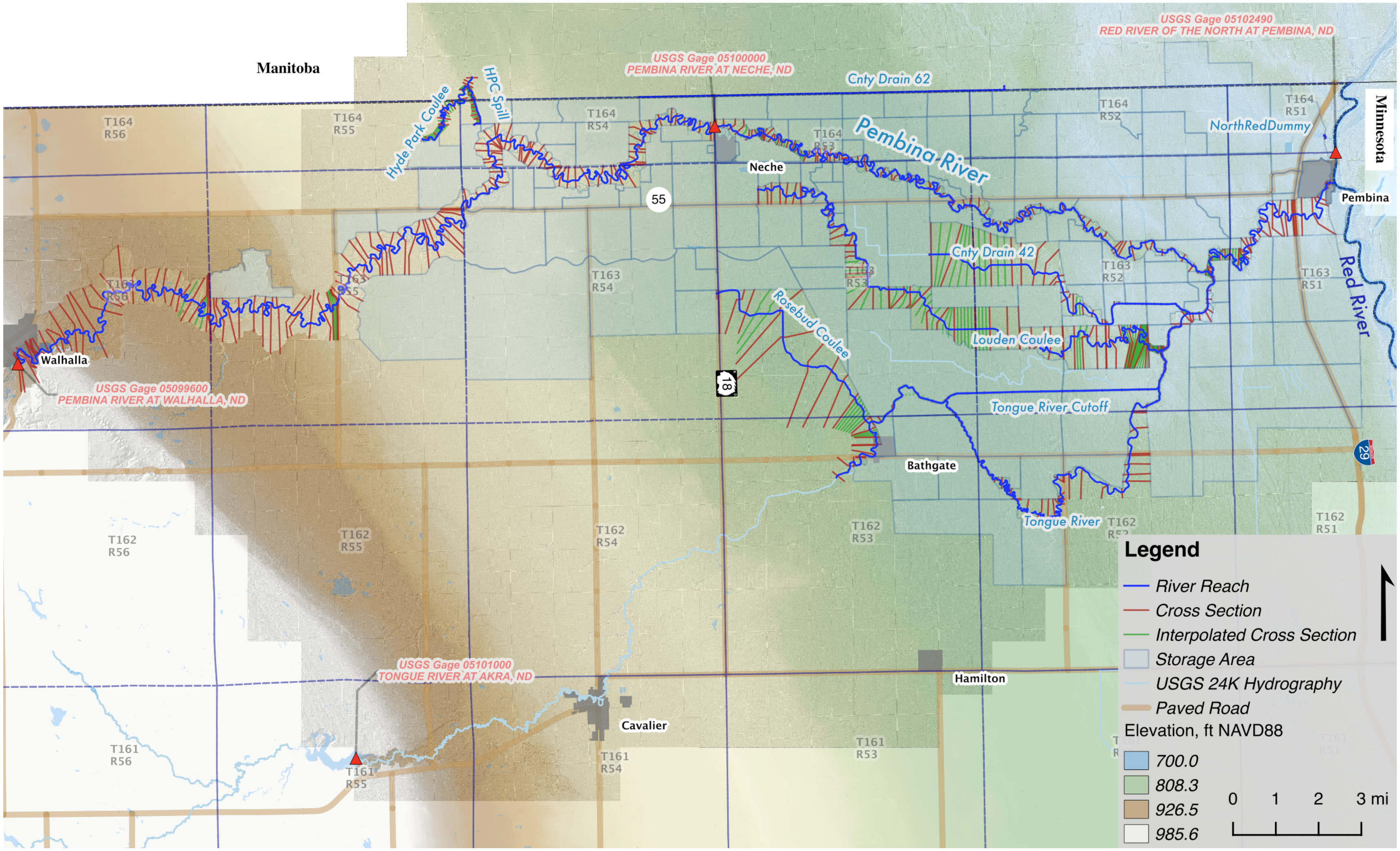

Figure 2: Model layout.

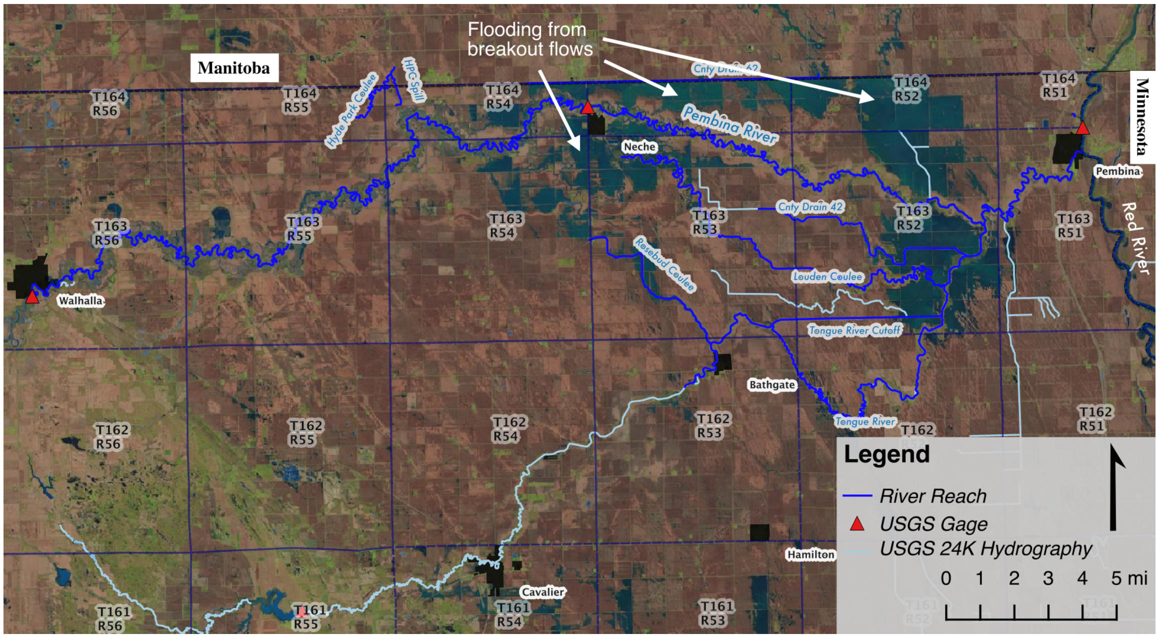

Figure 3: Landsat image collected April 25, 2013 showing overland flooding from Pembina and Tongue Rivers breakout flows within the Red River Valley. Landsat image courtesy of the USGS.

The majority of breakout flows occur upstream of Neche, ND. **Figure 3** shows a Landsat image collected on April 15, 2013, three days after the flood of record of 17,500 cubic feet per second (cfs) was measured at the USGS gage 05100000 Pembina River at Neche, ND. When the flow in the Pembina River reaches approximately 5,000 cfs, breakouts to the north, south, and east occur. Breakout flows to the north flow into County Drain 62 along the international border. Breakout flows to the south and east flow into County Drain 42, Louden Coulee, and Rosebud Coulee which flow into the Tongue River and eventually back into the Pembina River. Discharges measured at USGS gage 05100000 Pembina River at Neche, ND include measured flow within the Pembina River channel as well as breakout flows measured along County Highway 55 and State Highway 18 (C. Laveau, personal communication June 26, 2015).

