HH6: Souris River Plan of Study
HEC-ResSim Model Report

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Plates

Plate I – Souris River Basin Map

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Appendix A – *1989 Agreement Between the Government of Canada and the Government of the United States of America for Water Supply and Flood Control in the Souris River Basin (Annex A and Annex B)*

Appendix B – 2000 Amendment to *Annex B*

Appendix C – ResSim Flood and guide curve state variable documentation

Appendix D – ResSim Apportionment state variable documentation

Appendix E – Relations between Gross Evaporation and Potential Evapotranspiration in Rafferty, Boundary, and Grant Devine Reservoir

Appendix F – Souris River Plan of Study ResSim Model Stochastic Setup

Appendix G – Souris River Plan of Study ResSim Model Stochastic Setup – Jython Script

Workplan Summary

The Souris River Plan of Study is divided into components according to the work plan below.

DW4	Performance Indicators
HH1	Regional and Reconstructed Hydrology
HH2	Stochastic Hydrology
HH4	Forecasting
HH5	Climate Change
HH6	HEC-ResSim Reservoir Modeling (This Report)
HH7	HEC-RAS Hydraulic Modeling
HH8	HEC-PRM Development (not pursued)
HH9	Model Integration
HH10	Forecasting
PF1	Workshops

PF2	Modeling
PF3	Dam Safety Alternatives simulation

Acronyms and Abbreviations

AEP	Annual exceedance probability
CA	Canada
DSS	Data Storage System
ECCC	Environment and Climate Change Canada
FSL	Full Supply Level
GUI	Graphical User Interface
HEC	Hydrologic Engineering Center
IJC	International Joint Commission
ISRB	International Souris River Board
LiDAR	Light Detection and Ranging
PoS	Plan of Study
NDSWC	North Dakota State Water Commission
NRCS	Natural Resources Conservation Service
NWR	National Wildlife Refuge
NWS	National Weather Service
ResSim	Reservoir simulation software
US	United States
USACE	United States Army Corps of Engineers
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WSA	Saskatchewan Water Security Agency

Common Unit Abbreviations

ft^3/s	cubic feet per second
m^3/s	cubic meters per second
dam^3	cubic decameter
ac-ft	acre feet
ft	feet
m	meter
km	kilometer
mi	miles
in	inches
mm	millimeter

1. Introduction

A HEC-ResSim (version 3.3) model that simulates current operation of Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake (formerly Alameda Reservoir), and Lake Darling was developed for the Souris River Plan of Study task HH6: Reservoir Flow Release Plan (ISRB, 2018b). The model is based on previous ResSim models developed to support the Regional and Reconstructed Hydrology (HH1) dataset as part of the Plan of Study (USACE, 2013; ISRB, 2019) and an ongoing *USACE Flood Risk Reduction Feasibility Study* for the Souris River Basin (USACE, 2017). The model extends from the upstream end of the Canadian Reservoirs downstream through Westhope, ND. The model also includes a portion of the Des Lacs River from Foxholm, ND to its confluence with the Souris River at Burlington, ND. This report describes the model development, logic, assumptions, and verification of results.

The reservoirs operate as a system which is outlined within *Annexes A* and *B* of a *1989 Agreement* between the United States and Canada (Canada and USA, 1989). Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake, and Lake Darling collectively comprise the Souris River Project. Reservoir operations for high flows are described in Appendix A. *Annex B* describes water supply operations and was amended in 2000 (Canada and USA, 2000). *Annex B* outlines the water apportionment agreement between the United States and Canada. Changes to *Annex B* are described in Appendix B. The objective of the Souris River PoS is to evaluate the operation of the reservoir system and make potential recommendations for improvement.

The Souris River Project is complex and includes a diversion which transfers water by gravity from Boundary Reservoir to Rafferty Reservoir. There is also a separate pipeline which can pump water from Rafferty Reservoir to Boundary Reservoir. Additionally, operation of the Canadian reservoir system and Lake Darling is coordinated between two Federal governments, one state government, and two provincial governments and their respective water management agencies. The operation of Boundary Reservoir, Rafferty Reservoir, and Grant Devine Lake is based on the operating rules prescribed by *Annexes A* and *B*, the physical limitations of their outlet works, local flood control constraints, and prescribed water supply operations. The operation of Lake Darling is restricted by the guidelines prescribed by Annex*es* A and *B*, the physical limitations of its outlet works, the operating rules described in the USACE Lake Darling Water Control Manual (USACE, 2012), and prescribed water supply operations.

The primary objective of Annex A is to provide flood protection at Minot, North Dakota. Operators at Rafferty Reservoir, Grant Devine Lake, Boundary Reservoir, and Lake Darling reservoir attempt to meet the following operating objectives prescribed by *Annex A*:

1. Provide flood protection at Minot, North Dakota up to 5,000 ft^3/s (141.6 m^3/s)
2. Provide flood protection to urban and rural areas downstream of Rafferty Dam, Grant Devine Dam, and Lake Darling Dam
3. Ensure to the extent possible that the existing benefits from the supply of water in the Souris River basin and the supply of water to the Souris Basin Project (Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake, and Lake Darling) are not compromised

The objective of the ResSim model is to simulate reservoir operations and hydrologic routing to a degree of detail that is sufficient to reasonably compare existing operations as stated by the *1989 Agreement* with operating plan alternatives proposed as part of the PoS.

2 Reservoir System Background

2.1 Major Hydraulic Structures

Construction of Lake Darling Dam was completed in 1936. Lake Darling is located on the Souris River near the Ward-Renville County Line. Originally, its primary purpose was to provide water to support fish and waterfowl habitat at the J. Clark Salyer Wildlife Refuge (Salyer) located 177 km (110 mi) downstream, south of the international boundary near Westhope, ND. The lake was designed to hold a two year water supply for the J. Clark Salyer Wildlife Refuge.

Between 1994 and 1998, Lake Darling underwent a major rehabilitation that altered its flood control capacity. Lake Darling Dam was raised one half foot and a gated spillway was installed to replace the uncontrolled spillway and emergency spillway as part of the Souris River Project. Lake Darling Dam is operated by the USFWS during periods of low to moderate flows. During flood conditions, as defined in the *1989 Agreement*, Lake Darling Dam is operated by the USACE.

The 1998 Lake Darling Reservoir Water Control Manual indicates that modifications to the dam increased its top of dam elevation to 489.66 m NGVD 29 (1606.50 ft). As-Built construction drawings completed after the modifications to the Dam were finished, dated from 1998, show that sections of the dam embankment range from 489.61 m (1606.33 ft) to 489.66 m (1606.50 ft). Recent LiDAR measurement data for the area indicates that sections of the embankment are at elevation 489.51 m (1606.00 ft). To be conservative, a top of dam elevation of 489.51 m (1606.00 ft) was used in the ResSim model.

Construction of Boundary Damon Long Creek near Estevan, SK began in 1956 and was completed in 1958. Boundary Dam and Reservoir are owned and operated by SaskPower with operational guidance provided by WSA during declared flood events. The primary purpose of Boundary Reservoir is to provide cooling water for the nearby Boundary Dam Power Station. Modifications to the dam were completed in 2010. Prior to the rehabilitation effort the full capacity of the main spillway gates could not be utilized and operation relied heavily on use of the diversion channel. The original spillway structure was designed for a discharge of 425 m^3/s (15,000 ft^3/s) at a reservoir elevation of 560.9 m (1840.22 ft). The original spillway was also designed to pass the 1956 estimate of the PMF flood, 850 m^3/s (30,000 ft^3/s) at elevation 562.7 m (1846.13 ft), with limited damage to the structure (McPhail et al. 2010).

A dam safety review of Boundary Dam was completed in 2005 which identified deficiencies with insufficient spillway capacity of the main spillway and the condition of the spillway structure. A construction project to upgrade the gated spillway at Boundary Reservoir began in 2008 and was completed in 2010 to correct noted deficiencies with the spillway (McPhail et al. 2010). The final safe discharge capacity of the outlet works is 1,220 m^3/s (43,000 ft^3/s) which is slightly below the current PMF magnitude of 1,330 m^3/s (47,000 ft^3/s). As a result of the

rehabilitation work, SaskPower now relies primarily on the main spillway when making flood control releases.

A series of floods during the 1970s and growing energy development in Saskatchewan spurred the improvement of existing structures and the construction of new water management structures within the Souris River Basin. Specifically, the development of Shand Power Station at Estevan, SK resulted in a need for additional cooling water. The current water management system, consisting of Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake, and Lake Darling is known as the Souris River Project. The United States was interested in additional flood protection for Minot, ND (Minot) and surrounding areas and Saskatchewan was interested in additional water supply for its growing energy industry near Estevan. The United States purchased additional flood control storage in Rafferty Reservoir and Grant Devine Lake from Canada by funding the additional cost associated with constructing larger, dual purpose structures instead of smaller reservoirs intended solely for water supply.

Rafferty Reservoir is the largest reservoir in the system and was constructed on the Souris River near Estevan, SK in 1992 to provide flood control and water supply benefits. Rafferty Reservoir is managed by the Saskatchewan WSA. Boundary Reservoir was modified in 1993 so that Rafferty Reservoir can receive water from Boundary Reservoir via an open channel diversion (Boundary Diversion Channel) and send water to Boundary Reservoir by pumping it through a pipeline (Rafferty Pipeline).

After the construction of the Boundary to Rafferty Diversion Channel was completed, the added storage gained by Boundary's prescribed pre-flood drawdown from the *1989 Agreement* is now usually obtained by carrying out additional drawdown at Rafferty Reservoir. If the forecasted inflow to Rafferty Reservoir already requires Rafferty to be drawdown to its maximum allowable drawdown elevation, Boundary Reservoir is drawdown. This only occurs under rare circumstances.

In order to operate the Boundary diversion channel, there must be excess storage capacity available in Rafferty Reservoir to store the amount of water diverted. In the past, WSA would divert flow from Boundary Reservoir into Rafferty even if Rafferty was above its FSL elevation to have a single release point on the mainstem of the Souris River. The WSA no longer makes releases through the Boundary to Rafferty diversion channel unless there is a water management need. If Rafferty Reservoir is above the FSL of 550.5 m (1806.10 ft) flow is not diverted from Boundary Reservoir to Rafferty Reservoir via the diversion channel. If Rafferty Reservoir is below its FSL of 550.5 m (1806.10 ft) Boundary Reservoir will divert up to 45 m^3/s (1,590 ft^3/s) to Rafferty Reservoir. Any additional required releases from Boundary Reservoir above the 45 m^3/s (1,590 ft^3/s) limit would be discharged through the main gates of Boundary Dam.

Grant Devine Lake is located on Moose Mountain Creek near Alameda, SK. Grant Devine Lake started filling in 1992. Until 1997, storage in the reservoir pool was restricted by litigation. In 1993 SaskWater, a predecessor to the WSA, (Crown Corporation) worked out a temporary agreement to limit the Full Supply level to 552.14 m (1811.02 ft). SaskWater reached a final settlement in 1997 and the pool filled to its full supply level of 562.00 m (1843.83 ft) for the first

time in 1999. Grant Devine Lake is operated by the WSA to meet flood control and water supply objectives. The reservoir is typically used to fulfill Saskatchewan's apportionment obligation outlined in *Annex B*. Generally, during dry years, Saskatchewan must deliver a minimum of 50 percent of the natural flow to the Sherwood, ND border crossing (Sherwood), and during wet years Saskatchewan must deliver a minimum of 40 percent of the natural flow to Sherwood.

As outlined in *Annex A*, by February 1st, Rafferty Reservoir, Grant Devine Lake, and Lake Darling are drawdown to set elevations to provide for flood control storage. From February 1st until snowmelt begins, an additional drawdown may be required based on the snowmelt forecast. Downstream maximum flow targets at Sherwood and Minot are also set based on the snowmelt forecast. After the spring snowmelt, the reservoirs return to water supply operation. Currently, there is minimal guidance on flood operations caused by rainfall driven events. ***Table 1*** summarizes important reservoir elevations and storage levels.

Table 1 Summary of important reservoir elevations and storage levels.

	Rafferty Reservoir	Boundary Reservoir	Grant Devine Lake	Lake Darling
Top of Dam Elevation	555.70 m (1823.16 ft)	563.88 m (1850.00 ft)	568.50 m (1865.15 ft)	489.51 m (1606.00 ft)
Length at Top of Dam	1,299.97 m (4,265.00 ft)	334.98 m (1,099 ft)	1,250.00 m (4,101.05 ft)	1,158.24 m (3,800.00 ft)
Maximum Allowable Flood Level	554.000 m (1817.59 ft)	Equivalent to Full Supply	567.000 m (1860.24 ft)	487.985 m (1601.00 ft)
Storage	632,776 dam³ (513,000 ac-ft)	Equivalent to Full Supply	189,600 dam³ (153,711 ac-ft)	190,386 dam³ (154,348 ac-ft)
Full Supply Level	550.500 m (1806.10 ft)	560.832 m (1840.0 ft)	562.000 m (1843.83 ft)	486.766 m (1597.00 ft)
Storage	439,613 dam³ (356,400 ac-ft)	57,884 dam³ (46,927 ac-ft)	105,500 dam³ (85,530 ac-ft)	135,329 dam³ (109,713 ac-ft)
Surface Area	4,881 ha (12,061 ac)	569 ha (1,406 ac)	1,240 ha (3,061 ac)	4,400 ha (10,158 ac)
Normal Drawdown Level	549.500 m (1802.82 ft)	NA	561.000 m (1840.55 ft)	486.461 m (1596.00 ft)

Storage	392,371 dam³ (318,100 ac-ft)	NA	94,245 dam³ (76,406 ac-ft)	122,896 dam³ (99,633 ac-ft)
Maximum Required Drawdown Level	547.500 m (1796.26 ft)	557.784 m (1830.00 ft)	555.850 m (1823.65 ft)	484.937 m (1591.00 ft)
Storage	305,287 dam³ (247,500 ac-ft)	41,904 dam³ (33,972 ac-ft)	50,700 dam³ (41,103 ac-ft)	67,262 dam³ (54,530 ac-ft)
Minimum Supply Level	537.500 m (1763.45 ft)	553.212 m (1815.00 ft)	555.850 m (1823.65 ft)	480.670 m (1577.00 ft)
Storage	13,000 dam³ (10,539 ac-ft)	22,940 dam³ (18,598 ac-ft)	50,700 dam³ (41,103 ac-ft)	178 dam³ (144 ac-ft)
Total Flood Control Storage	327,489 dam³ (265,500 ac-ft)	15,980 dam³ (12,955 ac-ft)	138,900 dam³ (112,608 ac-ft)	123,124 dam³ (99,818 ac-ft)
Vertical Datum	CGVD28	CGVD28	CGVD28	NGVD29

2.2 National Wildlife Refuge Structures

In addition to Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake, and Lake Darling there are several hydraulic structures located in the two U.S. NWR within the study area. The Des Lacs NWR extends from the Canadian border to 12.87 km (8 mi) south of Kenmare, ND. The refuge includes 2,305 hectares (5,695 acres) of open water and 142 hectares (350 acres) of emergent marsh along a 45 km (28 mi) reach of the Des Lacs River. Dikes were constructed in the 1932 to create eight impoundments. The upstream extent of this analysis is just downstream of the National Wildlife Structures on the Des Lacs River. The effects of the Des Lacs NWR structures are modeled implicitly by using observed streamflow data collected downstream of the refuges as a model input.

The second U.S. National Wildlife Refuge is the J. Clark Salyer National Wildlife Refuge. The J. Clark Salyer NWR extends from the Canadian border near Westhope, ND south for about 80.46 km (50 mi) along the Souris River in Bottineau and McHenry counties, North Dakota. The refuge includes 95.20 km^2 (23,525 acres) of impounded riverine marshes and 10 km^2 (2,474 acres) of river, oxbows, and prairie marshes. The watershed contributing to the refuge covers about 23,310 km^2 (9,000 mi^2), of which approximately 40% contributes runoff to the river. In the 1930s, levees were constructed across the Souris River floodplain to retain water in five major impoundments. During the 1950s modifications were made to the structures to improve

wetland management. , In 1991-1992, the heights of the levees were increased once more as part of the Souris River Flood Control Project. Each dike is equipped with control structures to enable management of water levels. The J. Clark Salyer NWR structures are explicitly modeled as part of this study.

2.3 Vertical Datum

The *1989 Agreement* uses the Canadian Geodetic Vertical Datum of 1928 (CGVD 28) to specify elevations for the Canadian reservoirs (Rafferty Reservoir, Boundary Reservoir, and Grant Devine Lake) and the National Geodetic Vertical Datum of 1929 (NGVD 29) for the U.S. Reservoir (Lake Darling). Even though, the new reference standard for heights across Canada is the released Canadian Geodetic Vertical Datum of 2013 the CGVD 28 is still being utilized for the reservoirs in the basin. The transition to the new vertical datum is expected to start in the next few years.

A general formula for a conversion from the NGVD 29 datum to the NAVD 88 datum is shown below. A conversion factor of 0.352 m (1.12 ft) is applicable at the center of Lake Darling. A conversion factor of 0.378 m (1.24 ft) is applicable at the face of the Lake Darling Dam.

Equation 1 Approximate Conversion from NGVD 29 vertical datum to NAVD 88 vertical datum

$$[\text{NAVD 88 Elevation}] = [\text{NGVD 29 Elevation}] + [\text{Site Specific Conversion Factor}]$$

For Saskatchewan, an approximate conversion factor of 0.494 m (1.62 ft) is applicable at the international border and an approximate conversion factor of 0.530 m (1.74 ft) is applicable over the study area (Barr Engineering Company, 2018). Equation 2 shows how these conversion factors could be applied to estimate the NAVD 88 elevation for a given CGVD 28 elevation.

Equation 2 Approximate Conversion from CGVD 28 vertical datum to NAVD 88 vertical datum

$$[\text{NAVD 88 Elevation}] = [\text{CGVD 28 Elevation}] + [\text{Site Specific Conversion Factor}]$$

This Plan of Study is conducted at the request of the IJC which is made up of representatives from the United States Government and Canadian Government. To be consistent with elevation information represented in the *1989 Agreement* and to meet the needs of the IJC, the CGVD 28 datum is used in this study as the reference vertical datum for the Canadian reservoirs and the NGVD 29 datum is used as the reference vertical datum for the U.S. reservoirs.

The purpose of the conversion factors presented in this report is to identify the typical difference between the vertical control datums used in this study and the NAVD 88 datum. A separate analysis would be required to develop site specific, design level conversion factors between the NGVD 29 and NAVD 88 vertical datums and the CGVD 28 and NAVD 88 vertical datums.

3 Model Setup

A diagram displaying the setup of the ResSim model is displayed in ***Figure 1***. An overview of the basin is shown in Plate 1. The model extends from the Canadian reservoirs to the international

border crossing near Westhope, ND. The model was developed using HEC-ResSim version 3.3 with imperial units and runs on a daily time step. The model network consists of the four major reservoirs (Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake, and Lake Darling), two major diversions (Boundary Diversion Channel, Rafferty Pipeline), the five Salyer impoundments (Pool 320, Pool 326, Pool 332, Pool 341, and Pool 357), and a number of routing reaches.

Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake and Lake Darling are modeled to reflect the operating guidelines prescribed by *Annex A* and *Annex B* outlined in the *1989 Agreement*, as well as the Lake Darling Water Control Manual, historical operations and operating guidelines submitted by the Saskatchewan WSA, SaskPower, the U.S Fish and Wildlife Service and the USACE. Hydrologic routing reaches link the reservoirs to downstream points of interest. To capture flood wave timing and attenuation through the Salyer refuge structures, the Salyer impoundments are explicitly modeled. However, there is a limited amount of information available related to how the Salyer refuge is operated, thus the refuge structures are only coarsely modeled. A detailed description of how the Salyer structures are modeled can be found in the *2013 Regional and Reconstructed Hydrology Report* (USACE, 2013).

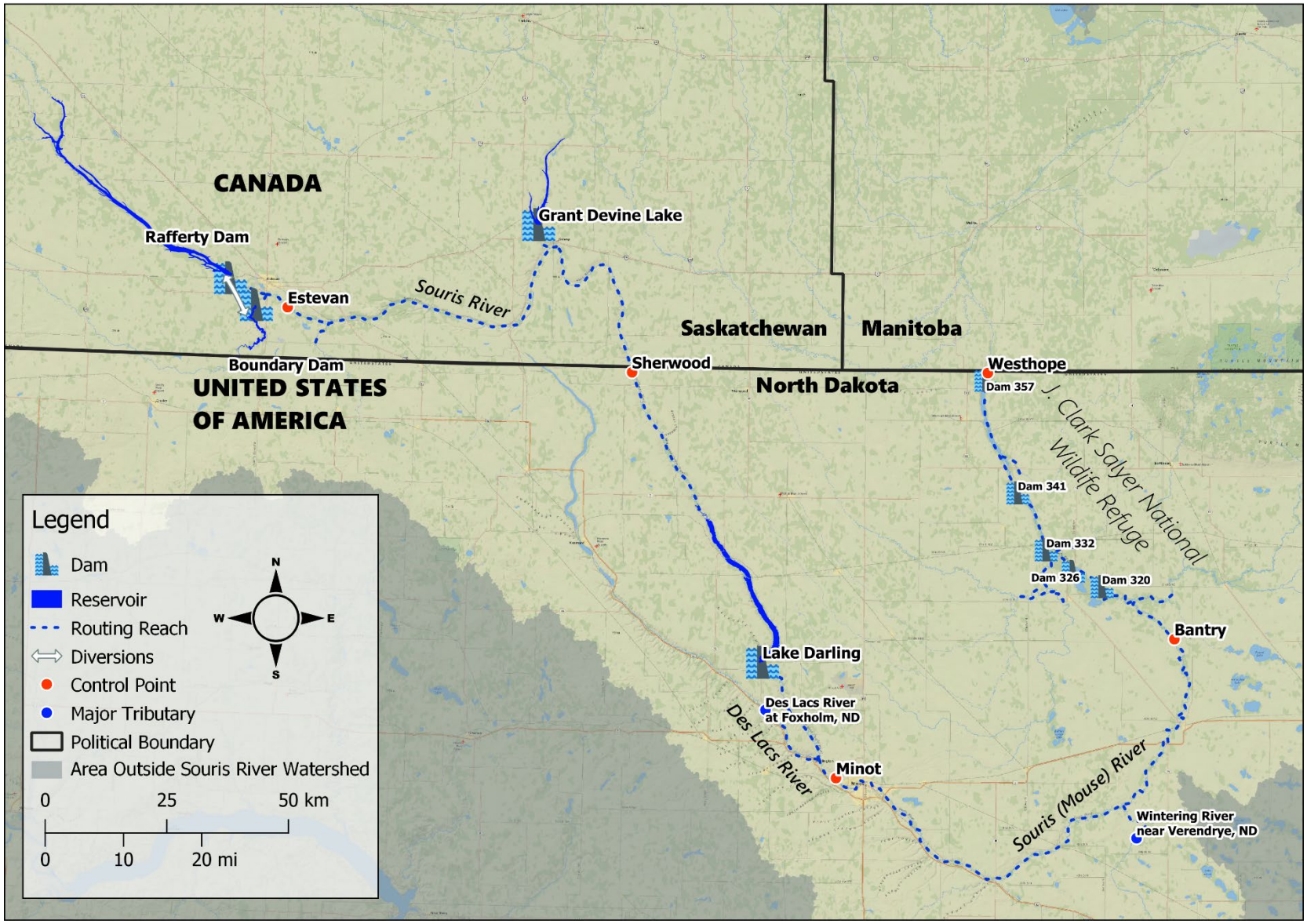


Figure 1 ResSim model schematic.

3.1 Reservoir Physical Data – Major Structures

ResSim requires relationships describing the physical characteristics of the reservoir including elevation-area-storage relationships, top of dam characteristics, and maximum outlet capacity curves. The ResSim model also requires inputs describing certain physical processes which result in significant losses from the reservoir overtime. Evaporation, direct precipitation, and seepage losses are taken into consideration and explicitly modeled where assumed to be significant.

3.1.1 Storage, area, and elevation relationships

The elevation-area-storage relationships adopted for Rafferty Reservoir and Grant Devine Lake are displayed in ***Table 2*** and ***Table 3***, respectively. Data for Rafferty Reservoir and Grant Devine Lake are adopted from Tables 3.2 and 3.4 within *Annex A* of the *1989 Agreement*.

Table 2 Rafferty Elevation-Area-Storage Data (CGVD28)

Elevation, meters	Elevation, feet	Storage, dam^3	Storage, acre-feet	Area, hectares	Area, acres
535	1755.25	0	0	0	0
537	1761.81	4,737	3,840	807	1,994
538	1765.09	16,159	13,100	1,464	3,618
540	1771.65	56,370	45,700	2,495	6,165
545	1788.06	209,075	169,500	3,574	8,831
546	1791.34	245,833	199,300	3,795	9,378
547	1794.62	284,811	230,900	4,022	9,938
547.5	1796.26	305,287	247,500	4,134	10,215
549	1801.18	369,674	299,700	4,480	11,070
549.5	1802.82	392,371	318,100	4,599	11,364
550	1804.46	416,547	337,700	4,719	11,661
550.5	1806.1	439,613	356,400	4,881	12,061
551	1807.74	464,406	376,500	5,045	12,466
551.5	1809.38	490,062	397,300	5,212	12,879
552	1811.02	516,582	418,800	5,407	13,361
552.5	1812.66	543,965	441,000	5,605	13,850
553	1814.3	572,459	464,100	5,807	14,349
553.5	1815.94	602,062	488,100	6,012	14,856
554	1817.59	632,776	513,000	6,222	15,375
555	1820.87	697,041	565,100	6,651	16,435

Table 3 Grant Devine Lake Elevation-Area-Storage Data (CGVD28)

Elevation, meters	Elevation, feet	Storage, dam^3	Storage, acre-feet	Area, hectares	Area, acres
528	1732.28	0	0	0	0
530	1738.84	110	90	11	27
532	1745.41	490	400	27	67
534	1751.97	1,170	950	41	101
536	1758.53	2,160	1,750	58	143
538	1765.09	3,500	2,840	77	190
540	1771.65	5,200	4,215	93	230
542	1778.21	7,370	5,975	124	306
544	1784.78	10,170	8,245	156	385
546	1791.34	13,700	11,110	200	494
548	1797.90	18,260	14,805	253	625
550	1804.46	23,970	19,430	318	785
552	1811.02	31,000	25,130	386	953
554	1817.59	39,800	32,265	495	1,222
555.85	1823.65	50,700	41,100	624	1,540
556	1824.15	51,100	41,425	635	1,567
558	1830.71	65,160	52,825	770	1,900
560	1837.27	82,990	67,280	1,010	2,493
561	1840.55	94,245	76,400	1,125	2,777
562	1843.83	105,500	85,530	1,240	3,061
564	1850.39	133,200	107,990	1,520	3,752
566	1856.96	167,800	136,040	1,940	4,789
567	1860.24	189,600	153,710	2,180	5,381
568	1863.52	211,400	171,385	2,420	5,974
569	1866.80	236,800	191,980	2,660	6,566

Boundary Reservoir and Lake Darling elevation-area-storage relationships have been recently updated with LiDAR information. The resulting curves indicate a five percent reduction in the available flood storage in both Boundary Reservoir and Lake Darling.

WSA and SaskPower provided updated curves for Boundary Reservoir based on LiDAR data collected in 2011. The 2011 LiDAR information had a vertical accuracy of 0.30 m (0.98 ft) and a horizontal accuracy of 0.45 m (1.48 ft) (WSA, 2018). The LiDAR information was used to develop contours using a 0.5 m (1.64 ft) interval. The lowest complete contour based on the LiDAR survey was at elevation 561.0 m (1840.55 ft) with an area of 573.2 hectares (1416 acres). The original elevation-area information for Boundary Reservoir from 1980 showed a slightly larger area of 599 hectares (1480 acres) at approximately the same FSL elevation of 560.83 m

(1840.0 ft). The previous elevation-area data from 1980 overestimated the area at the FSL elevation by approximately 5%. The explicit reason for the discrepancy is unknown was not determined because background information on how the 1980 elevation-area relationship was developed is not available (WSA, 2018).

Data below elevation 560.8 m (1840 ft) Canadian Geodetic Vertical Datum 1928 (CGVD28) are adopted from *Annex A* and adjusted to fit the LiDAR data by using a 0.95 adjustment factor (WSA, 2018) because SaskPower assumed the 2011 LiDAR data is more accurate than the 1980 data used in Annex A. LiDAR data was used to derive the curves for Boundary Reservoir above that elevation. The adopted elevation-area-storage relationship for Boundary Reservoir is shown in ***Table 4***.

Table 4 Boundary Reservoir Elevation-Area-Storage Data (CGVD28)

Elevation, meters	Elevation, feet	Storage, dam^3	Storage, acre-feet	Area, hectares	Area, acres
539.5	1770.01	0	0	0	0
540	1771.65	20	16	11	28
542	1778.22	530	430	43	106
544	1784.78	1,790	1,451	86	211
546	1791.34	4,120	3,340	151	373
548	1797.90	7,790	6,315	219	540
550	1804.46	12,700	10,296	275	679
552	1811.02	18,700	15,160	323	798
554	1817.59	25,700	20,835	374	925
556	1824.15	33,700	27,321	428	1056
558	1830.71	42,900	34,780	494	1221
560.8	1839.90	57,700	46,778	569	1406
561	*1840.55*	*58,900*	*47,751*	*573*	*1416*
561.5	*1842.19*	*61,800*	*50,102*	*589*	*1456*
562	*1843.83*	*64,800*	*52,534*	*598*	*1477*
562.5	*1845.47*	*67,800*	*54,966*	*605*	*1495*
563	*1847.11*	*70,800*	*57,398*	*612*	*1512*
563.5	*1848.75*	*73,900*	*59,912*	*619*	*1530*
563.9	*1850.07*	*76,200*	*61,776*	*625*	*1544*

An update to the Lake Darling's capacity curve was completed by the FWS in 1998 with bathymetric data collected during the early 1990s. The upper end of the capacity curve (above the water surface elevation) was updated in support of the 2013-2018 PoS assessment with LiDAR data collected during 2012 and 2013 (USACE, 2014a) and during 2016 and 2017 (NRCS, 2018).

The 2012/2013 LiDAR covered most of the reservoir, with the exception of the dam face which is near the Renville County border. The 2017 LiDAR covered Ward County, ND, which

included only the dam face. The 2012/2013 area and storage capacity relationships were generated at roughly one foot intervals using the "r.lake" algorithm repeatedly within GRASS GIS 7.4 (GRASS GIS, 2018). The capacity data generated is relative to the water surface elevation at the time the 2012/2013 LiDAR was collected. A discontinuity was identified between the elevation-area curves produced using the 2013 data and the 1998 data. To address this inconsistency an adjustment to the 2013 data was made. The adjustment was made by comparing several elevation profiles selected from the 2013 bare-earth LiDAR grid with the more recent and more accurate 2017 LiDAR data. Based on this comparison, an offset of -0.24 m (-0.79 ft) was applied to the 2013 elevation data. The application of this correction resulted in a good fit between the 1998 and corrected 2013 elevation-area curves. The adopted elevation-area-storage relationship is displayed in Table 5. The relationship for elevations below 486.2 m NGVD 29 (1595 ft) is based on the 1998 bathymetric survey data and above that elevation the adjusted 2013 LiDAR is used.

Table 5 Lake Darling Elevation-Capacity-Area Data (NGVD29 and NAVD88)

Elevation, feet NGVD29	Elevation, meters NGVD29	Elevation, feet NAVD88	Elevation, meters NAVD88	Storage, acre-feet	Storage, dam^3	Area, acres	Area, hectares
1575	480.060	1576.12	480.400	20	25	31.00	4
1576	480.365	1577.12	480.705	62	76	53.00	13
1577	480.670	1578.12	481.009	144	178	110.00	21
1578	480.974	1579.12	481.314	282	348	168.00	45
1579	481.279	1580.12	481.619	519	640	310.00	68
1580	481.584	1581.12	481.924	896	1,105	455.00	125
1581	481.889	1582.12	482.229	1,873	2,310	1524.00	184
1582	482.194	1583.12	482.533	3,908	4,820	2600.00	617
1583	482.498	1584.12	482.838	6,924	8,541	3525.00	1,052
1584	482.803	1585.12	483.143	10,844	13,376	4449.00	1,427
1585	483.108	1586.12	483.448	15,494	19,112	5024.00	1,800
1586	483.413	1587.12	483.753	20,701	25,534	5595.00	2,033
1587	483.718	1588.12	484.057	26,396	32,559	6027.00	2,264
1588	484.022	1589.12	484.362	32,509	40,099	6458.00	2,439
1589	484.327	1590.12	484.667	39,188	48,338	7181.00	2,613
1590	484.632	1591.12	484.972	46,577	57,452	7905.00	2,906
1591	484.937	1592.12	485.277	54,530	67,262	8334.00	3,199
1592	485.242	1593.12	485.581	62,897	77,582	8763.00	3,373
1593	485.546	1594.12	485.886	71,623	88,346	9082.00	3,546
1594	485.851	1595.12	486.191	80,649	99,479	9416.00	3,675
1595	486.156	1596.12	486.496	89,873	110,857	9591.30	3,801
1596	486.461	1597.12	486.801	99,633	122,896	9837.60	3,943
1597	486.766	1598.12	487.105	109,713	135,329	10158.20	4,044
1598	487.070	1599.12	487.410	120,135	148,184	10509.90	4,201
1599	487.375	1600.12	487.715	131,193	161,824	11117.10	4,411
1600	487.680	1601.12	488.020	142,494	175,764	11499.10	4,595
1601	487.985	1602.12	488.325	154,348	190,386	11850.20	4,754
1602	488.290	1603.12	488.629	166,466	205,333	12212.20	4,903
1603	488.594	1604.12	488.934	178,973	220,759	12561.10	5,037
1604	488.899	1605.12	489.239	191,721	236,484	12872.70	5,169
1605	489.204	1606.12	489.544	204,897	252,736	13257.40	5,319
1606	489.509	1607.12	489.849	218,607	269,647	13614.00	5,509
1607	489.814	1608.12	490.153	232,693	287,022	14004.30	5,667
1608	490.118	1609.12	490.458	246,779	304,397	14394.70	5,825

Storage capacity and pool area curves for the hydraulic structures in the National Wildlife Refuges which are represented in the ResSim model are shown in ***Table 6*** through ***Table 10*** below.

Table 6 Dam 357 Elevation-Area-Storage Data

Elevation, meters	Elevation, feet	Storage, dam^3	Storage, acre-feet	Area, hectares	Area, acres
428.24	1405.00	0	0	8	20
428.55	1406.00	59	48	31	76
428.85	1407.00	185	150	52	128
429.16	1408.00	401	325	89	221
429.46	1409.00	829	672	192	474
429.77	1410.00	1,765	1,431	423	1,044
430.07	1411.00	3,608	2,925	786	1,943
430.38	1412.00	6,644	5,386	1,206	2,979
430.68	1413.00	11,139	9,030	1,744	4,309
430.99	1414.00	16,880	13,685	2,024	5,001
431.29	1415.00	23,334	18,917	2,211	5,463
431.60	1416.00	30,134	24,430	2,251	5,563
431.90	1417.00	37,065	30,049	2,297	5,675
432.21	1418.00	44,127	35,774	2,337	5,775
432.51	1419.00	51,308	41,595	2,375	5,868
432.82	1420.00	58,616	47,520	2,421	5,982
433.12	1421.00	66,056	53,552	2,461	6,081
433.43	1422.00	73,618	59,682	2,501	6,179
433.73	1423.00	81,300	65,910	2,541	6,278
434.04	1424.00	89,106	72,238	2,581	6,377
434.34	1425.00	97,032	78,664	2,621	6,476

Table 7 Dam 341 Elevation-Area-Storage Data

Elevation, meters	Elevation, feet	Storage, dam^3	Storage, acre-feet	Area, hectares	Area, acres
428.24	1405.00	0	0	1	2
428.55	1406.00	14	11	8	19
428.85	1407.00	52	42	17	43
429.16	1408.00	117	95	25	63
429.46	1409.00	213	173	38	94
429.77	1410.00	349	283	51	125
430.07	1411.00	566	459	92	227
430.38	1412.00	905	734	131	323
430.68	1413.00	1,382	1,120	182	450
430.99	1414.00	2,278	1,847	406	1,003
431.29	1415.00	4,244	3,441	885	2,186
431.60	1416.00	7,057	5,721	961	2,374
431.90	1417.00	10,423	8,450	1,248	3,083
432.21	1418.00	14,302	11,595	1,298	3,208
432.51	1419.00	18,311	14,845	1,332	3,292
432.82	1420.00	22,410	18,168	1,357	3,354
433.12	1421.00	26,645	21,601	1,421	3,512
433.43	1422.00	30,994	25,127	1,432	3,539
433.73	1423.00	35,393	28,693	1,454	3,594
434.04	1424.00	39,853	32,309	1,472	3,637
434.34	1425.00	44,386	35,984	1,503	3,713

Table 8 Dam 332 Elevation-Area-Storage Data

Elevation, meters	Elevation, feet	Storage, dam³	Storage, acre-feet	Area, hectares	Area, acres
429.77	1410.00	0	0	4	10
430.07	1411.00	39	32	22	54
430.38	1412.00	115	93	27	67
430.68	1413.00	222	180	43	107
430.99	1414.00	395	320	70	174
431.29	1415.00	655	531	100	247
431.60	1416.00	1,134	919	214	529
431.90	1417.00	2,145	1,739	450	1,111
432.21	1418.00	5,015	4,066	1,434	3,544
432.51	1419.00	9,716	7,877	1,650	4,078
432.82	1420.00	14,933	12,106	1,773	4,380
433.12	1421.00	20,481	16,604	1,868	4,615
433.43	1422.00	26,291	21,314	1,945	4,806
433.73	1423.00	32,330	26,210	2,018	4,986
434.04	1424.00	38,602	31,295	2,098	5,184
434.34	1425.00	45,157	36,609	2,203	5,444

Table 9 Dam 326 Elevation-Area-Storage Data

Elevation, meters	Elevation, feet	Storage, dam³	Storage, acre-feet	Area, hectares	Area, acres
430.68	1413.00	0	0	8	19
430.99	1414.00	32	26	13	32
431.29	1415.00	79	64	18	44
431.60	1416.00	142	115	23	58
431.90	1417.00	788	639	401	990
432.21	1418.00	2,696	2,186	851	2,104
432.51	1419.00	6,092	4,939	1,377	3,403
432.82	1420.00	10,902	8,838	1,778	4,394
433.12	1421.00	16,888	13,691	2,150	5,313
433.43	1422.00	23,776	19,275	2,369	5,854
433.73	1423.00	31,067	25,186	2,416	5,969
434.04	1424.00	38,507	31,218	2,466	6,094
434.34	1425.00	46,064	37,344	2,493	6,159
434.64	1426.00	53,719	43,550	2,531	6,253
434.95	1427.00	61,473	49,836	2,557	6,319
435.25	1428.00	69,308	56,188	2,584	6,384
435.56	1429.00	77,222	62,604	2,610	6,449
435.86	1430.00	85,225	69,092	2,641	6,526

Table 10 Dam 320 Elevation-Area-Storage Data

Elevation, meters	Elevation, feet	Storage, dam³	Storage, acre-feet	Area, hectares	Area, acres
431.29	1415.00	0	0	4	9
431.60	1416.00	21	17	10	24
431.90	1417.00	59	48	16	39
432.21	1418.00	117	95	22	54
432.51	1419.00	194	157	28	70
432.82	1420.00	322	261	56	139
433.12	1421.00	633	513	148	365
433.43	1422.00	1,665	1,350	529	1,308
433.73	1423.00	3,786	3,069	862	2,131
434.04	1424.00	7,065	5,728	1,289	3,186
434.34	1425.00	11,525	9,343	1,637	4,044
434.64	1426.00	17,001	13,783	1,958	4,837
434.95	1427.00	23,382	18,956	2,229	5,508
435.25	1428.00	30,374	24,624	2,359	5,829
435.56	1429.00	37,746	30,601	2,478	6,124
435.86	1430.00	45,514	36,898	2,619	6,471

3.1.2 Outlet Works Capacity Curves

The WSA provided elevation-outlet capacity curves for Rafferty Reservoir, Grant Devine Lake and Boundary Reservoir as part of the *USACE 2013 Regional and Reconstructed Hydrology study* (USACE, 2013). Rafferty Reservoir and Grant Devine Lake are regulated by alternating between outlet structures as reservoir releases increase. For this reason, the physical capacity curves can play a significant role in flood control operations.

Rafferty Reservoir has a main spillway outlet, a low level outlet, and an irrigation gate. Discharges up to 4 m^3/s (141 ft^3/s) are typically made using the irrigation gates. For discharges between 4 m^3/s (141 ft^3/s) and 65 m^3/s (2,295.5 ft^3/s) the low level outlet structure is utilized. For discharges greater than 65 m^3/s (2,295.5 ft^3/s) the main spillway gates are operated. The irrigation gate must be closed to utilize the low level outlet and both the irrigation gates and the low level outlet must be closed when operating the spillway gates. Rafferty has an auxiliary outlet pipeline that can pump up to 0.297 m^3/s (10.5 ft^3/s) to Boundary Reservoir when Boundary Reservoir levels get low.

Grant Devine Lake has a main spillway outlet, a low flow outlet, and two irrigation gates (one with a low level invert and one with a high level invert). Discharges up to 63 m^3/s (2,225 ft^3/s) are made through the low level outlet. For discharges greater than 63 m^3/s (2,225 ft^3/s) the spillway gates are operated. The irrigation gate must be closed to utilize the low level outlet and both the irrigation gate and the low level outlet must be closed when operating the spillway gates. In the past, operators have had difficulties with the irrigation gates and thus they are not currently used. Only the low flow and the main spillway outlet are included in the ResSim model.

Boundary Reservoir has a riparian outlet structure and a spillway outlet to Long Creek, and a diverted outlet to Rafferty Reservoir. Boundary Reservoir can also receive flow via a pipeline from Rafferty Reservoir. There is minimal guidance related to how Boundary Reservoir's outlet works are utilized. Consequently, the ResSim model only utilizes the main spillway outlet and the diverted outlet as release points for Boundary Reservoir. The Boundary Diversion has a controlled outlet structure which has a physical maximum discharge capacity of 70 m^3/s (2,471.7 ft^3/s). The physical maximum discharge capacity of the diversion is greater than desired for operation of the diversion canal. A maximum flow limit of 45 m^3/s (1,590 ft^3/s) is applied by operators to prevent damage to the diversion channel and is modeled as a maximum flow rule in ResSim.

The outlet works at Lake Darling consist of a low flow outlet and a gated spillway. The low flow outlet is controlled by three rectangular conduits with sluice gates. There are no restrictions on sluice gate operation. The discharge capacity of Lake Darling's low flow outlets can be dependent on the tailwater elevation. The low flow outlet capacity curve for tailwater elevations below 481 m (1578.2 ft) is used in the model because at this elevation the flow rate is only dependent on pool elevation. This assumption may result in the model releasing more flow through the low flow outlets than is physically possible, but will not have a significant impact on overall operation because the capacity of gated spillway exceeds the low flow outlet capacity. The main spillway outlet is controlled by five tainter gates and discharge capacity curve used in the model is specified in the *Lake Darling Water Control Manual* (USACE, 2012). Although operators do not use the low flow outlet and gated spillway concurrently, the model currently allows for the two outlets to be used at the same time. The USACE St. Paul District water management section was consulted and the impact of using the two outlets concurrently is not considered operationally significant.

3.2 Reservoir Physical Data – NWR Structures

3.2.1 Storage, area, and elevation relationships

Five low-head dams with water control structures create pools along the 120.7 km (75 mi) of the Souris River included within the refuge. Each dam consists of a low earthen dike across the Souris River floodplain, a gated outlet structure constructed in the river channel and an uncontrolled spillway. Radial gates control discharge through the outlet structures. Pertinent structure data related to the five major control structures that form the J. Clark Salyer NWR is listed in ***Table 11***. The locations of the five control structures are displayed in ***Figure 2***.