HEC-RAS Model Parameters

Model Geometry

Horizontal and Vertical Datum

The HEC-RAS model was georeferenced using geographical information systems (GIS). All vertical elevations are in feet and reference North American Vertical Datum of 1988 (NAVD88) Geod03. The horizontal datum units are in international feet and reference Universal Transverse Mercator (UTM) Zone 14 Geodetic Reference System 1980 (GRS80). This unconventional horizontal datum was created by HEC-RAS when the original vector data, which was in UTM zone 14N (EPSG: 26914), was converted from meters to feet during the initial geometry import from GIS.

River Reaches and Cross-Sections

In addition to the Pembina River, the Tongue River and several other reaches were included in the model to capture the hydraulics at the Pembina and Tongue River confluence and to route breakout flows. The model includes the following reaches (**Figure 2**):

- Pembina River from Walhalla, ND to the Red River confluence at Pembina, ND
- Tongue River from Bathgate, ND to the Pembina River confluence (includes the Tongue River Cutoff channel)
- County Drain 62
- County Drain 42
- Louden Coulee
- Rosebud Coulee
- NorthRedDummy (a "dummy" reach to allow backwater from the Red River to enter storage areas)

Cross-sections were cut perpendicular to the predominant flow path along the channel and left and right overbanks along each reach. Cross-sections were generally spaced between 5,000 ft and 200 ft for each reach, and interpolated cross-sections were added in some areas for stability (**Figure 2**).

Cross-section elevation data was obtained from sampling bare-earth LiDAR rasters collected between April 19 and May 2, 2008 (Block A) as part of the Red River Basin Mapping Initiative (International Water Institute, 2008) using the HEC-GeoRAS plugin (Hydrologic Engineering Center, 2015) within ESRI ArcMap (ESRI, 2013) or the Q-RAS plugin (De Rosa, 2015) within QGIS (QGIS Development Team, 2015). Flows in the Pembina River during this time ranged from 700 to 300 cfs.

Bathymetry was not available; however, channel bottom elevations were estimated creating a synthetic channel below the water surface using the Channel Modification Tool within HEC-RAS. **Figure 4** shows the cross-section geometry of the Pembina River with and without the estimated channel bottom geometry at river mile 52.2471, the location of USGS gage 05100000 Pembina River at Neche, ND. The submerged channel dimensions for the Pembina River were estimated from the Neche gage stage and discharge information, and the slope was estimated from the general slope of the river. A synthetic channel bottom was used for all reaches to correct for noise in the LiDAR returns (e.g. cattails) and to aid in model stability. An effort was made to keep the synthetic channel as realistic as possible and not introduce additional cross-sectional area.

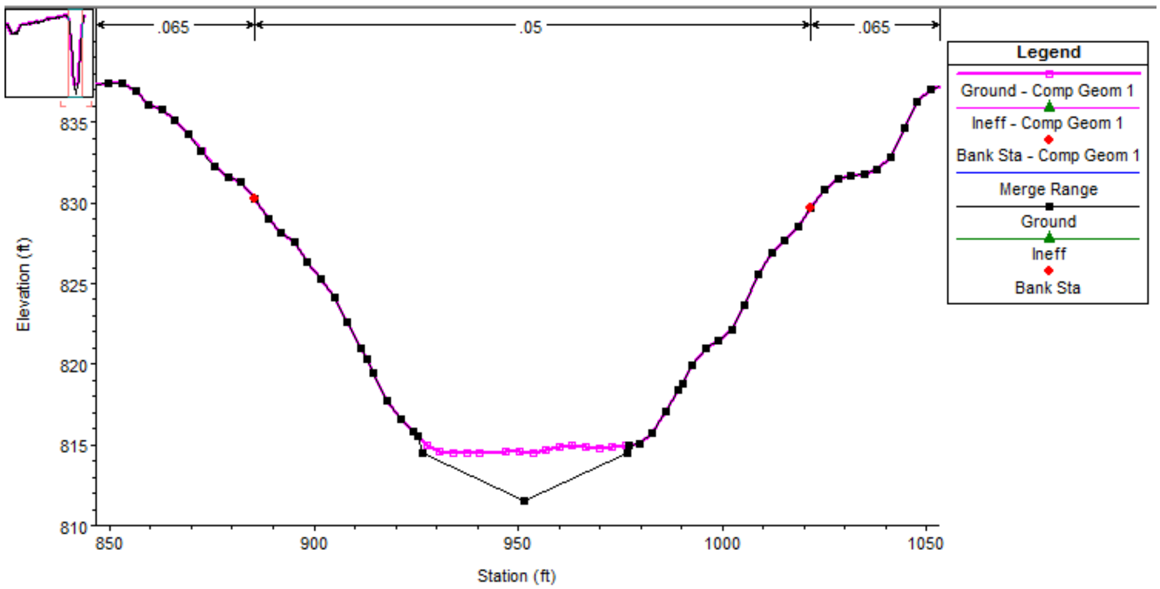

Figure 4: Cross-section terrain showing synthetic bathymetry (black line) and raw LiDAR elevations (pink line) for Pembina River cross-section 52.2471 (USGS gage 05100000).

Reaches typically were modeled with lateral structures along the natural levee crest. Many times this resulted in just the river channel represented as 1D flow, and the overbanks as storage areas.

At some locations "dummy" cross-sections were used to model an area with abrupt change. For example, an area like the confluence of County Drain 42 and the Tongue River presents a challenge for HEC-RAS because of the abrupt elevation change. Dummy cross-sections were used to smooth this transition.

Storage Areas

A total of 175 storage areas were used in the model. Generally the storage areas encompassed a section of land (one square mile); however, some larger and smaller storage areas were used depending on the level of detail and topography. Storage areas are named for the Township, Range, and Section that they occupy. Storage areas are interconnected by storage area connections and connected to river reaches with lateral structures.

An elevation storage relationship was derived from the 2008 LiDAR dataset using the HEC-GeoRAS plugin with ESRI ArcMap or by using a similar tool within GRASS-GIS (GRASS Development Team, 2013).

Bridges and Culverts

All crossings along the Pembina River were modeled explicitly as bridges within HEC-RAS. Most crossings along other reaches were also modeled explicitly; however, some crossings were not modeled due to their minimal impact on the overall model. Culverts used to transfer flow to and from the storage areas were modeled within lateral structures or storage area connections.

Geometry of the bridges and culverts were based on surveyed data, culvert inventory included in the the National Research Council Canada's Phase 3 Hydrodynamic Model (Faure and Jenkison, 2002), aerial photos and LiDAR data. Survey data was limited to a few bridges on the Pembina River, and many of the culvert dimensions were assumed. Survey data is included in **Appendix A**. The data source for each crossing is included in the comments section within the model.

Lateral Structures and Storage Area Connections

Lateral structures were based off LiDAR data and typically followed the natural levees or a road embankment near a reach to connect a reach to a storage area. Likewise, storage area connections also used LiDAR data along high ground or road embankments to connect storage areas to each other. The weir coefficients for each were varied based on the structure type, surrounding topography, and calibration. The ranges of values used based on terrain type are summarized in **Table 1**.

Terrain Type	Weir Coefficient
Paved Road	1.5 to 2.0
Gravel Road	0.7 to 1.5
Prairie Trail	0.5 to 1.0
Natural Levee or High Ground	0.3 to 1.0
Low Ground	0.1 to 0.5

Table 1: Summary of lateral structure and storage area connection weir coefficients.

Inline Structures

Two inline structures were included in the model. Pembina City Dam is a low head dam near the confluence of the Pembina and Red Rivers (river mile 0.27) and was modeled as an inline structure. The Tongue River Watershed Diversion structure located on the Tongue River near river mile 7.98 was also modeled as an inline structure. This structure diverts flows through a diversion channel (Tongue River Cutoff) during high flows.

Boundary and Initial Conditions

Where possible, daily average USGS stream gage flow data were used for reach boundary conditions. A complete list of boundary conditions are summarized in **Table 2**. Daily flow data from USGS gage 05099600 Pembina River at Walhalla, ND was used as the upstream boundary condition for the Pembina River.

Reach	Upstream Boundary Condition	Downstream Boundary Condition
Pembina River	Flow data from USGS gage 05099600 Pembina River at Walhalla, ND	Stage data from USGS gage 05102490 Red River of the North at Pembina, ND
Tongue River	Flow data from USGS gage 05101000 Tongue River at Akra, ND shifted by 1 day (min flow 10 cfs)	Junction with Pembina River
Rosebud Coulee	Storage Area 163-054-24 (min flow 5 cfs)	Junction with Tongue River
Louden Coulee	Storage Area 163-053-06 (min flow 5 cfs)	Junction with Tongue River
County Drain 42	Storage Area 163-053-11 (min flow 5 cfs)	Junction with Tongue River
County Drain 62	Storage Area 164-054-27 (min flow 5 cfs)	Normal Depth = 0.00013
Hyde Park Coulee	Synthetic hydrograph (constant 5 cfs)	Normal Depth = 0.0003
North Red Dummy	Storage Area 164-051-33 (min flow 5 cfs)	Stage data from USGS gage 05102490 Red River of the North at Pembina, ND

Table 2: Summary of boundary conditions.

Daily flow data from USGS gage 05101000 Tongue River at Akra, ND was used as the upstream boundary condition for the Tongue River. This gage is located over 15 miles upstream of the uppermost cross-section of the Tongue River in the model. To account for this discrepancy, the gage was shifted by one day, the approximate travel time between these locations as determined by using a travel time grid created as part of the Pembina River Hydrology model developed by the USACE (USACE, 2013).

A minimum flow of 5 cfs was used for all reaches with the exception of the Tongue River where a minimum of 10 cfs was used.

Daily stage data from USGS gage 05102490 Red River of the North at Pembina was used as a downstream boundary condition for the Pembina River. This gage was also used as a downstream boundary condition for the "dummy" reach, North Dummy Red, to allow backwater from the Red River to enter the adjacent storage areas, although values below elevation 766.85 ft were not used because it would cause the reach to become unstable.

Boundary conditions were used as the initial conditions for river reaches with the exception of reaches connected to storage areas. At these reaches outflows from the storage areas were used and a minimum of 5 cfs lateral inflow was used to prevent the reach from going dry. Initial conditions for storage areas typically were set to the minimum elevation. Where storage areas have lateral inflow boundary conditions or are connected to a reach, the initial elevation of the storage area was raised slightly for stability.

Manning's Roughness Coefficients

Manning's roughness coefficients were based on experience and calibration. Channel roughness coefficients varied from 0.045 to 0.060. Overbank roughness coefficients varied from 0.055 to 0.10. In many instances high overbank roughness coefficients were used to model ineffective flow rather than ineffective flow flags. A summary of the roughness coefficients is shown in **Table 3**.

Reach	Channel Roughness	Overbank Roughness
Pembina River	0.045 to 0.055	0.050 to 0.080
Tongue River	0.055	0.060
Rosebud Coulee	0.055 to 0.060	0.10
Louden Coulee	0.45	0.10
County Drain 42	0.050	0.080
County Drain 62	0.055	0.055
Hyde Park Coulee	0.45	0.065
North Red Dummy	0.055	0.10

Table 3: Summary of Manning's roughness coefficients.

Ineffective Flow and Levee Flags

Ineffective flow flags were used to model ineffective flow near bridges. Ineffective flow flags were sometimes used to model ineffective flow within oxbows or flow that is limited by other geographical constraints.

Levee flags were used on the Louden Coulee and Country Drain 42 reaches to prevent water from entering overbank areas below a certain elevation. If more detail was needed in this area, an alternative method would be to shorten the cross-sections to lie within the levees and use lateral structures and storage areas to represent the area behind the levee.

Model Calibration and Verification Events

The 2006 flood event was used to calibrate the model. Three flood events, 2009, 2011, and 2013, were used to verify the model results. The model was calibrated comparing stage and flow data from USGS gage 05100000 Pembina River at Neche, ND to simulated results and comparing the extent of simulated flooding with aerial photography.

Unsteady Flow Analysis Parameters

The same unsteady flow analysis parameters and model geometry were used for the calibration event and the verification events. The only change between the calibration event and the verification events were the inflow hydrographs and downstream stage boundary hydrographs. The model was run on a 4 or 6 minute time step using a theta value of 1. A theta value of 0.6 was also used with a shorter time step; however, it was found that the results did not measurably differ. The lateral structure stability factor and weir flow submergence decay exponent were raised to 3 for stability.

Stability and Errors

The model is stable for all events; however, small water surface errors occur within some storage areas and cross-sections for all simulations. Most of these errors are from storage areas with ditches where surface area does not vary much at lower elevations. Water surface errors within cross-sections are below 0.05 ft for all simulations.

2006 Flood Event (Calibration Event)

The 2006 flood event was used to calibrate the model. This flood event was caused by snowmelt and resulted in a peak discharge of 17,200 cfs measured at USGS gage 05099600 Pembina River at Walhalla, ND. This event coincided with a flood event along the Red River. **Figure 5** shows the simulated and observed elevation recorded at USGS gage 05100000 Pembina River at Neche, ND. Although the rising limb of the observed hydrograph is missing, the simulated hydrograph matches the general shape and peak. The rising limb is likely lower due to local inflows from snowmelt that were not included in the model.

Figure 5 also compares the calculated simulated total flow with the measured gage flow at the Neche gage. During major flood events, the USGS sums the breakout flows along State Highway 18 and County Highway 55 along with the measured flow within the channel. Simulated breakout flows passing through the storage area connections (denoted with a "G" prefix within the model) along Highway 18 and County Highway 55, along with flow passing through the County Drain 62/Highway 18 crossing, were summed to allow for comparison. The simulated and observed peaks generally match; however, the simulated flow is lower than the measured flow along the rising limb of the hydrograph. This is due to the localized snowmelt runoff that was not included in the simulation.