Table 11 NWR Structures Reservoir Data

Dam Crest				Gated Outlet				Spillway	
Dam Number	Units	Length	Elevation, NGVD 29	Number of Gates	Height of Abutments & Walls	Width	Invert Elevation, NGVD 29	Crest Elevation, NGVD 29	Crest Length
320	meters	4,877	435.47	3[a]	3.96	4.87	431.47	434.58	221
	feet	16,000	1,428.7		13	16	1,415.6	1,425.8	725
326	meters	2,896	434.77	3	3.96	4.87	431.05	433.79	212
	feet	9,500	1,426.4		13	16	1,414.2	1,423.2	694
332	meters	1,524	433.99	3	4.57	4.87	429.34	432.69	214
	feet	5,000	1,423.9		15	16	1,408.6	1,419.6	701
341	meters	1,006	433.33	3	4.57	4.87	428.91	432.27	177
	feet	3,300	1,421.7		15	16	1,407.2	1,418.2	580
357	meters	966	434.26	3[b]	4.87	4.87	428.24	432.21	213
	feet	3,170	1,424.8		16	16	1,405.	1,418.	700

[a]Additional Outlet, 4- foot corrugated metal pipe with stop-log control, for refuge management use (not modeled)
[b]Additional Outlets: two 4-foot wide by 4.5 foot high stop log sections in uncontrolled spillway, for refuge management use; 3-foot pipe with slide-gate control, no longer operational; two 2-foot reinforced concrete pipes with slide and orifice gate control, for low flow discharges (not modeled)

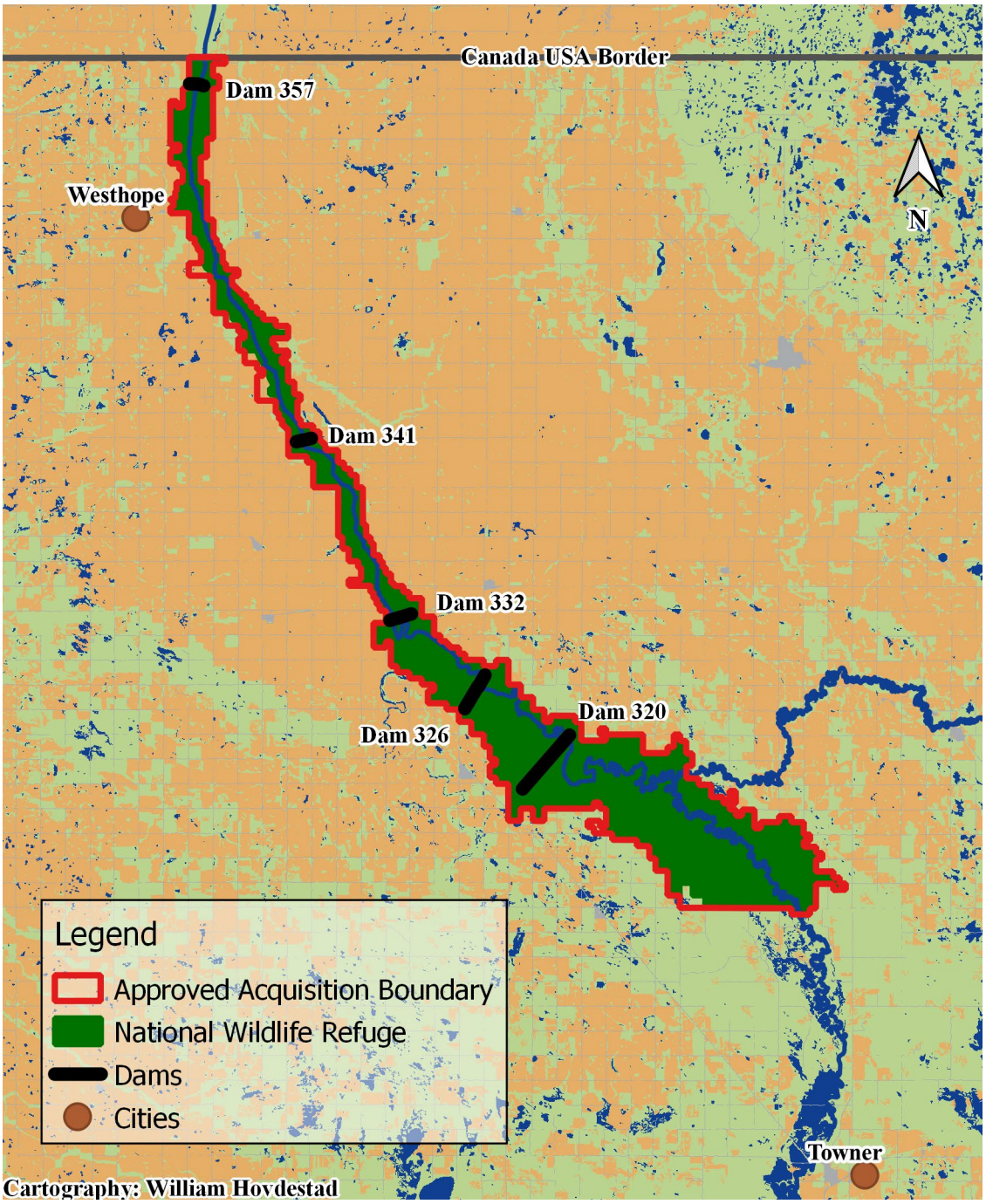


Figure 2 NWR Structures locations

3.2.2 Outlet Works Capacity Curves

Elevation--area-storage curves are inputted into the model for each NWR reservoir, as well as average monthly evaporation data collected near Minot, ND. Monthly evaporation relationships were derived as part of the *2013 Regional and Reconstructed Hydrology Study* (USACE, 2013). All storage volumes were calculated using 1988 area capacity tables.

The outlet works are modeled using an uncontrolled spillway structure with a weir coefficient of 2.6 and three controlled outlets. The maximum physical capacity of the three controlled outlets is modeled as a broad crested weir with a crest length of 4.8 m (16 ft) and a weir coefficient of 2.6. The model assumes zero "submergence" and thus does not apply an adjustment factor to account for tailwater conditions. The controlled outlet structures are at least partially submerged during the majority of period of record and therefore the maximum capacity of the controlled outlet structure is restricted by the tailwater. Because there are no continuous, daily tailwater elevation datasets readily available for the J. Clark Salyer NWR structures, it is not possible to explicitly model tailwater effects in HEC-ResSim. The adopted model likely overestimates releases made via the structures' controlled outlets.

Due to the simplifying assumptions being made, this model should not be utilized to evaluate refuge structure operation or to determine historic water levels and releases within the J. Clark Salyer NWR. This model can appropriately be applied as a means of routing flows through the entire refuge structure system in order to generate comparable model runs that can be utilized to evaluate the effects that changing the Souris River Project (Rafferty Dam, Alameda Dam, Boundary Dam, and Lake Darling Dam) operating plan has at downstream points of interest.

3.3 Model Inputs

3.3.1 Reservoir Inflows, Tributary Inflows & Local Flows (HH1 Dataset)

In 2013, the USACE completed the *Souris River Regional and Reconstructed Hydrology Study*. This effort consisted of generating continuous reservoir inflow, tributary flow and local flow records for the period of record from 1946 through 2011. Local flow is runoff which originates on the intervening drainage area between two gages or points of interest on a stream. The 2013 study extents spanned from the Canadian reservoirs to Wawanessa, Manitoba. The time series generated in 2013 were updated to include data collected between 1930 and 1945 and between 2011 and 2017 for the area between the Canadian reservoirs and Westhope, ND. The dataset compiled for 1930-2017 for the area between Canadian reservoirs and Westhope, ND are referred to as the HH1 dataset (ISRB, 2019). A summary of the time series generated as part of HH1 and used as inputs to ResSim are is presented in ***Table 12***.

ResSim requires input flow time series data for all junctions located at the upstream extents of the model. Rafferty Reservoir, Boundary Reservoir, and Grant Devine Lake each have an inflow junction located at an upstream extent of the ResSim model network. The HH1 report provides a more detailed description of how flow records were developed as inputs to the model.

Adopted inflows to Rafferty Reservoir from 1992 through 2017 were estimated using a reverse routing procedure. There is no observed streamflow data immediately upstream of Rafferty Reservoir. The observed flows from the Noonan and Crosby gages are used as inputs to the Boundary Reservoir element in the ResSim model. The Long Creek near Noonan, ND USGS Gage (ID 05113600) provides an estimate of inflows to Boundary Reservoir and captures approximately 95% of the contributing drainage area at the upstream end of the reservoir. Recorded flow at the Long Creek near Crosby gage (05NB026) are considered the most representative inflow time series for Boundary Reservoir for 1958 and 1959 and are adjusted using a drainage area factor to augment the Long Creek near Noonan USGS gage data.

Reverse routed inflows were estimated for Boundary Reservoir as part of the mass balance verification discussed in Section 3.3.6.1. Direct water use occurs from Boundary Reservoir in the form of water supply for the City of Estevan and cooling water/forced evaporation for the SaskPower plant on Boundary Reservoir. There is a large amount of uncertainty in the quantity of direct water use at Boundary Reservoir. WSA deemed it would be more accurate to use the Long Creek near Noonan, ND USGS Gage (ID 05113600) as inflows to Boundary Reservoir because it would be difficult to account for the uncertainty surrounding consumptive water use from Boundary Reservoir. This also allows water use from Boundary Reservoir to be specified explicitly in the model as a time series.

Table 12 Summary of inflow locations

Location	Type
Rafferty Reservoir	Inflow – Reverse Routed
Boundary Reservoir	Inflow – Observed data from the Long Creek near Noonan, ND USGS gage (ID 05113600)
Short Creek	Tributary Flow
Short Creek Confluence	Local Flow
Upstream Moose Mountain Creek	Local Flow
Grant Devine Reservoir	Inflow – Reverse Routed
Sherwood	Local Flow
Glen Ewen	Local Flow
Lake Darling	Local Flow
Des Lacs River- Foxholm	Tributary Flow
Burlington	Tributary Local Flow
Des Lacs Confluence	Local Flow
Minot	Local Flow
Velva	Local Flow
Verendrye	Local Flow
Wintering River	Tributary Flow
Bantry	Local Flow
Willow Creek	Tributary Flow
Salyer - Pool 320	Local Flow
Stone Creek	Tributary Flow
Deep River	Tributary Flow
Cut Bank Creek	Tributary Flow
Salyer - Pool 332	Local Flow
Salyer - Pool 341	Local Flow
Boundary Creek	Tributary Flow
Salyer - Pool 357	Local Flow

A comparison of the reverse routed inflows to Boundary Reservoir and the observed inflows from the Noonan, ND USGS Gage is shown in

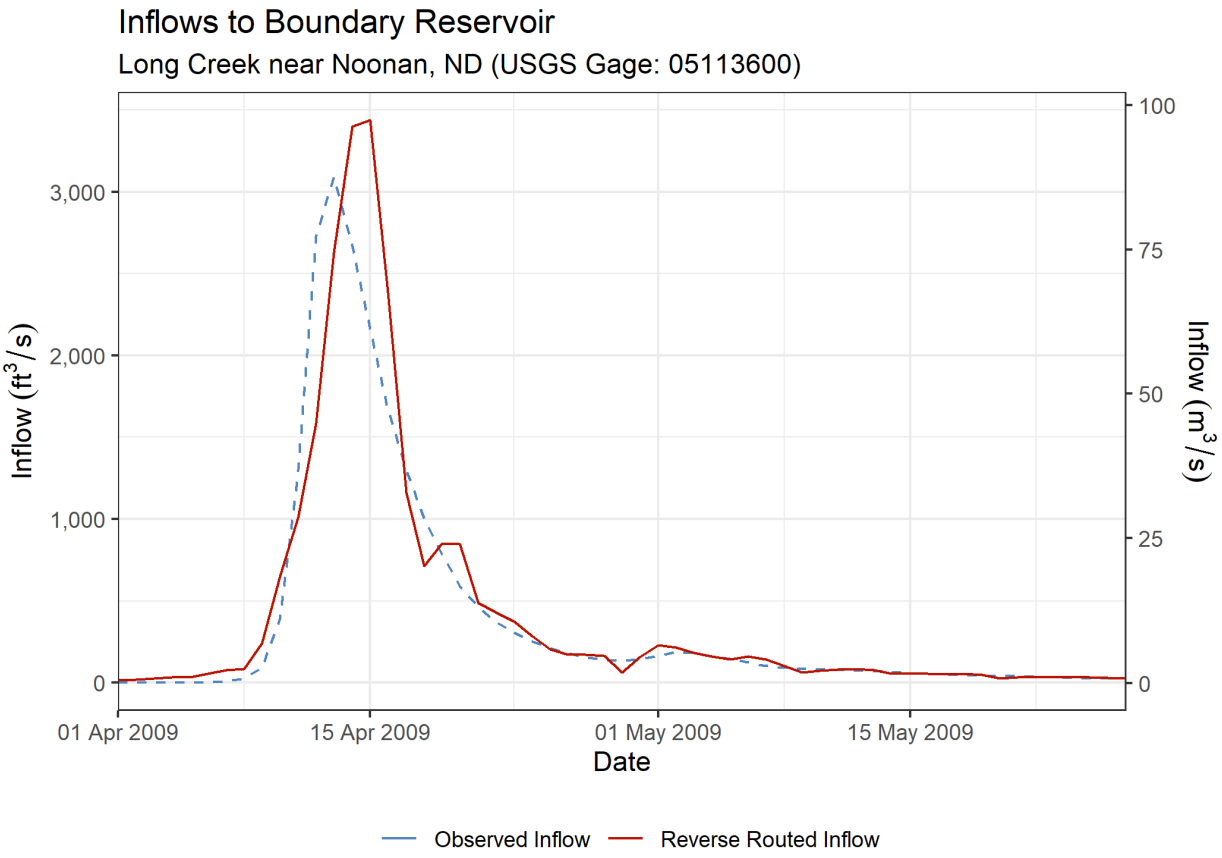


Figure 3 and

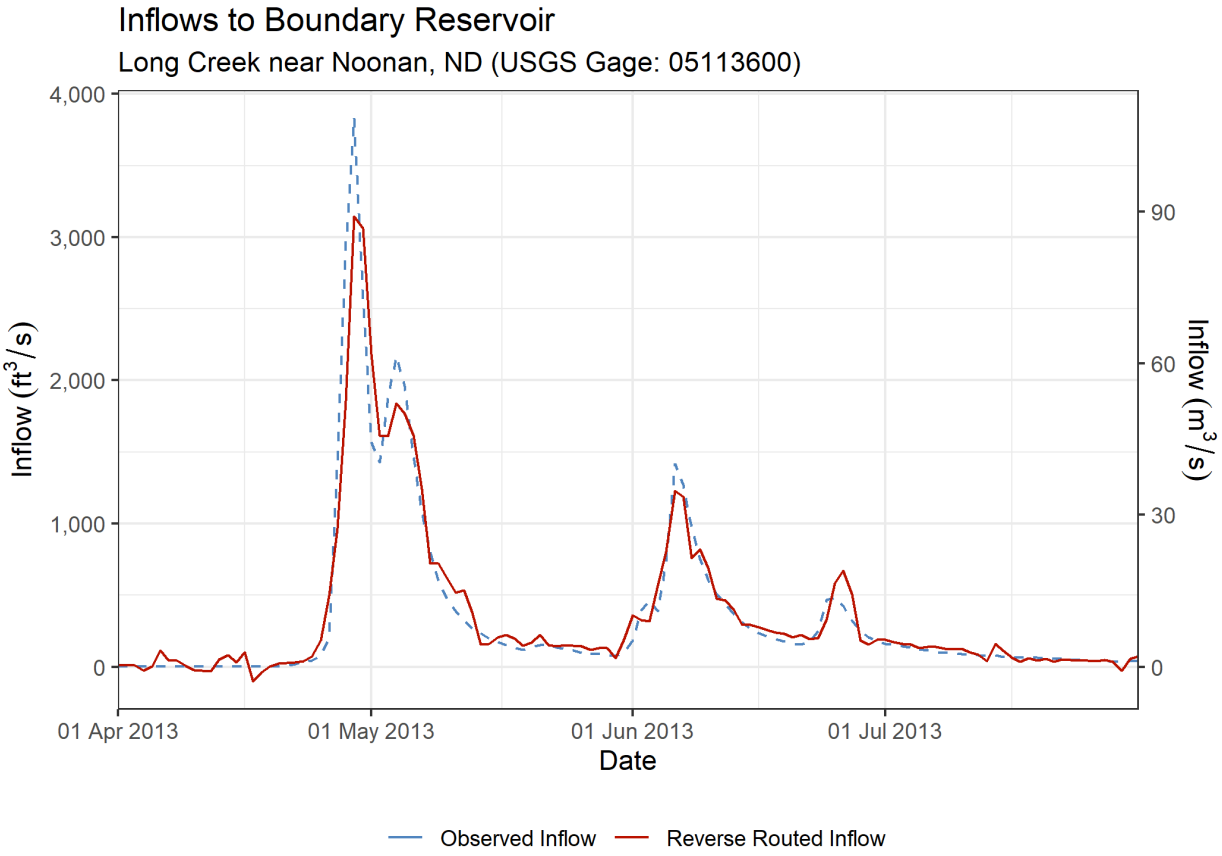


Figure 4 below for the 2009 and 2013 events, respectively. As the figures show, the reverse routed inflows provide a close estimate of the observed data with some differences in the peak event in 2009 and 2013.

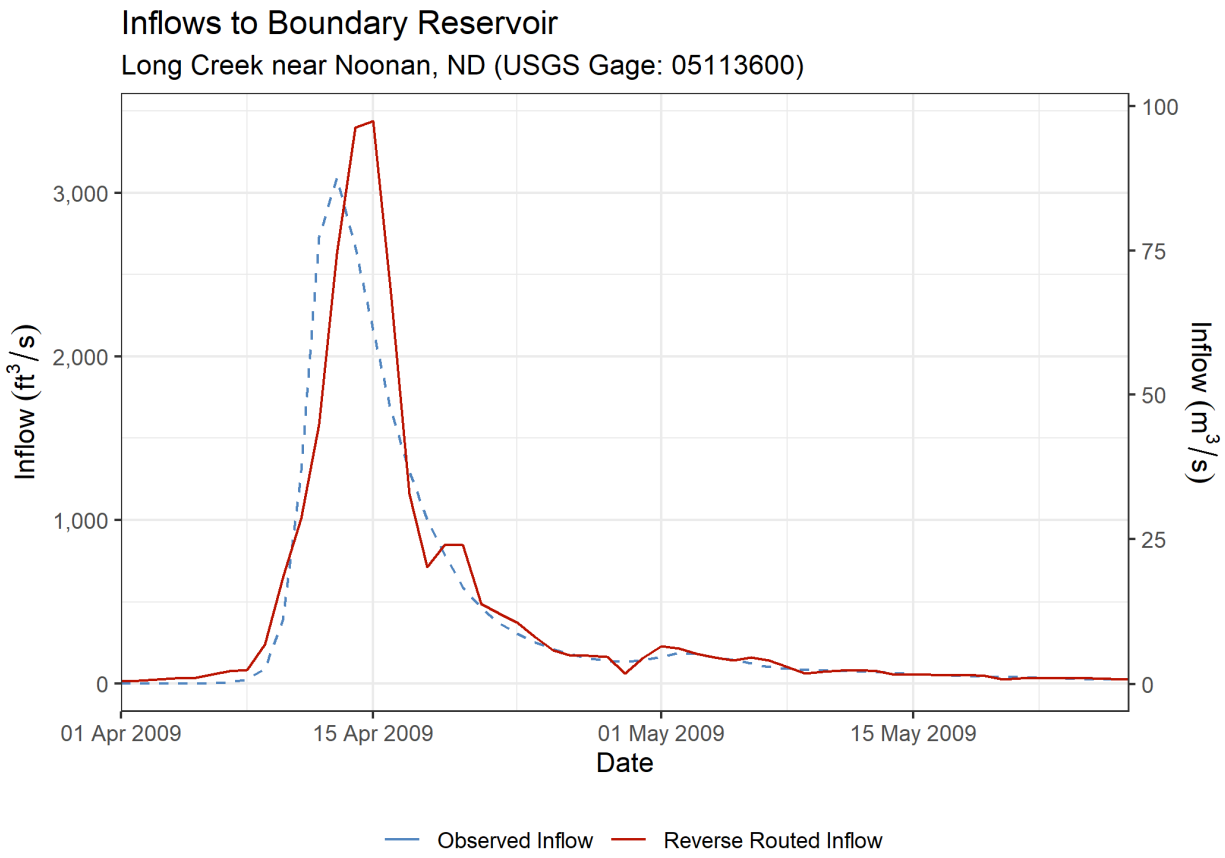


Figure 3 Comparison of observed and reverse routed inflow records to Boundary Reservoir - 2009

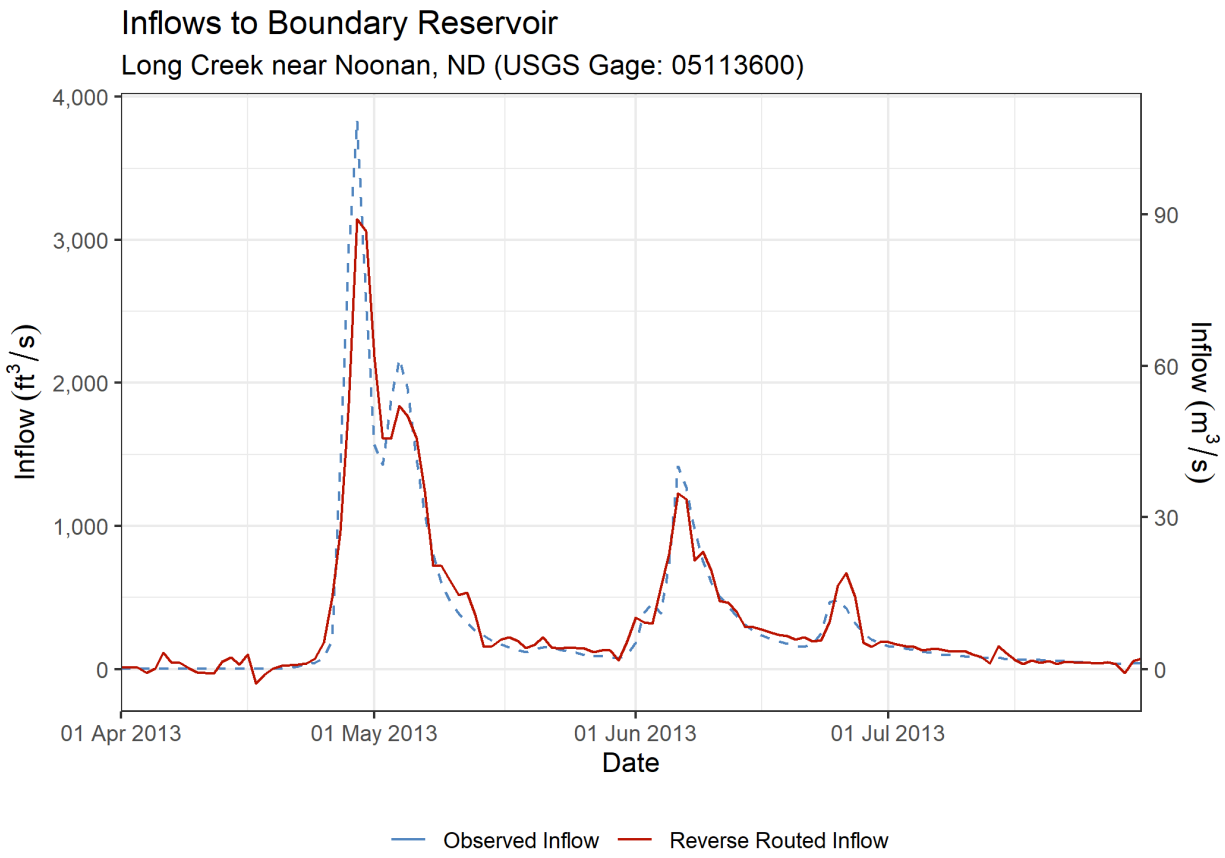


Figure 4 Comparison of observed and reverse routed inflow records to Boundary Reservoir - 2013

Adopted inflows to Grant Devine Lake were estimated using the reverse routing method from 1992 through 2017. The Moose Mountain Creek above Alameda, SK (Grant Devine) Reservoir gage (05ND010) is located upstream of Grant Devine Lake and provides observed flows from 1991 to present. The flow record for this gage was not adopted because the ungaged drainage area between the gage and the upstream end of Grant Devine Lake is more significant than the ungaged drainage area upstream of Boundary Reservoir. There is also little water use from Grant Devine Lake and the uncertainty associated with water use is less than the uncertainty in water use from Boundary Reservoir. A comparison of the reverse routed inflows to Grant Devine and the observed inflows from the Moose Mountain Creek above Alameda (Grant Devine) Reservoir gage

(05ND010) is shown in

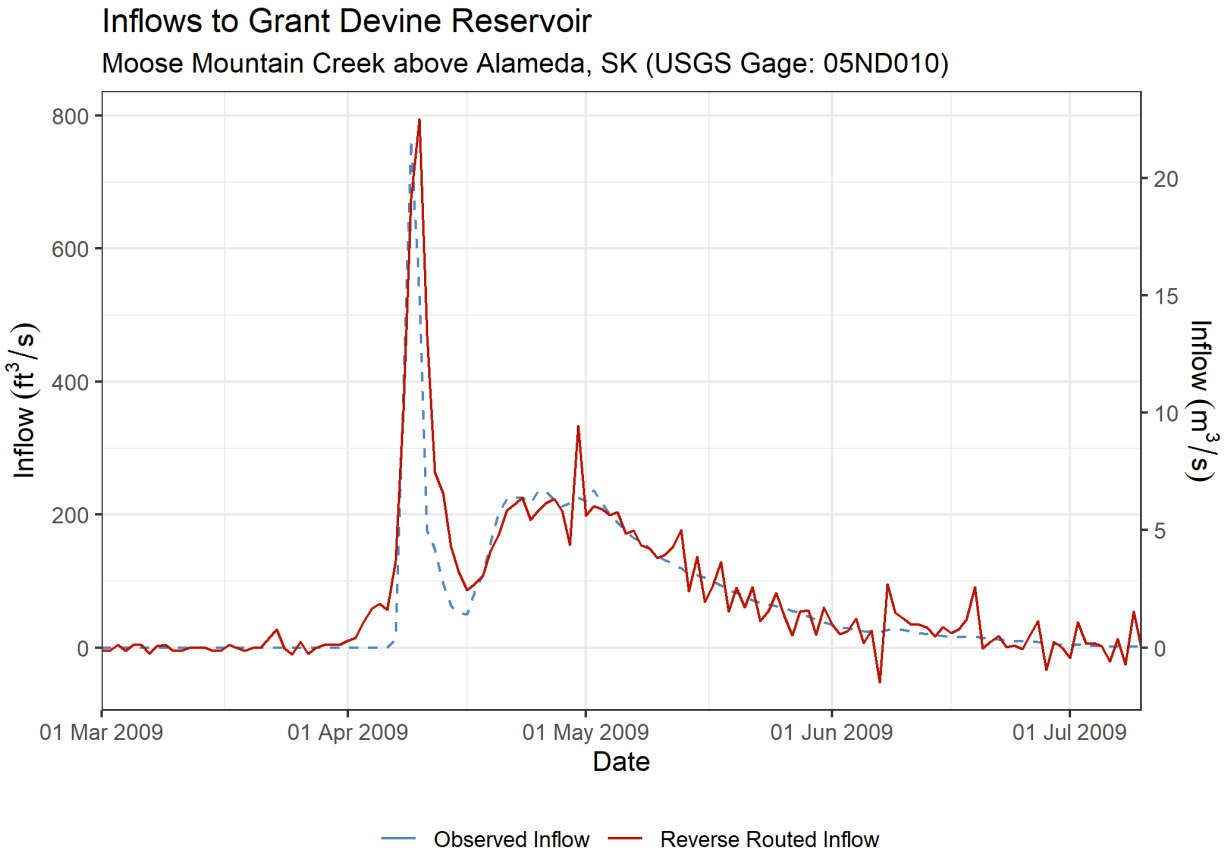


Figure 5 **and**

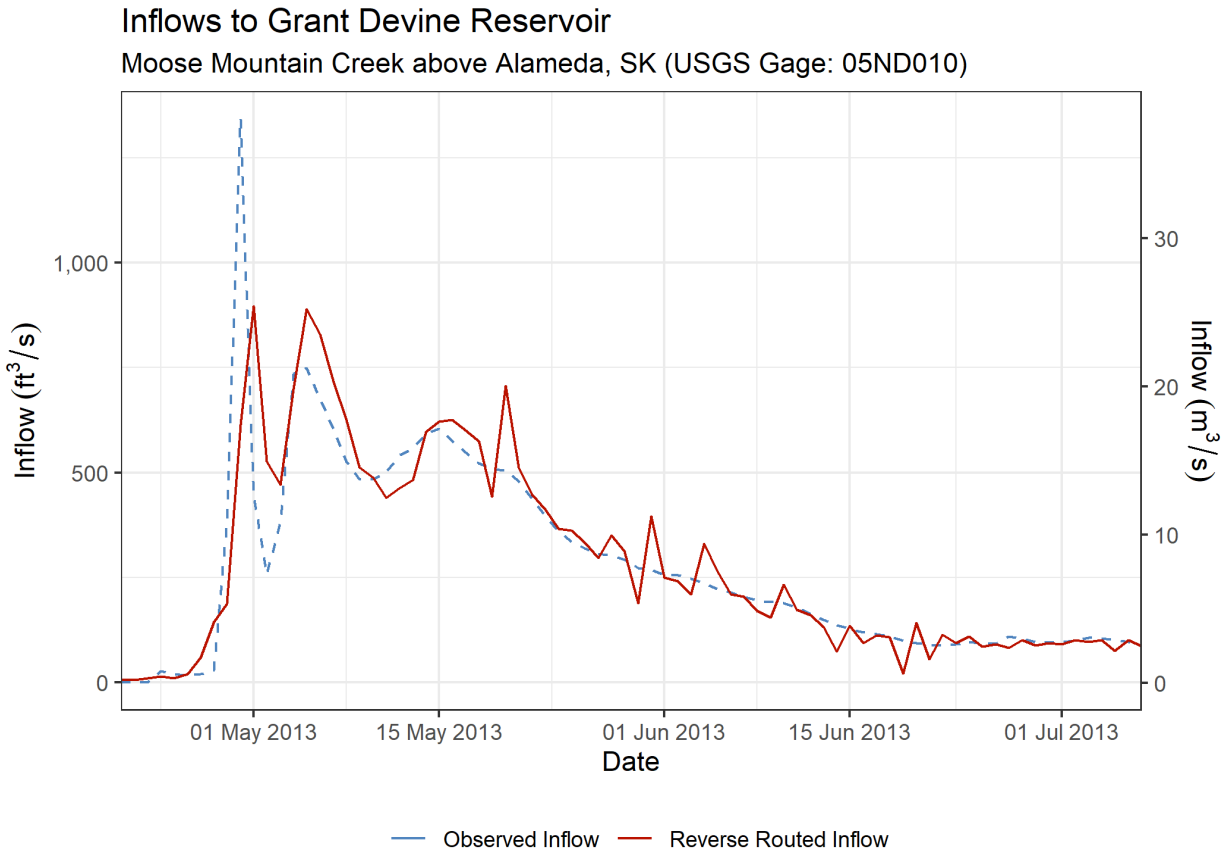


Figure 6 below for the 2009 and 2013 events, respectively. As the figures show, the reverse routed inflows provide a reasonable approximation of the observed data.

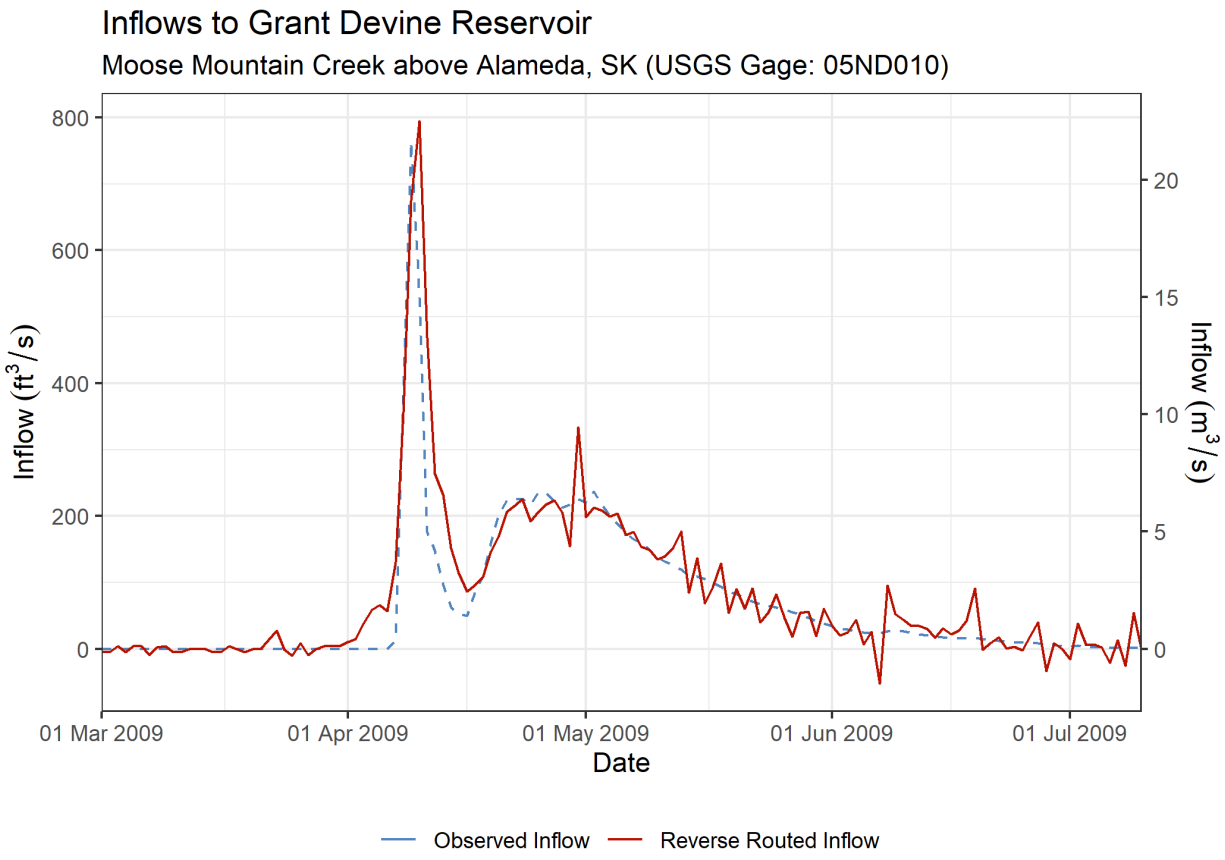


Figure 5 Comparison of observed and reverse routed inflow records to Grant Devine Lake - 2009

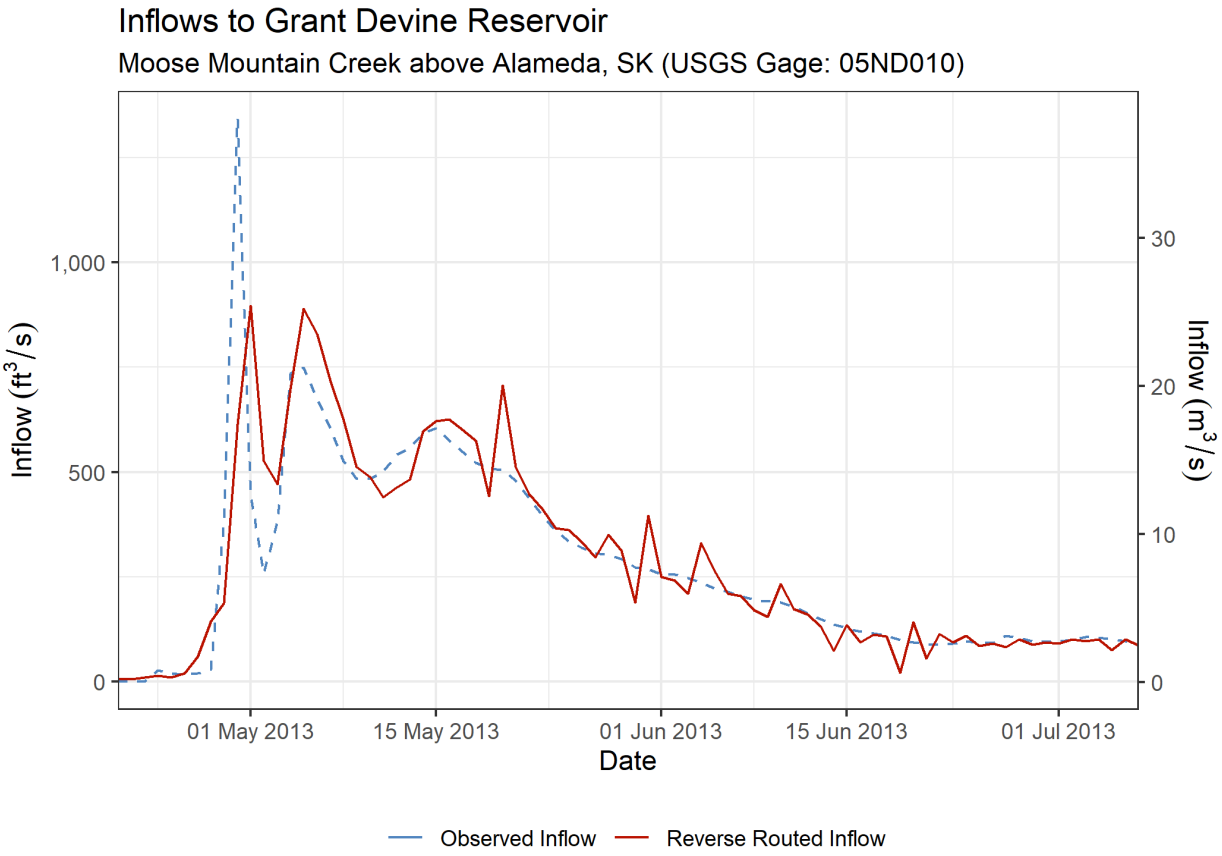


Figure 6 Comparison of observed and reverse routed inflow records to Grant Devine Lake - 2013

3.3.2 Negative Inflow and Local Flow Impacts to Model

Input flow time series are required at all the upstream most elements in ResSim. Additionally, local flow is added at elements throughout the model. For several of the reservoirs, inflows are developed using reverse reservoir routing. Many of the local flow inputs are estimated using the holdout method. The holdout method involves routing a hydrograph from an upstream junction to a downstream junction which has an observed hydrograph. The difference between the observed hydrograph at the downstream junction and the routed hydrograph represents the local flow contribution from the intervening drainage area along the routing reach. Both the holdout method and reverse routing rely on the principle of mass balance/conservation of mass. The HH1 report and the *2013 Regional and Reconstructed Hydrology study* (USACE 2013) describes how input flow records were developed for this model in greater detail.

Reverse routing and the holdout method produce flow records that include corrections for errors in observation and errors in hydrologic routing. The flow records generated also cumulatively account for losses or gains that were not explicitly included in their calculation, such as water use withdrawals and seepage losses. When the cumulative impact of unaccounted for net losses or negative errors is greater than the amount of runoff which reaches the reservoir or element in the model this results in a negative computed flow. The negative flows need to be carried

forward and applied because they satisfy the conservation of mass. However, hydrologic routing cannot be applied to negative flows in ResSim. This issue is particularly apparent when modeling unregulated flows because there are no additional inputs or stored volumes of water available to offset negative inputs at the upstream most elements.

Negative flows are set to zero when river reach routing operations are carried out by ResSim. Negative flows are only maintained when direct or null routing is applied. Negative inflows to reservoir elements are not an issue because reservoir elements have enough volume to compensate for negative inflows to the reservoir. When negative flows are zeroed out in a routing reach, negative volume is not accounted for in the system and the model ends up with a higher volume.

The amount of unaccounted for negative flow volume depends on the magnitude of negative flows in

the input flow records and the total flow being routed through the system. Before local flow is routed downstream, it is added to the flow contribution from the upstream routing reaches. When the flow from the upstream routing reach is greater than any negative flows within the local flow record, the net result is a positive flow value at the junction where local flow is being inserted. Mass will be maintained under this condition. When the negative local flow values are greater than the positive flow contribution from the upstream reaches, the net result includes negative flows. Because negative flows cannot be routed downstream, the negative volume is not accounted for in the system resulting in an overestimation of flow.

An example of how negative flows are zeroed out is illustrated Table 13 and Figure 7 below. Flows at the inlet of the Glen Ewen to Sherwood routing reach (Column 2, Table 13) are routed to the Sherwood junction in the model and combined with the local flow inputs for Sherwood (column 3, Table 13). The routed flows upstream of the Sherwood junction (column 2, Table 13) are combined with the local flows at Sherwood (column 3, Table 13) to determine the total flow at the Sherwood junction (column 4, Table 13). When the routed flows are large enough to offset the negative inflows resulting in a positive flow, mass is conserved. However, when local flows at Sherwood are combined with the positive, streamflow hydrograph routed from Glen Ewen to Sherwood the resulting streamflow hydrograph at Sherwood includes negative values, this calculation results in several overall negative flow values at the Sherwood junction which are shaded green in Table 13. When the negative flows at the Sherwood junction are routed through the routing reach downstream of the Sherwood junction, the negative flows are set to zero (yellow values, column 5, Table 13) and negative flow volume is lost from the system.

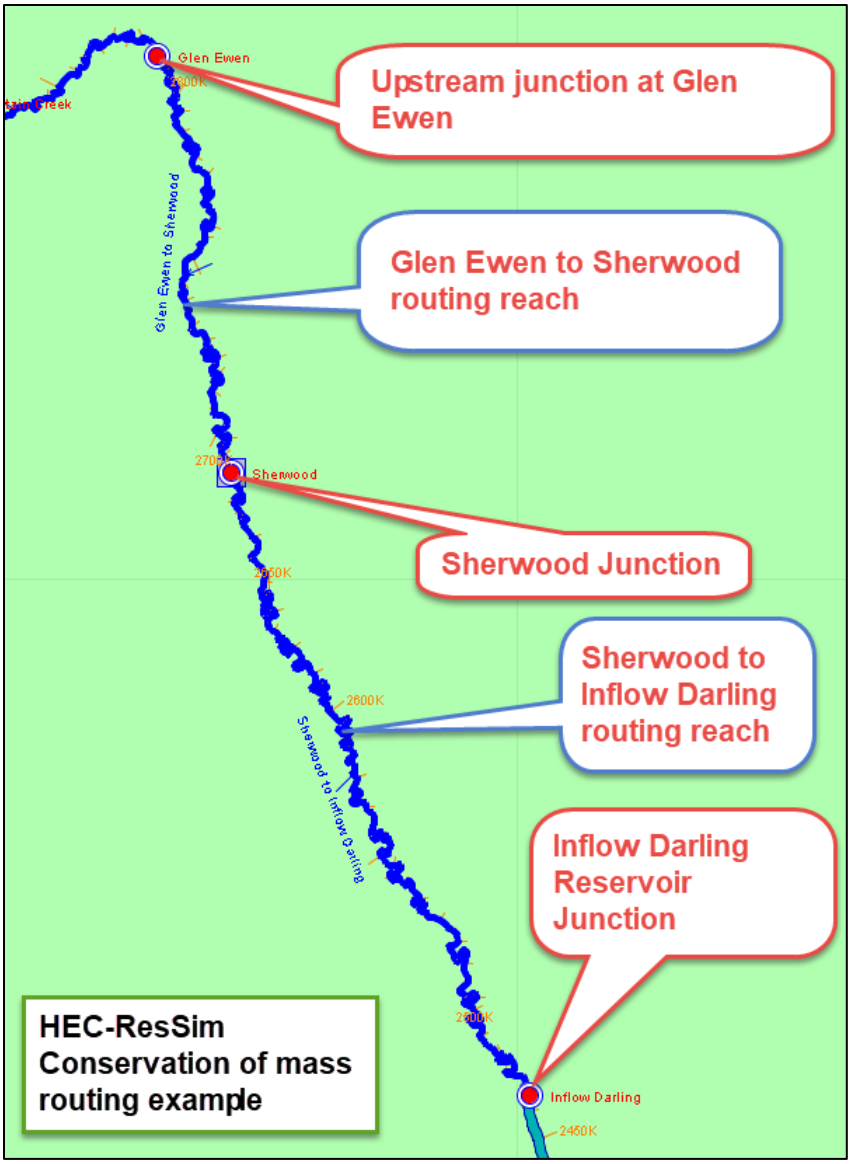


Figure 7 Negative flow routing example

Table 13 Sample ResSim calculation showing zeroed out negative flows

(1) Date	(2) Routing Reach: Glen Ewen to Sherwood (FLOW)	(3) Local Flow: Sherwood Junction	(4) Sherwood Junction Total Flow (FLOW)	(5) Routing Reach: Sherwood to Inflow Darling (FLOW)
	Flow from the routing reach upstream of the Sherwood junction, ft^3/s (m^3/s)	**Local flows computed for the Sherwood junction, ft^3/s (m^3/s)**	**Total flow at the Sherwood junction from the upstream routing reach and local flow inputs, ft^3/s (m^3/s) (4) = (2) + (3)**	**Flow routed through the routing reach downstream of Sherwood, ft^3/s (m^3/s)**
16 Apr 13, 24:00	32.95	-18.94	14.01	3.36
	(.93)	(-.54)	(.4)	(.1)
17 Apr 13, 24:00	42.95	-9.09	33.86	12.74
	(1.22)	(-.26)	(.96)	(.36)
18 Apr 13, 24:00	41.77	-17.27	24.51	28.85
	(1.18)	(-.49)	(.69)	(.82)
19 Apr 13, 24:00	42.16	-91.34	-49.18	21.68
	(1.19)	(-2.59)	(-1.39)	(.61)
20 Apr 13, 24:00	63.94	-196.51	-132.57	0.00
	(1.81)	(-5.56)	(-3.75)	(.)
21 Apr 13, 24:00	106.01	-211.37	-105.36	0.00
	(3.)	(-5.99)	(-2.98)	(.)
22 Apr 13, 24:00	143.59	-180.92	-37.34	0.00
	(4.07)	(-5.12)	(-1.06)	(.)
23 Apr 13, 24:00	157.77	-128.44	29.33	0.00
	(4.47)	(-3.64)	(.83)	(.)
24 Apr 13, 24:00	149.25	-66.52	82.74	15.45
	(4.23)	(-1.88)	(2.34)	(.44)

*Shifted row accounts for lag

A sensitivity analysis was performed at Sherwood and Minot to approximate how much negative volume was unaccounted for during four trial events. Sherwood and Minot were selected because they are important locations in the model for flood forecasting, computing the apportionment volume between the United States and Canada, and for flood risk management. A range of event magnitudes were selected to show the effect that flow in the system has on the amount of volume lost. A subset of events were selected from the index events which were scheduled to be used to evaluate modeling alternatives in future phases of the study.