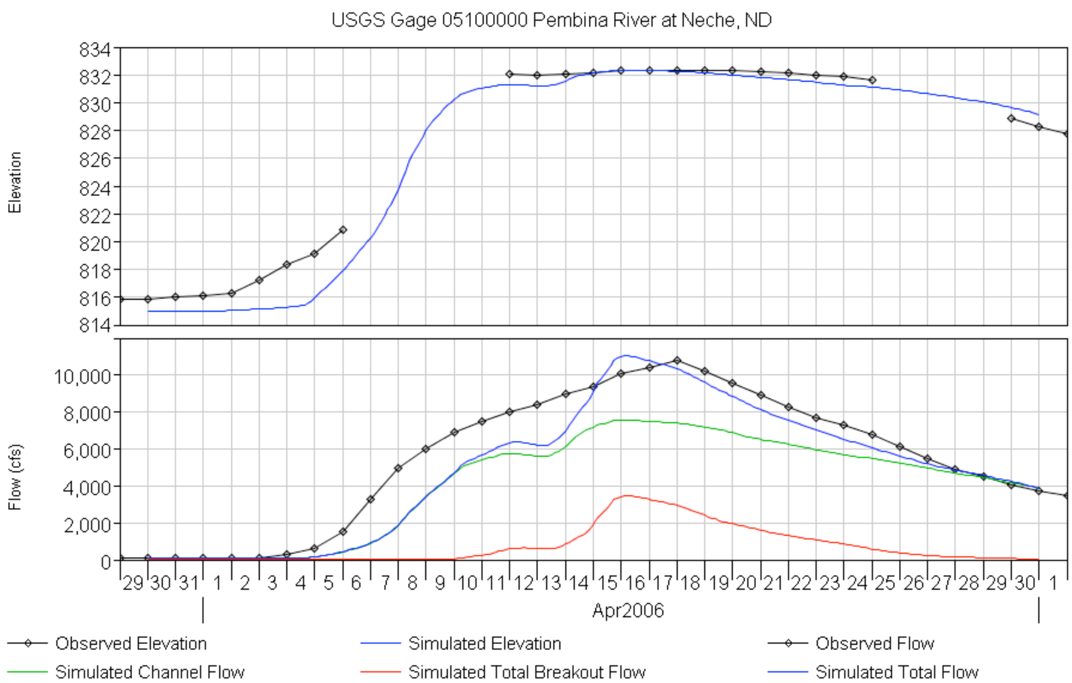

Figure 5: 2006 flood event simulated and observed stage and flow at USGS gage 05100000 Pembina River at Neche, ND.

Figure 6 shows the simulated flooded extent[1] overlying a mosaicked aerial photo collected by the SWC near the peak of the flood. Overall, the simulated flooding extent matched with the observed flooding extent. However, some areas do not match due to modeling 2D flow with storage areas, which uses level pool routing, specifically, the area south of County Drain 62 along the Canadian border within T164R63. The majority of that area appears to be inundated with sheet flow. This inundation cannot be simulated with storage areas.

[1] The simulated flood extent was calculated using RAS Mapper and the 2009 LiDAR data resampled to a 3-meter grid.

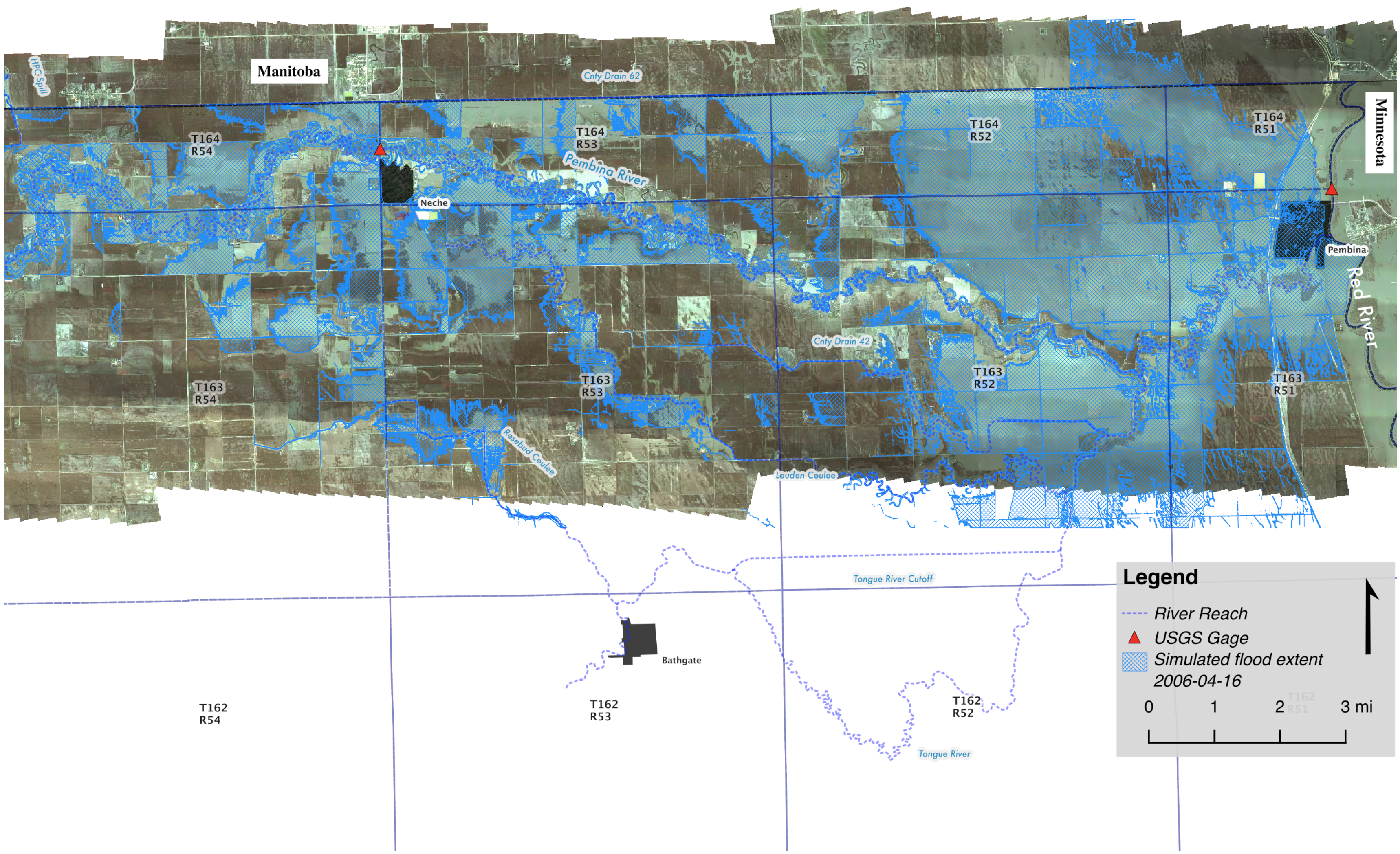

Figure 6: 2006 flood event simulated and observed flood extents. The aerial image was collected near the peak of the flood and the simulated flood extent of April 16, 2006 is shown.

Figure 7 shows the simulated flooded extent overlying a Landsat image collected on April 11, 2006. This image provides information about the rising limb of the flood event. Simulated flood extents from April 11 and April 13, two days after the image was collected, are also shown. The April 11 simulated flood extent is considerably less than the observed extent. The April 13 simulated flood extent compares better to the observed extent. This is likely due to localized inflows from snowmelt that were not included in the model.

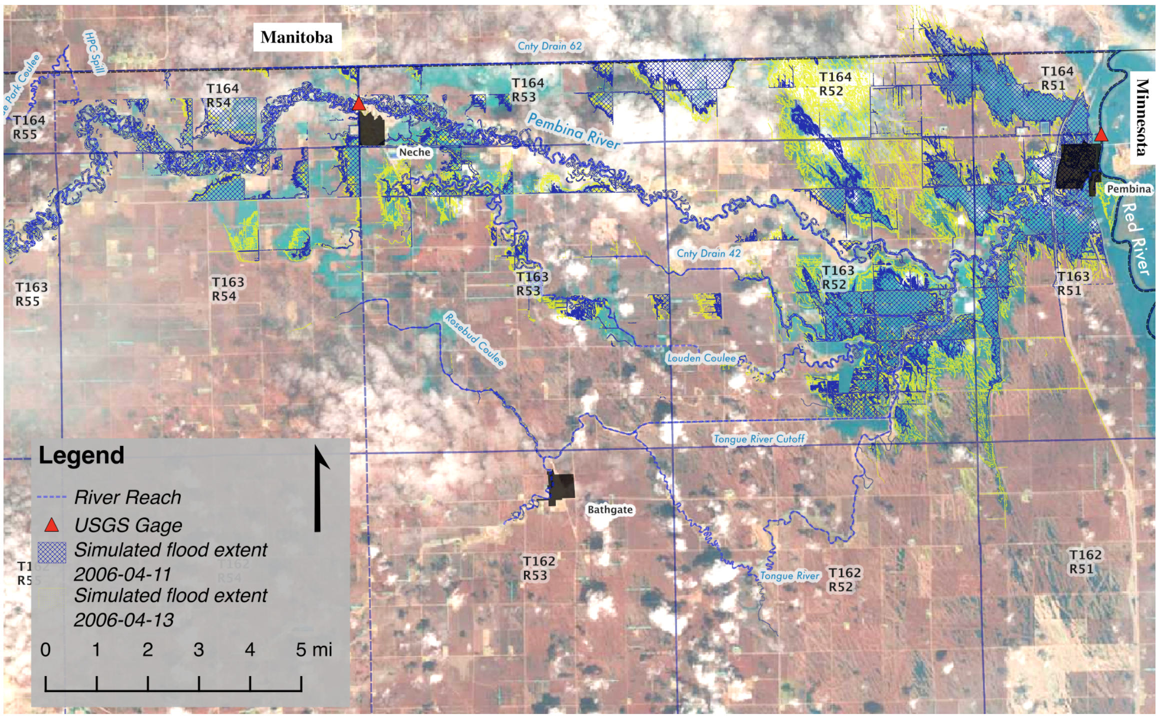

Figure 7: Simulated April 11, 2006 (blue) and April 13, 2006 (yellow) flood extents overlying an April 11, 2006 Landsat image. Landsat image courtesy of the USGS.

A Landsat image collected on April 27, 2006 and the simulated flood extent corresponding to that date are shown on **Figure 8**. This image provides information about the falling limb of the flood event. Generally the modeled flood extent corresponds with the observed extent, although it slightly overpredicts the inundation.

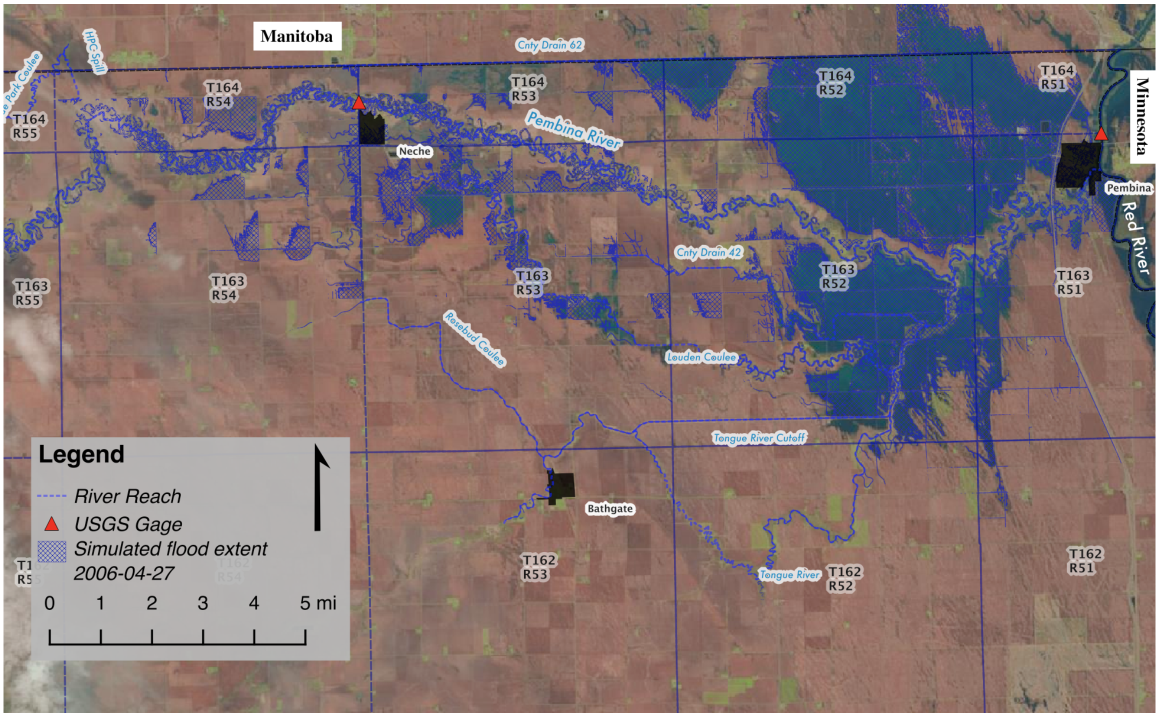

Figure 8: Simulated flood extents overlying an April 27, 2006 Landsat image.Landsat image courtesy of the USGS.

2009 Flood Event (Verification Event)

The 2009 flood event was also a snowmelt event that coincided with a flood event on the Red River. **Figure 9** shows the simulated and observed elevation recorded at USGS gage 05100000 Pembina River at Neche, ND. The simulated elevation reasonably matches the observed elevation.