- Index Years:
  - Low Flow → 1937, 1988, 2003
  - Average Flow → 1965, 1978, 1987
  - High Flow → 1969, 1976, 2011

Events selected were 1976 (a high flow event), 1978 (an average magnitude event), 2003 (a low flow event), and 2011 (a high flow event). The 1976 and 2011 events were selected because they represent a typical large flood and an extreme flood, respectively. The 1978 event was selected because it represented typical conditions in the basin when not in a severe flood or drought. Index years considered for assessing the low flow conditions were 1937, 1988, and 2003. Negative flows were assumed to have a greater impact on volume in the system during low flow years based on the discussion in the previous paragraphs. The 2003 event was selected for this negative flow analysis because it was the only index year which did not occur during a prolonged period of drought and the reservoirs were operating under the plan identified in Annex A and Annex B. The observed, regulated data from the 2003 event was influenced by the current operating plan which allowed for a better comparison to the simulated ResSim results.

To assess the magnitude of negative flows unaccounted for within the model, flow hydrographs were compared at the upstream and downstream ends of the routing reaches. The junctions selected to approximate the total unaccounted for negative flow volume by the time it reaches Sherwood and Minot are outlined below:

- Locations where Local Flows are analyzed upstream of Sherwood:
    - Estevan junction
    - Roche Percee junction
    - Oxbow junction
    - Glen Ewen junction
- Locations where Local Flows are analyzed upstream of Minot:
    - Sherwood junction
    - Foxholm Des Lacs junction
    - Des Lacs Confluence junction

The unaccounted for, negative flow volume is equivalent to the negative flow volume not offset by the upstream flow contribution. These values are summed up for all the junctions listed above. Note that this approximation of the negative flow volume ignores any lag and attenuation that might occur as a result of routing negative from upstream to downstream.

The sensitivity analysis was performed for Sherwood and Minot for the regulated case (ResSim pathname: FLOW) and the unregulated case (ResSim pathname: FLOW-UNREG) since different model calculations and decisions depend on these different types of time series. The results at Sherwood are shown in Table 14 and account for attenuation and lag

Table 15, below. The estimated percent error in volume (column 6) is determined using the amount reported by the ResSim model (column 4) at Sherwood and the estimated amount that would have been reported, had the zero flow values not been zeroed out (column 5). The amount of volume that would have been reported at the gage (column 5) is calculated as the sum of the amount of volume the ResSim model reported (column 4) and the negative flow volume zeroed out in the routing reaches (column 3) above Sherwood.

For regulated flow conditions, negative inflows do not significantly impact high and average events but may impact low flow events combined with minimum flow requirements. For example, if a negative local flow at Sherwood of 100 ft³/s (2.83 m³/s) occurs, the model would try to release something substantially greater than 100 ft³/s (2.83 m³/s) several days prior to account for travel time and attenuation. This is discussed within the calibration section and is included as a limitation in the model.

Table 14 Estimated missing negative flow volume at Sherwood, regulated case

Index Year		FLOW Regulated Case			
[1] Year	[2] Flood Event Description	[3] Estimated Negative Flow Volume Zeroed out by ResSim Model and Not Included at Sherwood, ac-ft (dam³)*	[4] Total Simulated Volume Available in ResSim Model at Sherwood, ac-ft (dam³)	[5] Estimated Volume at Sherwood Had Negative Flow Volumes Been Maintained (Not Zeroed Out) In ResSim Model, ac-ft (dam³)	[6] Estimated Percent Error in Volume (%)
1976	High flow year	-388.5	596,592.7	596,204.2	0.07
		(-479.2)	(735,898.18)	(735,418.98)	
1978	Average year	-1,528.7	50,358.9	48,830.2	3.13
		(-1,885.69)	(62,117.82)	(60,232.13)	
2003	Low flow year	-1.7	36,591.9	36,590.2	0.00
		(-2.13)	(45,136.19)	(45,134.06)	
2011	High flow year	0.0	1,706,245.0	1,706,245.0	0.00
		(.)	(2,104,656.51)	(2,104,656.51)	

*Estimate of zeroed out negative inflow volume does not account for attenuation and lag

Table 15 Estimated missing negative flow volume at Sherwood, unregulated case

Index Year		FLOW-UNREG Unregulated Case			
[1] Year	[2] Flood Event Description	[3] Estimated Negative Flow Volume Zeroed out by ResSim Model and Not Included at Sherwood, ac-ft (dam³)*	[4] Total Simulated Volume Available in ResSim Model at Sherwood, ac-ft (dam³)	[5] Estimated Volume at Sherwood Had Negative Flow Volumes Been Maintained (Not Zeroed Out) In ResSim Model, ac-ft (dam³)	[6] Estimated Percent Error in Volume (%)
1976	High flow year	-8,352.0	647,360.6	639,008.6	1.31
		(-10,302.24)	(798,520.55)	(788,218.31)	
1978	Average flow year	-2,018.8	120,402.6	118,383.9	1.71
		(-2,490.14)	(148,516.89)	(146,026.75)	
2003	Low flow year	-12,268.3	92,790.7	80,522.4	15.24
		(-15,133.01)	(114,457.51)	(99,324.49)	
2011	High flow year	-9,368.9	1,740,582.5	1,731,213.6	0.54
		(-11,556.53)	(2,147,011.84)	(2,135,455.31)	

*Estimate of zeroed out negative inflow volume does not account for attenuation and lag

The results for the regulated sensitivity analysis and unregulated sensitivity analysis at Minot are shown in ***Table 16*** and ***Table 17*** below. The estimated percent error in volume (column 6) is determined using the amount reported by the ResSim model (column 4) at Minot and the estimated amount that would have been reported (column 5) had negative flows been maintained in the system. The amount of volume that would have been reported at the gage (column 5) is calculated as the sum of the amount of volume the ResSim model reported (column 4) and the negative flow volume zeroed out in the routing reaches (column 3) above Minot.

For the regulated case, the estimated percent error in volume is low for the high flow events and the low flow event. The percent error for the average flow event is slightly larger, but overall the model still closely estimates the volume in the system. The regulated case typically has enough volume to preserve conservation of mass.

Table 16 Estimated missing negative flow volume at Minot, regulated case

Index Year		FLOW Regulated Case			
[1] Year	**[2] Flood Event Description**	**[3] Estimated Negative Flow Volume Zeroed out by ResSim Model and Not Included at Minot, ac-ft (dam³)***	**[4] Total Simulated Volume Available in ResSim Model at Minot, ac-ft (dam³)**	**[5] Estimated Volume at Minot Had Negative Flow Volumes Been Maintained (Not Zeroed Out) In ResSim Model, ac-ft (dam³)**	**[6] Estimated Percent Error in Volume (%)**
1976	High flow year	-867.3	731,068.4	730,201.1	0.12
		(-1,069.82)	(901,774.25)	(900,704.43)	
1978	Average year	-3,350.2	38,975.5	35,625.4	9.40
		(-4,132.46)	(48,076.41)	(43,943.95)	
2003	Low flow year	-606.5	28,534.9	27,928.4	2.17
		(-748.13)	(35,197.82)	(34,449.69)	
2011	High flow year	0.0	2,021,162.5	2,021,162.5	0.00
		(0.0)	(2,493,107.84)	(2,493,107.84)	

*Estimate of zeroed out negative inflow volume does not account for attenuation and lag

For the unregulated case at Minot, the amount of volume lost during the high and average flow years is negligible and would not impact the results of the model in a significant way. During the low flow event, the missing volume represents a 10% difference in the overall volume of the model.

Table 17 Estimated missing negative flow volume at Minot, unregulated case

Index Year		FLOW-UNREG Unregulated Case			
[1] Year	[2] Flood Event Description	[3] Estimated Negative Flow Volume Zeroed out by ResSim Model and Not Included at Minot, ac-ft (dam³)*	[4] Total Simulated Volume Available in ResSim Model at Minot, ac-ft (dam³)	[5] Estimated Volume at Minot Had Negative Flow Volumes Been Maintained (Not Zeroed Out) In ResSim Model, ac-ft (dam³)	[6] Estimated Percent Error in Volume (%)
1976	High flow year	-8,462.7	819,954.6	811,491.9	1.04
		(-10,438.77)	(1,011,415.54)	(1,000,976.77)	
1978	Average flow year	-2,201.8	166,763.2	164,561.5	1.34
		(-2,715.89)	(205,702.77)	(202,986.87)	
2003	Low flow year	-12,318.4	138,710.8	126,392.5	9.75
		(-15,194.74)	(171,100.08)	(155,905.34)	
2011	High flow year	-9,368.9	2,073,001.0	2,063,632.1	0.45
		(-11,556.53)	(2,557,050.7)	(2,545,494.17)	

*Estimate of zeroed out negative inflow volume does not account for attenuation and lag

3.3.2.1 Negative Flow Impact to Model Results

It is not anticipated that the negative flow values will have a significant impact on the results for the regulated case at Sherwood or Minot or for unregulated cases when high or moderate flows are present in the system. The cumulative, unregulated volume at Sherwood is used to trigger flood operations, maximum downstream release rules at Sherwood and Minot, and to initiate an extended drawdown at Lake Darling. A minimal amount of negative flow may not be accounted for within the computation of cumulative unregulated flow at Sherwood. Because these computations are only carried out for high flow conditions it can be assumed that the impact of not accounting for negative flows will have a negligible impact on modeled flood operations.

The error in model results at Sherwood or Minot is likely to be highest for the unregulated case, under low flow conditions. Negative values can cause oscillations in releases to maintain a minimum flow of 4 ft³/s (0.113 m³/s) at Sherwood. This could result in releasing more volume to fulfill the minimum flow requirement. However, the apportionment calculation uses the total inflow above Sherwood, which is not routed, and is not affected by the negative values.

3.3.3 Net Evaporation, Direct Water Use, and Seepage

Seepage loss, water usage, and not accounting for net evaporation (evaporation minus precipitation) on the pool will typically not have a large impact on modeled operations during wet years. During dry years, with minimal or no releases, not modeling these inputs and losses accurately will result in an accumulation of error that can significantly impact the model's ability to accurately simulate the reservoir pool elevation. The HEC-ResSim model developed in support of the PoS explicitly accounts for these inputs and losses to minimize error and also

position the model to be used with datasets other than those generated using historically observed flows. Table 18 summarizes inputs/losses explicitly modeled within ResSim.

Table 18 Summary of where Net Evaporation, Direct Water Usage and Seepage is modeled

	Modeling Approach	Rafferty Reservoir	Boundary Reservoir	Grant Devine Lake	Lake Darling
Net Evaporation	**External Time series**	x	x	x	x
Direct Water Use	**External Time series**	Included in Seepage	x	-	-
Seepage Loss	**Constant Loss Function**	x	-	-	-
Pumped Pipeline Flows	**Operational Rules**	x	x	-	-

3.3.3.1 Net Evaporation

Direct precipitation on the pool can be a significant source of inflow during dry years and is dependent on the reservoir surface area. Likewise, evaporation can be a significant loss that varies with reservoir surface area. An external net evaporation time series is used to account for the impacts of direct precipitation and evaporation for all reservoirs (ISRB, 2019). Details related to how this net evaporation time series was generated is described within the HH1 report documentation.

3.3.3.2 J. Clark Salyer National Wildlife Refuge Gross Evaporation

The J. Clark Salyer National Wildlife Refuge used monthly, gross evaporation data based on pan evaporation data collected in Minot, ND by the National Oceanic and Atmospheric Administrations (NOAA) National Climatic Data Center (NCDC). The class A pan evaporation factor was used to adjusted recorded pan evaporation to gross evaporation. Additional information can be found in the HH1 documentation.

3.3.3.3 Direct Water Use

Direct water usages consist of water being withdrawn directly from the reservoir pool. There is uncertainty in the quantity of direct water use which occurs at Boundary Reservoir and it is known that this quantity varies from year to year. As a result, inflows to Boundary Reservoir are defined using the observed flow record from the Long Creek near Noonan, ND USGS gage (ID 05113600).

Two external time series representing direct water use by the City of Estevan and SaskPower are applied to Boundary Reservoir (ISRB, 2019). The water use by SaskPower includes the forced evaporation loss at Boundary Reservoir induced by the power plant for cooling operations. There are currently four separate water allocations from Boundary Reservoir which account for a maximum total diversion from the Reservoir of 14,851 dam^3 (12,040 acre-feet). Approximately 80% of this total diversion is allocated to SaskPower through two licenses and 20% is allocated to the City of Estevan. ***Table 19*** shows the individual water use licenses and the total diversion allocated for each license (WSA, 2019). Because actually water use is unavailable for most

diversions, the model assumes all the water licensed is used each year with the exception of the Rafferty to Boundary diversion.

Table 19 Current Water license from Boundary Reservoir

License Information		Allocation		Losses		Total Diversion (Allocation plus Losses)	
License #	Use Category	(dam^3)	(ac-ft)	(dam^3)	(ac-ft)	(dam^3)	(ac-ft)
9093	Municipal	1,752	1,420	0	0	1,752	1,420
16736	Industrial	1,300	1,054	0	0	1,300	1,054
5904	Industrial	8,000	6,486	2,455	1,990	10,455	8,476
1047	Municipal	1,332	1,080	12	10	1,344	1,090
Total		**12,384**	**10,040**	**2,467**	**2,000**	**14,851**	**12,040**

The direct water use at Boundary Reservoir includes permitted water use by SaskPower, as well as forced evaporation from Boundary Reservoir which occurs as a result of the Reservoir being used as cooling water for the SaskPower plant. Forced evaporation from Boundary Reservoir is accounted by the water use licenses which SaskPower maintains. SaskPower reports on the annual water balance of Boundary Reservoir. It is assumed that the water licenses held by SaskPower include all the consumptive use allotted to SaskPower including forced evaporation which is accounted for in the water balance calculation (WSA, 2019).

The estimated water use volume from Boundary reservoir applied in the model is equivalent to the total volume that has been granted for SaskPower (11,755 dam^3/year [9,530 acre-feet/year] including losses) and the City of Estevan (3,096 dam^3/year [2,510 acre-feet/year]). The annual volumes are distributed on a monthly basis according to ***Table 20*** and ***Table 21*** (WSA 2019b). The total diversion volume and estimated monthly distribution of the water use was used to generate a time series of water use for each month of the year and is input into the ResSim model.

Table 20 Estimated monthly distribution of SaskPower water use from Boundary Reservoir

Total Diversion Volume	Estimated monthly distribution (%) of SaskPower Water Usage from Boundary Reservoir											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
11,755 dam^3 (9,530 ac-ft)	8.1	6.5	6.1	6.1	6.2	7	7	9.3	11.4	11.4	11.4	9.5

Table 21 Estimated monthly distribution of water use from Boundary Reservoir for Estevan

Total Diversion Volume	Estimated monthly (%) distribution of water usage from the City of Estevan.											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3,096 dam^3 (2,510 ac-ft)	7.5	7.5	8	8	8.3	9	10	10	8.2	8	8	7.5

Relatively little direct water use on the order of 0.02 m^3/s to 0.05 m^3/s (1 ft^3/s to 2 ft^3/s) occurs at Rafferty Reservoir (ISRB, 2019). This water use was not explicitly accounted for, but implicitly included as part of the assumed seepage loss.

3.3.3.4 Seepage Loss

As part of HH1, reverse reservoir routing is used to estimate inflow records to the reservoirs. Reverse routing relies on a mass balance computation and thus the resulting inflow record will include any errors in observed data and the cumulative effect of any losses or gains that were not explicitly accounted for. When the cumulative impact of net losses not directly accounted for is greater than the amount of runoff which reached the reservoir (or other sources of inflow not explicitly accounted for) this results in a negative computed inflow. Studying significant and reoccurring instances of negative inflows can provide insight into unaccounted for losses.

Such a loss was found after examining the originally computed inflow record to Rafferty Reservoir. ***Table 22*** shows the average monthly reverse routed inflows for Rafferty Reservoir from 1992-2017. During the winter months, when the reservoir is iced over, a negative inflow of roughly 0.283 m^3/s (10 ft^3/s) was computed using reverse routing. Since evaporation is typically negligible during the winter months and there does not appear to be direct water use that can explain this loss, it can likely be attributed to seepage. A minimal amount of direct water usage does occur, but it is an order of magnitude lower than the computed negative, inflow volumes.

Table 22 HH1 derived average monthly Rafferty Reservoir inflows with and without seepage from 1992-2017

Month	Avg. Monthly Inflow, ft^3/s	Avg. Monthly Inflow, m^3/s	Avg. Monthly Inflow w/ seepage, ft^3/s	Avg. Monthly Inflow w/ seepage, m^3/s
1	-8.7	-0.25	2.4	0.07
2	-9.7	-0.27	1.4	0.04
3	108	3.06	119.2	3.38
4	533.3	15.10	545.1	15.44
5	250.1	7.08	262.3	7.43
6	285.3	8.08	297.5	8.43
7	101.7	2.88	113.8	3.22
8	17.3	0.49	29.3	0.83
9	-4.3	-0.12	7.5	0.21
10	-14.7	-0.42	-3	-0.08
11	-29.8	-0.84	-18.1	-0.51
12	-11.8	-0.33	-0.5	-0.01

A seepage loss that is assumed to be constant at all pool elevations is unlikely and would result in disproportionally high losses when the pool is low. Estimates of seepage loss rates based on local soil properties were provided by the WSA for Rafferty Reservoir (WSA, 2019). These relationships were used to develop a function which assigns a seepage loss to the reservoir for a given observed pool elevation. A linear seepage relationship varying from 0.51 m^3/s (18 ft^3/s) at

the Maximum Allowable Flood Level (MAFL) of 554.0 m (1817.59 ft) to 0 m^3/s (0 ft^3/s) when the pool is dry is used. This results in an average seepage of roughly 0.283 m^3/s (10 ft^3/s). The seepage loss is assumed to include the known (but, relatively insignificant) direct water use.

Inflows were recomputed using the seepage function. The average monthly inflows computed after seepage is directly accounted for are summarized in ***Table 22***, which shows that when seepage is considered in the calculation, the average inflow value is closer to zero which is what is expected during the winter months.

3.3.4 Downstream Water Use

Water use that occurs downstream of the reservoirs was considered in model development. Within the study area, significant water usages, defined as appropriations that exceed 6,167 dam^3/year (5,000 acre-feet/year), occur to meet the water supply needs of the Minot municipal and rural water systems and the Eaton Irrigation District (North Dakota State Water Commission, 2018). Water use permits are issued and the requestor of the permit can take less than the permit amount, but not more. Records of observed water usage are not available to use in this modeling effort. The water systems at Minot are permitted for 18,500 dam^3 (15,000 acre-feet) per year; however, records of significant water use has not been recorded to date. The Eaton Irrigation District withdraws about 15,400 dam^3 (12,500 acre-feet) per year for flood irrigation near Towner, ND (NDSWC, 2018). It is estimated that approximately 40% of the volume of water removed by the Eaton Irrigation District project is returned to the Souris River Basin (NDSWC, 2019).

Flow diversions are included in ResSim to model consumptive water use at Minot and between Towner, ND (Towner) and Bantry, ND (Bantry) as part of Eaton Irrigation. When modeling historical flows, consumptive use is implicitly accounted for within the local flows computed as part of the HH1 dataset. Thus, the diversion relationships are defined as zero when using HH1 products as model inputs. When datasets produced using precipitation-runoff models, stochastic hydrology, or climate changed traces are used in the ResSim model, the Eaton Irrigation water use is modeled explicitly using a timeseries along with a 40% return flow rate.

3.3.5 Hydrologic Routing

Routing is a process used to estimate the temporal and spatial variations of a flood hydrograph as it moves through a river reach. The effects of storage and flow resistance within a river reach are reflected by changes in the hydrograph shape and timing as the flood wave moves from upstream to downstream. Hydrologic routing is typically used in watershed simulation studies. This approach is adequate as long as there are no significant backwater effects or discontinuities in the water surface because of jumps or bores.

Hydrologic routing parameters in ResSim are adopted from the hydrologic routing model developed as part of the *2013 Regional and Reconstructed Hydrology Study*. The 2013 routing relationships were adopted based on the guidance in Engineering Manual 1110-2-1417 (USACE, 1994). The *2013 Regional and Reconstructed Hydrology Study* routing model was used to generate the HH1 dataset. As part of HH1, local flow hydrographs were approximated by routing observed flows to a downstream gaged location and assuming the difference between observed

flows at the downstream location and the routed flows observed at the upstream location is equivalent to the local flow contribution. Thus, the computed local flows are inherently dependent on and tied to the routing model applied.

Modified Puls, Muskingum, Muskingum Cunge, and direct (null) routing methods are used to route flows. Negative flows, which are common within the HH1 dataset, are set to zero in ResSim when a non-null routing method is applied. The Salyer refuge structures also play a significant role in routing flows from the Willow Creek confluence to Westhope. Table 23 summarizes the routing methods used within the model (all other reaches were modeled using direct routing).

Table 23 Summary of routing methods

Reach	Routing Method	Source
Estevan to Roche Percee	Modified Puls Routing	HH1 - 2012 hydraulic model (URS, 2012)
Roche Percee to Moose Mountain Creek	Modified Puls Routing	HH1 - 2012 hydraulic model (URS, 2012)
Oxbow to Glen Ewen	Modified Puls Routing	HH1 - 2012 hydraulic model (URS, 2012)
Glen Ewen to Sherwood	Modified Puls Routing	HH1 - 2012 hydraulic model (URS, 2012)
Sherwood to Lake Darling	Muskingum	HH1 - Ward County FIS –HEC-ResSim model (Houston Engineering, 2013)
Lake Darling to the Des Lacs River	Muskingum Cunge	HH1 - Des Lacs HEC-HMS model (WEST, 2013)
Des Lacs River - Foxholm, ND to Burlington, ND	Muskingum Cunge	HH1 - Des Lacs HEC-HMS model (WEST, 2013)
Des Lacs River to Minot, ND	Muskingum Cunge	HH1 - Des Lacs HEC-HMS model (WEST, 2013)
Logan to Verendrye	Muskingum Cunge	HH1-2013 Hydraulic Model (Barr Engineering, 2013)
Towner to Bantry	Muskingum	HH1-2013 Observed Flow Data (USACE, 2013)
Bantry to Willow Creek	Muskingum Cunge	HH1-2013 Hydraulic Model (Barr Engineering, 2013)

3.3.5.1 Routing: Souris River upstream of Sherwood Crossing

As is indicated in ***Table 24***, the average slope of the Souris River between the Canadian Reservoir projects (Grant Devine, Boundary and Rafferty) and Sherwood Crossing is less than 0.38 meters per kilometer (2 feet per mile). According to the guidance provided in Table 9-3 in EM- 1110-2-1417, when channel slopes are less than 0.38 meters per kilometer (2 feet per mile), hydraulic routing techniques (diffusion wave and full dynamic wave) or Muskingum-Cunge hydrologic routing are the preferred routing methods.

For flat reaches it is difficult to come up with a representative storage-discharge relationship. For a flat reach, the dynamic properties of a flood wave create a looped relation between storage and discharge (called hysteresis). The transverse water surface slope and storage are greater during the rising stages of a flood wave than during the falling stages. The loop effect makes it difficult

to model flood flows with a single storage-discharge relationship, based on typical routing parameters. Error increases in hydrologic routing as channel slope decreases. The HEC-ResSim model is limited to hydrologic routing techniques.

A calibrated unsteady HEC-RAS model of the Souris River developed by URS Corporation, Engineering and Design Company (URS, 2012) for the river reaches between Rafferty Reservoir and Sherwood, ND was utilized to calibrate modified puls hydrologic routing parameters utilizing 0.5, 0.75, 1, 1.25, 1.5 and 2 times the 2011 event. For the routing reach on the Souris River between Rafferty Reservoir and Estevan, SK null or direct routing was adopted. The adopted routing parameters are displayed in Table 24. The adopted storage discharge relationships are displayed in Table 25**,**

Table 26, Table 27**,** Table 28, and

Figure ***8***, Figure 9, Figure 10, and Figure 11.

Table 24 Routing method details for the Souris River upstream of Sherwood Crossing

Reach	Routing Method		Channel Slope (ft/mi)	Channel Slope (m/km)
	Adopted Routing Method	**Subreach Parameter Information**		
Souris River: Outflow Rafferty to Long Creek Confluence	Null Routing	Null	0.957	0.181
Long Creek: Outflow Boundary to Long Creek Confluence	Null Routing	Null	Null	Null
Souris River: Long Creek Confluence to Estevan	Null Routing	Null	Null	Null
Souris River: Estevan to Short Creek Confluence	Modified Puls Routing	Number of Subreaches: 1	1.384	0.262

Short Creek: Input Short Creek to Short Creek Confluence	Null Routing	Null	Null	Null
Souris River: Short Creek Confluence to Roche Percee	Null Routing	Null	Null	Null
Souris River: Roche Percee to Upstream of Moose Mountain Creek	Modified Puls Routing	Number of Subreaches: 6	0.874	0.166
Souris River: Upstream Moose Mountain Creek to Moose Mountain Creek	Null Routing	Null	Null	Null
Moose Mountain Creek: Outflow Grant Devine to Moose Mountain Confluence	Null Routing	Null	Null	Null
Souris River: Moose Mountain Confluence to Oxbow	Null Routing	Null	Null	Null
Souris River: Oxbow to Glen Ewen	Modified Puls Routing	Number of Subreaches: 1	1.264	0.239
Souris River Glen Ewen to Sherwood	Modified Puls Routing	Number of Subreaches: 2	1.239	0.235

Table 25 Routing Storage-Discharge Relationship for Mod Puls Routing – Souris River Estevan, SK to Roche Percee, SK

Estevan to Short Creek			
Volume		**Flow**	
(ac-ft)	**(dam^3)**	**(ft^3/s)**	**(m^3/s)**
-	-	-	-
1,738	2,143	1,304	36.9
2,607	3,214	2,011	57.0
3,551	4,378	2,655	75.2
4,463	5,503	3,261	92.4
5,590	6,892	4,022	113.9
6,816	8,404	4,923	139.4
8,385	10,339	6,033	170.9
9,677	11,932	7,011	198.6
10,969	13,525	8,043	227.8
12,190	15,030	9,076	257.0
13,633	16,809	10,288	291.4
14,891	18,361	11,467	324.7
16,512	20,359	12,935	366.3
18,227	22,474	15,109	427.9
20,031	24,698	17,757	502.9

21,480	26,485	20,561	582.3
24,180	29,814	26,439	748.8
26,142	32,233	30,272	857.3
30,088	37,099	37,011	1,048.2
34,457	42,485	42,663	1,208.2
36,900	45,498	45,489	1,288.2
39,557	48,774	47,971	1,358.5

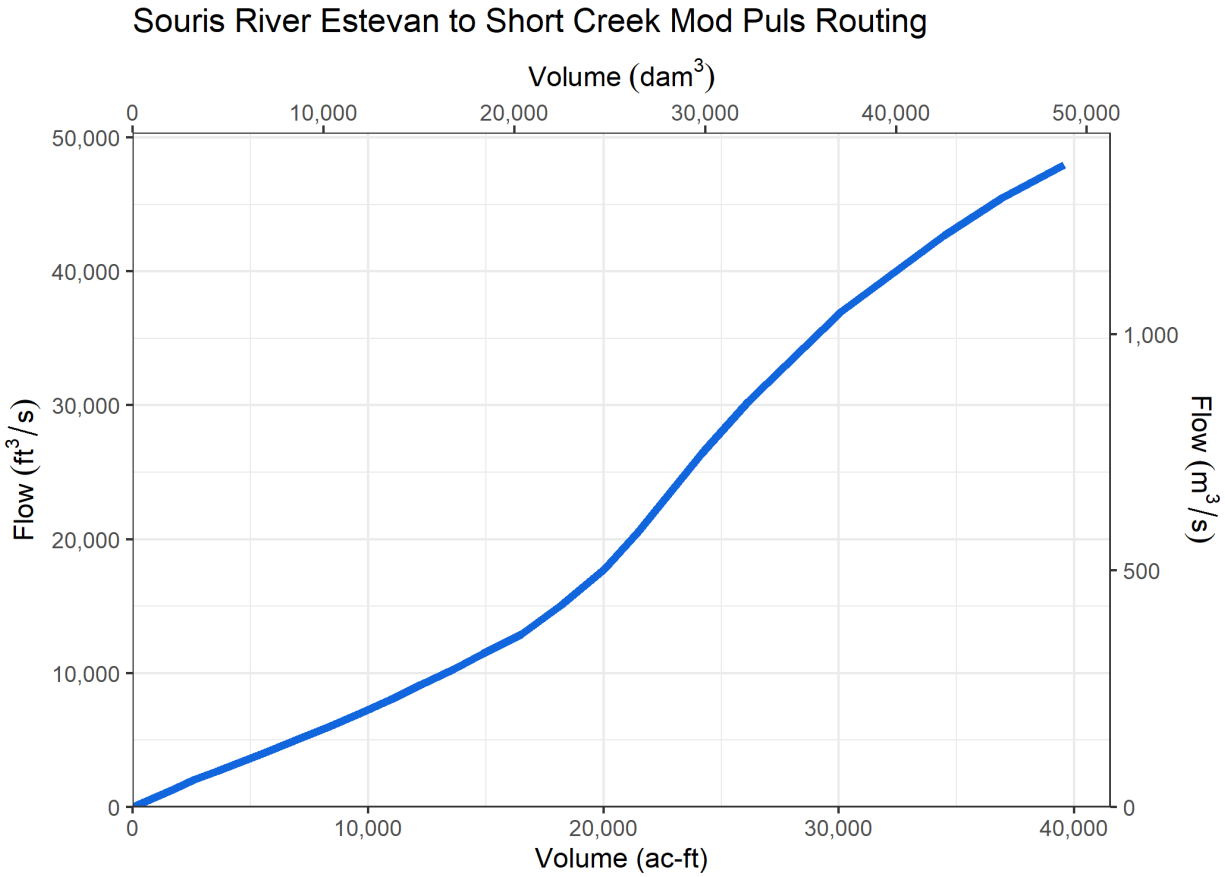


Figure 8 Graph representation of Table 25

Table 26 Routing Storage-Discharge Relationship for Mod Puls Routing – Souris River Roche Percee to Upstream of Moose Mountain Creek

Roche Percee to Moose MTN Creek			
Volume		Flow	
(ac-ft)	(dam^3)	(ft^3/s)	(m^3/s)
0	0	0	0
4,496.0	5,544	750	21.2
8,834.0	10,892	1,625	46.0
13,729.0	16,928	2,750	77.9
19,000.0	23,427	3,916	110.9
23,286.0	28,712	4,845	137.2
29,714.0	36,637	6,173	174.8
34,527.0	42,572	7,125	201.8
38,806.0	47,848	8,000	226.6
43,488.0	53,621	9,063	256.7
49,243.0	60,717	10,563	299.1
54,586.0	67,305	12,125	343.4
59,628.0	73,521	13,688	387.6
64,203.0	79,162	15,813	447.8
69,466.0	85,652	18,688	529.2
76,207.0	93,963	23,000	651.4
83,523.0	102,984	28,000	793.0
93,553.0	115,351	34,688	982.4
104,980.0	129,440	41,875	1,185.9
113,283.0	139,678	46,500	1,316.9
120,438.0	148,500	50,500	1,430.2

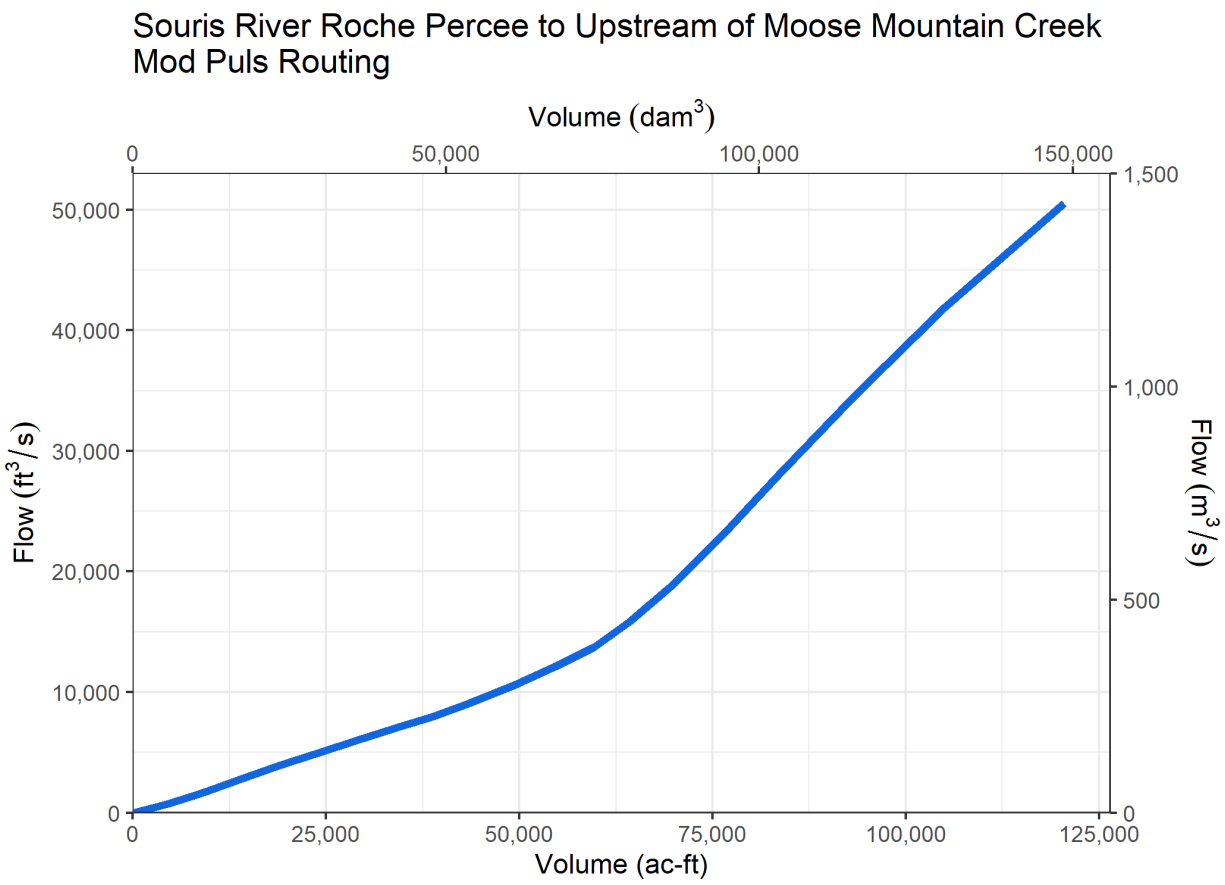


Figure 9 Graph representation of Table 26

Table 27 Routing Storage-Discharge Relationship for Mod Puls Routing – Souris River Oxbow to Glen Ewen

Oxbow to Glen Ewen			
Volume		Flow	
(ac-ft)	(dam^3)	(ft^3/s)	(m^3/s)
-	-	-	-
3,643.0	4,492	996	28.2
5,571.0	6,869	1,659	47.0
7,776.0	9,588	2,652	75.1
9,857.0	12,154	3,451	97.7
12,143.0	14,972	4,381	124.1
13,852.0	17,080	5,022	142.2
15,578.0	19,208	5,739	162.5
17,962.0	22,147	6,783	192.1
19,935.0	24,580	7,630	216.1
21,571.0	26,597	8,496	240.6
23,100.0	28,482	9,326	264.1
24,786.0	30,561	10,487	297.0
26,374.0	32,519	11,578	327.9
28,500.0	35,141	13,274	375.9
30,043.0	37,043	14,823	419.8
31,429.0	38,752	16,062	454.9
32,825.0	40,473	17,709	501.5
32,901.0	40,567	17,731	502.1
34,343.0	42,345	19,892	563.3
35,704.0	44,023	22,079	625.3
36,911.0	45,511	24,196	685.2
38,597.0	47,590	27,065	766.5
40,857.0	50,377	30,652	868.1
47,023.0	57,979	37,696	1,067.6
51,873.0	63,959	42,978	1,217.1
59,436.0	73,285	50,935	1,442.5
63,765.0	78,622	54,759	1,550.8
63,823.0	78,694	54,760	1,550.8

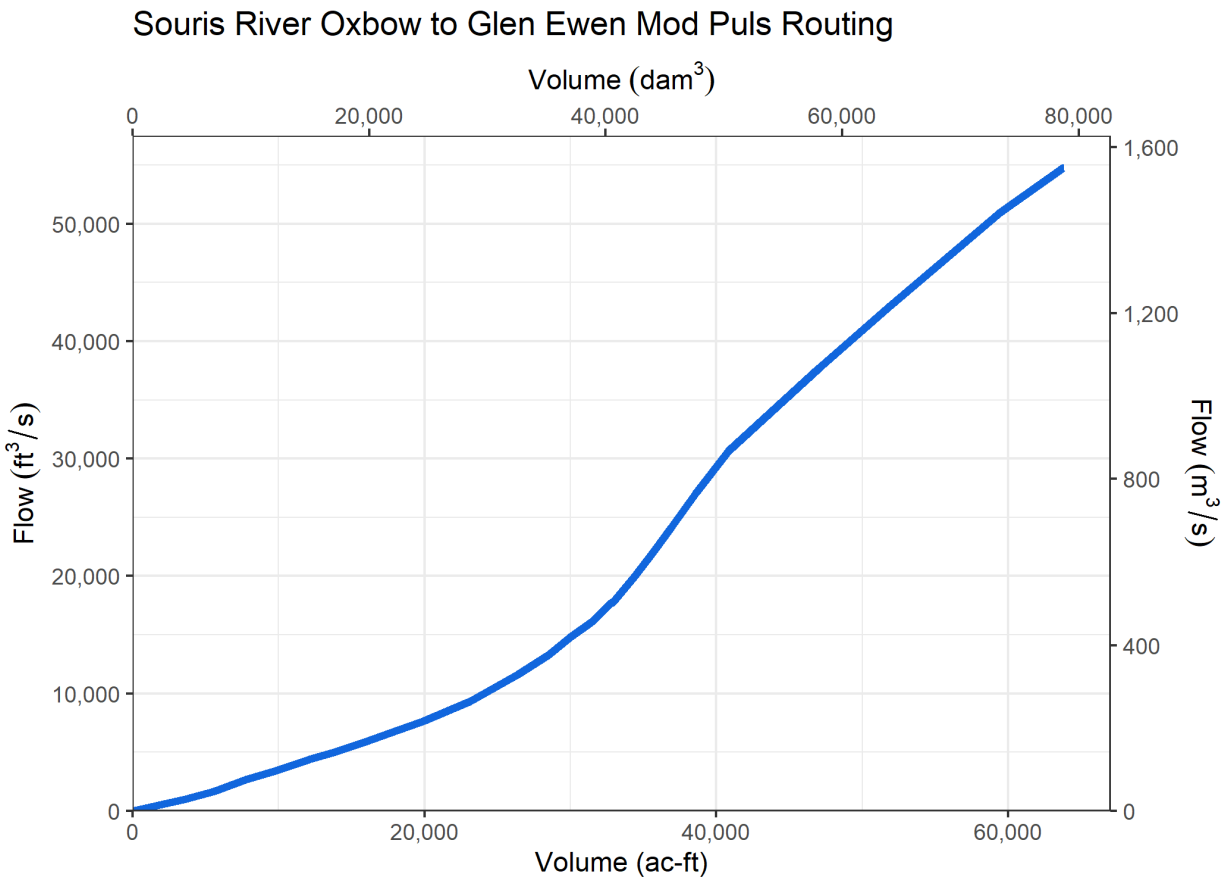


Figure 10 Graph representation of Table 27

Table 28 Routing Storage-Discharge Relationship for Mod Puls Routing – Souris River Glen Ewen to Sherwood

Glen Ewen to Sherwood			
Volume		Flow	
(ac-ft)	(dam^3)	(ft^3/s)	(m^3/s)
-	-	-	-
1,951.0	2,406	815	23.1
5,780.0	7,127	1,890	53.5
8,808.0	10,860	2,652	75.1
11,239.0	13,858	3,457	97.9
13,959.0	17,211	4,314	122.2
16,561.0	20,420	5,399	152.9
19,425.0	23,951	6,441	182.4
21,033.0	25,934	7,304	206.8
23,112.0	28,497	8,543	241.9
25,684.0	31,668	10,239	290.0
27,833.0	34,318	11,935	338.0
29,771.0	36,708	13,696	387.9
31,180.0	38,445	14,935	423.0
32,343.0	39,879	16,304	461.7
33,928.0	41,833	18,717	530.1
34,788.0	42,894	20,641	584.6
35,756.0	44,087	22,614	640.4
36,740.0	45,300	25,313	716.9
38,288.0	47,209	28,418	804.8
42,989.0	53,005	36,091	1,022.1
45,897.0	56,591	40,183	1,138.0
49,801.0	61,405	45,837	1,298.1
55,241.0	68,112	55,221	1,563.9
55,252.0	68,126	55,255	1,564.8

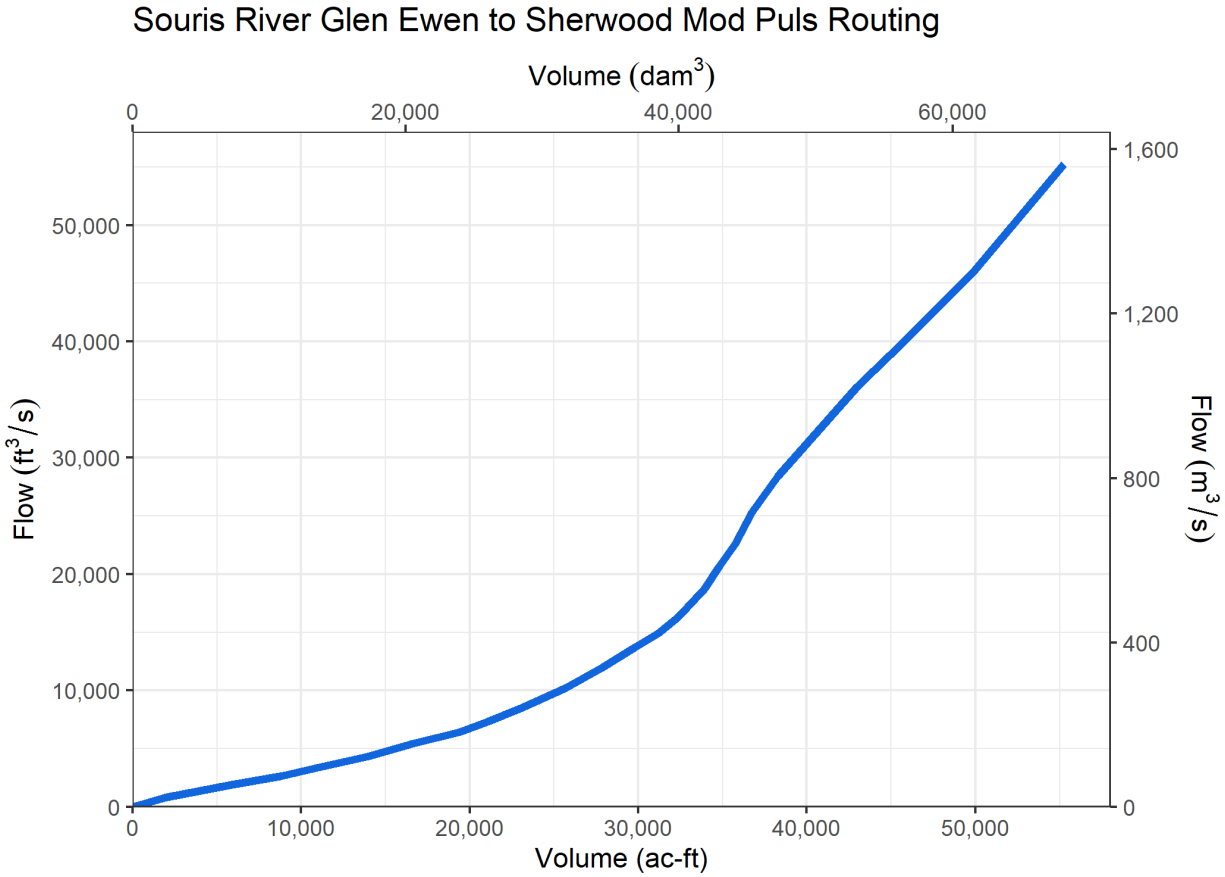


Figure 11 Graph representation of Table 28

3.3.5.2 Routing: Souris River between Sherwood Crossing and Minot, ND

A calibrated unsteady HEC-RAS model of the Souris River (Barr Engineering, 2013) and downstream extent of the model is Sherwood, ND. Various hydrologic models have been developed between Sherwood, ND and Minot, ND. Routing methods and parameters for the river reaches between Sherwood, ND and Minot, ND were adopted from the *Ward County FIS Study* HEC-ResSim model developed by Houston Engineering (Houston Engineering,2013) and the Des Lacs River HEC-HMS model developed by WEST Consultants (WEST, 2013). The adopted routing method utilized for each reach is displayed in ***Table 29***. The 8-point cross sections utilized for Muskingum Cunge Routing are displayed in ***Figure 12***, ***Figure 13***, and ***Figure 14***.