Figure 9 also shows the simulated and measured total flow at the Neche gage. This event had two distinct flow peaks, and the model captured this. The model underpredicted the rising limb of the hydrograph and the peak flows, which is likely caused by local inflows from snowmelt which were not included in the model. The timing of the peaks were captured in the model, and overall the model simulated the measured flows at the gage.

Figure 10 shows the simulated flood extent and a Landsat image collected on April 27, 2009. The image is banded due to a broken sensor on the Landsat 7 satellite. This image was collected during the receding limb of the flood. Again the simulated flood extent matches with the observed extent; however, the model slightly overpredicts the extent.

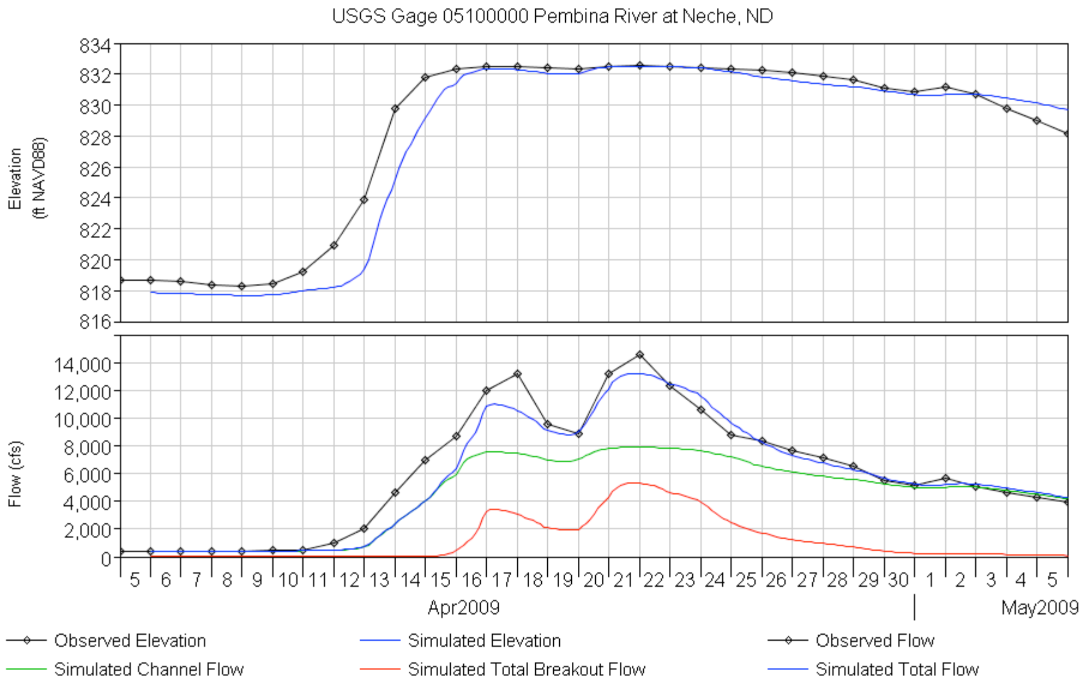

Figure 9: 2009 flood event simulated and observed stage and flow at USGS gage 05100000 Pembina River at Neche, ND.

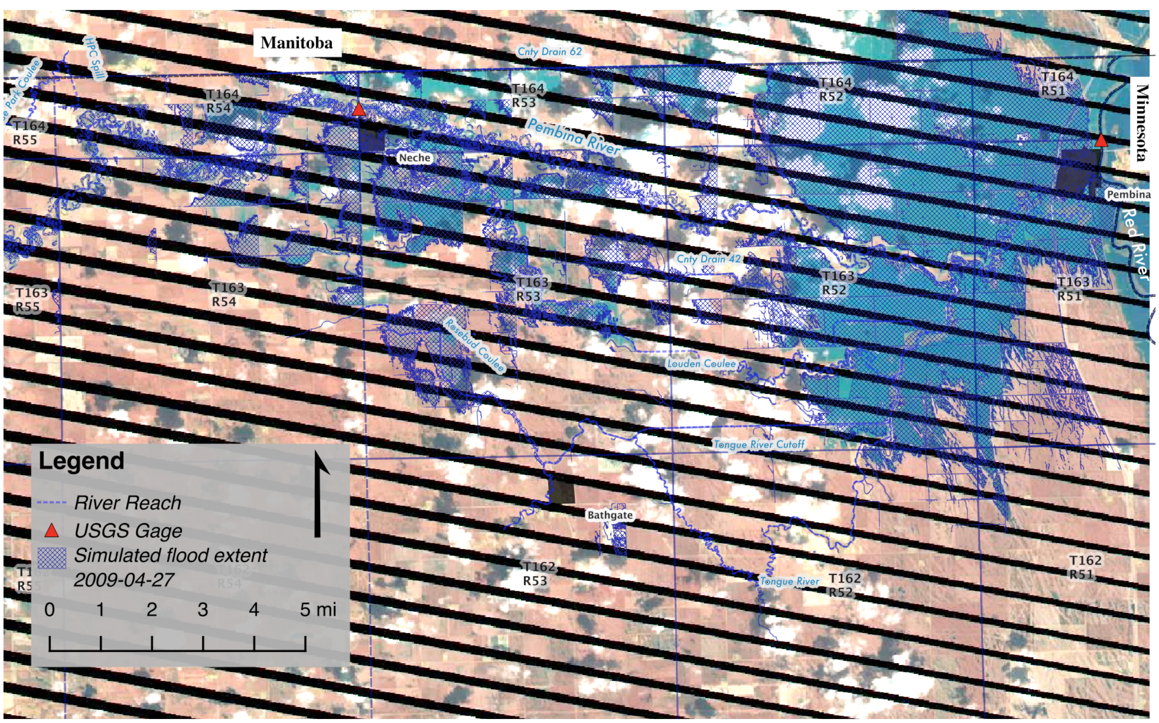

Figure 10: Simulated flood extents overlying an April 27, 2009 Landsat image. Landsat image courtesy of the USGS.

2011 Flood Event (Verification Event)

The 2011 flood event was a snowmelt event that coincided again with a flood event on the Red River. **Figure 11** shows the simulated and observed elevation recorded at USGS gage 05100000 Pembina River at Neche, ND. Although there is some missing stage data, the simulated elevation matches the observed elevation near the peak.

Figure 11 also shows the simulated and measured total flow at the Neche gage. Again, this event had two distinct flow peaks, and the model captured this. The model underpredicted flows during the rising limb of the hydrograph, likely due to localized runoff that was not modeled. Overall the model matches the measured flows.

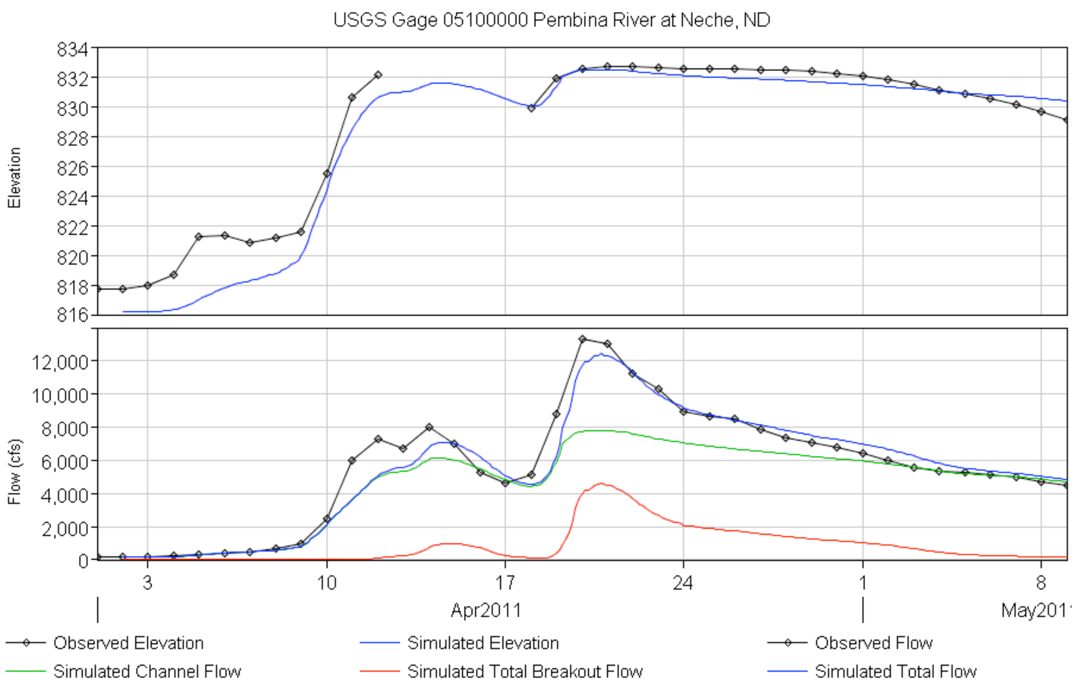

Figure 11: 2011 flood event simulated and observed stage and flow at USGS gage 05100000 Pembina River at Neche, ND.

Figure 12 shows simulated flood extents overlying a Landsat image collected on April 25, 2011. This image was collected during the receding limb of the flood. The simulated flood extent generally matches the observed extent, although the headwaters of Rosebud Coulee show inundation that was not observed. This is due to natural levees that are modeled using ineffective flow flags rather than levee flags or storage areas.

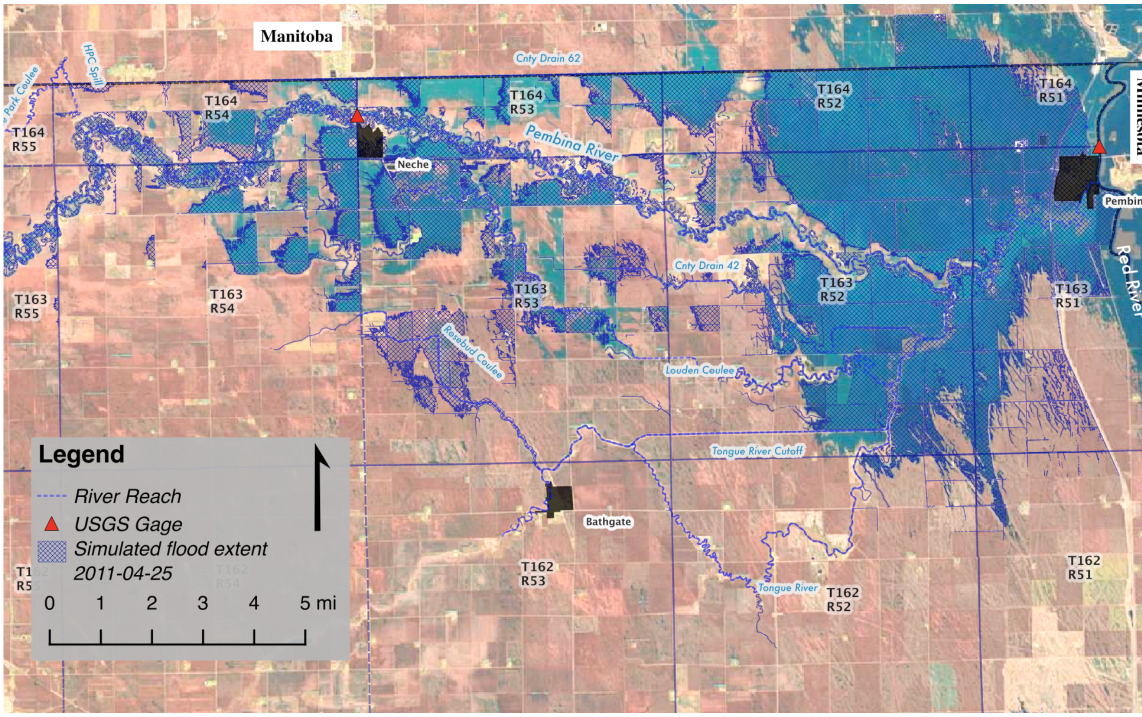

Figure 12: Simulated flood extents overlying an April 25, 2011 Landsat image. Landsat image courtesy of the USGS.

2013 Flood Event (Verification Event)

The 2013 flood event is the flood of record at the Neche gage and differs from other events because it was caused by rainfall. Heavy snowpack melted gradually during April, reducing storage capacity in the soil, and was followed by heavy rainfall during May. Also, the Red River was not flooding, so there was no backwater from the Red River affecting the Pembina River.

Simulated and observed elevations recorded at USGS gage 05100000 Pembina River at Neche, ND are shown in **Figure 13**. The first peak occurring on May 2nd was caused by snowmelt, and the second peak was caused from heavy rainfall. Over two days 6 inches or more of rain fell over a large area along the Cavalier and Pembina County border. The simulated elevation matches reasonably the rainfall elevation peak.

The simulated and measured total flow recorded at USGS gage 05100000 Pembina River at Neche, ND is also shown in **Figure 13**. The model generally matches the rainfall peak occurring around May 23rd; however, the snowmelt peak was underpredicted.