Table 29 Adopted routing parameters between Sherwood Crossing and Minot, ND

Reach	Routing Method		
	Adopted Routing Method	Parameter Information	Source
Souris River: Sherwood to Inflow Darling	Muskingum	K= 29, X=0.36, Number Subreaches = 1	Ward County FIS –HEC-ResSim model (Houston Engineering, 2013)
Souris River: Outflow Darling to Foxholm Souris River	Null Routing	Null	Null
Souris River: Foxholm Souris River to Des Lacs Confluence	Muskingum-Cunge	8 point cross section	Des Lacs HEC-HMS model (WEST, 2013)
Des Lacs River: Foxholm Des Lacs to Burlington	Muskingum-Cunge	8 point cross section	Des Lacs HEC-HMS model (WEST, 2013)
Des Lacs River: Burlington to Des Lacs Confluence	Null Routing	Null	Null
Souris River: Des Lacs Confluence to Minot, ND	Muskingum-Cunge	8 point cross section	Des Lacs HEC-HMS model (WEST, 2013)

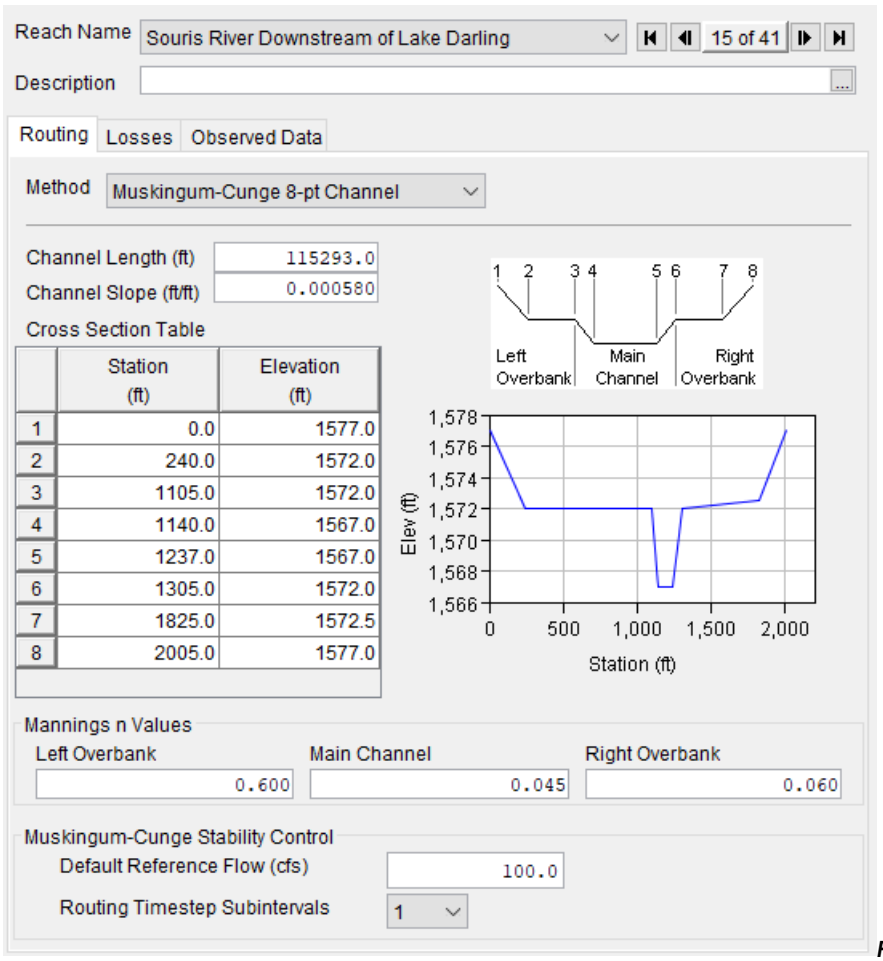


Figure 12 Muskingum Cunge Routing Parameters- Souris River: Foxholm Souris River to Des Lacs Confluence

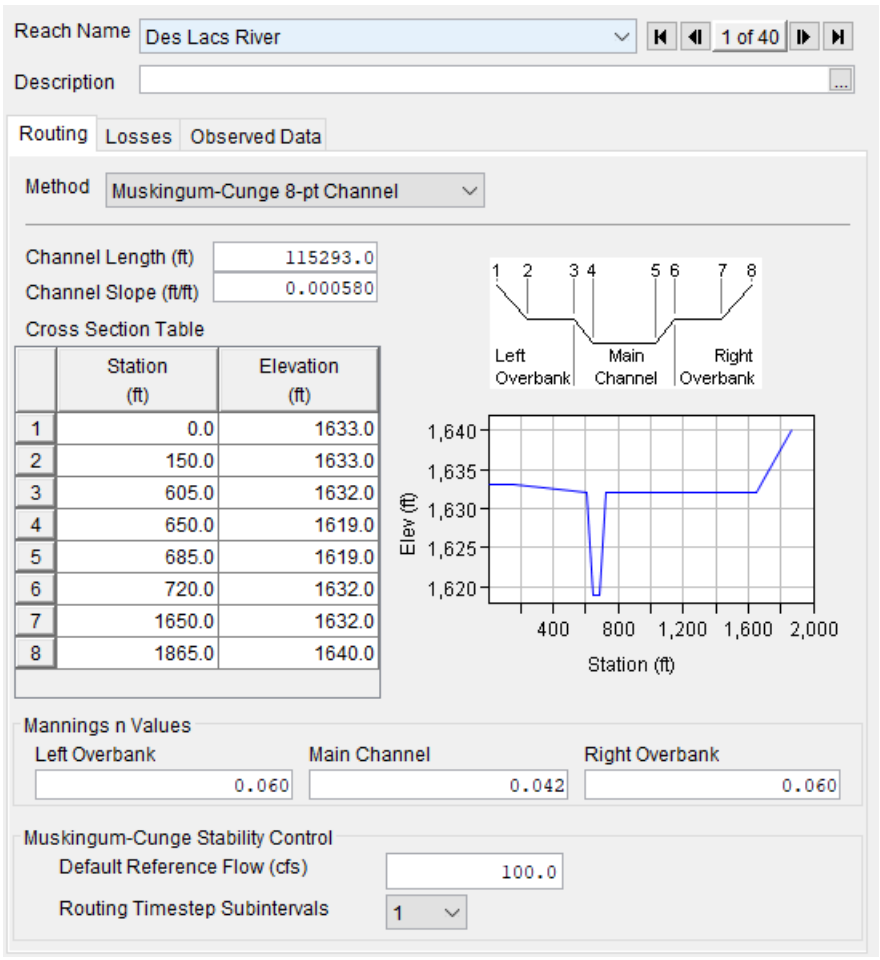


Figure 13 Muskingum Cunge Routing Parameters – Des Lacs River: Foxholm Des Lacs to Burlington

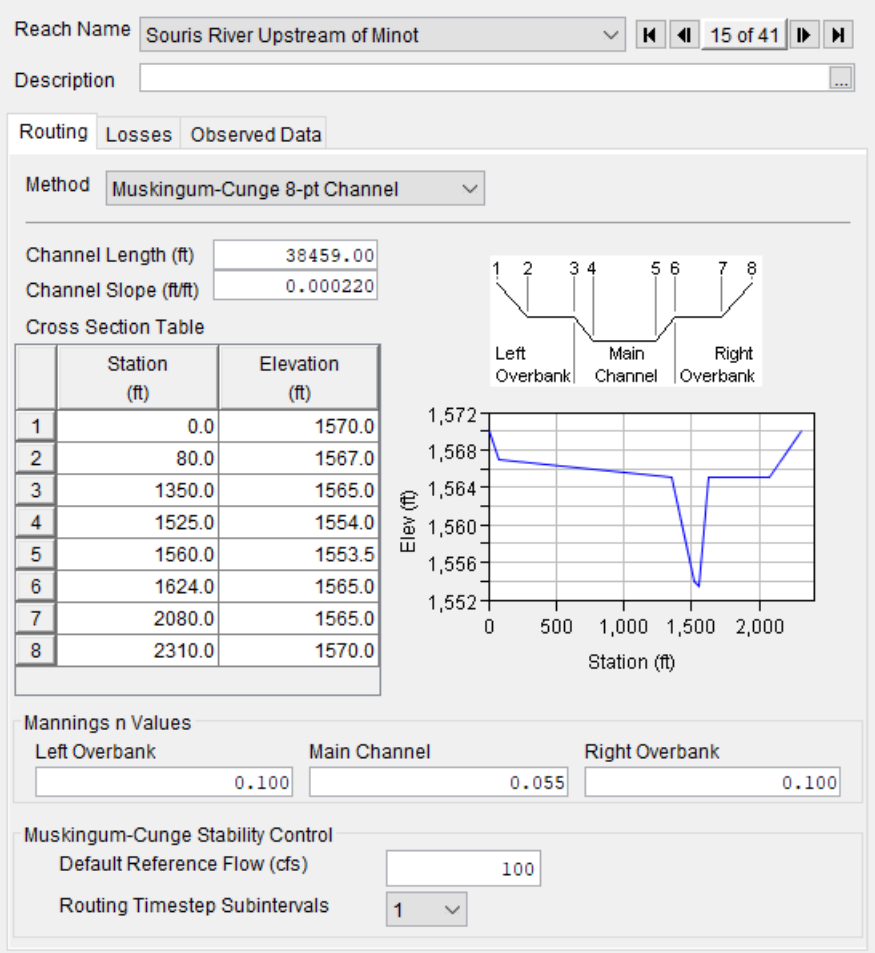


Figure 14 Muskingum Cunge Routing Parameters- Souris River: Des Lacs Confluence to Minot

3.3.5.3 Routing: Souris River between Minot, ND and Verendrye, ND

Barr Engineering developed a preliminary unsteady HEC-RAS hydraulic routing model of the Souris River that includes the Souris River between Minot, ND and Verendrye, ND. Cross section data is extracted from the unsteady HEC-RAS model in order to develop Muskingum Cunge 8 point cross section routing parameters for the river reaches between Minot, ND and Velva, ND and Velva, ND and Verendrye, ND. A summary of the routing parameters for the Souris River between Minot, ND and Verendrye, ND is displayed in ***Table 30***. The adopted routing parameters are displayed in *Figure 15* and *Figure 16*.

Table 30 Adopted routing parameters between Minot, ND and Verendrye, ND

Reach	Routing Method		
	Adopted Routing Method	**Parameter Information**	**Source**
Souris River: Minot to Logan	Null Routing	Null	Null
Souris River: Logan to Velva	Muskingum-Cunge	8 point cross section	Unsteady HEC-RAS Model (Barr Engineering, 2013)
Souris River: Velva to Verendrye	Muskingum-Cunge	8 point cross section	Unsteady HEC-RAS Model (Barr Engineering, 2013)

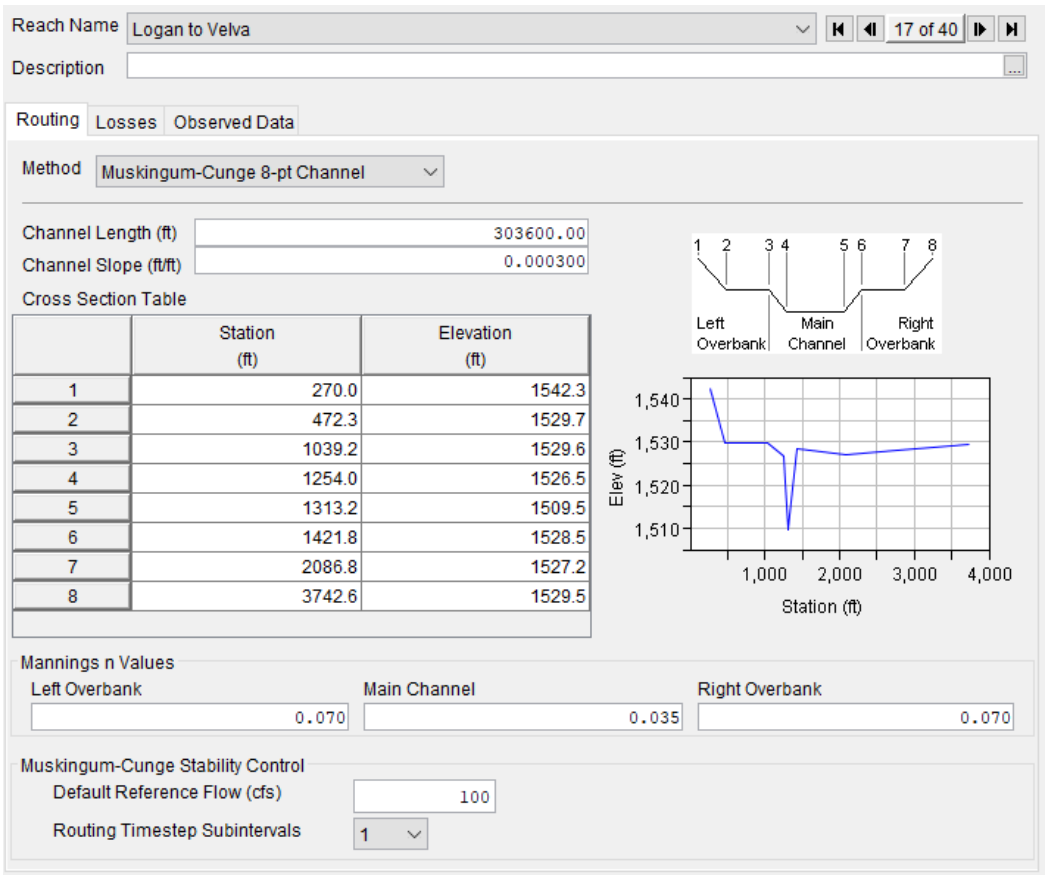


Figure 15 Routing Parameters Souris River: Logan, ND to Velva, ND

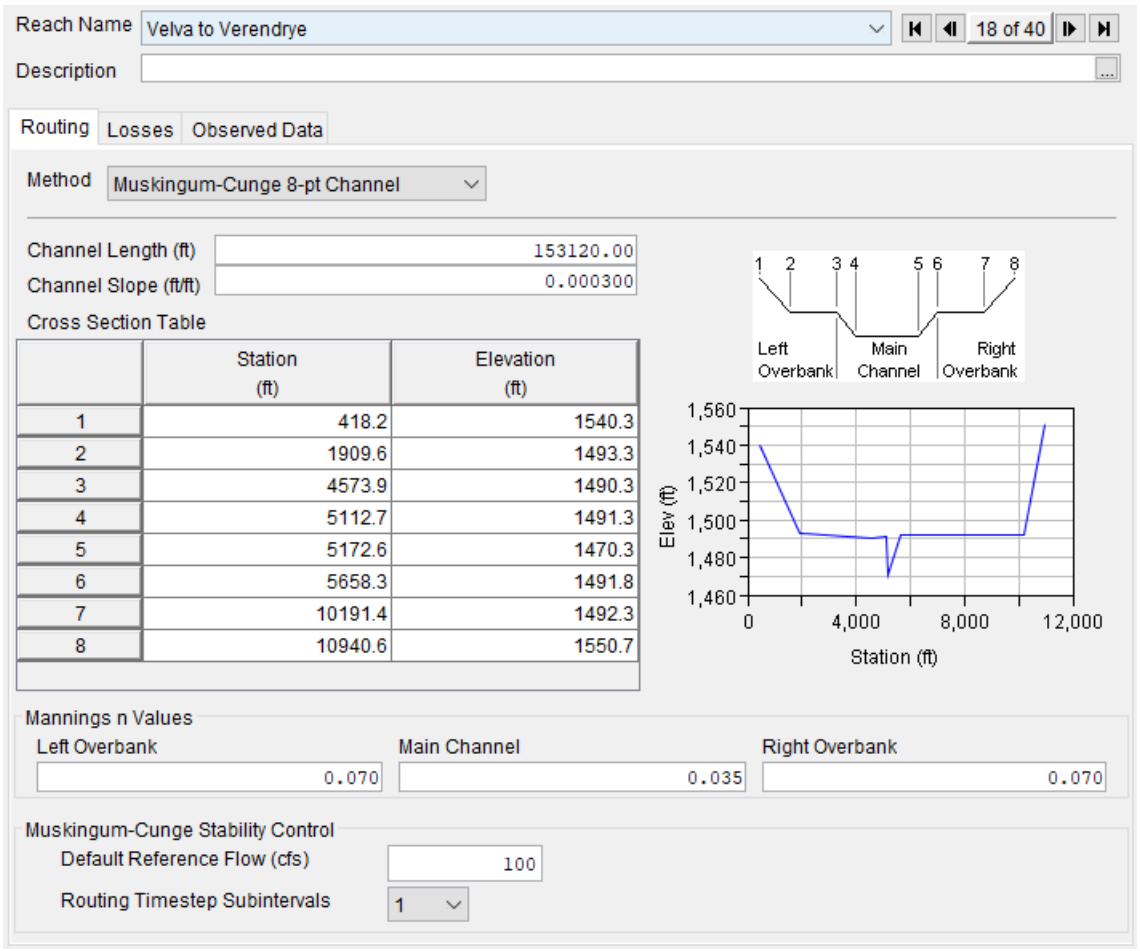


Figure 16 Routing Parameters Souris River: Velva, ND to Verendrye, ND

3.3.5.4 Routing: Souris River between Verendrye, ND and Bantry, ND

Muskingum routing is utilized to route flows from Verendrye, ND to Bantry, ND. Muskingum routing is adopted because it is difficult to obtain a single representative cross-section between Verendrye and Bantry. Additionally, the Eaton Irrigation project, formed by Eaton Dam, is located along the Souris River between Verendrye and Bantry. Eaton Dam was constructed in the 1930s. Each spring, the dam directs water into storage ponds along the Souris River reach between Verendrye and Bantry to meet agricultural water use requirements.

Routing parameters were developed by combining observed daily streamflow measurements recorded on the Wintering River with observed daily streamflow measurements recorded on the Souris River at Verendrye, ND and then adjusting Muskingum K and x parameter values along the routing reach between Verendrye and Bantry until the routed flows matched the observed flows at Bantry. A Muskingum K value of 96 hours and a Muskingum x of 0.3 were utilized to route flows between Bantry, ND and Verendrye, ND.

Table 31 Adopted routing parameters between Verendrye, ND and Bantry, ND

Reach	Routing Method		
	Adopted Routing Method	Parameter Information	Source
Souris River: Verendrye to Wintering River Confluence	Null Routing	Null	Null
Wintering River: Wintering River Input to Wintering River Confluence	Null Routing	Null	Null
Souris River: Wintering River Confluence to Towner	Null Routing	Null	Null
Souris River: Towner to Bantry	Muskingum	K= 96, X=0.30, Number Subreaches = 1	Null

3.3.5.5 Routing: Souris River between Bantry, ND and Westhope, ND

Direct/null routing is utilized to route flows along the Souris River between Willow Creek and Westhope, ND, as well as between gage sites on the intervening tributaries and their confluence with the Souris River. Muskingum Cunge 8-point cross section routing adopted from the Barr Engineering unsteady HEC-RAS model is utilized to route flows from the USGS gage site at Bantry, ND to the Souris River's confluence with Willow Creek (Barr Engineering, 2013). The adopted routing parameters are displayed in ***Figure 17***.

Table 32 Adopted routing parameters between Bantry, ND and Westhope, ND

Reach	Routing Method		
	Adopted Routing Method	Parameter Information	Source
Souris River: Bantry to Willow Creek Confluence	Muskingum-Cunge	8 point cross section	Unsteady HEC-RAS Model (Barr Engineering, 2013)
Willow Creek: Willow Creek Input to Willow Creek Confluence	Null Routing	Null	
Souris River: Willow Creek Confluence to US Dam 320	Null Routing	Null	
Souris River: DS Dam 320 to US Dam 326	Null Routing	Null	
Souris River: DS Dam 326 to Stone Creek Confluence	Null Routing	Null	
Cut Bank Creek: Cut Bank Creek Input to Cut Bank Creek Confluence	Null Routing	Null	
Deep River: Deep River Input to Cut Bank Creek Confluence	Null Routing	Null	
Cut Bank Creek: Cut Bank Creek Confluence to Deep River Confluence	Null Routing	Null	
Stone Creek: Stone Creek Input to Stone Creek Confluence	Null Routing	Null	
Stone Creek: Stone Creek Confluence to Deep River Confluence	Null Routing	Null	
Souris River: DS Dam 332 to US Dam 341	Null Routing	Null	
Souris River: DS Dam 341 to Boundary Creek Confluence	Null Routing	Null	
Boundary Creek: Boundary Creek Input to Boundary Creek Confluence	Null Routing	Null	
Souris River: DS Dam 357 to Westhope	Null Routing	Null	

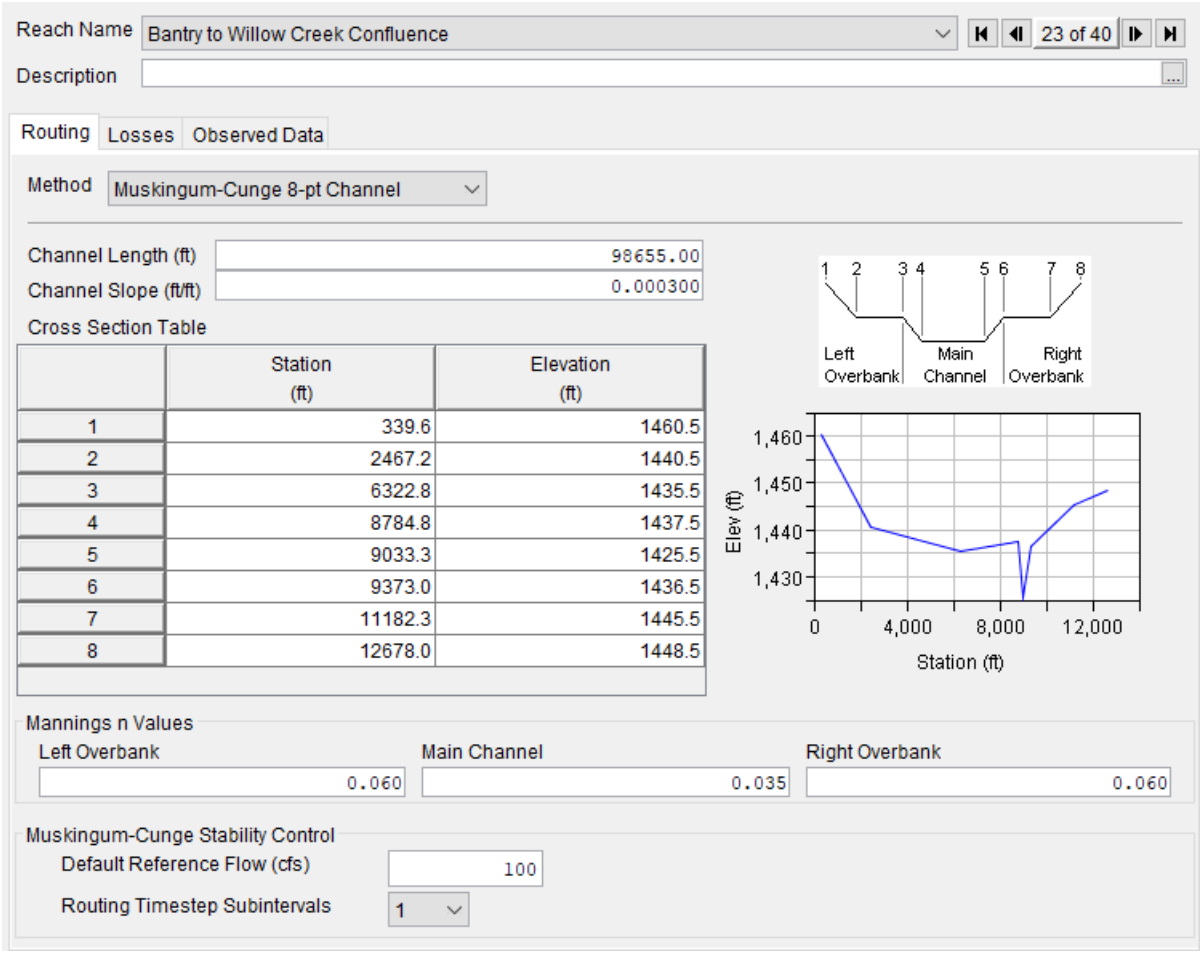
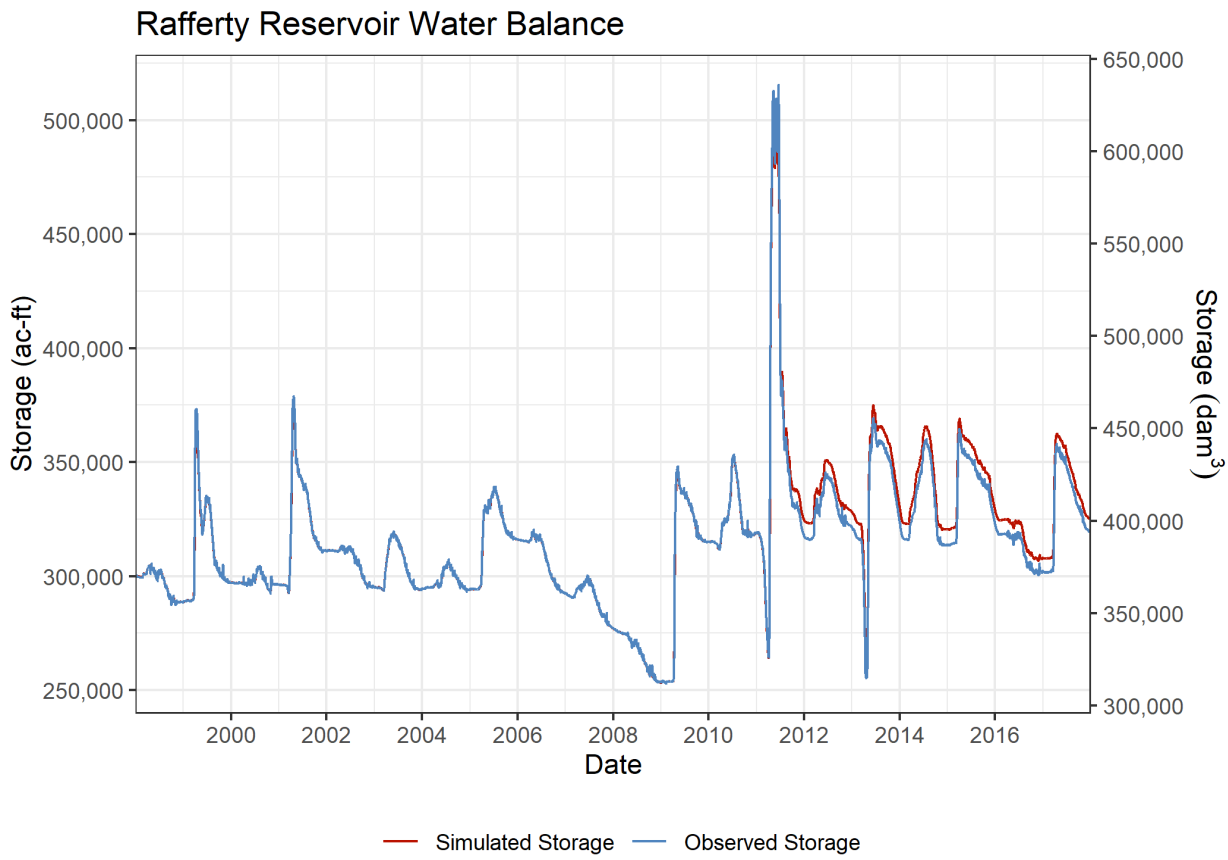


Figure 17 Routing Parameters Souris River: Bantry to Willow Creek Confluence

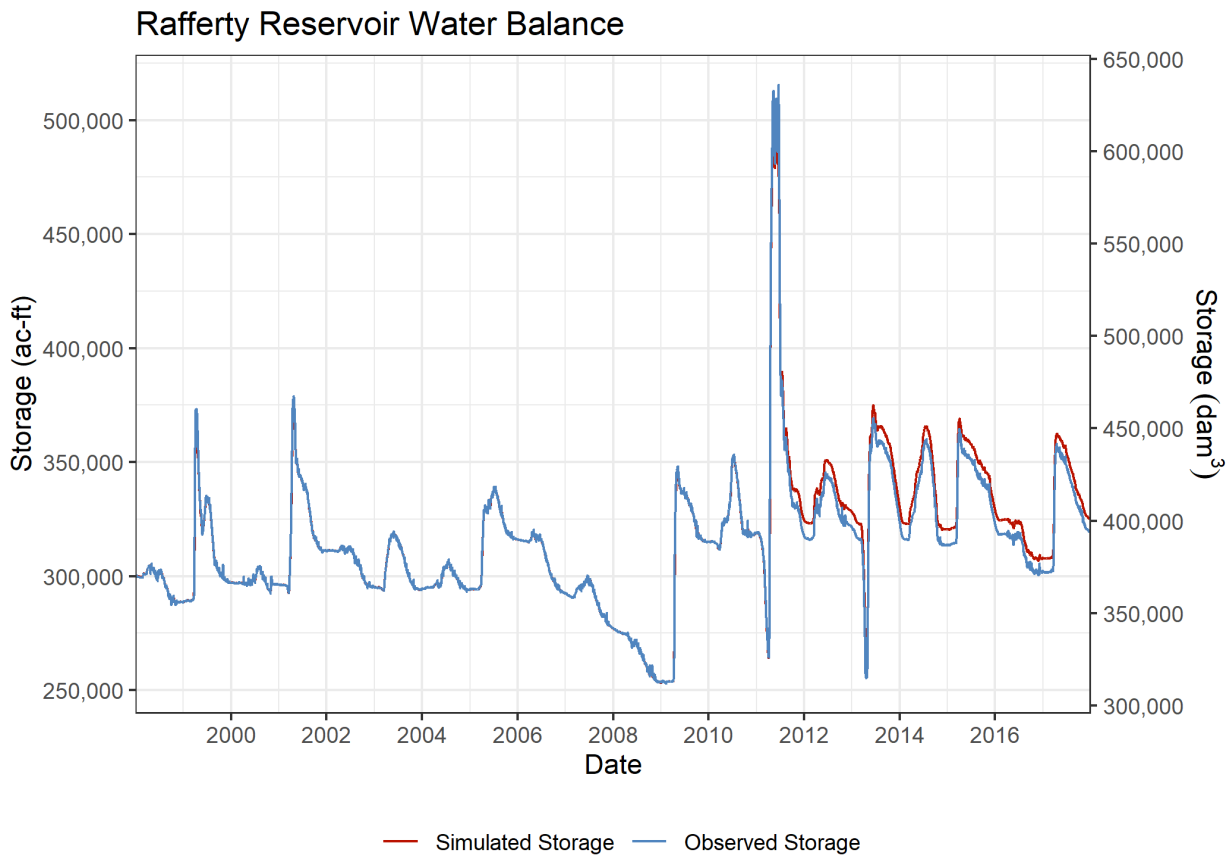
3.3.6 Verification of Model Inputs Using Water Balance Based Approach

ResSim is used to verify that the physical inputs (net evaporation, seepage, water use, runoff contributions, and physical capacity curves) to each reservoir are accounted for consistently between the ResSim model and the HH1 products. The period of record between 1998 and 2017 is used for verification of the model inputs.

Reservoir releases are defined to be equivalent to historically observed releases using release overrides in ResSim to verify the physical inputs to the model. With release overrides applied, the guide curve and all other rules are ignored but the physical inputs to the reservoir model including the computed inflows, storage-area-elevation capacity curves, outlet capacity curves and losses due to evaporation, seepage, and direct use are applied. The capacity curves, inflows, and losses are consistent with the relationships and datasets used to derive the HH1 dataset if the modeled storage (or pool elevation since each elevation value is tied to a single storage value) in the reservoir closely matches the observed storage (or pool elevation).



OBJ ***18*** shows the observed and simulated storage for Rafferty Reservoir when releases are defined to be equivalent to observed releases. There are slight differences between the two datasets, amounting to approximately 6,170 dam^3 (5,000 acre-feet). These differences can attributed to rounding differences between how the HH1 inflows were computed and how inputs are being defined and used in ResSim. The inflow datasets were developed using a reverse routing spreadsheet which rounds values differently than the ResSim model. The difference between the observed maximum and observed minimum storage during the period is roughly 310,000 dam^3 (250,000 acre-feet). The small difference between the observed and simulated storage is roughly 2% of the observed range in storage.



OBJ ***1818 Rafferty Reservoir Verification of Model Inputs Using Water Balance Based Approach (modeled outflows = observed outflows)***

The simulated storage within Grant Devine closely matches the observed storage with negligible differences as shown in

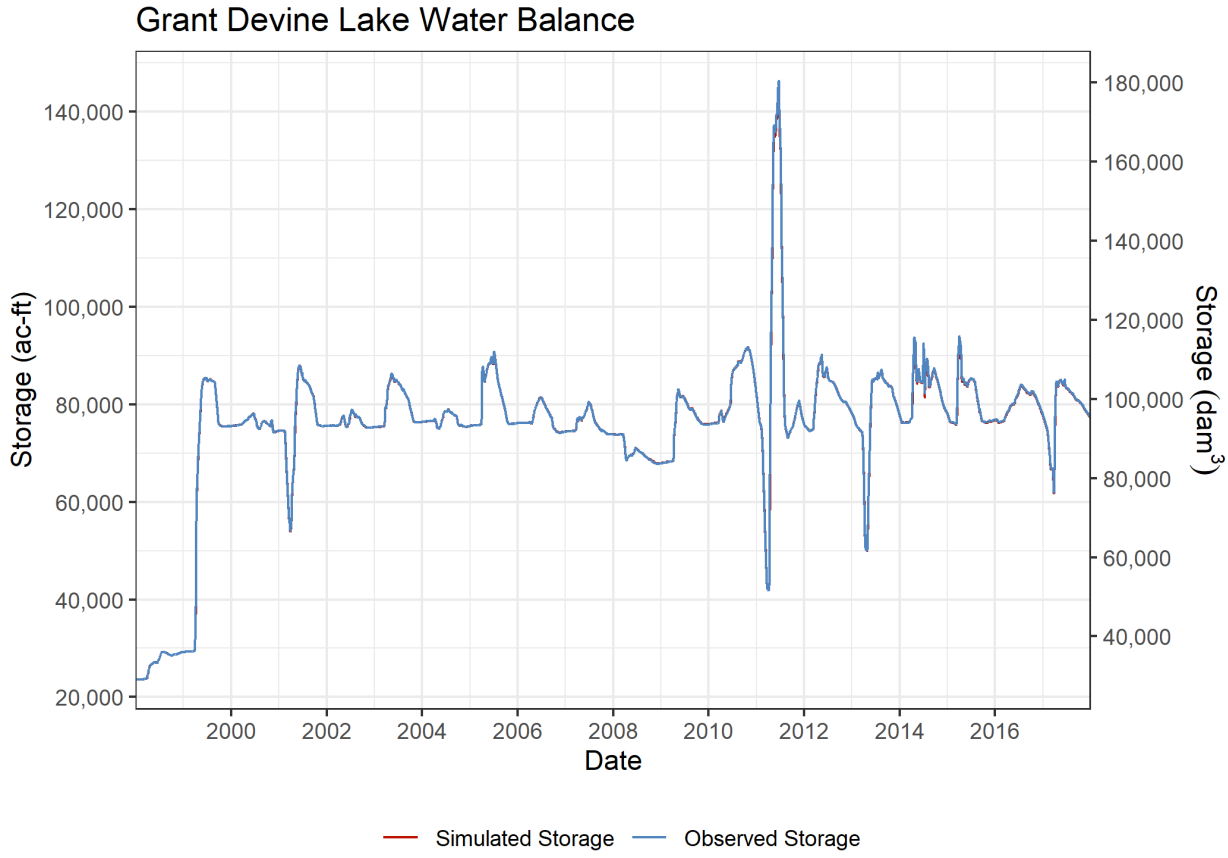


*Figure **19**.*

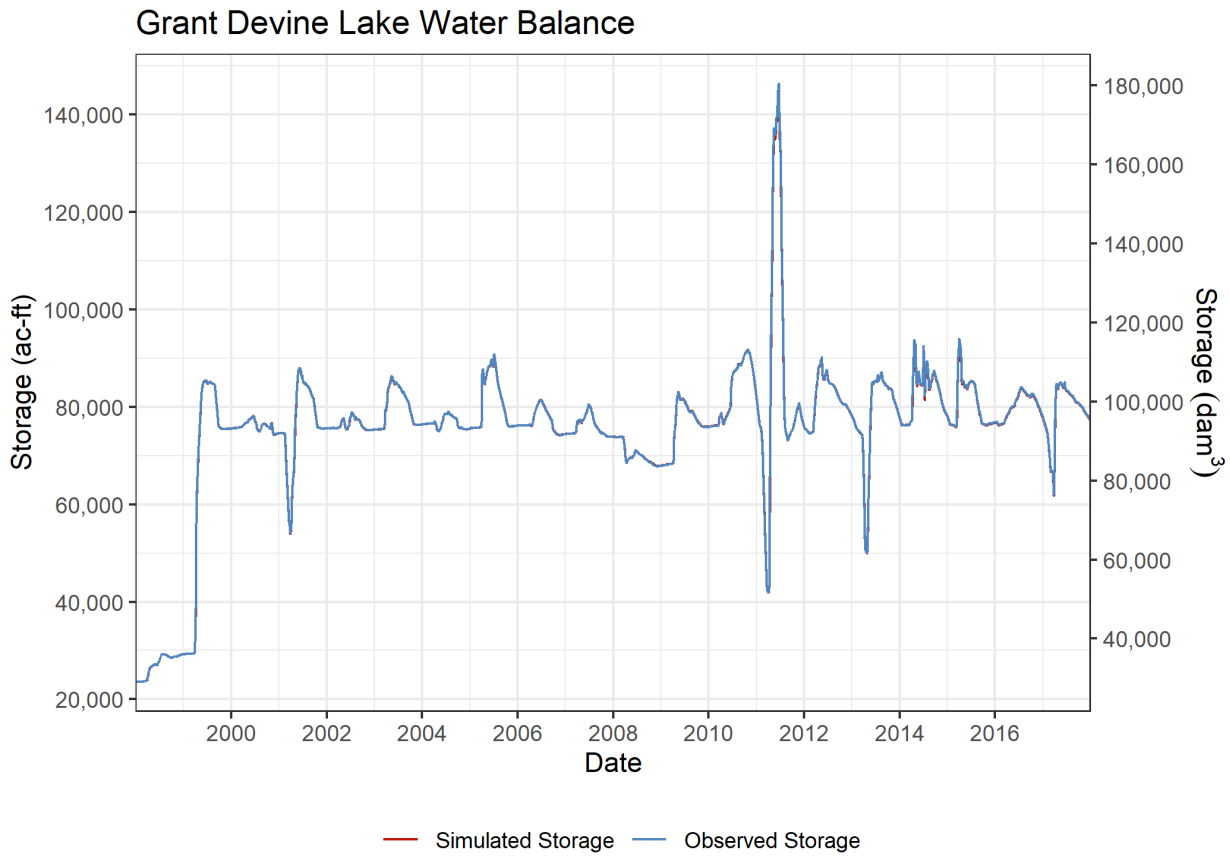


Figure 19 Grant Devine Verification of Model Inputs Using Water Balance Based Approach (modeled outflows = observed outflows)

The simulated storage within Lake Darling also matches the observed outflows closely (***Figure 20***). The difference between the observed and simulated storage is roughly 1% of the observed storage range. This small difference can be attributed to rounding differences. To carry out the verification of model inputs at Lake Darling, a ResSim network without the upstream reservoirs is used. The upstream extent of this truncated network is Sherwood gage. Observed flows at Sherwood are routed downstream to Lake Darling and combined with a local flow hydrograph defined in HH1 to approximate historical inflows to Lake Darling.

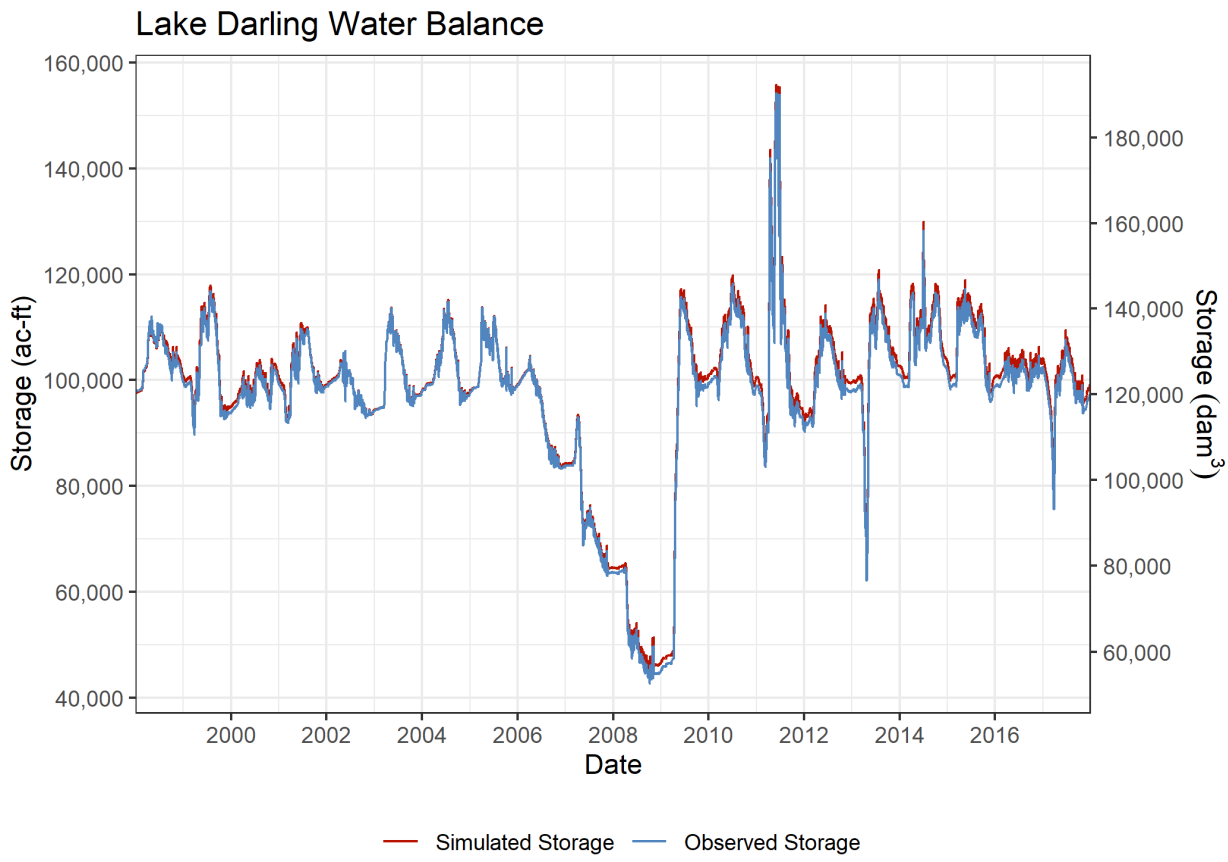


Figure 20 Lake Darling Verification of Model Inputs Using Water Balance Based Approach (modeled outflows = observed outflows)

3.3.6.1 Boundary Reservoir Mass Balance Verification

The inflows for Boundary Reservoir are defined within the final model runs using the flows recorded at the Long Creek near Noonan, ND USGS gage (ID 05113600). Recorded flows upstream of Boundary were adopted because the streamflow gage captures approximately 95% of the drainage area and it was assumed to be the most accurate inflow record taking into consideration all the water uses from Boundary.

A mass balance based verification run was carried out to validate that the elevation-area-storage relationship, net evaporation, piped flow from Rafferty, water usages and diverted outflows from Boundary are inputted in the model correctly. To verify the mass balance computation, inflows to Boundary Reservoir were computed using a reverse routing procedure. Components of the water balance for Boundary Reservoir necessary to estimate the inflow are listed in ***Table 33*** along with where the data was obtained. All data was verified to ensure that the time series information used in the Rafferty Reservoir reverse routing calculation and the Boundary Reservoir reverse routing calculation are consistent.

Table 33 Components of volume to account for in Boundary Reservoir Mass Balance Sensitivity Analysis

Reverse Routing Component	Notes
Outflow from reservoir	Long Creek near Estevan ECCC gaging station 05NB001
Boundary Diversion Canal	Rafferty Reservoir reverse routing spreadsheet/ResSim model – observed flows
Storage volume	Observed changes in daily pool elevation
Rafferty to Boundary Pipeline	Rafferty Reservoir reverse routing spreadsheet/ResSim model
Net Evaporation	From WSA, includes net effect of direct precipitation on the pool and natural evaporation
Water Use - Pipeline to Estevan	From WSA, included in Rafferty Reservoir reverse routing spreadsheet and the ResSim model data
Water Use - Sask. Power and forced evaporation from power plant cooling	From WSA. WSA assumed the full permitted amount of water was used each year and distributed this amount on a monthly basis by assuming a monthly usage distribution

The reverse routed inflows were input into the Boundary Reservoir model and release overrides using observed data was used for the main spillway at Boundary Reservoir, the diversion canal from Boundary Reservoir to Rafferty Reservoir, and the pipeline flow from Rafferty Reservoir to Boundary Reservoir. The simulation was performed for the 1998-2017 period of record and the results are shown in

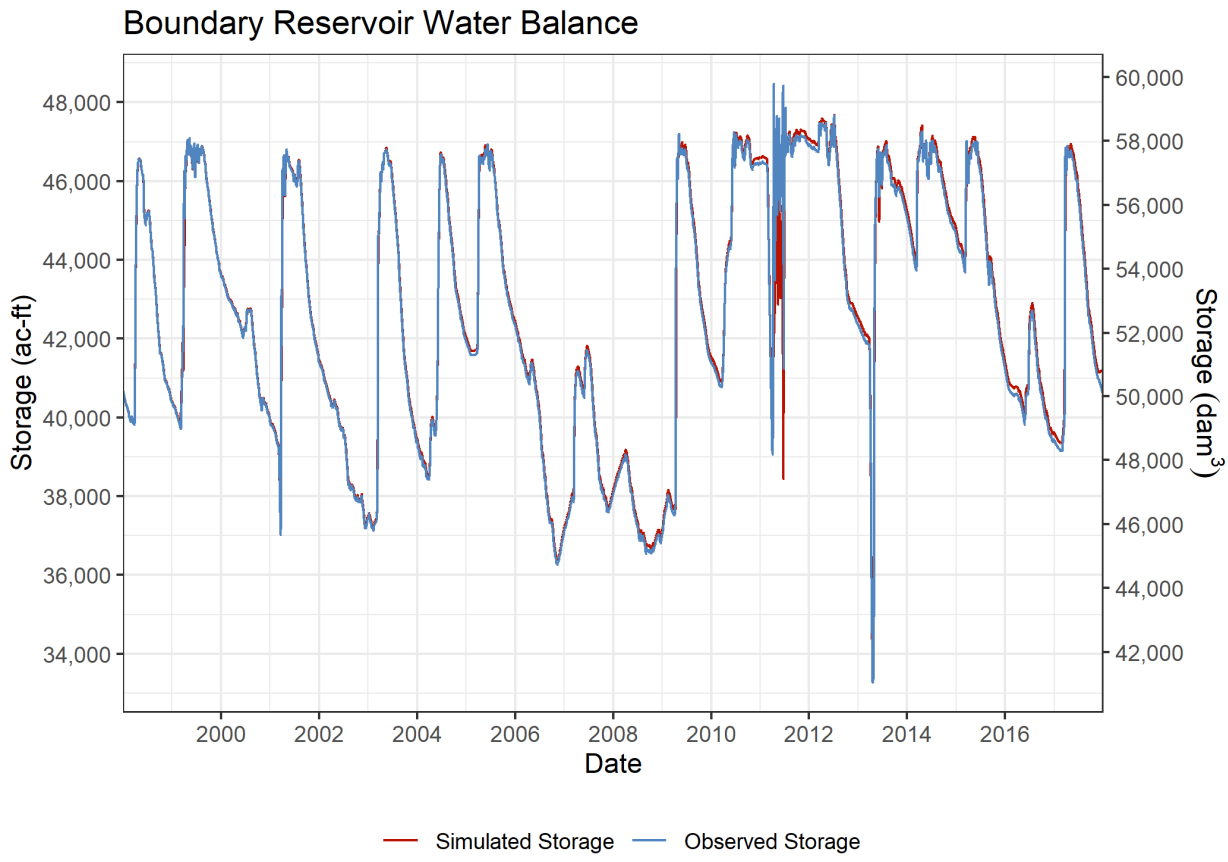


Figure 21 below. The results verify the mass balance for Boundary Reservoir.

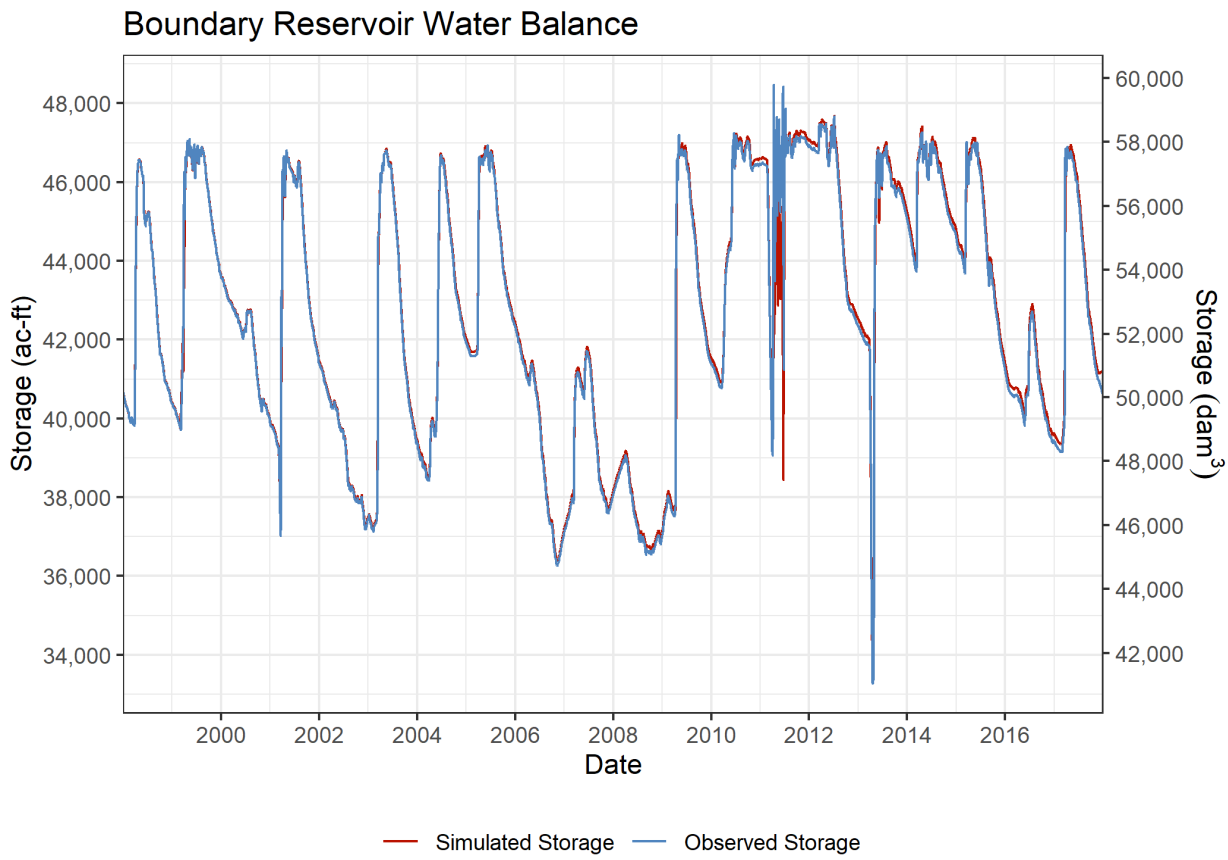


Figure 21 Boundary Reservoir Sensitivity Test – Verification of Model Inputs Using Water Balance Based Approach (modeled outflows equal observed outflows) and Inflows computed from reverse routing method

4 Reservoir Operation

Operational rules used to model the Souris River Project in ResSim are defined for Boundary Reservoir, Rafferty Reservoir, Grant Devine Lake, and Lake Darling Reservoir using *Annexes A and B* of the *1989 Agreement*, the Lake Darling Water Control Manual, information from dam operators, historical trends, and professional judgment.

4.1 Summary of Current Reservoir Operations

Current reservoir operation is primarily guided by *Annexes A and B* of the *1989 Agreement*. Flood operations for snowmelt events are detailed within *Annex A*, and international water supply constraints are described in *Annex B*.

To provide storage for spring snowmelt runoff, *Annex A* requires an annual drawdown target to be met by February 1st at Rafferty Reservoir, Grant Devine Lake, and Lake Darling. The drawdown typically begins in late October. On February 1st, a snowmelt runoff forecast is issued by the ISRB Flow-Forecasting Committee. Flood operations are triggered if the forecasted

runoff volume is projected to exceed a given threshold at Sherwood. Additional drawdown may be required at Rafferty Reservoir, Grant Devine Lake and Lake Darling prior to the onset of spring snowmelt when flood operations are initiated. If flood conditions are projected, downstream maximum flow limits at Sherwood and Minot are increased in accordance with the procedures within *Annex A*.

During the spring melt, flows are governed by maximum flow targets at Sherwood and Minot and other local, downstream flow constraints. Reservoirs are able to store water up to the top of their flood control pools. Reservoir operators attempt to time reservoir releases to be the least impactful by taking into consideration the timing of uncontrolled local and tributary flows.

After the spring melt, reservoirs are returned to their FSL and maximum flow targets at Sherwood and Minot are lowered to the values specified by *Annex A*. Water supply apportionment objectives are followed during and after the spring melt. During the spring runoff period, the quantity of runoff equivalent to 50 percent of the first 50,000 dam^3 (40,500 acre-feet) of computed natural flow at Sherwood is passed to North Dakota. On June 1st, the cumulative natural flow volume at Sherwood is assessed, along with the elevation of Lake Darling to estimate the apportionment ratio required for the year. Depending on the natural annual volume that passes Sherwood and the elevation of Lake Darling on June 1st, Saskatchewan will either deliver a minimum of 40 percent or 50 percent to North Dakota. This apportionment ratio is periodically calculated throughout the year to ensure that a large deficit or surplus does not accumulate. On October 1st, apportionment is checked again so that any deficit can be reconciled by the end of the calendar year. Grant Devine Lake is primarily used to fulfill the apportionment volume requirements. Rafferty Reservoir can be used to fulfill the apportionment objective if Grant Devine Lake is unable to do so.

In addition to the apportionment agreement, Rafferty Reservoir, Boundary Reservoir and Lake Darling support local water supply usages. The City of Estevan, SK and SaskPower consumptively use water from Boundary Reservoir. During periods of low flow, water can be pumped from Rafferty to Boundary via a pipeline to help fulfill the City of Estevan and SaskPower's water supply needs. Lake Darling supplies water to the Eaton Irrigation project, located near Towner, ND and the Salyer NWR. Lake Darling generally provides water supply releases during the spring of low flow years.

Operation of the Souris River Project for spring floods and to satisfy the required apportionment of flows between the United States and Canada is dependent upon runoff forecasts. The critical runoff estimates used in the Operating Plan laid out in *Annex A and B* are:

- 30 day, 50 percent forecasted Sherwood unregulated runoff volume
- 30 day, 50 percent forecasted local flow between the Canadian Reservoirs and Sherwood
- 30 day, 50 percent forecasted Sherwood uncontrolled runoff volume
- 90 day, 90 percent forecasted inflows to the Canadian Reservoirs
- Cumulative natural flow volume at Sherwood.

Data used to develop the runoff estimates are gathered by ECCC and the WSA in Canada and the NWS in the United States. The ISRB defines the natural flows used to make the apportionment calculation. Proxies for these forecasted quantities of flow are used in the model based on model inputs. The ResSim model makes use of the local flow between Lake Darling and the Wintering River confluence as a proxy to trigger water supply releases for Eaton Irrigation and the J. Clark Salyer NWR. A summary of these datasets is included in ***Table 34***.

Table 34 Summary of critical runoff estimates used to operate the Souris River Project

Variable	Location	Definition	Modeled Equivalent	Application
30 day, 50 percent Unregulated Flow	Sherwood	The forecasted maximum 30 day cumulative runoff that would have occurred at Sherwood if Rafferty Dam, Boundary Dam and Grant Devine Dam were not in place. This includes runoff from Yellow Grass and Tatagwa Marshes.	Maximum, 30 day, cumulative volume of inflows of Canadian reservoirs and local inflows routed to Sherwood and combined with local flows – negative values are assumed to be zero	• Defines whether flood operations are necessary prior to spring melt • Maximum Flow limits at Sherwood & Minot
30 day, 50 percent Local Flow	Canadian Reservoirs to Sherwood	The forecasted maximum 30 day cumulative local flow contribution between the Canadian reservoirs and Sherwood.	Maximum, 30 day, cumulative volume of local flow and tributary contributions between the Canadian Dams and Sherwood: Short Creek + Local Flows Local Flows = Estevan to Roche Percee + Roche Percee to Moose Mountain Creek + Oxbow to Glen Ewen + Glen Ewen to Sherwood – does not use routed flows. This local flow calculation does not account for effects of flood wave attenuation and lag as the hydrographs move downstream to Sherwood.	• Defines whether flood operations are necessary prior to spring melt
90 day, 90 percent Unregulated Flow (inflow)	Canadian Reservoirs	The maximum 90 day consecutive unregulated runoff with a 90 percent probability of being equaled or exceeded by the actual runoff. Long Creek near Noonan, Inflow into Rafferty Reservoir, and Inflow into Grant Devine Lake. Inflows into Rafferty Reservoir do not include the flows from the Boundary Diversion.	Maximum, 90 day, cumulative inflow volume inflows to the Canadian reservoirs multiplied by a 50 percent reduction factor to be representative of the 90 percent confidence forecast.	• Drawdown of Rafferty, Grant Devine and Boundary Reservoirs
30 day, 50 percent Uncontrolled Flow	Sherwood	The maximum 30, consecutive days of runoff that cannot be controlled by the available flood control storage. In *Annex A* uncontrolled flow is defined as the excess flow that cannot be controlled by Rafferty and Grant Devine Reservoir. Uncontrolled flow is the local flow defined in row two	30 day, local flow plus the excess runoff calculated at the Canadian reservoirs. This local flow calculation does not account for effects of flood wave attenuation and lag as the hydrographs move downstream to Sherwood.	• Drawdown of Lake Darling

		plus the releases made from Rafferty and Grant Devine Reservoir		
Natural Flow	Sherwood	Natural flow is approximated by subtracting an estimation of the flows contributing to the Souris River from the Yellow Grass Ditch (stream gage 05NB011) and the Tatagwa Lake Drain (stream gage 05NB018) from the computed, unregulated flow record at Sherwood.	Calculated in the apportionment state variable. State variable name: 'sherwood_vol_acc_nat' or 'volAccNat' in the script as the script is executed.	• Apportionment • • Criteria, Sherwood Minimum Flow
Local Flow Downstream of Lake Darling	Lake Darling to Confluence with the Wintering River	The cumulative local flow volume from the outlet of Lake Darling to the Wintering River Confluence for the calendar year period of January 1st through May 31st. This period was selected based on information of how the Eaton Irrigation District operates and uses water in the basin.	Calculated in the apportionment state variable script. The model uses the ResSim "FLOW-CUMLOC" at the Wintering River confluence. The FLOW-CUMLOC term accounts for lag and attenuation and will zero out negative flow records if routed through reaches which do not use the null routing technique.	• Defines Lake Darling Water Control Releases for J. Clark NWR & Eaton Irrigation

4.2 Modeling Approach

Within ResSim the Souris River Project is operated using a single network. The reservoirs are modeled using target pool elevations (guide curves), minimum flow rules, and maximum flow rules. State variables were developed to simulate the complexities of *Annex A* and *Annex B*. In reality, snowmelt forecasts are used for reservoir operation, but for modeling purposes, the inflow hydrographs are used to make an approximation of what these forecasts would have been. For example, the model determines flood status by using the input hydrographs with perfect foresight rather than a best estimate forecast.

4.2.1 State Variable Rules and Local Time series

Some model rules are implemented by using state variable scripts. These scripts allow for customizable calculations that are completed at every time step and can access model variables. State variables are used for operations that cannot be addressed through conventional ResSim rules defined in the ResSim GUI. Within the model, state variables related to low flow rules (i.e. minimum flow and apportionment rules) are named with an "app_" prefix and state variables related to high flow rules begin with a "a_fld" prefix (i.e. guide curve and maximum flow rules).

Multiple state variables or values can be calculated by a single master state variable. The master state variable does the calculations and writes to "slave" state variables and state variable local time series. Master and slave variables are available for use when defining ResSim operation rules. State variable local time series can be written to HEC-DSSVue but are not available to operational rules. They are used to troubleshoot and view intermediate calculations. Two master state variables were developed for the Souris ResSim model. Each master state variable is denoted with a "MASTER" in its name. A summary of the state variables used in the model is included in ***Table 35***.

Table 35 Summary of state variables used in the model

State Variable Name	Description
a_fld_MASTER_gc_gd	Master state variable that calculates flood status, guide curves, and maximum flow limits for downstream constraints. Stores local time series calculations (i.e. intermediate calculations for spring drawdown calculations) and Grant Devine guide curve.
a_fld_gc_bound	Boundary Reservoir Guide Curve. Computed in the state variable script using the 'guideCurve()' function in the script
a_fld_gc_dar	Lake Darling Guide Curve. Computed in the state variable script using the 'guideCurve()' function in the script
a_fld_gc_raf	Rafferty Reservoir Guide Curve. Computed in the state variable script using the 'guideCurve()' function in the script
a_fld_minotMax	Maximum flow limit at Minot. The logic in the script is follows the guidance in *Annex A* for determining the maximum allowable flow at Minot
a_fld_gc_320	J. Clark Salyer Pool 320 guide curve. Computed on a five year cycle that pauses if a flood event occurs.
a_fld_gc_326	J. Clark Salyer Pool 326 guide curve. Computed on a five year cycle that pauses if a flood event occurs.
a_fld_gc_332	J. Clark Salyer Pool 332 guide curve. Computed on a five year cycle that pauses if a flood event occurs.
a_fld_gc_341	J. Clark Salyer Pool 341 guide curve. Computed on a five year cycle that pauses if a flood event occurs.
a_fld_gc_357	J. Clark Salyer Pool 357 guide curve. Computed on a five year cycle that pauses if a flood event occurs.
a_fld_sherwoodMax	Maximum flow limit at Sherwood. The maximum flows at Sherwood determined in the script follow guidance in *Annex A* (Section 4.3.1, page A-27)
a_fld_status	Flood operation trigger. This trigger is used to determine if flood conditions are expected in the basin and if an extended drawdown is needed between February 1st and March 15th to allow the reservoirs to reduce flood risk for downstream locations while meeting water supply requirements. A 'a_fld_status' equal to 1 indicates a flood is forecasted in the basin, a value equal to 0 indicates non-flood conditions are present and a standard drawdown is used.
app_4cfsMinGD	Minimum 4 ft^3/s trigger rule at Sherwood fulfilled by Grant Devine releases. This is a trigger to maintain a minimum flow of 4 ft^3/s at Sherwood. *Annex B* requires that flow at the Sherwood Crossing should not be less than 0.113 m^3/s (4 ft^3/s). If the value of this state variable trigger is equal to 1, releases are made from Grant Devine Reservoir to ensure at least 4 ft^3/s of flow is available at Sherwood Crossing. There is logic in the state variable script which dictates whether releases are made from Grant Devine Reservoir or Rafferty Reservoir. The rule is only applied between March 1st and November 15th to prevent unrealistic releases caused by negative flows.
app_4cfsMinRaf	Minimum 4 ft^3/s rule at Sherwood fulfilled by Rafferty releases. *Annex B* requires that flow at the Sherwood Crossing should not be less than 0.113 m^3/s (4 ft^3/s). If the value of this state variable trigger is equal to 1, releases are made from Rafferty Reservoir to ensure at least 4 ft^3/s of flow is available at Sherwood Crossing. There is logic in the state variable script which dictates whether releases are made from Rafferty Reservoir or Grant

	Devine Reservoir. The rule is only applied between March 1st and November 15th to prevent unrealistic releases caused by negative flows.
app_MASTER_min_release_GD	Master state variable that calculates apportionment and low flow releases from Rafferty and Grant Devine to ensure apportionment requirements described in *Annex B* and the Amendment to *Annex B* are fulfilled. Stores time series calculations (i.e. intermediate calculations for apportionment) and minimum release at Grant Devine.
app_below_dar_vol	April and May cumulative flow volume at Wintering River to be used for Lake Darling water supply releases for J. Clark and Eaton Irrigation. The volume used to compute this term is the ResSim FLOW-CUMLOC parameter for the Wintering River Confluence junction element in the model. The FLOW-CUMLOC term represents the cumulative, routed local flows at points throughout the model. The FLOW-CUMLOC term is reset to zero at the outlet of a reservoir. The FLOW-CUMLOC term accounts for lag and attenuation as it is routed through the ResSim model. If negative flow values are included in this term, they will be zeroed out when routed through non-null or direct routing reaches. This would result in an overestimation of volume. The impact of this error would be higher for low flow scenarios compared to high flow scenarios. Section 3.3.2 provides more detail about the impact of zeroing out negative flows when performing routing calculations. The FLOW-CUMLOC term used to compute the state variable is the cumulative local flow volume from the outlet of Lake Darling to the Wintering River Confluence for the calendar year period of January 1st through May 31st. This period was selected based on information of how the Eaton Irrigation District operates and uses water in the basin. The FLOW-CUMLOC term accounts for lag and attenuation.
app_boundminrelease	Minimum release rate required at Boundary Reservoir based on a five day inflow volume forecast. This determines the minimum release needed from Boundary Reservoir when Boundary is below its Guide Curve elevation.
app_min_release_raf	Minimum apportionment release required at Rafferty Reservoir to meet the Apportionment requirements described in *Annex B* and the Amendment to *Annex B*.

4.2.2 Annex A Flood Operations and Maximum Flow Limits

4.2.2.1 Flood or non-flood operations

On February 1st, if the best estimate (50%), forecasted, maximum consecutive 30 day unregulated volume is greater than 216,100 dam^3 (175,200 acre-feet) at Sherwood or if the best estimate forecasted (50%), 30 day local flow between the Canadian reservoirs and Sherwood is greater than 37,000 dam^3 (30,000 acre-feet), flood control operations are specified during spring runoff. To model this constraint, the state variable "a_fld_MASTER_gc_gd" calculates an approximation of the 30 day unregulated volume and the 30 day local flow by evaluating unregulated flows and local flows for a 90 day look ahead period and storing the greatest 30 day volumes. The maximum 30 days of unregulated flow at Sherwood and the maximum 30 days of local inflow below the Canadian dams through Sherwood are assumed to be equivalent to the flood forecast.

The model was hard coded to define the 2009 event as a flood event. The modeled 2009 event had a 30 day unregulated volume at Sherwood that was slightly less than 216,100 dam^3 (175,200 acre-feet) which is needed to trigger flood operations. The historical record indicates that the reservoir system was operated for flood control in 2009.

Flood status is held unconditionally through June 1st to prevent an early termination of flood operations during the period leading up to the spring runoff. After June 1st, flood operations will terminate when flows at Minot fall below 14.2 m^3/s (500 ft^3/s) and when Lake Darling is less than its summer top of flood pool elevation of 487.07 m (1598 ft).

4.2.2.2 Lake Darling Summer Top of Flood Control

The top of flood control at Lake Darling varies depending whether there is a spring or summer flood. A spring flood event is defined as a snowmelt event and subsequent precipitation events that occur before June 1st or after Lake Darling returns to full supply level and flows at Minot decrease below 14.2 m^3/s (500 ft^3/s). During this time period, the top of flood control is allowed to reach elevation 487.98 m (1601 ft) at Lake Darling. Summer floods are floods which occur after June 1st. The top of flood control during a summer flood is elevation 487.07 m (1598 ft). The variable top of flood control at Lake Darling is modeled in ResSim using a zone which is a function of date and the "a_fld_status" state variable from the master "a_fld_MASTER_gc_gd" state variable script. This allows the top of flood control to change from elevation 487.9 m (1601 ft) during a spring flood to elevation 487 m (1598 ft) during a summer flood.

4.2.2.3 Reservoir Drawdown and Guide Curves

Reservoir drawdown and guide curves follow the procedures outlined in *Annex A*. During the summer months the guide curves are set to the reservoirs' FSL or Normal Pool Elevations.

At the beginning of the fall drawdown, the guide curve is set using a linear function from the current, modeled elevation to the February 1st (normal) drawdown elevation. If the current, modeled elevation falls below the normal drawdown target, the guide curve is set to the normal drawdown elevation. ***Table 36*** summarizes the critical pool elevations which define the guide curves for each reservoir.

Table 36 Reservoir guide curve and drawdown summary

	Units	Rafferty Reservoir	Boundary Reservoir	Grant Devine Lake	Lake Darling
Maximum Allowable Flood Level	meters	554.000	Equivalent to Full Supply	567.000	87.985
	feet	1817.59		1860.24	1601.00
Full Supply Level	meters	550.500	560.832 m	562.000	486.766
	feet	1806.10	1840.0 ft	1843.83	1597.00
Normal Drawdown Period		Oct20-Feb1	Full Supply through Feb 1	Oct20-Feb1	Oct20-Feb1
Normal Drawdown Feb1 Elevation	meters	549.500	Full Supply through Feb 1	561.000	486.461
	feet	1802.82		1840.55	1596.00

Extended Drawdown Period		Feb1-Mar15	Feb1-Mar15	Feb1-Mar15	Feb1-Mar15
Extended Drawdown Elevation		Plate A-1 and 90 day, 90 percent inflow forecast	Plate A-2 and 90 day, 90 percent inflow forecast*	Plate A-3 and 90 day, 90 percent inflow forecast	Plate A-4, 30 day, uncontrolled inflow forecast at Sherwood
Assumed Snowmelt Date/Return to FSL		Mar15	Mar15	Mar15	Mar15
Maximum Drawdown	meters	547.500	557.784	555.850	484.937
	feet	1796.26	1830.00	1823.65	1591.00

*The spring drawdown volume at Boundary Reservoir is applied to Rafferty Reservoir when possible.

If flood operations are triggered, the reservoirs are drawn down below their normal February 1st drawdown elevations between February 1st and the start of spring runoff. To determine a suitable spring runoff date to use for modeling purposes, a cyclic analysis of mean daily flow data for the Long Creek near Noonan, ND USGS gage was performed. The Noonan gage was selected because it has a long period of record (1959-2018) and it is upstream of Boundary Reservoir and does not include effects of regulation in the dataset. The cyclic analysis computes a set of cyclic statistics from a regular interval time series dataset. Daily data is apportioned into 365 bins, one for each day of the year, and a statistical analysis is performed on all data which occurred on a particular date. For example, all mean daily flow data recorded on June 25th for the entire period of record would make up a single bin, and statistics are computed based on this resultant data set. The format of the resultant data set is a pseudo time series for an arbitrary water year which is used to represent the data.

Each pseudo time series represents a different statistical parameter. The cyclic analysis computes percentiles for the 5%, 10%, 25%, 50% (median value), 75%, 90%, and 95% percentiles. For example, the 50th percentile indicates that for a given day, half the flow values in the observed daily flow record recorded on that date are above the plotted line and half are below. Flows represented by the 95th percentile line indicate that 95% of flows recorded on that date are below the plotted value indicated by the line and 5% are above. This type of analysis gives insight into the seasonal runoff characteristics of a watershed. ***Figure 22*** below shows that the start of spring runoff begins in approximately the middle of March, consequently, March 15th was selected as the extended spring drawdown target deadline. For most melt events, this date is conservative and precedes the actual start of runoff; however, it accommodates both early and late spring runoff events that may be encountered during period of record simulations. The date for the extended drawdown period can be changed in the script as needed to analyze alternatives.

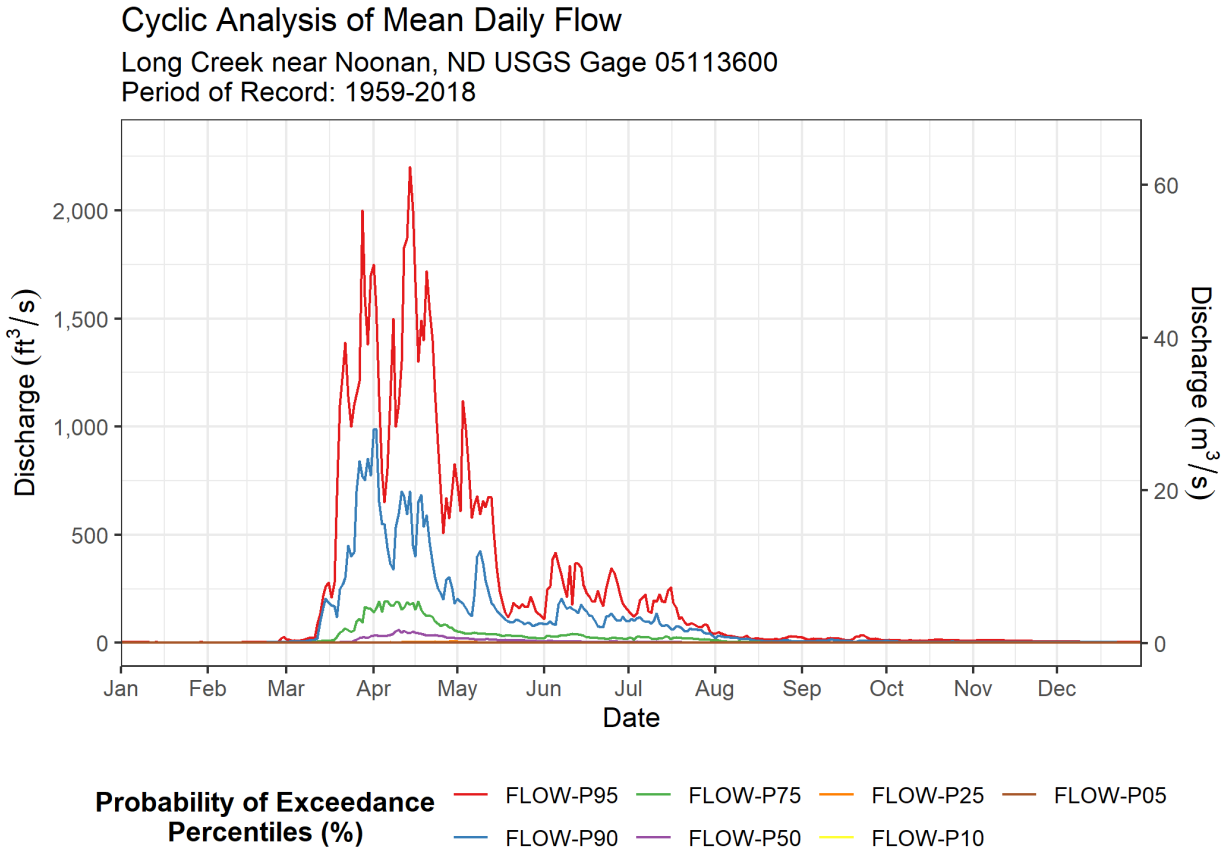


Figure 22 Cyclic analysis of Long Creek near Noonan, ND USGS gage data

The extended drawdown target pool elevation is determined by using the procedures outlined in Section 4.3.5 of *Annex A*. The extended drawdown target elevations at the Canadian reservoirs are based on the relationships in *Annex A* and the maximum 90 day, 90% forecasted inflow volume to each reservoir. The 90 day, 90 percent runoff volume is the unregulated runoff forecasted with a 90% probability of being equaled or exceeded by the actual runoff. The drawdown at Boundary Reservoir is often applied to Rafferty Reservoir so that Boundary Reservoir can remain at its FSL. The extended drawdown target elevations at Lake Darling are based on the relationship presented in Plate A-4 of *Annex A* and the best estimate 50%, 30 day, uncontrolled inflow forecast at Sherwood.

Drawdown targets within the model are based on the observed dataset. The model has perfect foresight when estimating the required drawdown. The forecast has a considerable degree of uncertainty associated with it in reality. This is one critical difference between how the ResSim model mimics operations compared to how real time operation is performed in accordance with *Annex A*.

A determination of the target drawdown elevation is made using the state variable script "a_fld_MASTER_gc_gd". The script looks ahead 120 days from February 1st to capture the melt period and calculates the maximum 90 day inflow volume to Rafferty Reservoir, Grant Devine

Lake, and Boundary Reservoir and the maximum 30 day, cumulative, uncontrolled flow volume at Sherwood.

There is a high degree of uncertainty with forecast estimates. This is due to uncertainty in accuracy of the data, uncertainty in the rate of snowpack accumulation, uncertainty in the timing of the melt, and uncertainty in the melt rate. Additionally, forecasts are issued months in advance of a flood event and conditions in the basin can change rapidly depending on weather conditions. Consequently, it is normal for large differences to exist between the forecasted runoff values and the observed. ***Table 37***, ***Table 38***, and ***Table 39*** below show the differences between the forecasted 90-day, 90% inflow volumes and the observed volumes for Rafferty Reservoir, Grant Devine Reservoir, and Boundary Reservoir.

A reduction factor of 50% (0.5) is used in the "a_fld_MASTER_gc_gd" script to convert observed inflows into estimates of the 90-day, 90% forecast that are used to determine spring drawdown targets. The reduction factor was selected based on how well it matched historical values for all reservoirs. The tables below show that when a reduction factor of 0.5 is applied to the observed historical 90-day inflow volume there is still considerable difference between the historic, forecasted 90-day 90% inflows and the 90-day, 90% inflows being used as a proxy within the ResSim model. However, the reduction factor based estimate is on the same order of magnitude as the actual, forecasted values.

Table 37 Difference between maximum 90-day, 90% forecasted inflow and observed inflow (Rafferty Reservoir)

Inflows to Rafferty Reservoir				
Flood Year	**Historical Official Max 90-day, 90% Runoff Volume, Forecast, ac-ft (dam^3)**	**90-day Volume, Observed, ac-ft (dam^3)**	**Feb. 1st 90-day, Runoff Volume, Observed Multiplied by 50%, ac-ft (dam^3)**	**Percent Difference, Forecasted 90-day, 90% Inflow vs. 50% of Observed Inflow, %**
2009	16,220	96,525	48,263	-66.4
	(19,999)	(119,015)	(59,508)	
2013	44,605	141,917	70,958	-37.1
	(54,998)	(174,984)	(87,491)	
2017	13,787	44,702	22,351	-38.3
	(16,999)	(55,118)	(27,559)	

Table 38 Difference between maximum 90-day, 90% forecasted inflow and observed inflow (Grant Devine Reservoir)

Inflows to Grant Devine (Alameda) Reservoir				
Flood Year	**Historical Official Max 90-day, 90% Runoff Volume, Forecast, ac-ft (dam^3)**	**90-day Volume, Observed, ac-ft (dam^3)**	**Feb. 1st 90-day, Runoff Volume, Observed Multiplied by 50%, ac-ft (dam^3)**	**Percent Difference, Forecasted 90-day, 90% Inflow vs. 50% of Observed Inflow, %**
2009	12,165	18,799	9,399	29.4
	(14,999)	(23,179)	(11,589)	
2013	19,464	48,928	24,464	-20.4
	(23,999)	(60,328)	(30,164)	
2017	29,196	34,662	17,331	68.5
	(35,999)	(42,738)	(21,369)	

Table 39 Difference between maximum 90-day, 90% forecasted inflow and observed inflow (Boundary Reservoir)

Inflows to Boundary Reservoir (Long Creek Noonan Gage)				
Flood Year	**Historical Official Max 90-day, 90% Runoff Volume, Forecast, ac-ft (dam^3)**	**90-day Volume, Observed, ac-ft (dam^3)**	**Feb. 1st 90-day, Runoff Volume, Observed Multiplied by 50%, ac-ft (dam^3)**	**Percent Difference, Forecasted 90-day, 90% Inflow vs. 50% of Observed Inflow, %**
2009	16,220	47,265	23,633	29.4
	(19,999)	(58,278)	(29,139)	
2013	52,715	86,907	43,453	-20.4
	(64,998)	(107,156)	(53,578)	
2017	15,409	36,247	18,123	68.5
	(18,999)	(44,693)	(22,346)	

The steps used by the state variable script to calculate the drawdown targets are described as follows:

1. Calculate the 90 day inflow volume for Rafferty Reservoir, Grant Devine Lake, and local Sherwood flows by taking the maximum cumulative 90 day inflow volume total that occurs from a 120 day window that starts on February 1st.
2. The 90 day inflow volume for Rafferty Reservoir is calculated following the procedure in step 1. A reduction factor of 0.50 is applied to approximate the 90% confidence forecast volume, and the drawdown elevation is interpolated from Plate A-1 in *Annex A*. If the value interpolated from the plate exceeds the maximum drawdown elevation, the maximum drawdown is used.
    a. Excess runoff that cannot be stored in the reservoir is calculated by subtracting the 30 day anticipated runoff volume from the reservoir storage

available, calculated using the drawdown level and the maximum flood elevation.

3. The procedure in step 2 is applied to Grant Devine Lake using Plate A-3 in *Annex A* to calculate the drawdown level and forecasted excess runoff.
4. The 30 day uncontrolled runoff volume at Sherwood is calculated by summing the local, 30 day Sherwood runoff with the excess runoff from steps 2 and 3.
5. The Lake Darling drawdown is interpolated by using the 30 day uncontrolled runoff volume at Sherwood with Plate A-4 in *Annex A*.
6. A drawdown volume is calculated for Boundary Reservoir by calculating a potential drawdown using the methods in steps 2 and 3 and converting the drawdown elevation to a storage volume. If Rafferty Reservoir can accommodate Boundary's entire drawdown volume without being drawndown past the maximum drawdown elevation at Rafferty Reservoir, the flood storage gained by the drawdown in Boundary Reservoir is applied to Rafferty Reservoir. A new Rafferty Reservoir drawdown is calculated by subtracting the Boundary Reservoir drawdown storage from the previous Rafferty Reservoir drawdown.
    a. During the spring drawdown calculation, the model checks if there is room in Rafferty Reservoir for Boundary's drawdown volume calculated by Plate A-2 in *Annex A*.
        i. The model currently does not accommodate the drawdown scenario where Rafferty Reservoir only partially has room to accommodate Boundary's required drawdown volume. This scenario would be rare in practice because the storage volume in Rafferty Reservoir is significantly greater than the storage volume in Boundary Reservoir (see ***Table 40*** below).
        ii. WSA indicated that they could do a partial drawdown at Boundary Reservoir if Rafferty Reservoir could not accommodate the entire storage volume from Boundary, but this is unlikely. Most probably, both reservoirs would instead be drawndown.
    b. If there is not enough room in Rafferty Reservoir to accommodate Boundary's drawdown, Boundary will be drawndown independently. During the spring melt, all runoff into Boundary that cannot be stored up to Boundary's FSL will be diverted to Rafferty until Rafferty reaches its FSL.
7. Excess runoff from Boundary Reservoir is calculated. If excess run exists, the 30 day uncontrolled runoff volume at Sherwood (step 4) and the Lake Darling drawdown (step 5) are recalculated.

Table 40 Total storage between the Maximum Required Drawdown elevation and Maximum Storage Elevation for Rafferty Reservoir and Boundary Reservoir

Reservoir	Storage Volume Available at Maximum Required Drawdown, ac-ft (dam³)	Storage Volume Available at Maximum Storage Level, ac-ft (dam³)	Operational Flood Storage Available between Maximum Storage Level and Maximum Drawdown Level, ac-ft (dam³)
Rafferty Reservoir	247,500	513,000	265,500
	(305,168)	(632,529)	(327,362)
Boundary Reservoir	36,259	49,845	13,586
	(44,707)	(61,459)	(16,752)

4.2.2.4 Sherwood and Minot Downstream Maximum Flow Limits

Within the model, downstream maximum flow limits at Sherwood and Minot are updated based on the time of year, flood operation status, and inflow forecasts. These flow limits are calculated within the "a_fld_MASTER_gc_gd" state variable.

During flood conditions, the downstream, maximum flow limits at Sherwood and Minot are estimated following the guidelines presented in Section 4.3.5 of *Annex A*. The maximum allowable flow at Sherwood is defined based on the best estimate (50%), 30 day, unregulated (uncontrolled) Sherwood inflow forecast. To define the maximum allowable flow limit at Sherwood, the model uses the state variable script "a_fld_MASTER_gc_gd". The script is used to calculate an approximation of the maximum 30 day unregulated volume using a 120 day look ahead period starting on February 1st. The script identifies and stores the greatest 30 consecutive days of flow volume at Sherwood. The modeled maximum 30 days of unregulated flow at Sherwood is assumed to be equivalent to a flood forecast (no adjustment factor is applied). This unregulated 30 day volume is used with Plate A-5 to define the maximum flood control limit at Sherwood and is used with Plate A-6 to define the maximum flood control limit at Minot.

Annex A specifies the maximum flow target at Sherwood seasonally, but lacks the same level of detail for in defining the maximum target flow at Minot. The maximum target flow at Sherwood is defined as follows:

a. June 1 to August 31: 11 m³/s (400 ft³/s)
b. September 1 to January 31: 14 m³/s (500 ft³/s)
c. February 1 to March 15: 60 m³/s (2,120 ft³/s)
d. March 16 to May 31 (Non-flood year): 91 m³/s (3,200 ft³/s)
e. March 16 to end of flood operations (Flood-year): determined by Plate A-5 (up to 113.26 m³/s, 4,000 ft³/s)

The application of Plate A-5 results in a higher maximum flow limit at Sherwood during non-flood years than would be applied during some flood years for the period between March 16th and May 31 (***Figure 23***). A maximum allowable flow of 91 m³/s (3,200 ft³/s) is not reached at Sherwood, until the 30 day, unregulated volume at Sherwood exceeds 275,000 dam³ (223,000 acre-feet).