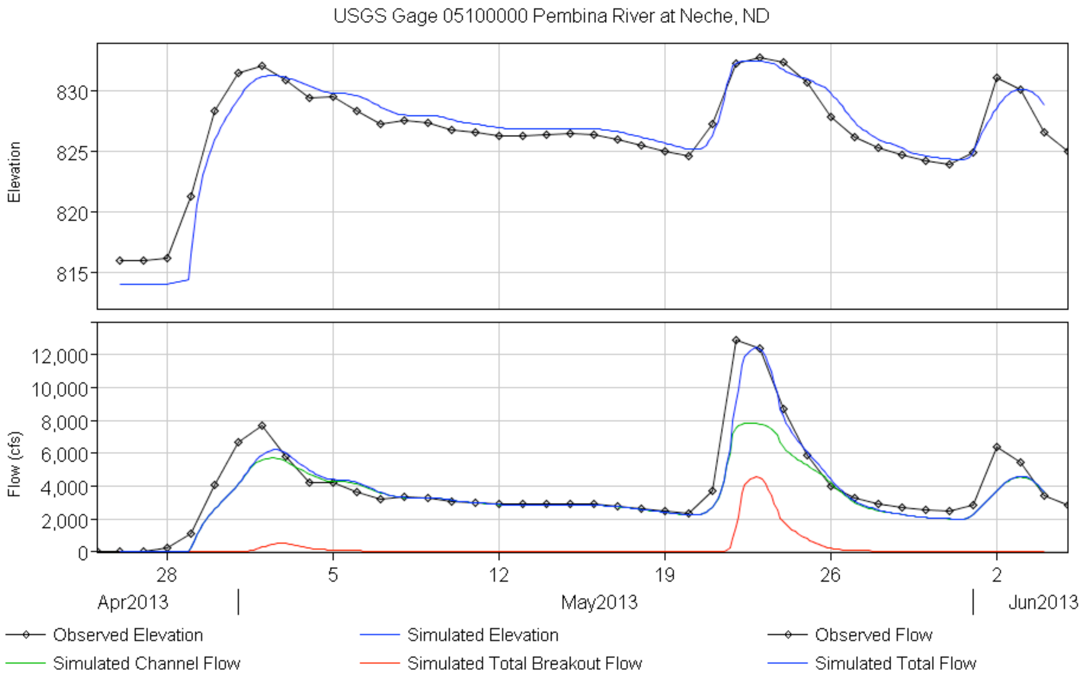

Figure 13: 2013 flood event simulated and observed stage and flow at USGS gage 05100000 Pembina River at Neche, ND.

Simulated flood extents overlying a Landsat image collected on May 23, 2013 are shown in **Figure 14**. This image was collected near the peak of the flood. The modeled extents generally matched the observed extents with the exception of the area near the Tongue River confluence. It is likely that localized runoff caused a larger area of inundation than what was modeled. Flow from USGS gage 05101000 Tongue River at Akra, ND was used for the upstream boundary condition for the modeled Tongue River reach, which is located over 15 miles upstream of the modeled extents. This ungaged area received a considerable amount of rainfall that was not represented in the model.

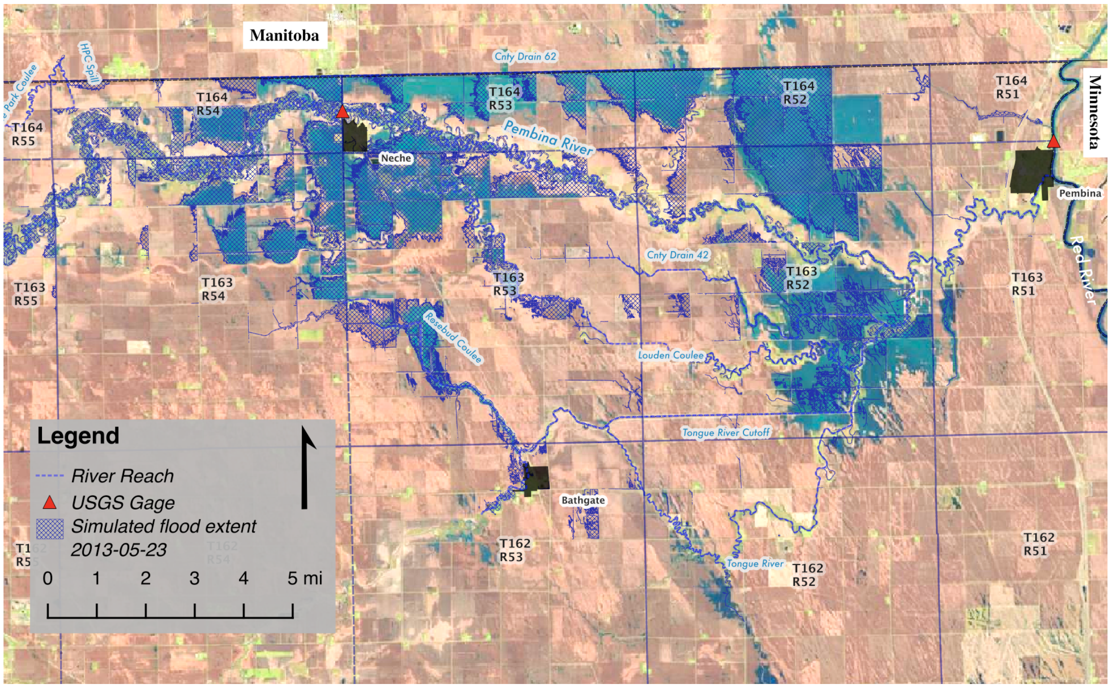

Figure 14: Simulated flood extents overlying a May 23, 2013 Landsat image. Landsat image courtesy of the USGS.

Summary of Events

Table 4 summarizes the comparison of the calibration and verification peak elevations and flows to those measured at the Neche gage for each event. The model reasonably simulated the peak elevations and flows. The simulated elevations were within 0.25 ft of the measured peak elevations. The simulated peak flows were within 10 percent of the measured flows. The timing of the simulated peak stages generally matched the observed peak stages considering daily averaged peak data was used.

Event	Observed Peak Elevation, ft NAVD88	Simulated Peak Elevation, ft NAVD88	Diff., ft	Observed Peak Flow, cfs	Simulated Peak Flow, cfs	Diff., cfs	Peak Elevation Timing Diff., days
Calibration 2006	832.35	832.35	0.00	10,800	11,050	-250	1.90
Verification 2009	832.53	832.52	-0.01	14,600	13,225	1,375	0.13
Verification 2011	832.65	832.47	-0.18	13,300	12,460	840	0.38
Verification 2014	832.74	832.49	-0.25	12,900	12,440	460	0.25

Table 4: Summary of simulated and measured peak elevations and flows at USGS gage 05100000 Pembina River at Neche, ND.

Conclusion and Future Improvements

The SWC has completed a model of the Pembina River from Walhalla, ND to its confluence with the Red River of the North as part of an agreement with the USACE. The purpose of the model is to provide insight on regional flooding problems along the Pembina River within the Red River Valley and to provide inflow hydrographs for a larger Red River of the North hydraulic model developed by the USACE.

The model has been calibrated, and the results have been verified using multiple events. The model reasonably predicts stages and flows at Neche, ND and flooding extents for large flood events. This model was not intended for detailed work such as FEMA flood insurance studies or USACE levee certification.

Although this model provides a good foundation and general understanding of the hydraulics along the Pembina River, further improvements are recommended to increase its utility. Suggested future improvements include the following:

- Extending the modeled portion of the Tongue River up to USGS gage 05101000 Tongue River at Akra, ND.
- Extending the model into Canada.
- Incorporating 2D flow into the model.
- Refining the geometry of Louden Coulee, County Drain 42, Rosebud Coulee, and the Tongue River.

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