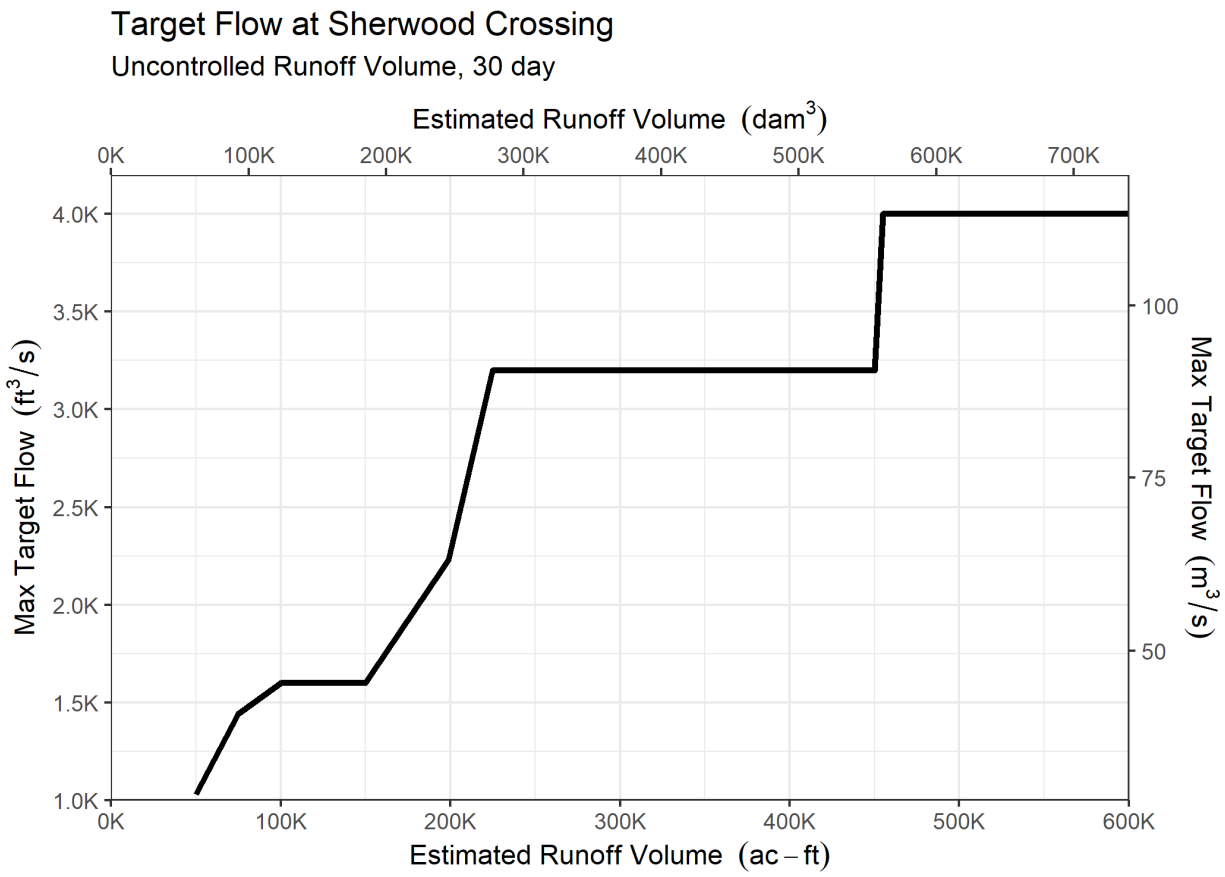


Figure 23 Plate A-5 Sherwood maximum flow limit adapted from Annex A

Annex A is less clear when defining the maximum flow target at Minot. *Annex A* indicates that the Minot maximum flow can exceed the Sherwood maximum allowable flow during drawdown, so that Lake Darling can be lowered. The maximum allowable flows at Minot adopted within the model are defined to be consistent with the Sherwood maximum flow targets. Within the model, the maximum allowable flows at Minot are defined as follows:

a. June 1 to January 31: 14 m³/s (500 ft³/s)
b. February 1 to March 15: 74 m³/s (2,620 ft³/s)
c. March 16 to May 31 (Non-flood year): 105 m³/s (3,700 ft³/s)
d. March 16 to end of flood operations (Flood-year): determined by Plate A-6 (up to 141.58 m^3/s, 5,000 ft³/s)
e. May 15 to May 31: Following flood operations, if the pool is at or below full supply after May 15 and before June 1, the maximum flow target is lowered to 71 m³/s (2,500 ft³/s) from the value specified by Plate A-6.

4.2.3 Local Maximum Flow Limits

Local maximum flow constraints at Estevan and just downstream of Grant Devine Lake are included in the model. These constraints are not specified within *Annex A*, but are used by the Saskatchewan Water Security Agency to manage the reservoirs to prevent localized flooding.

The downstream maximum flow constraints at Estevan vary seasonally. Rafferty Reservoir and Boundary Reservoir can be operated in parallel to limit maximum flows at Estevan, SK (WSA, 2018). The maximum flow constraints were discussed with the WSA to determine how best to incorporate them into the model. It was decided that maximum flow constraints would be added to the model as a function of pool elevation at Rafferty Reservoir. Boundary Reservoir did not have enough storage to use these constraints, so they were not applied to its releases. The agreed upon Estevan maximum flow limits are shown in ***Table 41*** below.

Table 41 Maximum flow limits at Estevan applied to Rafferty Reservoir

Rafferty Elevation		Max Flow at Estevan		Impacts
(m)	(ft)	(m^3/s)	(ft^3/s)	
> 554	> 1818	Outflow = Inflow		Some houses flood at 100 m^3/s (3531.47 ft^3/s)
553-554	1814-1818	90	3,178	Bridge on Haul Road overtopped
552-553	1811-1814	70	2,472	Shand Crossing Overtopped
551.5-552	1809-1811	60	2,119	Out of bank, Vaughn Crossing overtopped, Low-level Crossing on Haul Road overtopped
551-551.5	1808-1809	27*	953*	Campsites at Hidden Valley flooded*
<551	<1808	20*	706*	No Impacts*

*During spring drawdown (February 1 to March 15) the limit is raised to 35 m^3/s (1,236 ft^3/s) to permit maximum drawdown.

Directly downstream of Grant Devine Lake there are several maximum flow constraints (WSA, 2018) as shown in ***Table 42***. The maximum flow constraints were discussed with the Saskatchewan WSA to determine how best to incorporate them into the model. It was decided that maximum flow constraints would be added to the model as a function of pool elevation at Grant Devine Reservoir.

Table 42 Maximum release limits for Grant Devine Reservoir

Grant Devine		Max Outflow		Impacts
(m)	(ft)	(m^3/s)	(ft^3/s)	
≥ 567	≥ 1860	320	11,301	Capacity of railroad crossing
565-567	1854-1860	100	3,531	Out of bank flows on Moose Mountain Creek below the dam
564-565	1850-1854	50	1,766	Culvert Crossing is overtopped
563-564	1847-1850	35[1]	1,236[1]	Low Level Outlet outflow spills into Spillway Stilling Basin resulting in the need for a fish salvage
<563	<1847	20[1]	706[1]	No impacts

[1]During spring drawdown (Feb 1 to March 15) the limit is raised to 35 m^3/s (1,236 ft^3/s) to permit maximum drawdown.

4.2.3.1 Prioritization of Maximum Flow Limits

Different maximum flow limits exist to reduce flooding at areas downstream of Grant Devine Lake, Rafferty Reservoir and Boundary Reservoir, as well as at Sherwood, ND. When multiple maximum release limits are modeled using different rules within a single zone of a reservoir in ResSim, ResSim will always meet the most restrictive (smallest) maximum release in an attempt to satisfy as many of the maximum release rules as possible. This setup works well for modeling the current operating plan outlined in *Annex A*. The model is intended to be used to simulate the current operating plan and to assess proposed changes to the operating plan. Consideration of how proposed maximum flow constraints may conflict with each other should be exercised when assessing proposed operating alternatives. For example, the local maximum flow limits described in Section 4.2.3 have the potential to conflict with changes in the Sherwood maximum flow limit. If a proposed operating plan attempts to increase the maximum allowable flows at Sherwood, this could result in no noticeable difference in releases from the reservoirs because they prioritize the more restrictive local maximum flow constraints.

4.2.4 National Wildlife Refuge Structures Water Management Concept

Control structures are utilized to regulate flows primarily for wildlife and waterfowl purposes and for a secondary purpose of flood control. Water Management is done in coordination with Canada through the ISRB..

The J. Clark Salyer Wildlife Refuge Structures are operated to control emergent vegetation, stimulate other aquatic organisms and provide nesting, feeding and resting areas for migratory birds. The ability to manipulate water is dependent upon the timing and volume of runoff received during any given year. Both of these factors have fluctuated dramatically over the period of record, making it difficult to design a model that can accurately simulate historic operations. Additionally, sparse observed pool elevation and flow data is available at the J. Clark sites which can be used to aid in the development of the model.

Ideally, high flows are utilized to flood marshes at levels sufficient to drown out the extensive cattail stands and condition the pools for drawdown. Removing cattail stands creates open water or mudflats which will support more desirable emergent plants. Once the pool is relatively free of the dense monotypic stands of cattail, the entire pool should go into drawdown status.

As part of the January 1987 *Feature Design Memorandum No.14 Refuge Structures- Lake Darling Flood Control Project Souris River, North Dakota*, a computer model was developed to provide guidance for water management (USACE, 1987). ***Table 43*** illustrates a sample management scheme which optimizes drawdown levels for each pool. Under this plan, Pools 320 and 326 are drawndown together in year one. Pools 341 and 357 are drawndown together in year three, while Pool 332 is drawndown in year five. Another management option (HF), is also show in ***Table 43***, and would be used during flood periods.

Table 43 NWR Structures Sample Water Management Concept

		YEAR					
Pool	**Units**	1	2	3	4	5	HF
320	meters	432.11	433.64	433.94	433.94	434.58	434.58
	feet	1417.7	1422.7	1423.7	1423.7	1425.8	1425.8
326	meters	431.93	432.88	433.03	433.03	433.18	433.18
	feet	1417.1	1420.2	1420.7	1420.7	1421.2	1421.2
332	meters	431.93	432.24	432.24	432.54	431.47	432.54
	feet	1417.1	1418.1	1418.1	1419.1	1415.6	1419.1
341	meters	431.47	431.78	428.91	431.17	431.47	431.78
	feet	1415.6	1416.6	1407.2	1414.6	1415.6	1416.6
357	meters	430.68	431.54	428.91	430.5	430.68	431.54
	feet	1413	1415.8	1407.2	1412.4	1413	1415.8
Notes							
1) Entries are pool elevations in NGVD29							
2) Pool Drawdown conditions are underlined							
3) HF Option used during high flow years (Flood Recurrence Interval > 10 years)							
4) Boxed Entries Reflect High Flow Conditions or Management to Control Cattail							

Operators of the J. Clark Salyer National Wildlife Refuge vary the operating sequence of the reservoirs based upon observed vegetative patterns and based on when flood events occur. Target elevations operators attempt to raise and drawdown the pools to are dependent on observed conditions and real time operating decisions that vary considerably from the year to year. The *2013 Regional and Reconstructed Hydrology Study* contains more detailed information about how the NWR structures were used in the original reconstructed hydrology ResSim model (USACE, 2013).

The operating plan was adopted after consulting with the USFWS Project Leader of the Souris River basin complex and after reviewing the USFWS Annual Report to International Souris River Board regarding operation of the Souris River NWR structures.

The water management objectives for the J. Clark Salyer are modeled as follows:

1. The pools are operated cyclically to control emergent vegetation, stimulate other aquatic organisms and provide nesting, feeding and resting areas for migratory birds. The optimum pool drawdown and high flow schedule is defined in ***Table 43***.
2. Operation is done in coordination with the Upper Souris NWR to obtain water from Lake Darling in order to meet spring water needs. Water stored in Lake Darling is used to supplement spring and summer flows on J. Clark Salyer NWR during extended or extreme drought, or during the regenerative marsh phase following drawdown of priority impoundments.
3. When a pool raise is called for the target elevation is generally met by May 15th (as defined in ***Table 43***). Extended periods of high water surface elevations are necessary to encourage growth of emergent and submergent vegetation and provide habitat for

migrating and breeding waterfowl and other wetland dependent wildlife. The water level in these pools will be allowed to slowly decline through September in order to mimic a natural, seasonal water level decline.

4. When water management chooses to lower a given pool, the drawdown objective is generally met by June 1st (as defined in ***Table 43***) and then held at the specified level over the summer and fall to facilitate plant growth.
5. A minimum of 0.57 m^3/s (20 ft^3/s) is released to Manitoba from June 1st through October 30th, pursuant to the International Agreement Operating Plan.
6. Once management objectives are met outflows were matched to inflows through fall and into winter.
7. Release flows in excess of 3,000 ft^3/s are discharged over the uncontrolled spillway

The cyclic drawdown and raise of the NWR pools is mimicked in HEC-ResSim using a fluctuating top of conservation (guide curve) elevation computed in the "a_fld_MASTER_gc_gd" state variable. It is assumed that the flood years (HF years) identified when developing the HEC-ResSim model for the Upper Souris Reservoir System (Rafferty, Boundary, Grant Devine, and Lake Darling) would also dictate flood operation downstream at the J. Clark Salyer Refuge structures. It appears that although operators follow the general principles of the optimum drawdown schedule and suggested target elevations, operation of the refuge structures varies greatly from year to year. For modeling purposes it is assumed that the year of operation cycle is selected by the starting year of the simulation. For years ending with a zero or five, year five is selected for the beginning of the cycle. For years ending with a one or a six, year two of the cycle is selected and so on. Flood years will pause the cycle. This adopted method for defining the guide curves at the J. Clark Salyer structures supports stochastic modeling efforts and climate changed traces modeling efforts.

A minimum release rule is also inputted in the model for the refuge structures in order to ensure that minimum releases of 20 ft^3/s reaches Manitoba throughout the summer and early fall. A maximum release rule is also included in the model that specifies that the maximum controlled release is 3,000 ft^3/s. Releases in excess of 3,000 ft^3/s are made via the uncontrolled spillway.

4.3 *Annex B* Apportionment and Minimum Releases

The language issued in the *December 2000 Amendment to the Agreement between Canada and the United States for the Water Supply and Flood Control of the Souris River Basin* supersedes *Annex B* of the *1989 Agreement* (Canada and USA, 2000). The amendment to *Annex B* includes three rules that are included in the current version of the ResSim model:

1. Apportionment: A 50 percent/50 percent or 60 percent/40 percent split of the annual natural volume measured at Sherwood must be distributed between Saskatchewan and North Dakota.
2. A minimum flow of 4 ft^3/s (0.11 m^3/s) at Sherwood must be maintained when 4 ft^3/s would have occurred naturally.
3. A minimum flow of 20 ft^3/s (0.57 m^3/s) at Westhope must be maintained from June through October.

4.3.1 Apportionment

The apportionment calculation performed by the ISRB to manage the Souris River Project is documented in the Procedures for the Apportionment of Flows on the Souris River (ISRB, 2018a). The apportionment criteria is targeted at meeting water supply objectives and guarantees that North Dakota will receive 50 percent of the first 50,000 dam^3 (40,500 acre-feet) of the natural flow volume at Sherwood and either 50 percent or 40 percent of the annual, total natural volume of flow measured at Sherwood. The criteria dictating whether Saskatchewan needs to provide North Dakota with 40 percent or 50 percent of the naturally occurring flow at Sherwood is included in the 2000 amendment to *Annex B*. Saskatchewan is to provide 50 percent of the naturally occurring flow at Sherwood to North Dakota unless:

- The annual natural flow volume at Sherwood exceeds 50,000 dam^3 (40,500 acre-feet) and either:
    - The current year elevation of Lake Darling on June 1st is greater than 486.095 m (1594.8 ft) OR
    - The current year elevation of Lake Darling on June 1st is greater than 485.79 m (1593.8 ft) and since the last occurrence of a Lake Darling June 1st elevation of greater than 486.095 m (1594.8 ft) feet the elevation of Lake Darling has *not* been less than 485.79 m (1593.8 ft) on June 1st.

If the above exceptions are met, Saskatchewan is to provide 50 percent of the first 50,000 dam^3 (40,500 acre-feet) of the natural flow volume at Sherwood and supply a minimum of 40 percent of the annual, total natural flow volume at Sherwood to North Dakota.

Because of the differences in how the ISRB calculates inflow, minor diversions, and how inflow was calculated in the HH1 dataset and differences in discretionary reservoir operation, an approximation of the apportionment calculation is appropriate for the ResSim model.

The apportionment is fulfilled in the model using a state variable script called "app_MASTER_min_release_GD." The script accumulates the volume of the unregulated flow at Sherwood for each calendar year. Natural flow is approximated by subtracting an estimation of the flows contributing to the Souris River from the Yellow Grass Ditch (stream gage 05NB011, period of record: 1957-present) and the Tatagwa Lake Drain (stream gage 05NB018 period of record: 1960-present) from the computed, total inflow record above Sherwood. It is important to note that when the model computes the apportionment, it uses the observed data to determine a surplus or deficit and uses observed records to forecast how much additional apportionment volume will be needed. The model has near-perfect foresight, but in reality, the process of meeting the apportionment is met by iteratively checking the current apportionment, making necessary releases from the reservoirs, and then checking to see if the apportionment is met.

4.3.1.1 Yellow Grass and Tatagwa Drains

Alterations to natural drainage patterns have occurred throughout the Souris River Basin including the upstream headwaters region. Initial land drainage near the Yellow Grass Marsh began in the early 1900s (Souris River Basin Study Board, 1978). Under natural conditions, the

Yellow Grass Marsh does not start contributing to the Souris River until 57 km^2 (14,000 acres) of natural depressional storage is filled and the marsh reaches its natural overflow elevation of 569.82 m (1869.5 ft); vertical datum not specified in Souris River Basin Study Board, 1978. Drainage of the marsh was improved by the construction of the Yellow Grass Ditch which connects two sections of the Souris River channel above and below the marsh (Souris River Basin Study Board, 1978). The ditch was reconstructed in 1963 and 1964, and additional work was completed in 1972.

Present-day drainage patterns have significantly increased the volume of outflow from Yellow Grass Marsh when compared to the natural conditions. The Yellow Grass Ditch and drainage into the Yellow Grass Marsh increased peak outflow from the marsh for small and moderate flood events, up to and including the 4% AEP (25-year) flood event, as defined by the *1978 Souris River Basin Study Board* report. For larger floods, peak outflow from the Yellow Grass Marsh were estimated to be less under the natural conditions compared to the present-day conditions primarily due to the effect of the road network in the area (Souris River Basin Study Board, 1978).

The Tatagwa Lake Drain drains the Tatagwa Marshes located southwest of Weyburn in the upper portion of the Souris Basin (ISRB, 2018a). The project was established in the 1950s and later improved in the 1970s. Under normal flow conditions, a large volume of water would not naturally flow into the Souris River (ISRB, 2018a).

If the Tatagwa Yellow Grass drain systems were not in place, the flows captured by the Yellow Grass Ditch and Tatagwa Lake Drain gages would not contribute to the Souris River in most events. Without the man-made drains, the drainage areas captured by these two gage site would only start contributing to the Souris River during extreme events like 2011 and not during typical flow conditions. Thus, these flows are excluded from the natural flow record used to compute the apportionment volume.

The observed flow records available for Yellow Grass Ditch and the Tatagwa Lake Drain are only available for a portion of the period of analysis being adopted for this assessment. Thus, to carry out the apportionment calculation consistently throughout the entire historical period of record, as well when simulating synthetic inflows produced by the USGS's stochastic water balance model, a relationship between Rafferty Reservoir inflows and observed flows at Yellow Grass Ditch and the Tatagwa Lake drain was derived. The relationship is based on a linear regression between the annual volume of inflow to Rafferty Reservoir and the upstream natural non-contributing volume (Yellow Grass Ditch & Tatagwa Drain) reported annually by the ISRB (***Figure 24***). This information is available for 1996 through 2017. Data from year 2011 was excluded as an outlier when developing the relationship because during the 2011 event the flows from the drainage areas captured by the Yellow Grass and Tatagwa gages would have contributed to the Souris even under un-drained conditions. The relationship that was derived is used in the model to estimate the non-contributing volume for all simulation years, including 2011 in the model.

Applying a linear regression relationship to aid in the estimation of the natural flow volume at Sherwood is an approximation and does not account for the natural variability of the flow record for the Yellow Grass or Tatagwa Lake drains. The coefficient of determination ($R^2 = 0.9348$) indicates that the linear relationship based on Rafferty Inflows offers a good approximation of the volume of water from Yellow Grass drain and Tatagwa drain, as expected since the two parameters are not independent. Additionally, a simple linear regression equation can easily be incorporated into the HH2 (stochastic hydrology simulations) and HH4 (forecasting simulations) study efforts. The regression relationship is applied consistently and should have no impact in the ranking and selection of alternative simulations.

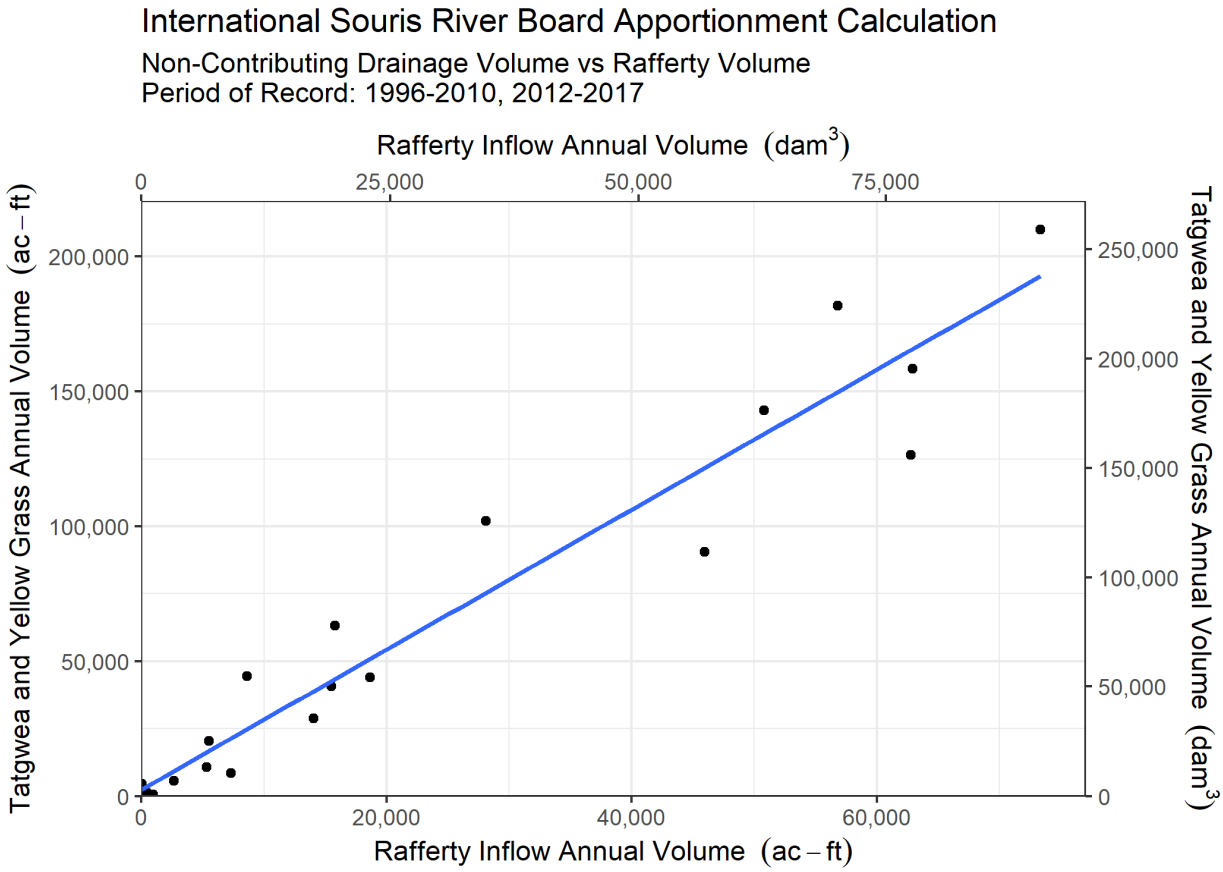


Figure 24 Linear regression relationship between the annual Rafferty Reservoir inflow volume and the Yellow Grass and Tatagwa stream gage volume as determined by the ISRB apportionment calculation

4.3.1.2 Modeling Approach for Estimating the Apportionment in ResSim

The approach used to model apportionment is similar to what is applied in practice by the ISRB. The apportionment state variable (app_MASTER_min_release_GD) is calculated April 1st through December 31st. All apportionment releases are either made from Rafferty Reservoir Dam using the "app_min_Release_Raf" slave state variable or Grant Devine Dam using the "app_MASTER_min_release_GD" master state variable. The general logic of the script is below:

1. From April 1st through the end of the year, the unregulated and regulated volume accumulated since January 1st is calculated at Sherwood on a daily basis.
2. The natural cumulative volume at Sherwood is estimated by subtracting the approximation of the natural, non-contributing volume (Yellow Grass & Tatagwa flow) from the total inflow volume above Sherwood. The total inflow volume is calculated by summing Rafferty Reservoir, Boundary Reservoir, and Grant Devine Lake inflows along with the local inflows. The inflow is not routed to preserve the negative values.
3. The annual natural flow volume at Sherwood accumulated for the calendar year to date and the Lake Darling's June 1st pool elevation are used to determine if a 50 percent SK/50 percent ND split or 60 percent SK /40 percent ND split should be enforced for the remainder of the calendar year. A 50 percent SK/50 percent ND split is always applied before June 1st.
4. The minimum apportionment volume to be delivered to North Dakota annually is calculated by multiplying the approximated natural flow volume at Sherwood by the apportionment target ratio. The natural flow volume is computed using the value at the current time step because this information is available to the model.
5. To determine whether North Dakota has received flows in surplus of the volume required by the apportionment, the minimum apportionment volume is subtracted from the regulated, cumulative flow volume at Sherwood calculated in step 4.
6. Between April 1st and October 1st, if a negative surplus (i.e. deficit) exceeds 1,480 dam^3 (1,200 acre-feet), a minimum release is calculated and applied by the model.
    a. The purpose of using a deficit of 1,480 dam^3 (1,200 acre-feet) as the trigger to determine when an apportionment release is required is to ensure the deficit does not grow too large and to prevent the model from needing to adjust the apportionment release discharge too frequently. In practice, operators at the reservoirs would not make adjustments to the apportionment discharge on a daily basis and they also would not make adjustments unless an appreciable apportionment deficit existed.
    b. The apportionment is calculated daily and if a deficit of 1,480 dam^3 (1,200 acre-feet) or more exists and a release rate is approximated to make up the deficit within 28 days. This release is held for 28 days and may or may not make up the deficit in that time. If the deficit is not met and is again more than 1,480 dam^3 (1,200 acre-feet), a new release will be calculated for a subsequent 28 day period until the deficit is met. Operators typically would not be able to adjust the outflows from a reservoir to meet the apportionment on a daily basis.
7. The process the state variable script uses to define the apportionment calculations is summarized below.
    a. The minimum apportionment release is determined by approximating the volume needed to fulfil the deficit over a forecasted 28 day period from the day the necessity of an apportionment release is first triggered. The minimum release is defined to be equivalent to the expected 28 day volume plus the deficit volume determined in the model when the apportionment was triggered.

i. The volume required to make up for the deficit within the 28 day period is computed by summing the natural inflow volume above Sherwood over 28 days, multiplying by the apportionment target ratio, adding the deficit volume to this 28 day expected volume, and dividing by 28 days to determine the minimum flow rate per day required to fulfil the deficit. The minimum release rate is approximate and does not account for inflow generated by direct precipitation on the pool.
ii. The apportionment release estimated by the state variable script can be large. To limit the releases so that they more accurately model the observed flows, the state variable script uses 150 ft^3/s (4.25 m^3/s) as a maximum apportionment release between April 1st and October 1st. This is the flow rate that has typically been observed for apportionment releases in the past. It should be noted that the apportionment is checked each time step and is adjusted based on basin conditions.
iii. After October 1st, apportionment releases larger than 150 ft^3/s (4.25 m^3/s) can be made over a shorter period of time to satisfy the apportionment volume requirement. In most cases, there should result in a minimal need for apportionment releases by October 1st.

8. Between April 1st and October 1st, the minimum apportionment release is assigned to either Grant Devine Lake or Rafferty Reservoir and held until the deficit is negated.
9. If an apportionment deficit still exists by October 1st, and Grant Devine Lake and Rafferty Reservoir are below their respective February 1st normal drawdown targets, the model will attempt to fulfil any remaining apportionment deficit for the year by delivering the forecasted deficit by the end of October. This calculation is performed by estimating the required apportionment volume for the remainder of the year and attempting to deliver it within three weeks (by October 21st). A three week period has been selected to account for the travel time to Sherwood of approximately 10 days. This ensures that the apportionment volume is delivered to Sherwood by the end of October. If Rafferty Reservoir and Grant Devine Reservoir are above their normal February 1st drawdown elevations on October 1st, it is assumed that the drawdown releases will fulfill any remaining apportionment deficit as of October 1st. The desired releases are continued until the apportionment is satisfied.
    a. The assumption that the drawdown of the reservoirs can fulfill any remaining apportionment deficit is valid because prior to October 1st the state variable script monitors the estimated apportionment deficit each time step. If a deficit of at least 1,480 dam^3 (1,200 acre-feet) exists prior to October 1st, the ResSim model computes a minimum apportionment release needed to bring the deficit to zero. Because of this logic (outlined in Step 6), the remaining deficit on October 1st should never be significantly greater than 1,480 dam^3 (1,200 acre-feet). Drawdown at Rafferty Reservoir from FSL (550.50 m, 1806.10 ft) to normal drawdown (549.4 m, 1802.82 ft) will release 47,242 dam^3 (38,300 acre-feet) of storage. Drawdown at Grant Devine from FSL (561.9 m, 1843.83 ft) to normal drawdown (560.9 m, 1840.55 ft) will release as much as 11,261 dam^3 (9,130 acre-

feet) of water. Collectively, if either of the two reservoirs is above their standard drawdown and the deficit is maintained to approximately 1,480 dam^3 (1,200 acre-feet) throughout the year, the drawdown of the reservoirs should satisfy the apportionment requirement.

10. Whether the release is made by Grant Devine or Rafferty is determined by pool levels and is summarized below (WSA, 2018).
    a. If Grant Devine Lake is above its FSL, the apportionment release is made from Grant Devine Lake.
    b. If Grant Devine Lake is not above FSL, and Rafferty Reservoir is above FSL, the apportionment release is made from Rafferty Reservoir.
    c. If neither Grant Devine nor Rafferty Reservoir are above FSL, but Grant Devine Lake is above its normal February 1st drawdown level, the release is made from Grant Devine Lake.
    d. If Grant Devine is below its normal February 1st drawdown level, but Rafferty Reservoir is above its normal drawdown level, the apportionment release is made from Rafferty Reservoir.
    e. If neither Grant Devine nor Rafferty Reservoir are above their February 1st drawdown level, and Grant Devine Lake is above its inactive pool level, the apportionment release is made from Grant Devine Lake.
    f. If Grant Devine Lake is below its inactive pool level, the apportionment release will be made from Rafferty Reservoir.

There is no firm guidance which governs the magnitude of apportionment releases. The logic in the apportionment script is how the apportionment releases are modeled to meet the annual apportionment volume requirement as closely as possible and will not necessarily match the observed apportionment releases. When comparing simulated apportionment results to observed apportionment information, it is critical to use the simulated apportionment volume as the basis for comparison rather than the magnitude of the discrete apportionment releases.

4.3.2 Annex B Minimum Flow Requirements

Two minimum flow requirements are included in the model as per the 2000 Amendment to *Annex B* (Canada and USA, 2000).

4.3.2.1 Sherwood Crossing 4 ft^3/s Minimum Flow Requirement

The 2000 Amendment to *Annex B* states that, "*Saskatchewan shall, so far as is practicable, regulate its diversion, storage, and uses in such a manner that the flow in the Souris River channel at the Sherwood Crossing shall not be less than 0.113 cubic metres per second (4 cubic feet per second) when that much flow would have occurred under the conditions of water use development prevailing in the Saskatchewan portion of the Souris River basin prior to construction of the Boundary Dam, Rafferty Dam and Alameda [Grant Devine] Dam*."

It is assumed that the flows contributing to the Souris River from the Yellow Grass Ditch and Tatagwa Lake Drain should be subtracted from the unregulated flows at Sherwood to represent natural flow conditions. Therefore, a 0.113 m^3/s (4 ft^3/s) minimum flow rule is

activated within the model whenever the 11 day average, natural flow is greater than 0.113 m^3/s (4 ft^3/s). This rule applies between March 1st and November 15th of the year to prevent unrealistic releases during the winter triggered by negative inflow. The HH1 dataset is based on gaged data which is not as reliable during the wintertime and negative flows were causing releases during the winter that were not realistic. The 11 day average is computed using a moving average which includes the current value, the five values before the current value, and the five values after the current value. Natural flow is approximated by subtracting an estimate of the contributions to the Souris from the Yellow Grass Ditch and Tatagwa Lake flows by using the linear relationship displayed in ***Figure 24***. The minimum release is made by either Grant Devine Lake or Rafferty Reservoir using the criteria laid out in step 10 of the apportionment logic outlined in Section 4.3.1.2. Within the model, this value is calculated in the apportionment master state variable, "app_MASTER_min_release_GD" using the slave state variable "app_4cfsMinGD" if releases are needed from Grant Devine or "app_4cfsMinRaf" if releases are made from Rafferty Reservoir.

4.3.2.2 Westhope Crossing 20 ft^3/s Minimum Flow Requirement

Annex B states that, *"In addition to the waters of the Souris River basin which originate in the Province of Manitoba, that Province shall have the right, except during periods of severe drought, to receive for its own use and North Dakota shall deliver from any available source during the months of June, July, August, September, and October of each year, six thousand and sixty-nine (6,069) acre-feet of water at the Westhope Crossing regulated so far as practicable at the rate of twenty (20) cubic feet per second except as set forth hereinafter: provided, that in delivering such water to Manitoba no account shall be taken of water crossing the boundary at a rate in excess of the said 20 cubic feet per second*."

This operating requirement is interpreted to be a minimum release requirement of 0.566 m^3/s (20 ft^3/s) at Westhope, ND. The minimum release requirement is applied within the model between June 1st and November 1st. A 0.566 m^3/s (20 ft^3/s) minimum release rule is applied to the four, upstream most, Salyer refuge reservoirs (Pools 320, 326, 332, & 341). The downstream most Salyer refuge impoundment, Pool 357, is located just upstream of Westhope and uses a minimum downstream control flow rule for Westhope of 0.566 m^3/s (20 ft^3/s), rather than a minimum release rule.

4.3.3 Lake Darling Water Supply Minimum Flow Requirement

Lake Darling primarily supplies water to the J. Clark Salyer National Wildlife Refuge and the Eaton Irrigation Project. Lake Darling is also authorized to provide water supply to municipal and rural water permit holders near Minot. To date, no substantial water supply releases have been made from Lake Darling for Minot municipal and rural water permit holders.

The Eaton Irrigation Project is a large flood irrigation district near Towner, ND that requires a minimum of 12,334 dam^3 (10,000 acre-feet) of water. The NDSWC indicated that in practice approximately 15,418 dam^3 (12,500 acre-feet) of water is supplied to the Eaton Irrigation District between the months of April and May (NDSWC, 2018). The *16th Biennial Report of the State Engineer to the Governor of North Dakota for 1933-1934* indicates that

design of the Eaton Irrigation District project began in approximately 1933 to artificially secure flooding of hay meadows along the Souris River in McHenry and Bottineau Counties. Residents of McHenry and Bottineau Counties desired a means to artificially flood hay meadows because meadows which were inundated early in the spring produced a better hay yield (Kennedy, R. E., 1935).

The features of the Eaton Irrigation District project were constructed under a Works Progress Administration agreement by the Civilian Conservation Corps (NDSWC, 2019). According to the *1988 Souris River Basin Project General Plan Report and Final Environmental Impact Statement* study, the Eaton Irrigation District established a right to a minimum of 12,334 dam^3 (10,000 acre-feet) of annual spring runoff with a priority senior to the J. Clark Wildlife Refuge structures in a formal agreement in 1936. Project features for the Eaton Irrigation District were completed between 1936 and 1937. The McHenry Bounty Board for Flood Irrigation (Eaton) and the North Dakota Biological Survey entered into an agreement in November of 1935.

The water supply requirements for the Salyer refuge depend on the refuge structure's operational objectives for that particular year. The operation of the refuge structures varies on an annual basis based on habitat needs. Little information is recorded about exact use volume needed for the wildlife structures (USFWS, 2018). For instance, for a given year, a pool may need additional water in order to hold a high pool to flood out invasive cattails. Generally, water supply releases for the Salyer refuge are made during the spring months to mimic what would have occurred naturally (without Rafferty, Boundary, Grant Devine and Lake Darling). In the model, it was assumed that the Salyer wildlife structures also require 15,418 dam^3 (12,500 acre-feet) of water supply for a total volume threshold of 30,837 dam^3 (25,000 acre-feet) needed to meet water supply requirements for the Eaton Irrigation Project and the Salyer wildlife structures.

Discussion with the NDSWC indicate that the Eaton Irrigation project fills their water right usage by May 1st of each year. Water is stored and used through May and early June. Any unused water is released back to the Souris River June 15th (NDSWC, 2018). For the purposes of this study, it is assumed that any excess volume of water not needed for the Eaton Irrigation District will be passed by June 1st each year.

Releases made from Lake Darling for the Eaton Irrigation District and the Salyer refuge are highly variable and are based on operator's discretion. Due to the great amount of variability associated with water supply operation and the lack of well-defined release requirements, it is difficult to identify and define consistent release rules to fulfil Lake Darling's water supply objectives. Through trial and error, a linear relationship was defined within the model to specify minimum water supply releases from Lake Darling. Minimum water supply releases are assumed to be dependent on the cumulative local flow volume between Lake Darling Dam and the confluence of the Wintering River with the Souris River between January 1st and May 31st. This period is selected to account for potential early and late spring runoff periods and recognizes the target dates for passing excess storage volume out of the Eaton Irrigation District. Flows preceding the spring runoff period are not significant enough to

affect how Lake Darling would be operated to meet water supply needs. Releases in the model are made between April 1st and May 15th to meet water use requirements for the Eaton Irrigation District and the downstream refuge structures. May 15th is selected as a release end date to account for the approximate two week travel time from Lake Darling to the Salyer Wildlife Structures. The relationship defined for April 1st through May 15th and is shown in ***Figure 25.***

The 2006 through 2008 dry period was used to determine water supply releases from Lake Darling to meet the 30,840 dam^3 (25,000 acre-feet) volume requirement of the Eaton Irrigation Project and the Salyer structures. During these years Lake Darling's pool elevation remained below FSL. The historical releases from Lake Darling during this period were used to estimate a typical minimum release rate. It was determined that Eaton and Salyer's water supply needs could be met by applying a minimum flow limit of 7.08 m^3/s (250 ft^3/s). For years when the forecasted local flow runoff volume between Lake Darling and the Wintering River confluence is greater than 30,840 dam^3 (25,000 acre-feet), no minimum releases are necessary from Lake Darling Reservoir to provide water to the downstream projects.

For years when the forecasted local flow runoff volume between Lake Darling and the Wintering River confluence is less than 30,840 dam^3 (25,000 acre-feet), releases will be required from Lake Darling Reservoir. The releases are scaled accordingly depending on how much volume is needed to supply a total of 30,840 dam^3 (25,000 acre-feet) to the downstream projects. If the estimated local runoff volume is close to 30,840 dam^3 (25,000 acre-feet), releases from Lake Darling are small. If the estimated local runoff volume is significantly below 30,840 dam^3 (25,000 acre-feet), releases from Lake Darling can be as large as 7.08 m^3/s (250 ft^3/s).

Lake Darling's water supply demand is modeled as a minimum release rule. The cumulative, local flow volume at the Wintering River's confluence with the Souris River from January 1st through May 31st is calculated on April 1st of each year within the "app_MASTER_min_release_GD" state variable.

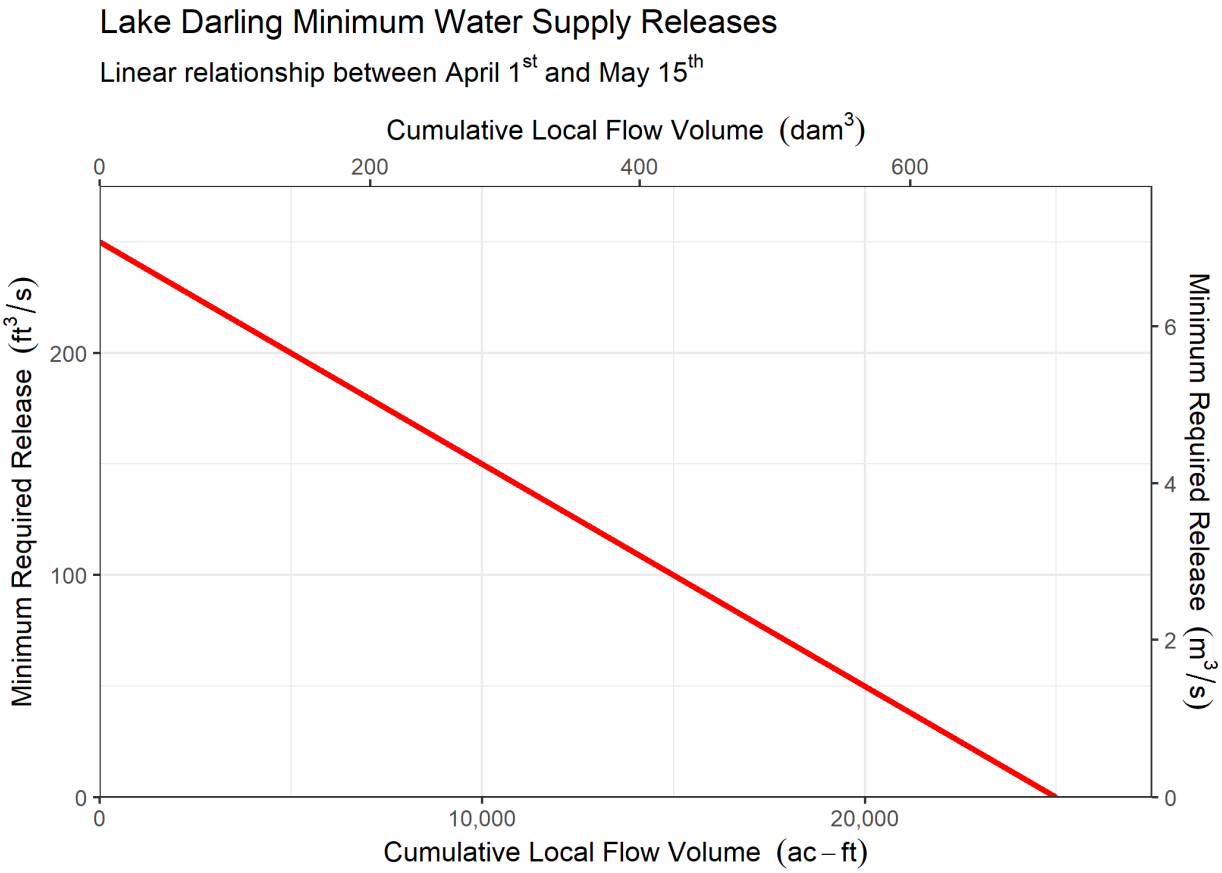


Figure 25 Relationship between the April 1st and May 15th minimum discharge rate at Lake Darling vs. cumulative local flow volume for Souris River at its confluence with the Wintering River

The Eaton Irrigation District uses an estimated 15,400 dam³ (12,500 acre-feet) of water annually. Within the baseline HH6 model simulation runs, the consumptive water use of the Eaton Irrigation District is implicitly accounted for in the local flow records developed as part of the HH1 Reconstructed Hydrology for the Souris River Basin between Towner, ND and Bantry, ND.

To explicitly model consumptive water use of the Eaton Irrigation Project when conducting stochastic model simulations a diversion element is used. Diverted outflows are modeled as a time series. It was assumed that Eaton water use begins on April 1st and lasts for 60 days until June 1st. To meet a flow volume of 15,400 dam³ (12,500 acre-feet) during this 60-day period, a constant, diverted discharge of 2.97 m^3/s (105 ft^3/s) is assumed between April 1st and June 1st. A 40% return ratio of flow back to the Souris River is applied by the diversion element based on information provided by the NDSWC (NDSWC, 2019).

4.3.4 Boundary Reservoir Diversion & Water Supply Operation

Rafferty Reservoir and Boundary Reservoir are operated as a system to provide adequate cooling water for the Boundary Dam Power Station (SaskPower) and other water users. Present day operation of the Boundary diversion differs from how it was operated in the past. In the past, the Boundary to Rafferty diversion channel was operated as long as Rafferty was less than its maximum storage level of 554.0 m (1817.59 ft) and a flood was forecasted. The diversion

channel was also allowed to operate if Rafferty Reservoir were below its FSL elevation of 550.5 m (1806.10 ft) and no flood was forecasted in the basin. The change in operation of the occurred in 2012.

Current operation of the Boundary to Rafferty diversion channel states that if the pool elevation of Rafferty Reservoir is above its FSL elevation of 550.5 m (1806.10 ft) releases from Boundary Reservoir to Rafferty Reservoir will not occur. Additionally, Boundary Reservoir will not send flow to Rafferty Reservoir via the diversion if Rafferty Reservoir is making releases. Present day operations are reflected in the ResSim model.

During a potential summer flood the logic in the model aims to have Rafferty Reservoir and Boundary Reservoir at their respective FSL elevations, which would prevent diversion from Boundary Reservoir to Rafferty Reservoir from occurring. If the pool elevation of Rafferty Reservoir is less than the FSL elevation of 550.5 m (1806.10 ft) then releases from Boundary Reservoir to Rafferty Reservoir through the diversion channel will be allowed as long as Rafferty is not making a release. Flows through the Boundary to Rafferty Diversion are assumed to be zero during the winter (20 October – 15 March) to facilitate drawdown.

Although the physical capacity of the Boundary diversion is greater than 70 m^3/s (2,500 ft^3/s), releases from Boundary via the Boundary Diversion are limited to a maximum flow of 45 m^3/s (1,590 ft^3/s) to prevent damage to the diversion channel (WSA, 2018). Releases in excess of 45 m^3/s (1,590 ft^3/s) are made through Boundary Reservoir's main spillway.

During the non-winter months (May 15th through December 15th), Rafferty Reservoir can supply water to Boundary Reservoir via a pipeline. Modeled operation of the Rafferty Pipeline follow the clause on SaskPower's license for the works. Deliveries are triggered when Boundary Reservoir's pool is less than 559.5 m (1835.63 ft), Rafferty Reservoir is above 540 m (1771.65 ft), and Grant Devine Lake is above 552 m (1811.02 ft).

Pipeline flows are modeled as a constant, specified maximum release of 0.297 m^3/s (10.5 ft^3/s) and are based on information provided by the WSA. The seasonal operation limit prevents the pipeline for exceeding the licensed use of 7,300 dam^3 (5,900 acre-feet) (WSA, 2018). As part of HH1, piped flow from Rafferty to Boundary was explicitly accounted for as a time series dependent on pool elevation when computing the inflow record to Rafferty Reservoir.

ResSim cannot model the transfer of water back and forth between reservoirs. To support this functionality a "dummy" reservoir is used to model flows from Rafferty to Boundary. The "dummy" reservoir requires a placeholder inflow time series set to zero for the entire period of record. The "dummy" reservoir is given a large amount of starting storage volume to ensure that it always has volume to make releases over the period of record for any realistic simulation time period.

Figure 26 shows a schematic of how the system is modeled. Within the model, Boundary Reservoir can directly transfer water to Rafferty Reservoir using a diverted outlet to model the Boundary Diversion. To model piped releases from Rafferty to Boundary, Rafferty has a diverted outlet. Rafferty's diverted outlet is not connected to any downstream elements. An intermediary,

“dummy” reservoir is setup using the same rule logic as is specified within Rafferty Reservoir to determine releases via Rafferty’s diverted outlet pipeline. The flows diverted from Rafferty Reservoir are equivalent to the flows being released via the dummy reservoir. Outflows from the dummy reservoir are fed into Boundary Reservoir via a diverted outlet.

Figure 26 Boundary Diversion and Rafferty Pipeline model element schematic

4.4 Rate of Change Rules

Reservoirs are generally operated with constraints on how quickly discharge or pool elevation may be increased or decreased. While not specifically included in the 1989 International Agreement, flow rate of change limitations are generally implemented by reservoir operators in the actual operations of each reservoir. The ROI rules at Rafferty, Grant Devine, and Lake Darling reservoirs included in this model were developed based on guidance from the Saskatchewan WSA and USACE and are modified slightly to correspond to historic release records. No ROI rule was included at Boundary Reservoir. The rate of increase rules for Rafferty Reservoir, Grant Devine Lake, and Lake Darling are summarized in Table 44. The rate of decrease for the three reservoirs is limted to a 0.007 m (0.023 ft) drop in reservoir pool.

The rate of change rules limit the drawdown slighlty. Due to a software limitation the reservoirs stop discharging a few days before they reach their drawdown elevation. This has negligible effect on the results.

Table 44 Summary of rate of increase limit

Release		Rate of Change	
m^3/s	ft^3/s	m^3/s /hr	ft^3/s /hr
Rafferty Reservoir			
0	0	0.28	10
1	35	0.85	30
10	353	1.42	50
42.5	1500	2.41	85
100	3500	4.96	175
150	5300	12.46	440
Grant Devine Lake			
0	0	0.42	15
1	35	0.71	25
10	353	1.70	60
100	3531	4.96	175
150	5300	12.46	440
Lake Darling			
0	0	0.12	4.375
1	35	0.25	8.75
10	353	1.25	44
100	3531	4.96	175
150	5300	12.39	437.5

4.5 Summary of Operational Zones

Generally, four operational zones are used to describe operation of each of the reservoirs. Operational zones are summarized in ***Table 45***. A zone above the top of the flood control zone is included in the model for Boundary Reservoir. This additional zone prevents Boundary's pool from rising above elevation 561.137 m (1841.0 ft) to better mimic observed operations. Lake Darling's Top of Flood Control elevation varies seasonally. During spring runoff (20 March – 31 May) the top of flood control is 487.985 m (1601 ft), during the rest of the year the top of flood control is 487.070 m (1598 ft). After spring runoff, the top of flood control transitions to 487.070 m (1598 ft) if flow at Minot has fallen below 14.16 m^3/s (500 ft^3/s) and the pool has fallen below 487.070 m (1598 ft).

A top of dam zone was included for the Souris River Project Reservoirs to provide the capability to model extreme events. ResSim uses the top of dam elevation to estimate the discharge which would occur in the event the dam was overtopped. When ResSim computes a pool elevation which exceeds the defined top of dam elevation the reservoir will release from any active outlets based on the physical capacity of the outlets. If there is an uncontrolled outlet, it will spill. If the capacity of all the modeled outlets are exceeded, ResSim will overtop the dam itself using a default weir coefficient of 3.0, the length of the dam, and the head calculated as the water surface elevation minus the elevation of the top of the dam.

Table 45 Summary of reservoir operating zones

Zone	Units	Rafferty Reservoir	Boundary Reservoir	Grant Devine Lake	Lake Darling
Top of Dam	meters	555.70	561.137	568.50	489.51
	feet	1823.16	1841.0	1865.15	1606.0
Maximum Allowable Flood Level (MAFL)/Flood Control Zone	meters	554.0	560.832	567.0	Spring: 487.985 Summer/Fall: 487.070
	feet	1817.59	1840.0	1860.24	Spring: 1601.0 Summer/Fall: 1598.0
Conservation (Guide Curve)		Varies	Varies	Varies	Varies
Inactive Pool	meters	537.5	553.212	537.972	480.670
	feet	1763.45	1815.0	1765.0	1577.0

4.6 Summary of Operating Rules

4.6.1 Operating Rules Souris River Project

Table 46, Table 47, Table 48, and ***Table 49*** summarize the rules for Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake, and Lake Darling, respectively. The order of the rules within the tables reflect the priority in which they are applied by the model.

Table 46 Summary of Rafferty Reservoir rules

Zone	Rule	Description
Top of Dam	***The top of dam zone extends from the maximum allowable flood level (MAFL) zone to the physical top of the dam. This zone is for extreme event operation.***	
	If Block: Within 0.5 ft (0.15 m) of MAFL	This rule helps keep continuity between the top of dam zone and MAFL zone by forcing a release that is 2% more than inflow.
	PipelineOff	This rule ensures the Rafferty to Boundary Pipeline is off when the reservoir is above the top of the MAFL zone
	If Block: Gate Switch	Restricts flow to one gate for a given discharge. Based on previous discharge
Maximum Allowable Flood Level (MAFL)	***The MAFL zone contains the rules applicable to flood control operations.***	
	If Block: Sherwood Min Operation, Rule: minFlow4cfsSherwoodRaf	Minimum 0.11 m^3/s (4 ft^3/s) required at Sherwood (if it would have occurred naturally). Based on the "app_4cfsMinRaf" state variable
	app_min_flow_Dam	Minimum flow at Sherwood required to meet apportionment- calculated within "app_min_release_GD."
	If Block: divertToBoundary	Diverts a constant flow of 0.30 m^3/s (10.5 ft^3/s) through Rafferty Pipeline to Boundary Reservoir if certain criteria are met (15 May – 14 Dec)
	ds_EstevanMax-1	Maximum flow limit at Estevan which is tied to pool elevations at Rafferty Reservoir, based on discussion with WSA
	ds_sherwood_sv	Maximum flow limit at Sherwood defined by "a_fld_MASTER_gc_GD"
	If Block: Gate Switch	Restricts flow to one gate for a given discharge. Based on current discharge
Conservation	***The model guide curve, or top of conservation pool elevation, is calculated within "a_fld_MASTER_GC_GD." The guide curve varies seasonally and is dependent on whether a spring flood is forecasted***	
	If Block: Sherwood Min Operation, Rule: minFlow4cfsSherwoodRaf	Minimum 0.11 m^3/s (4 ft^3/s) required at Sherwood (if it would've occurred naturally)
	app_min_flow_Dam	Minimum flow at Sherwood to meet apportionment- calculated within "app_min_release_GD"
	If Block: DivertToBoundary	Diverts a constant flow of 0.30 m^3/s (10.5 ft^3/s) through Rafferty Pipeline to Boundary Reservoir if certain criteria are met (15 May – 14 Dec)
	ds_EstevanMax-1	Maximum flow limit at Estevan which is tied to pool elevations at Rafferty Reservoir, based on discussion with WSA
	ds_sherwood_sv	Maximum flow limit at Sherwood calculated within "a_fld_MASTER_gc_GD"
	If Block: Gate Switch	Restricts flow to one gate for a given discharge. Based on current discharge.
Inactive	***No flow can be released from this zone***	

dummy_zone	***The dummy_zone is added to Rafferty Reservoir below the inactive zone as a modeling technique to help force the compute block in the model to include parameters from the state variable scripts***	
	connectToSherwood	Forces all model elements between Rafferty Reservoir and Sherwood to be in the same compute block.
	connectToGrantDevine	Forces all model elements between Rafferty Reservoir and Grant Devine Reservoir to be in the same compute block.
	connectToDarling	Forces all model elements between Rafferty Reservoir and Lake Darling Reservoir to be in the same compute block.

Table 47 Summary of Boundary Reservoir rules

Zone	Rule	Description
Top Of Dam	*The top of dam zone extends from the above flood control (AbvFC) zone to the physical top of the dam. This zone is for extreme event operation.*	
	If Block: OperateDiversion2	This If Block contains the rules which allow the Boundary Diversion Channel to be operated to send flow from Boundary Reservoir to Rafferty Reservoir.
Maximum Allowable Flood Level (MAFL)	***The MAFL zone contains the rules applicable to flood control operations.***	
	If Block: OperateDiversion2	This If Block contains the rules which allow the Boundary Diversion Channel to be operated to send flow from Boundary Reservoir to Rafferty Reservoir.
Conservation	***The model guide curve, or top of conservation pool elevation, is calculated within "a_fld_MASTER_GC_GD."***	
	If Block: OperateDiversion2	This If Block contains the rules which allow the Boundary Diversion Channel to be operated to send flow from Boundary Reservoir to Rafferty Reservoir.
Inactive	***The zone elevation to define the inactive zone of the reservoir where there is no control over releases from the reservoir***	

Table 48 Summary of Grant Devine Lake rules

Zone	Rule	Description
Top Of Dam	***The top of dam zone extends from the maximum allowable flood level (MAFL) zone to the physical top of the dam. This zone is for extreme event operation***	
	If Block: Within 0.5 ft (0.15 m) of MAFL	This rule helps keep continuity between the top of dam zone and MAFL zone by forcing a release that is 2% more than inflow.
	If Block: Gate Switch	Restricts flow to one gate for a given discharge. The irrigation gates are not typically used at Grant Devine
Maximum Allowable Flood Level (MAFL)	***The MAFL zone contains the rules applicable to flood control operations***	
	If Block: Min Sherwood Operation GD Rule: minFlow4cfsSherGD	Minimum 0.11 m^3/s (4 ft^3/s) required at Sherwood (when it would've occurred naturally)

	app_min_Dam	Minimum flow at Sherwood required by apportionment- calculated within "app_MASTER_min_release_GD"
	MaxReleasesGD_Dam	Limits maximum releases from Grant Devine Reservoir based on the current pool elevation of the reservoir. Elevations are tied to maximum release rates based on discussion with WSA.
	ds_sherwood_sv	Maximum flow limit at Sherwood calculated within "a_fld_MASTER_gc_GD"
	If Block: Gate Switch	Restricts flow to one gate for a given discharge. The irrigation gates are not typically used at Grant Devine.
Conservation	***The model guide curve, or top of conservation pool elevation, is calculated within "a_fld_MASTER_GC_GD." The guide curve varies seasonally and is dependent on whether a spring flood is forecasted***	
	minFlow4cfsSherGD	Minimum 0.11 m^3/s (4 ft^3/s) required at Sherwood (when it would've occurred naturally)
	app_min_Dam	Minimum flow at Sherwood required by apportionment- calculated within "app_MASTER_min_release_GD"
	MaxReleasesGD_Dam	Limits maximum releases from Grant Devine Reservoir based on the current pool elevation of the reservoir. Elevations are tied to maximum release rates based on discussion with WSA.
	ds_sherwood_sv	Maximum flow limit at Sherwood calculated within "a_fld_MASTER_gc_GD"
	If Block: Gate Switch	Restricts flow to one gate for a given discharge. The irrigation gates are not typically used at Grant Devine.
Inactive	***The zone elevation to define the inactive zone of the reservoir where there is no control over releases from the reservoir***	

Table 49 Summary of Lake Darling rules

Zone	Rule	Description
Top Of Dam	***The top of dam zone extends from the maximum allowable flood level (MAFL) zone to the physical top of the dam. This zone is for extreme event operation***	
	If Block: Within 0.5 ft (0.15 m) of MAFL	This rule helps keep continuity between the top of dam zone and MAFL zone by forcing a release that is 2% more than inflow.
Maximum Allowable Flood Level (MAFL)	***The MAFL zone contains the rules applicable to flood control operations during the spring runoff period. The maximum allowable flood control pool up to elevation 1601 feet (487.98 m) is only available during spring runoff.***	
Flood Control	***The top of flood control elevation varies at Lake Darling. In the spring (before June 1st) it is defined as 1601 feet (487.98 m), while for the remainder of the year top of flood control is 1598 feet (487.07 m). This zone is defined and the top of the zone (1601 ft (487.98 m) in the spring, 1598 ft (487.07 m) in the summer) is modeled using two variables: date and the "a_fld_status" state variable computed in the "a_fld_MASTER_GC_GD" state variable script.***	
	DS_Minot_sv	Maximum flow limit at Minot calculated within "a_fld_MASTER_gc_GD"
Conservation	***The model guide curve, or top of conservation pool elevation, is calculated within "a_fld_MASTER_GC_GD." The guide curve varies seasonally and is dependent on whether a spring flood is forecasted***	
	DS_Minot_sv	Maximum flow limit at Minot calculated within "a_fld_MASTER_gc_GD"
	Eaton_Salyer_WS_min_rel	Minimum release limit for Eaton Irrigation and Salyer Refuge based on the state variable "app_below_dar_vol" calculated within "app_MASTER_min_release_GD"
Inactive	***The zone elevation to define the inactive zone of the reservoir where there is no control over releases from the reservoir***	

4.6.2 Operating Rules National Wildlife Refuge Structures

A summary of the rules used for the J. Clark Salyer National Wildlife Refuge Dams 320, 326, 332, 341, and 357is outlined in Table 50.

Table 50 Summary of Dam 320, 326, 332, 341, and 357 rules

Zone	Rule	Description
Flood Control	***The flood control zone contains the rules applicable to flood control operations***	
	Max CTL Release	A maximum release rule which specified maximum controlled releases of 84.95 m^3/s (3,000 ft^3/s) - releases in excess of this amount are made through the uncontrolled spillway
	minFlowWesthope	Minimum downstream constraint release rule to ensure that minimum releases of 0.56 m^3/s (20 ft^3/s) reach Manitoba at the Westhope crossing during summer and fall
Conservation	***The model guide curve, or top of conservation pool elevation***	
	Max CTL Release	A maximum release rule which specified maximum controlled releases of 84.95 m^3/s (3,000 ft^3/s) - releases in excess of this amount are made through the uncontrolled spillway
	minFlowWesthope	Minimum release rule to ensure that minimum releases of 0.56 m^3/s (20 ft^3/s) reach Manitoba at the Westhope crossing during summer and fall
Inactive	***The zone elevation to define the inactive zone of the reservoir where there is no control over releases from the reservoir***	

4.6.3 Initial Conditions

A period of record simulation (1930 through 2017) is used to establish baseline reservoir operations for the Souris River Project. Initial conditions are specified for January 1st, 1930 and are based on normal pool conditions. Normal pool conditions represent the average of the January 1st pools during non-drought years. J. Clark Refuge Structures are assumed to be at their guide curve (conservation pool) elevations on January 1st, 1930. No releases are being made from the refuge structures. The starting, January 1st, 1930 pool conditions for the Souris River Project reservoirs are summarized in ***Table 51***. All pools are assumed to be at or below their guide curve/conservation pool elevations so no releases are being made from the reservoirs on January 1st, 1930.

Table 51 Starting Pool Elevations – 1930-2017 Analysis

Reservoir	Starting Pool Elevation (feet)	Starting Pool Elevation (meters)	Significance
Rafferty	1802.82	549.50	Normal 1 Feb Drawdown
Boundary	1836.77	559.85	Normal 1 Jan Pool[1]
Grant Devine	1840.55	561.00	Normal 1 Feb Drawdown
Lake Darling	1596.00	486.46	Normal 1 Feb Drawdown
Dam 357	1414.10	431.02	1 Jan Guide Curve Elevation
Dam 341	1414.70	431.20	1 Jan Guide Curve Elevation
Dam 332	1417.00	431.90	1 Jan Guide Curve Elevation
Dam 326	1420.20	432.88	1 Jan Guide Curve Elevation
Dam 320	1423.30	433.82	1 Jan Guide Curve Elevation

[1] Normal pool conditions represent the average of the 1 Jan pools during non-drought years. A period of record simulation run from 1930-2017 was analyzed to generate a reasonable representation of normal pool.

Multiple parameters in the model are computed using the state variable scripts discussed in Sections 4.2.1 and 4.3.1. An initial input must be provided for each of the state variable components. The initial values for the state variable script are not critical to model results because they are recomputed by the state variable script immediately on the first time step and are overwritten with the correct value.

An additional set of initial pool conditions representing a low pool starting condition is analyzed to assess the 1930s drought sequence. A period of record simulation run from 1930-2017 was analyzed to generate a series of reasonable initial pool conditions representative of low pool conditions. Low pool conditions represent the average of the January 1st pools during drought sequences. These values are displayed in ***Table 52***. Drought sequences were identified from 1957-1969 and 1984-1996. The time window for the 1930s drought simulation starts on January 15, 1930. The model initialization (warm-up) period starts on Jan 1, 1930. J. Clark Refuge Structures are assumed to be at their guide curve (conservation pool) elevations on January 1st, 1930. All Souris River project pools are assumed to be at or below their guide curve/conservation pool elevations so no releases are being made from the reservoirs on 01 Jan 1930 for either the low initial pool scenario.

Table 52 Starting Pool Elevations- Low Pool Initial Conditions – 1930s drought

Reservoir	Starting Pool Elevation (feet)	Starting Pool Elevation (meters)	Normal 1 Feb Target Elevation (feet)	Normal 1 Feb Target Elevation (meters)
Rafferty	1789.49	545.44	1802.82	549.50
Boundary	1834.59	559.18	1840.00	560.80
Grant Devine	1834.79	559.24	1840.55	561.00
Lake Darling	1592.07	485.26	1596.00	486.46

4.7 Model Compatibility with Stochastic and Climate Change Simulations

The ResSim model developed as part of the HH6 effort for the Plan of Study was setup to perform continuous simulations for the period of record from 1930-2017 using observed data and the HH1 reconstructed hydrology dataset. This model was used to represent present day operating conditions in the basin. Components of the model were modified to make it compatible for performing simulations using stochastically generated synthetic streamflow inputs. Many of the changes made to ensure compatibility with stochastically generated inputs will make the model more easily amendable to being forced with flow data produced using rainfall-runoff models like MESH. This is imperative if the ResSim model is to be used to assess climate changed traces and to aid in real-time forecasting in the future.

The time period used to assess stochastic traces is the year 3000 through the year 3099. A brief description summarizing the changes which have been made to the ResSim model to enable it to use stochastically generated inputs is included below:

The guide curves for each of the J. Clark Structures is redefined as a function of a state variable computed by the model (see Section 4.2.4 for more detail). Previously, the guide curves were

modeled using a predefined external timeseries for 1930-2017. Using state variables to define the guide curves allows them to be generated dynamically making them compatible with alternate simulation windows.

A diversion relationship was defined for the Eaton Irrigation Project. The HH1 product implicitly accounts for the impacts of the Eaton Irrigation Project. When synthetically generated inputs are used or flows produced using a runoff model, the effects of Eaton Irrigation have to be directly accounted for. To model the stochastic traces a time series was developed to mimic Eaton Irrigation District water usages for water years 3000 through 3099 (see Section 4.3.3 for more detail).

Time series like the inflows to the Dummy Reservoir (Section 4.3.4), Boundary Dam water supply inputs (Section 3.3.3) have to be extended to cover alternate simulation windows. These time series are extended to encompass 3000 through 3099 to model stochastic traces. It is assumed that the amount and timing of water use for Estevan and SaskPower would be equivalent to present day usages when applied in conjunction with stochastic traces.

Evaporation from Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake, and Lake Darling was input as a net evaporation time series in the HH6 baseline version of the model. Net evaporation is gross evaporation (i.e. lake evaporation) minus observed precipitation. The 1930-2017 baseline simulation and the other verification simulations discussed in this report relied upon calculated estimates to generate the net evaporation time series. The stochastic model only produces precipitation and potential evapotranspiration (PET) time series. To generate a net evaporation time series that can be used in conjunction with stochastic traces, statistical analysis was performed to define the relationship between gross evaporation and PET (Appendix E).

Appendix F summarizes changes made to the model to support the modeling of stochastically generated inputs and how to import stochastic data generated by the USGS. An additional Jython script ("buildStochasticDSS.py") was developed to .import output from the stochastic USGS model into a DSS file that could be run in ResSim. A copy of the Jython script is provided in Appendix G.

5 Model Verification

The objective in verifying a reservoir model is not to exactly match observed pool elevations and outflows, but rather to verify that the model generally follows historical operations and makes operational decisions in accordance to the rules described in *Annex A* and *Annex B*. This process is different than the calibration/validation process that is typically applied to vet hydrologic models because hydrologic models have parameters which can be adjusted. In this case, verification is performed to ensure physical and operational rules correctly model reservoir behavior.

Typically, reservoir operation includes operational flexibility that is not specified by the operating plan. Real time operating decisions can deviate from what is prescribed by formal operating guidelines based on conditions in the watershed at the time of a flood or drought event. These discretionary decisions are difficult to capture with a reservoir model because they are

based on real time information (forecasts, specific circumstances, etc.). Additionally, *Annex A* does not include much guidance pertaining to flood operations in response to rainfall runoff events. This leads to discretionary decisions being made in response to summer and late fall events. Where modeled operations deviate from historical operations, the differences between observed and modeled releases in a reservoir model can typically be explained based on the circumstances relevant to a specific event.

Because the upstream end of a reservoir is often impacted by backwater effects and becomes part of the reservoir's water surface profile during large events, gaged reservoir inflow records are typically unavailable. Reservoir inflow records must be computed using reverse reservoir routing that rely on observed reservoir outflows and pool elevations or defined using gages located a considerable distance upstream. Due to unaccounted for intervening drainage area, direct losses, wind seiche effects, and oscillations in reservoir pool elevation, the reservoir inflow records used can have some irregularities that can impact model verification.

Between 1998 and 2017 Rafferty Reservoir, Boundary Reservoir, Grant Devine Lake and Lake Darling were operated in accordance to the current operating guidelines specified in the *1989 Agreement*, with a minor modification to apportionment that began in 2003. The ResSim model is verified using the period of record from 2006 through 2009. This portion of the period of record was selected to test rule logic because these years include three low flow years preceding a flood year in 2009. The 2001, 2011 and 2013 events are used to verify flood control operations. The period of record from 1998 through 2017 is used to further verify model performance when run for a longer period of time.

5.1 2006-2009 Verification Period

5.1.1 Verification: Rafferty Reservoir

Figure 27 shows relevant simulated and observed daily elevation, daily outflow and accumulated flow volume for Rafferty Reservoir for the 2006-2009 simulation period. The upper viewport contains the observed and simulated pool elevation, as well as the computed guide curve (conservation pool elevation), and the top of the flood control pool. The middle viewport contains the observed and simulated discharge to the Souris River. The lower viewport shows the simulated and observed cumulative, annual discharge volume. Simulated values are represented by a blue line and observed releases are represented by a black line in the plots. When comparing the simulated and observed results during low flow years it is best to compare cumulative annual outflow volume rather than day-to-day releases because it is difficult to capture the timing of the apportionment releases in the model.

The observed and simulated pool levels match well, which serves to verify the rules governing operation of the reservoir. The simulated releases from Rafferty Reservoir for 2006-2008 (dry years) are at times less than the observed releases from the reservoir, but neither observed or modeled outflows are significantly large. The model preferentially makes releases from Grant Devine during dry years. Operators also preferentially make low flow releases from Grant Devine, but will occasionally make discretionary releases from Rafferty when model logic would dictate a release from Grant Devine. Overall, the model is doing a reasonable job replicating historic releases from Rafferty during low flow years. ***Table 53*** shows the differences between the

simulated and observed annual discharge volume from Rafferty Reservoir from 2006 through 2009.

Because a series of dry years preceded 2009, the pool at Rafferty was well below its target, guide curve elevation. In order to reach and maintain the FSL, Rafferty only makes minimal releases to meet the apportionment. The model is not able to mimic the timing of the apportionment releases as they would have occurred in real time because when apportionment releases are made is highly discretionary. The model tends to spread apportionment releases out over longer periods of time rather than making releases over a shorter duration as appears to have been done in 2009. Additionally, the model appears to be underestimating the portion of the apportionment being met by Rafferty in 2009. The model is relying more on Grant Devine to make apportionment releases in 2009. In general, Grant Devine is preferentially used to meet apportionment so the model is relying on a reasonable assumption. If cumulative volume is compared at Sherwood in 2009 it is evident that the overall magnitude of the apportionment releases (net effect of releases from Rafferty plus Grant Devine) being made by the model reasonably replicate the amount of observed volume reaching Sherwood Crossing.

Overall, the releases from Rafferty are smaller than what was observed in reality but the simulated and observed pool elevations match each other closely. This is an indication that the model reasonably replicates historic operations. Since study focuses on comparative analysis between different proposed operating schemes, the current apportionment releases should provide a sufficient approximation of what actually occurs.

Table 53 Simulated vs. Observed Annual Discharge Volume: Rafferty Reservoir

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume
2006	23 (28)	598 (738)	-575 (-709)	-96
2007	519 (640)	959 (1,183)	-440 (-542)	-46
2008	15 (18)	143 (176)	-128 (-158)	-90
2009	21,955 (27,070)	32,039 (39,504)	-10,084 (-12,433)	-31
Total	22,512 (27,757)	33,739 (41,600)	-11,227 (-13,843)	-33

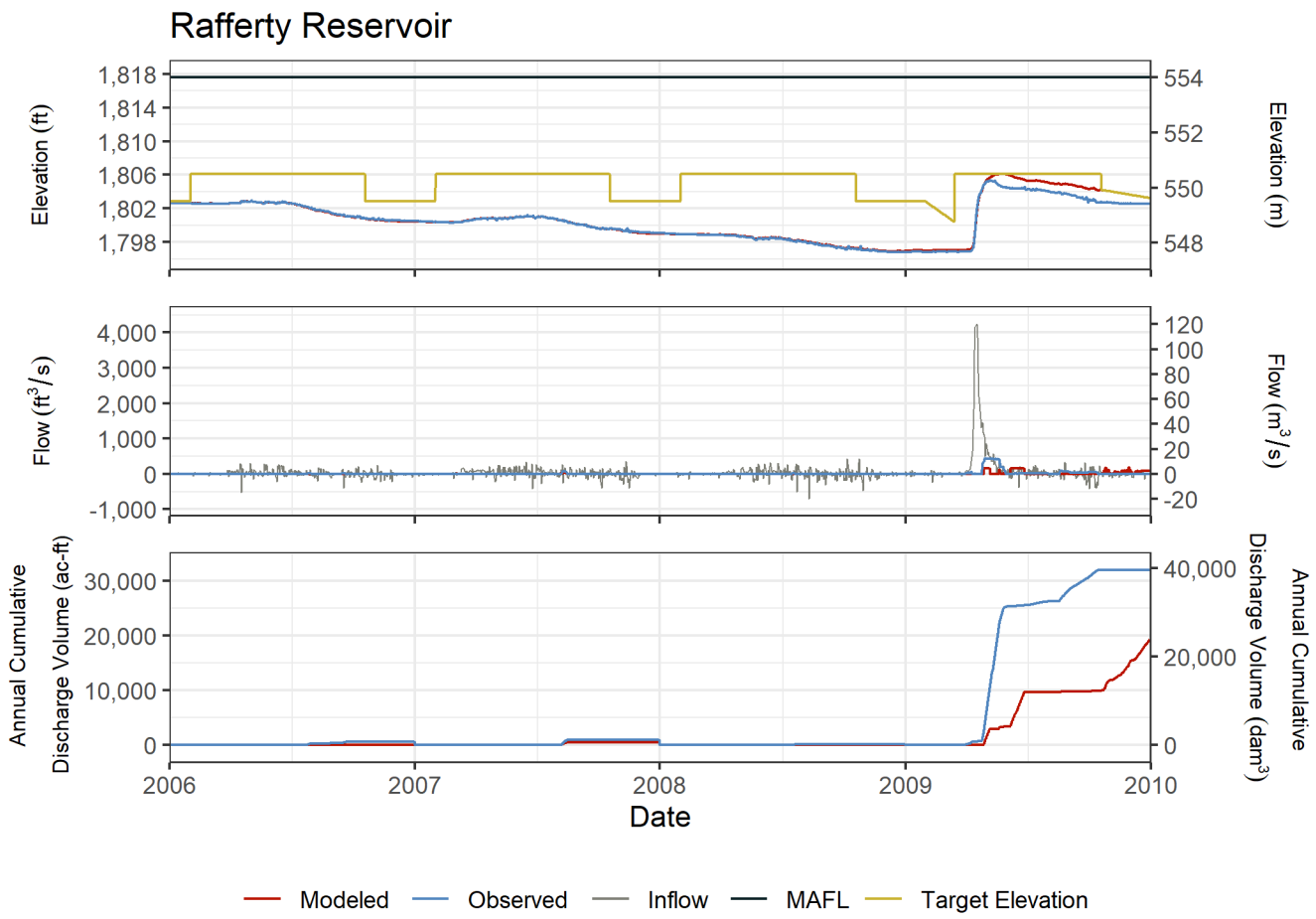


Figure 27 Rafferty Reservoir simulated and observed pool level, discharge, and cumulative annual discharge volume to the Souris River from 2006-2009

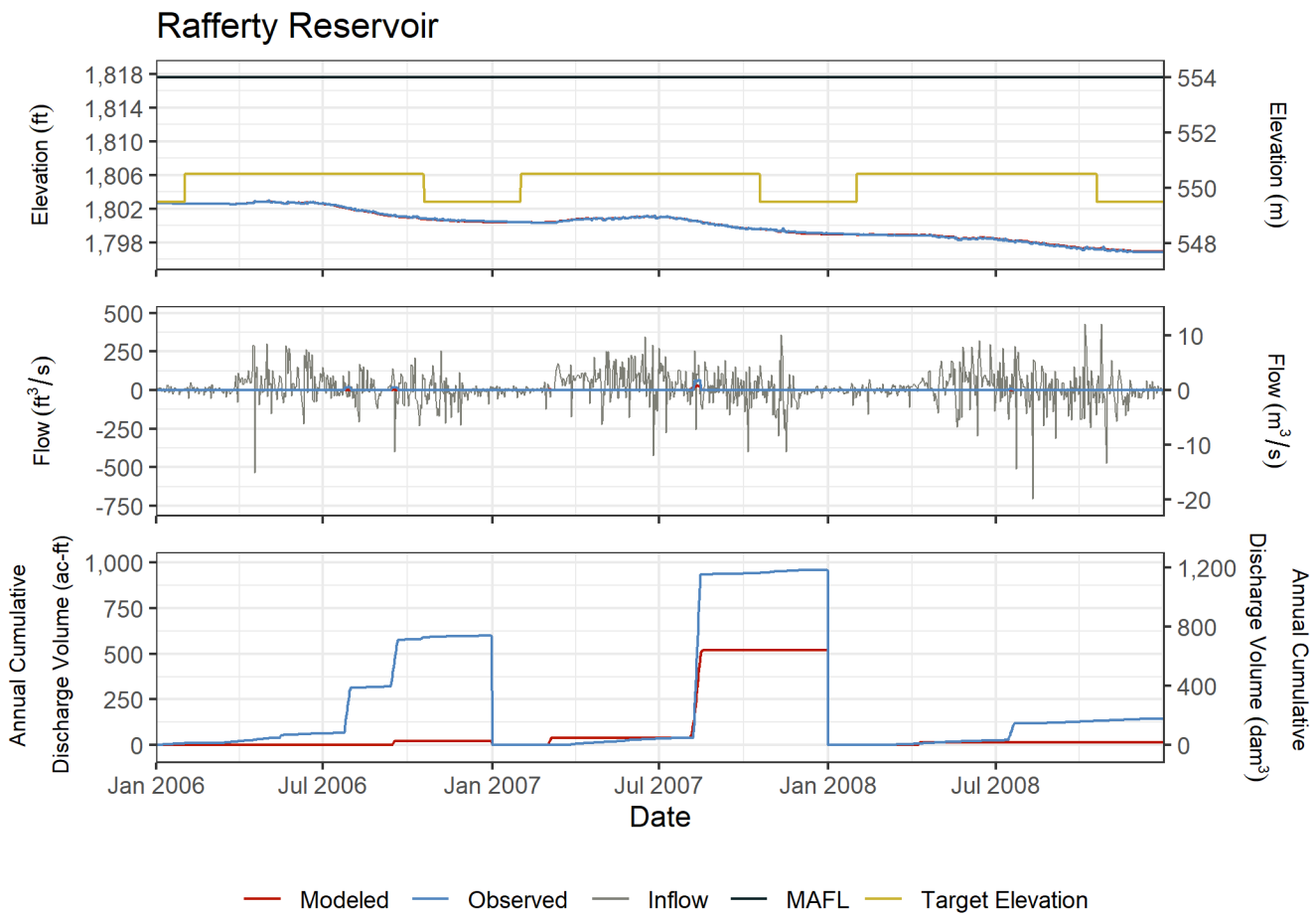


Figure 28 Rafferty Reservoir simulated and observed pool level, discharge, and cumulative annual discharge volume to the Souris River from 2006-2008

Figure 29 shows observed simulated and observed pool and discharge information via the Rafferty Pipeline (flows from Rafferty Reservoir to Boundary Reservoir). Only the observed, annual volume of water being transferred from Rafferty to Boundary is reported by the ISRB, so the timing of the historic discharges through the Rafferty Pipeline is unknown. *Table 54* shows the difference in magnitude and the percent difference between the simulated and observed annual Rafferty pipeline volume. Overall the amount of simulated volume through the pipeline is on the same order of magnitude as the observed volume. It is also important to note that WSA only issued a water rights license to SaskPower for this pipeline in August of 2012. Prior to that, SaskPower was required to obtain a temporary permit each year it was used. As such, past operations may not reflect the operating conditions on the license which were coded in the model.

Table 54 Simulated vs. Observed Annual Discharge Volume: Rafferty Reservoir Pipeline

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume
2006	3,666 (4,520)	2,246 (2,769)	1,420 (1,752)	63
2007	3,270 (4,032)	2,910 (3,588)	360 (444)	12
2008	4,457 (5,495)	6,226 (7,677)	-1,769 (-335)	-28
2009	0 (0)	851 (1,049)	-851 (-161)	-
Total	11,392 (14,047)	12,233 (15,083)	-841 (-159)	-7

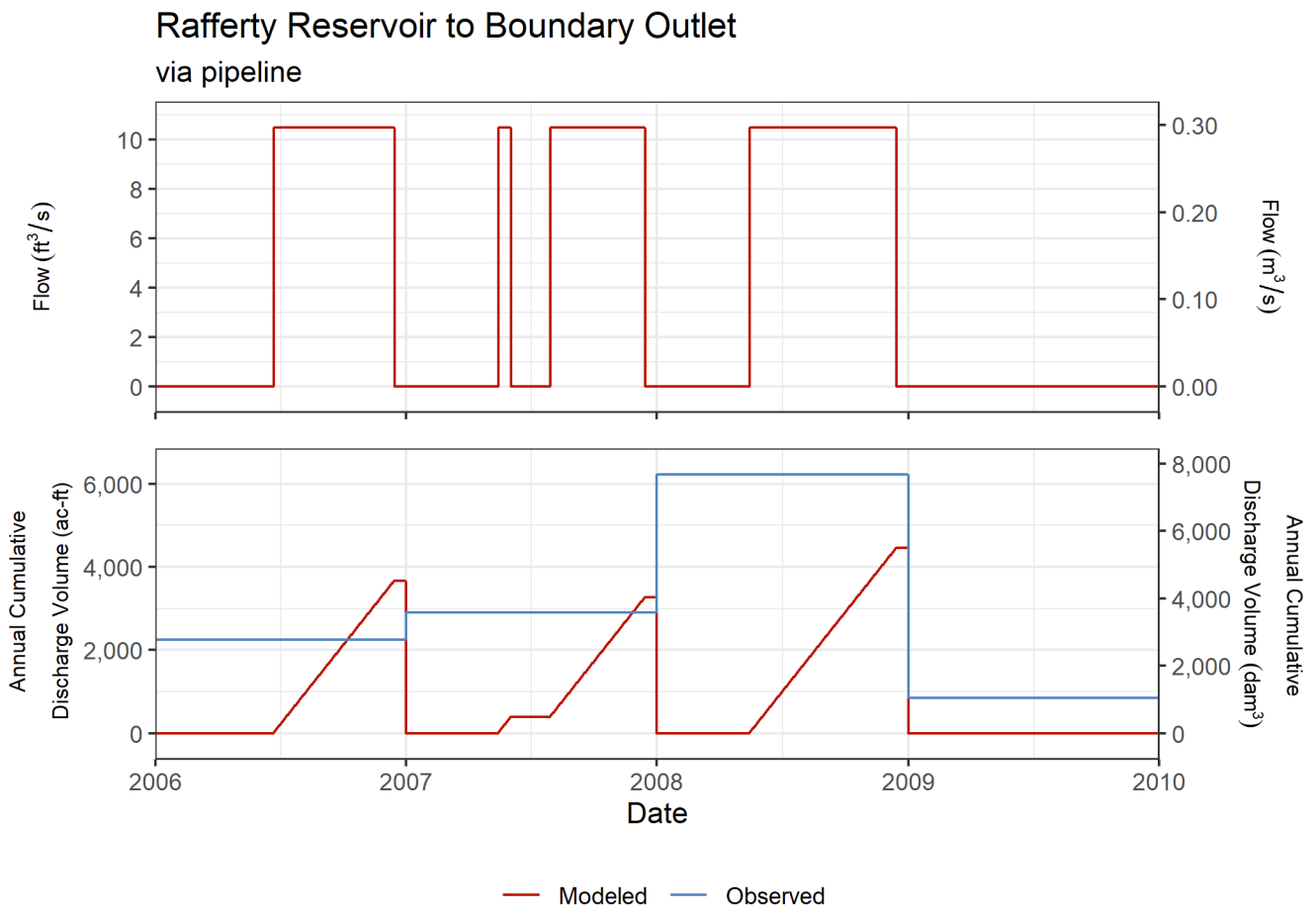


Figure 29 Rafferty Reservoir simulated and observed pool level, discharge to Boundary Reservoir, and cumulative annual discharge volume to Boundary Reservoir via the Pipeline from 2006-2009

5.1.2 Verification: Boundary Reservoir

Figure 30 displays observed and simulated daily elevation, daily total outflow (diversion plus main spillway) and accumulated total outflow volume for Boundary Reservoir. The modeled pool elevation generally follows the observed elevation. As a result of relatively high demands and its small storage capacity, Boundary's pool elevation is highly dependent on water use, which includes forced evaporation from the power plant cooling water.

It is likely that the modeled elevation of Boundary Reservoir often exceeds the observed elevation because it is a small reservoir and small changes in inflow or water use can result in large discrepancies in pool elevation. Actual water use and inflows were not known with great accuracy and vary from year to year, so errors in the modeled approximation of these loses result in a less than ideal fit.

The simulated discharge peak of 39.4 m^3/s (1,391 ft^3/s) in 2009 is driven by the guide curve and diversion rule and matches the observed peak of (43 m^3/s) 1,519 ft^3/s closely with a difference of 3.6 m^3/s (128 ft^3/s).

When comparing the simulated and observed results during low flow years it is best to compare end of year volume of outflow rather than day-to-day releases because it is impossible to capture the timing of the apportionment releases in the model.

Table 55 shows the difference between the simulated and observed annual discharge volume from Boundary Reservoir. The table shows that simulated volumes closely approximates the observed volume in each year of the simulation. The differences in the volumes for 2006 through 2009 are driven by the fact that in reality, operators allowed small releases whereas in the model none of the conditions were met to make releases. The model does an accurate job of simulating the observed release volume from Boundary Reservoir during the 2009 flood event. Overall, the simulated results closely match the value of the observed annual discharge volume.

Table 55 Simulated vs. Observed Annual Discharge Volume: Boundary Reservoir

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume
2006	0	174 (214)	-174 (-214)	-100
2007	0	264 (325)	-264 (-325)	-100
2008	0	111 (137)	-111 (-137)	-100
2009	13,169 (16,237)	9,899 (12,206)	3,270 (4,031)	33
Total	13,169 (16,237)	10,447 (12,882)	2,721 (3,355)	26

Figure 31 shows simulated and observed simulated discharges to Rafferty Reservoir via the Boundary Diversion. *Table 56* shows the simulated and observed annual discharge volume from Boundary Diversion. The model mimics what occurred during the 2006 through 2008 time period and does not release any flow through the diversion channel. The peak and volume of discharges during 2009 match the observed discharge through the diversion relatively well with a difference of only 22%.

Table 56 Simulated vs. Observed Annual Discharge Volume: Boundary Diversion Channel

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume
2006	0 (0)	0 (0)	0 (0)	-
2007	0 (0)	0 (0)	0 (0)	-
2008	0 (0)	0 (0)	0 (0)	-
2009	20,564 (25,356)	26,519 (32,711)	-5,965 (-7,355)	-22

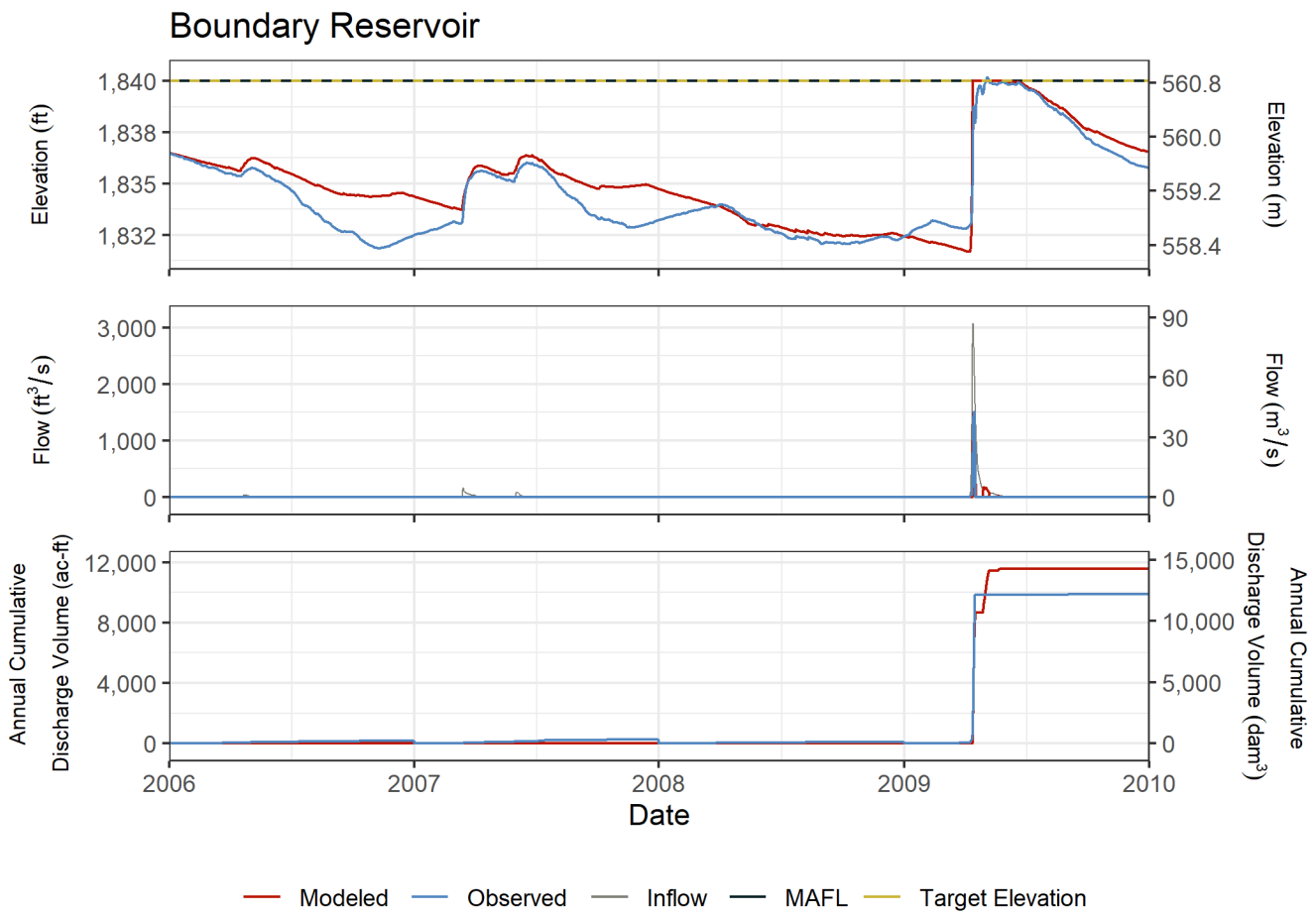


Figure 30 Boundary Reservoir simulated and observed pool level, discharge (from dam and diversion), and cumulative annual discharge volume to Long Creek from 2006-2009

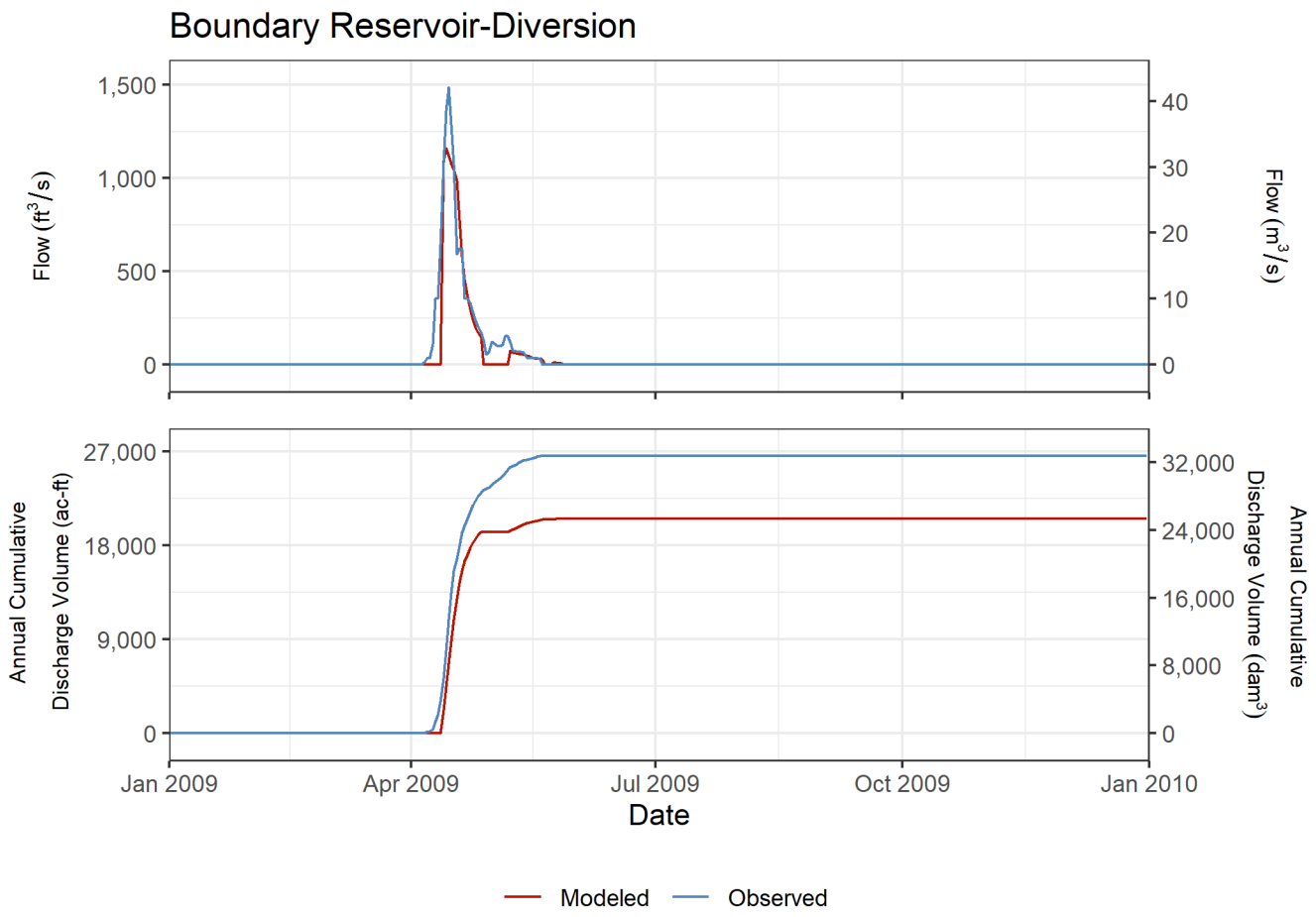


Figure 31 Boundary Reservoir Diversion simulated and observed discharge and cumulative annual discharge volume to Rafferty Reservoir Diversion from 2006-2009

5.1.3 Verification: Grant Devine Lake

Figure 32 shows observed and simulated daily elevation, daily outflow, and annual cumulative volume of discharge for Grant Devine Lake. The simulated pool elevation is slightly lower than the observed pool elevation for about half of the simulation, but in general the simulated results match the observed data well. Since the pool level is below guide curve, only minimum flow rules, such as the apportionment or minimum flow requirement at Sherwood, dictate the releases. The guide curve logic in the model is aimed at limiting releases as much as possible to raise the pool elevation to its conservation pool (FSL during the summer months).

Table 57 shows a comparison between the simulated and observed annual discharge volume from Grant Devine Lake. The table indicates that the simulated discharge volume is higher than the observed discharge volume during the low flow years. During the high flow event in 2009, the simulated volume is less than the observed volume. Overall, the difference between the modeled and observed information is minimal.

The simulated releases from Grant Devine Reservoir for the 2006 to 2009 period do not match the observed releases well. When comparing the simulation results to the observed results for low flow periods, it is more important to compare the end of year total volume than it is to compare the releases. This is because the minimum flow logic in the apportionment script focuses on matching the required apportionment volume and not on matching the day-to-day observed, apportionment releases. In reality, there is little to no guidance which describes how apportionment releases must be made and how large or small these releases should be over a specified duration. The end of year volumes for Grant Devine appear to reasonably match the observed volumes which indicate that overall, the model is able to represent reservoir operations.

Table 57 Simulated vs. Observed Annual Discharge Volume: Grant Devine Lake

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume
2006	5,220 (6,436)	4,727 (5,828)	493 (608)	10
2007	12,146 (14,976)	10,510 (12,958)	1,637 (2,018)	16
2008	783 (966)	5,994 (7,390)	-5,210 (-6,424)	-87
2009	15,024 (18,525)	8,616 (10,624)	6,408 (7,901)	74
Total	33,174 (40,903)	29,846 (36,801)	3,327 (4,103)	11

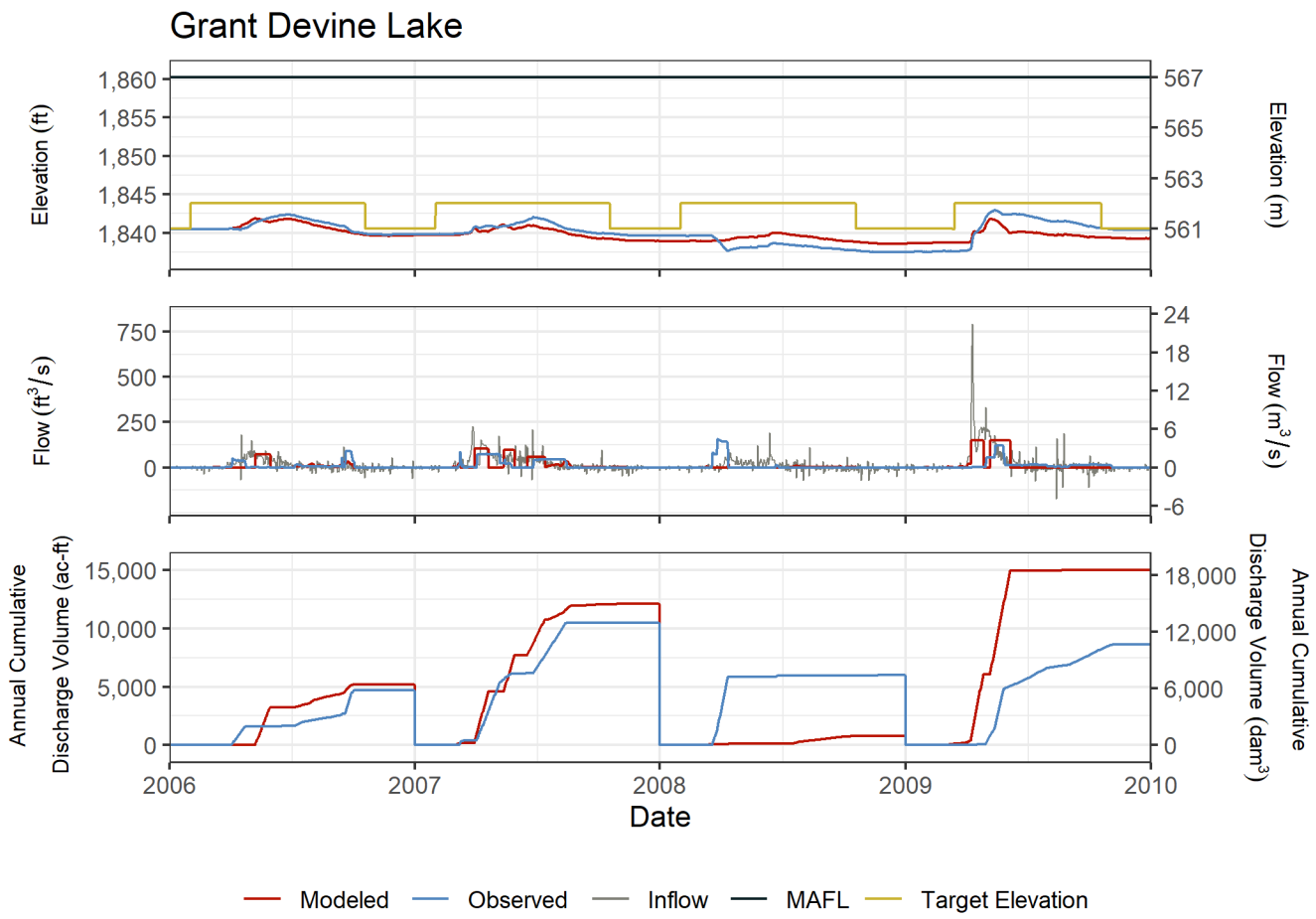


Figure 32 Grant Devine Lake simulated and observed pool level, discharge, and cumulative annual discharge volume from 2006-2009

5.1.4 Verification: Lake Darling

Lake Darling's modeled operations are more difficult to verify than the other reservoirs because of the discretionary water supply releases (see Section 4.3.3) and differences between the observed and simulated releases at upstream reservoirs that affect inflows. Releases made for water supply can vary widely from year to year and exact release volumes are not recorded on a regular basis. Section 4.3.3 outlines the assumptions which were made based on the best available information to model water supply releases. Additionally, any small errors in releases from the upstream ResSim reservoirs will carry downstream and act to further increase the error at Lake Darling.

Figure 33 contains the verification information for Lake Darling. The timing of the simulated releases generally matches the observed releases, but there are significant differences between the magnitudes of observed and modeled releases. Table 58 shows the difference between the simulated and observed annual flow volume for Lake Darling Reservoir. The magnitude of the differences range from 4% to 75%. The model is able to replicate observed pool elevations operations relatively well in 2006.

The main differences between the simulated and observed pool elevation occur beginning on April 1, 2007 as a result of the assumed water supply release made from the Lake Darling Reservoir for the Eaton irrigation district and downstream water supply to the J. Clark Salyer National Wildlife Refuge structures. As the plot shows, the model releases 52% less volume than what was observed in 2007. This results in a much higher simulated pool elevation. In 2008, the model releases similar flows as were observed to satisfy the water supply requirements of the Eaton irrigation district and the downstream refuge structures. The difference between the simulated and observed pool elevation in 2008 is a result of the residual difference from 2007, when the simulated releases were far less than the observed releases.

The simulated, annual volume released in 2009 matches the observed volume released reasonably well, and the simulated pool elevation matches the observed pool elevation. The simulated and observed releases do not match well in 2009. Initially, the releases in 2009 begin in May as the simulated pool approaches the guide curve. When the simulated pool elevation is greater than the conservation pool (guide curve) elevation, the Lake Darling reservoir model makes releases in accordance with the guidelines specified in Plate A-6 of *Annex A*.

The releases from Lake Darling oscillate from May through the end of the year in 2009. Of the four reservoirs which make up the Souris River Project, Lake Darling has the fewest modeled rules governing its releases. As a result, the model defaults to its guide curve logic and makes whatever releases are required to reach the guide curve as fast as possible.

Overall, the model performs well and does a reasonable good job of estimating the observed pool elevation and observed volume even though some of the simulated releases do not match the observed data. This is an indication that the operational rules and constraints describing operation of Lake Darling Reservoir adequately models the behavior of this reservoir and how it is operated.

Table 58 Simulated vs. Observed Annual Discharge Volume: Lake Darling

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume
2006	14,032 (17,302)	8,015 (9,883)	6,017 (7,419)	75
2007	13,843 (17,069)	29,021 (35,783)	-15,177 (-18,714)	-52
2008	17,481 (21,554)	15,452 (19,053)	2,029 (2,501)	13
2009	23,931 (29,508)	22,952 (28,299)	980 (1,208)	4
Total	69,288 (85,432)	75,440 (93,017)	-6,152 (-7,585)	-8

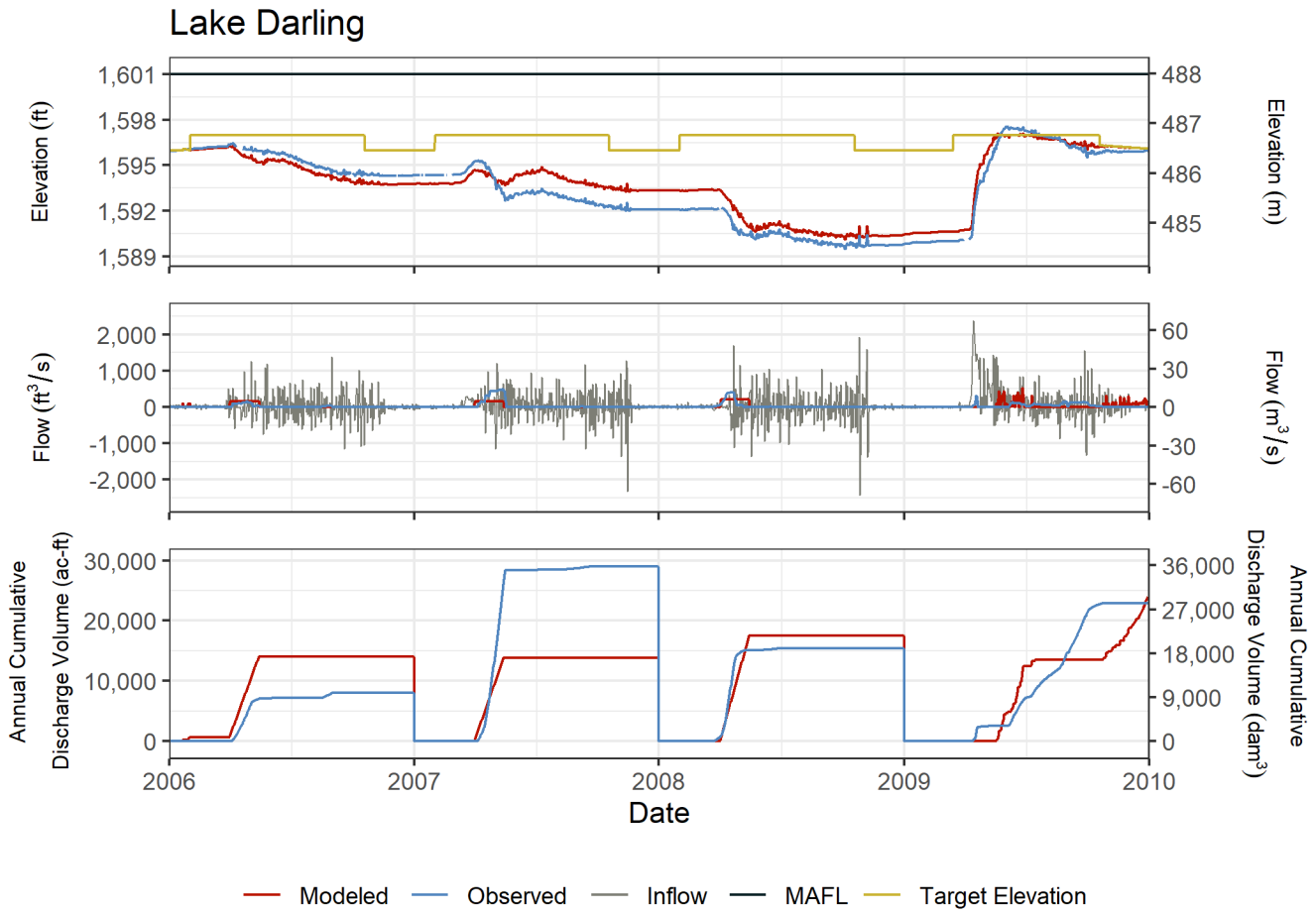


Figure 33 Lake Darling simulated and observed pool level, discharge, and cumulative annual discharge volume from 2006-2009

5.1.5 Verification at Downstream Control Points

The reservoirs are operated for multiple downstream control points. The figures in this section show the modeled and observed discharges and cumulative annual flow volumes at Estevan, Sherwood, Minot, Bantry, and Westhope, respectively. At Estevan, Sherwood, and Minot, maximum allowable flow limits are also shown where relevant. Observed flows at Estevan were estimated by summing the Souris River below Rafferty Reservoir and Long Creek below Boundary Reservoir observed discharges.

A summary of simulated and observed annual volume as well as simulated and observed peak daily discharge is shown in ***Table 59*** below. While there are differences in how the model operates the reservoirs compared to how they are operated in reality, the model is still able to provide reasonably accurate estimates of annual flow volume and peak discharge at the critical downstream sites. Estevan, Sherwood, Minot and Westhope are selected for this comparison because these are currently key downstream control points. Results at Bantry are also displayed because this location experiences frequent flooding and is located in the vicinity of the Eaton Irrigation District.

Table 59 Simulated vs. observed discharge volume and peak at key control points in the model

Site	Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Percent Change Volume	Simulated Peak Daily Flow, ft^3/s (m^3/s)	Observed Peak Daily Flow, ft^3/s (m^3/s)	Percent Change Peak Flow
Estevan	2006	23 (28)	772 (952)	-97	5 (0.2)	20 (0.6)	-74
	2007	519 (640)	1,223 (1,508)	-58	29 (0.8)	66 (1.9)	-55
	2008	15 (18)	254 (313)	-94	5 (0.2)	8 (0.2)	-33
	2009	30,959 (38,173)	41,938 (51,709)	-26	1,499 (42.4)	1,538 (43.5)	-3
	Total	31,516 (38,859)	44,186 (54,482)	-29	-	-	-
Sherwood	2006	10,841 (13,367)	10,217 (12,598)	6	98 (2.8)	133 (3.8)	-26
	2007	20,279 (25,004)	18,677 (23,028)	9	163 (4.6)	175 (5.0)	-7
	2008	10,025 (12,361)	13,730 (16,929)	-27	198 (5.6)	285 (8.1)	-31
	2009	73,796 (90,991)	76,169 (93,917)	-3	1,307 (37.0)	1,320 (37.4)	-1
	Total	114,942 (141,723)	118,793 (146,471)	-3	-	-	-

Minot	2006	16,850 (20,776)	10,656 (13,139)	58	250 (7.1)	142 (4.0)	76
	2007	18,277 (22,536)	32,415 (39,967)	-44	243 (6.9)	487 (13.8)	-50
	2008	19,324 (23,826)	17,172 (21,173)	13	370 (10.5)	435 (12.3)	-15
	2009	72,961 (89,961)	73,106 (90,139)	0	3,258 (92.3)	3,260 (92.3)	0
	Total	127,412 (157,099)	133,349 (164,420)	-4	-	-	-
Bantry	2006	27,726 (34,187)	26,383 (32,531)	5	261 (7.4)	438 (12.4)	-40
	2007	42,426 (52,312)	59,308 (73,126)	-28	485 (13.7)	675 (19.1)	-28
	2008	27,870 (34,363)	27,307 (33,670)	2	292 (8.3)	278 (7.9)	5
	2009	199,181 (245,590)	227,525 (280,538)	-12	7,074 (200.3)	6,910 (195.7)	2
	Total	297,203 (366,451)	340,523 (419,865)	-13	-	-	-
Westhope	2006	126,143 (155,534)	126,632 (156,137)	0	3,000 (85.0)	1,700 (48.1)	76
	2007	31,646 (39,019)	39,793 (49,065)	-20	519 (14.7)	495 (14.0)	5
	2008	6,045 (7,454)	9,446 (11,647)	-36	20 (0.6)	130 (3.7)	-85
	2009	355,681 (438,555)	427,581 (527,207)	-17	7,266 (205.8)	5,700 (161.4)	27
	Total	519,515 (640,562)	603,451 (744,055)	-14	-	-	-

Figure 34 and ***Figure 35*** show simulated and estimated observed releases and annual cumulative volumes at Estevan. Between 2006 and 2008 the differences between the simulated and observed discharge at Estevan is due to releases made from Rafferty Reservoir. The ResSim model preferentially makes releases from Grant Devine Reservoir to meet low flow and apportionment volume requirements. This assumption is in line with WSA's standard operating procedures. In reality some of the apportionment releases were made from Rafferty, thus the model underestimates flows at Estevan. These low flow releases from Rafferty were made at the operator's discretion and thus cannot be captured within the model. The model reasonably replicates the magnitude of flows at Estevan: minimal flows in 2006-2008, with a moderate volume of flow being released in 2009.

Figure 36, the simulated 2009 peak discharge closely matches the observed peak discharge at Estevan (3% difference). During the rest of the year, the simulated discharge matches the observed discharge reasonably well. The differences between the simulated flow and the observed flow at Estevan after April 20, 2009 is caused by the apportionment release logic. This

is because the apportionment script in the model focuses on matching the required apportionment volume and not on matching the day-to-day observed, apportionment releases.

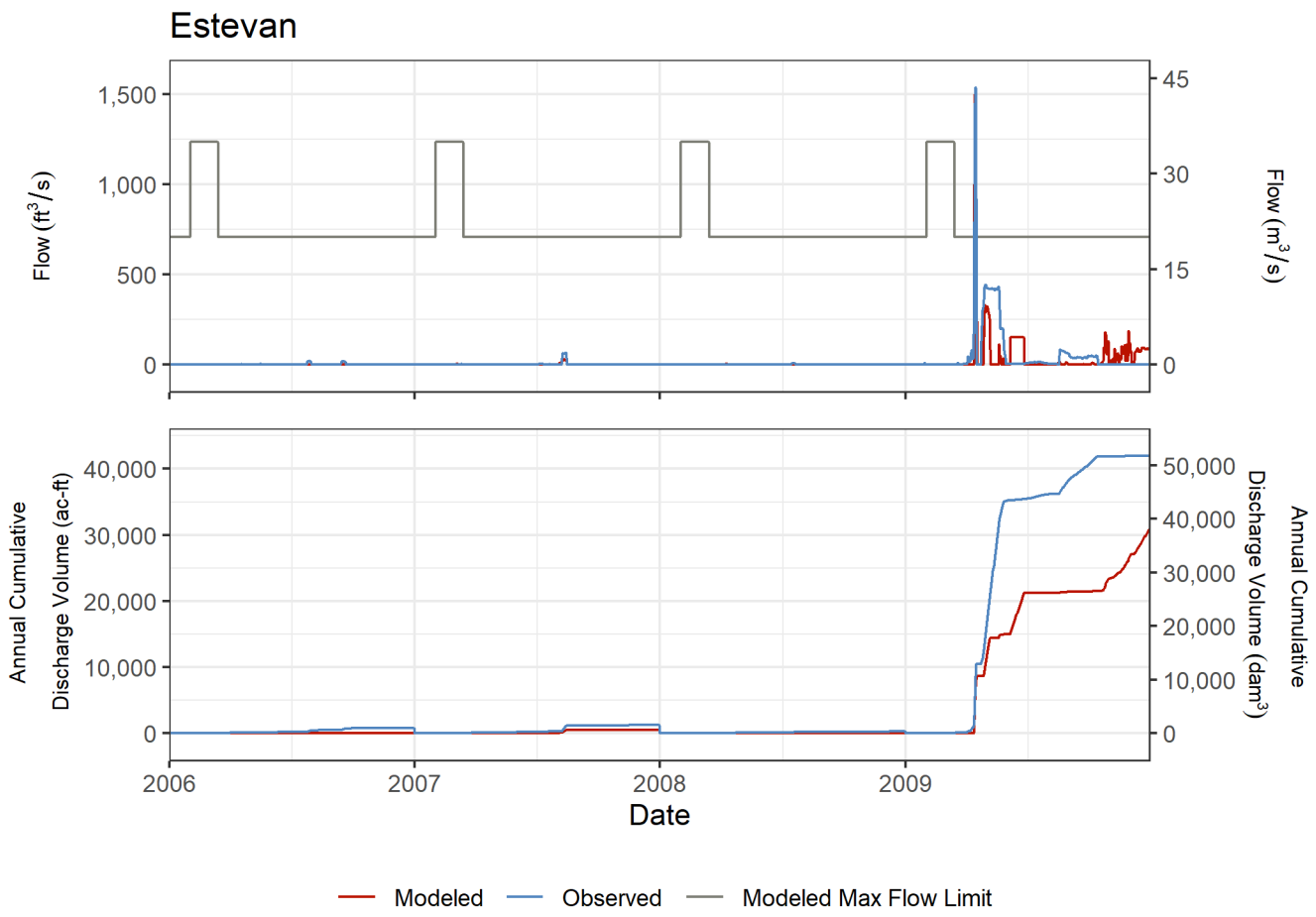


Figure 34 Estevan, SK simulated and estimated observed discharge, cumulative annual discharge volume, and maximum flow limit 2006-2009

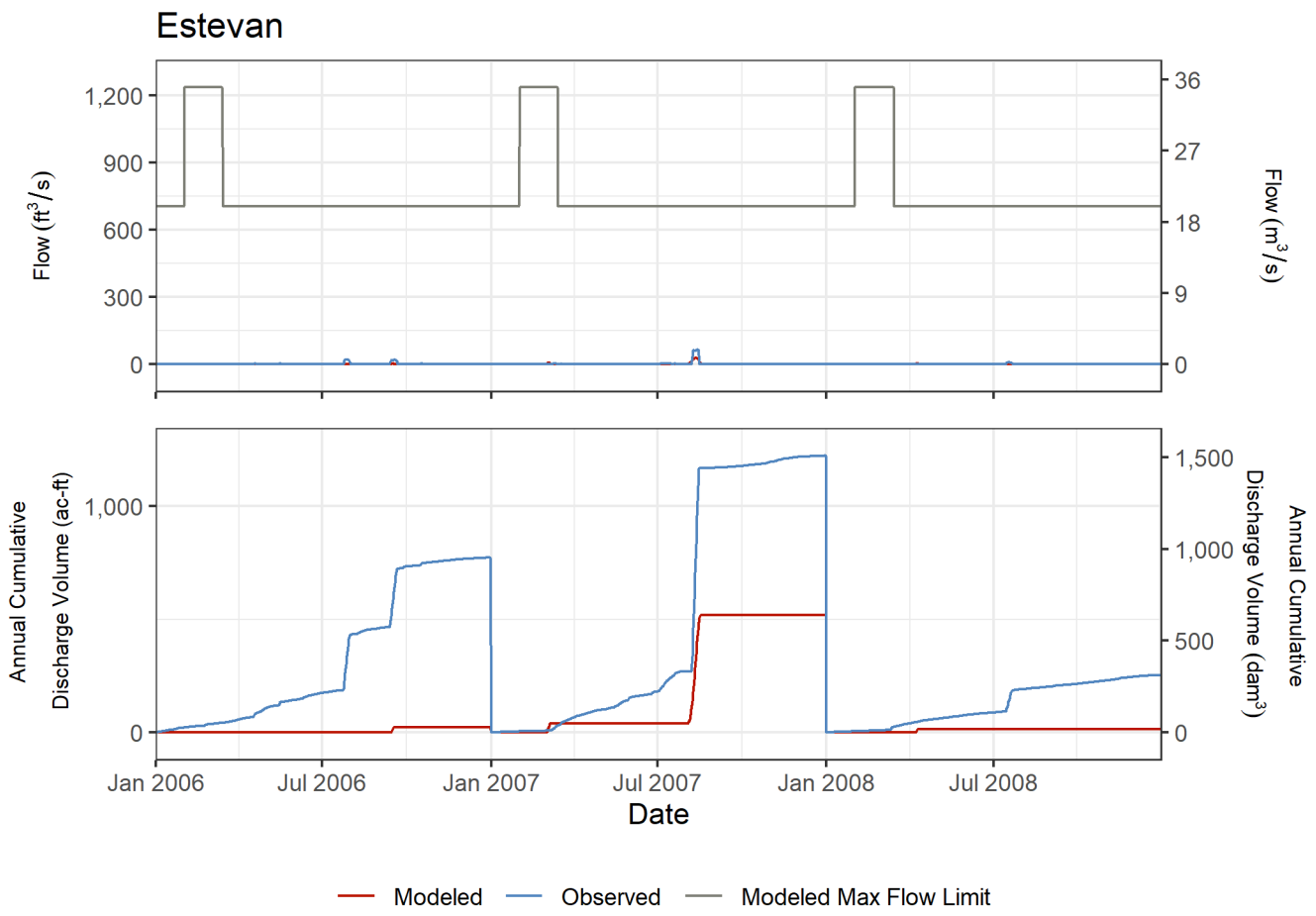


Figure 35 Estevan, SK simulated and estimated observed discharge, cumulative annual discharge

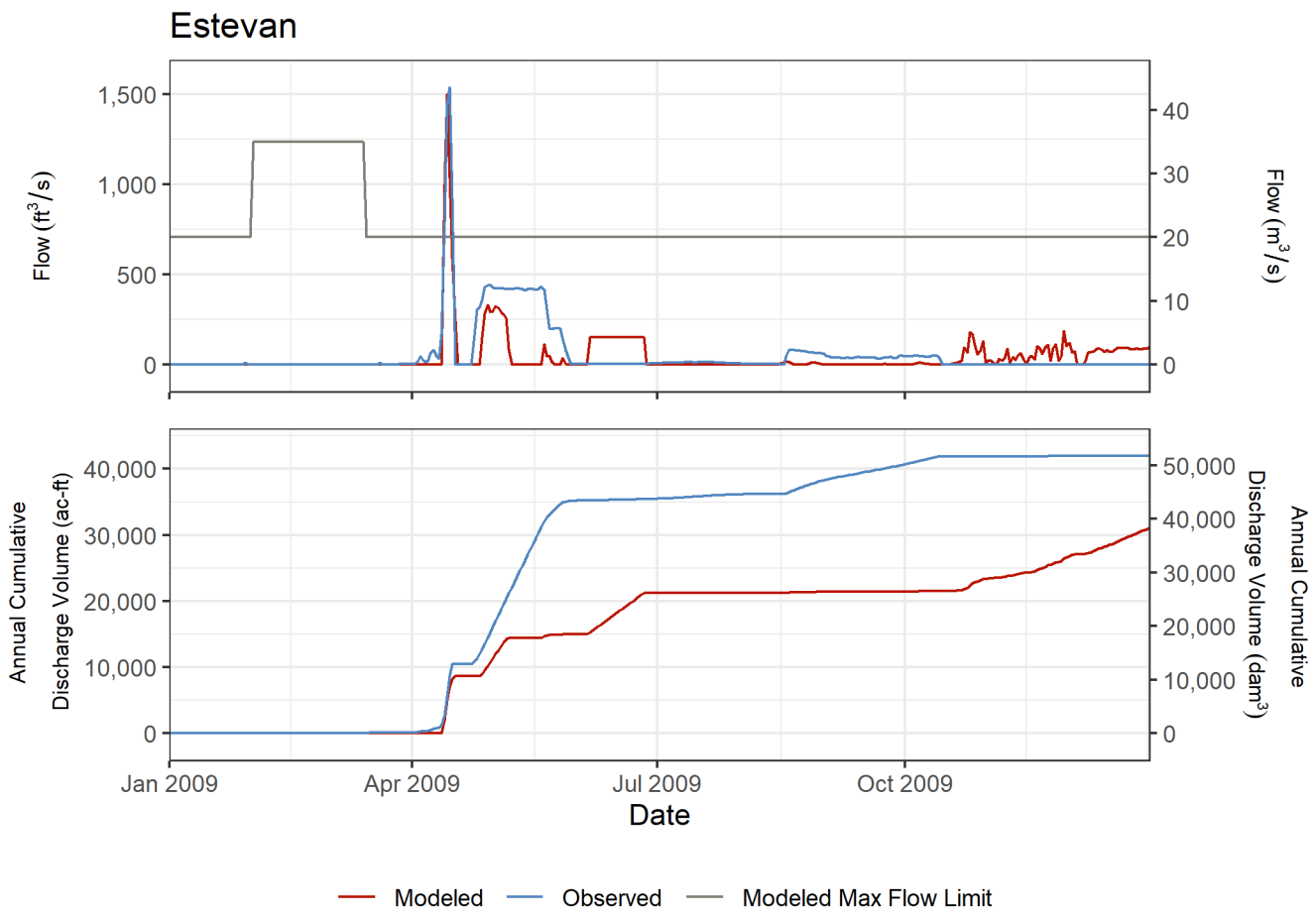


Figure 36 Estevan, SK simulated and estimated, observed discharge, cumulative annual discharge volume, and maximum flow limit 2009

The simulated and observed discharge and annual cumulative volume results for Sherwood Crossing are shown in ***Figure 37*** below. For the 2006 through 2008 time period, the simulated and observed discharge and volume closely match. This is an indication that the apportionment logic is being modeled accurately.

Figure 38 shows a log plot of simulated and observed discharges at Sherwood along with the maximum and minimum constraints as determined by ResSim. The 4 ft^3/s (0.11 m^3/s) minimum flow rule is generally being met. There are some small differences between the simulated and observed discharge from 2006 through 2008.

During the 2009 flood event, the model accurately simulated the timing, magnitude, and discharge of the peak event. The simulated peak discharge was 23% less than the observed peak. In May 2009 there was a second peak event which the model also captures reasonably well, but under estimates releases slightly. A review of the May 2009 model releases for Rafferty Reservoir and Grant Devine Reservoir indicates that these reservoirs (especially Rafferty Reservoir) release less flow than what was observed because they are constrained by the apportionment release rule logic. The reservoirs modeled upstream of Sherwood collectively do an adequate job of modeling flow and volume at the Sherwood Crossing.

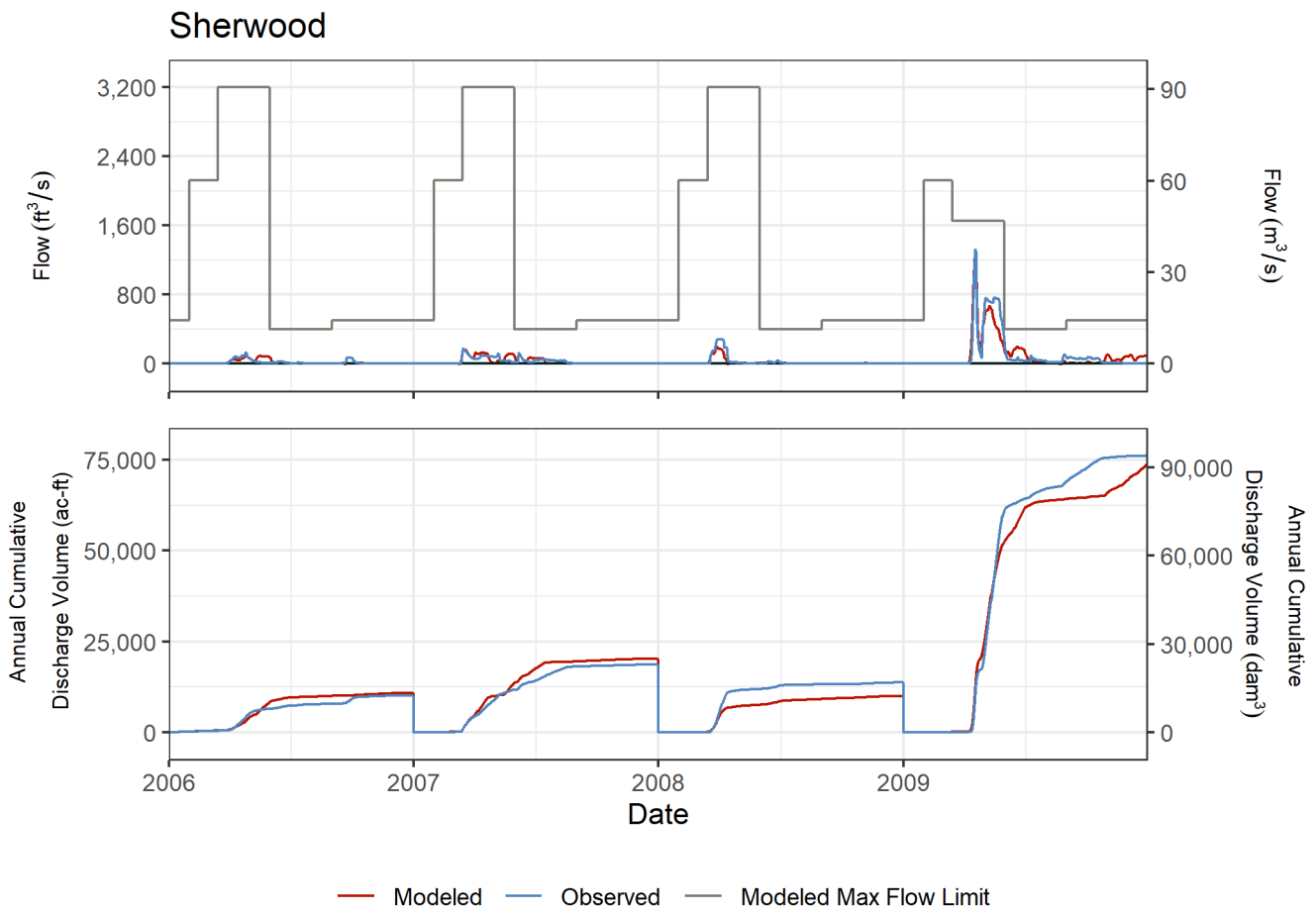


Figure 37 Sherwood, ND Simulated and observed discharge, cumulative annual discharge volume, and maximum flow limit 2006-2009

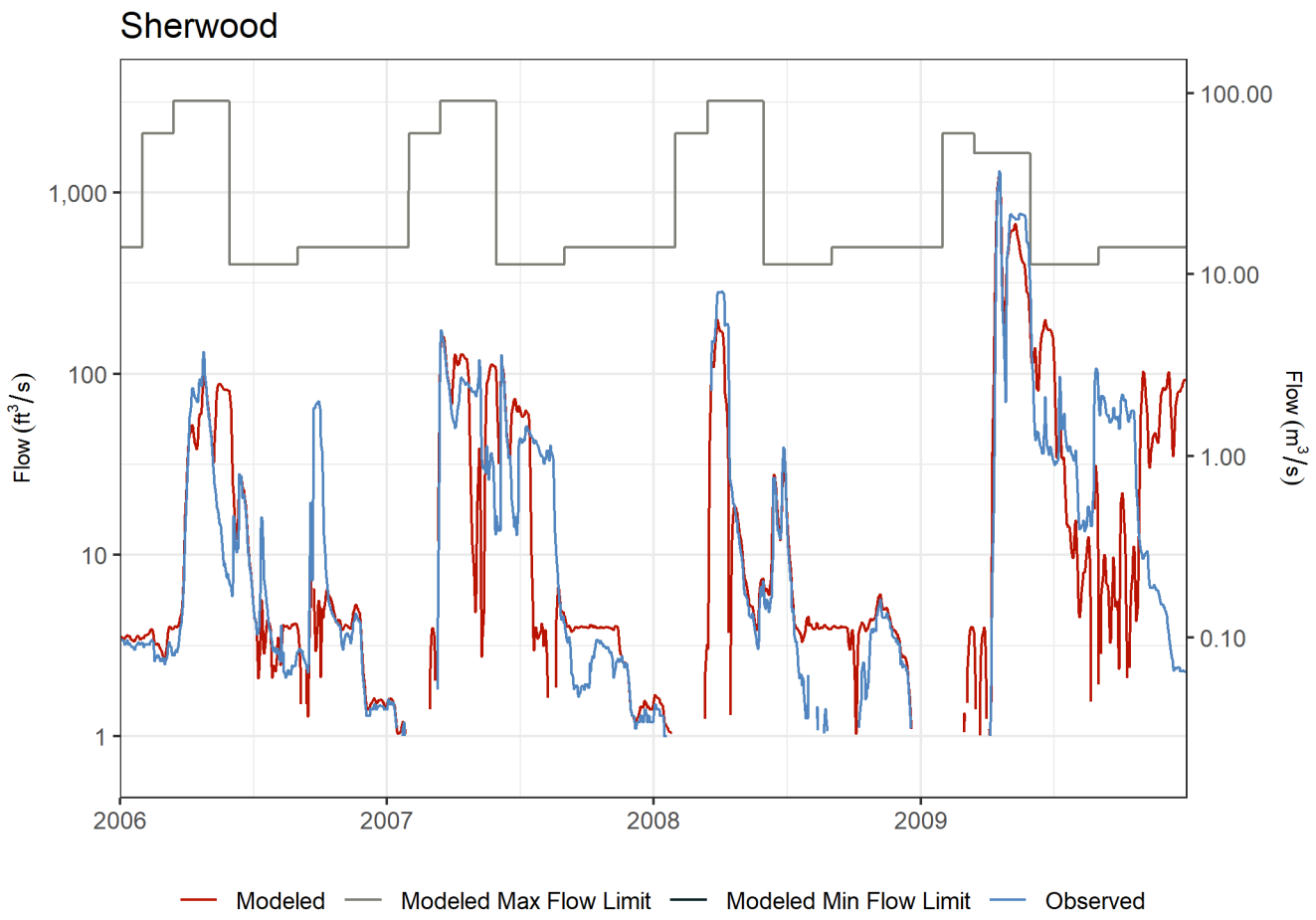


Figure 38 Sherwood, ND Simulated and observed discharge and flow limits 2006-2009 (log scale)

Figure 39 and *Figure 40* show the ResSim results at Minot for the 2006-2008 and 2009 time periods, respectively. The timing of the simulated releases at Minot matches the observed data well for 2006 through 2008, but there are some differences in the magnitude of the simulated flow and volume relative to the observed flows. The most significant differences occur in 2007. The closest upstream reservoir to Minot is Lake Darling. Lake Darling is difficult to model for low flows due to the limited available guidance related to operations targeted at maintaining water supply for the Eaton Irrigation District and the J. Clark Salyer National Wildlife Refuge structures. Releases made for water supply can vary widely from year to year and water supply release volumes are not recorded on a regular basis. Section 4.3.3 outlines the assumptions which were made, based on the best available information, to model water supply releases from Lake Darling.

The main differences between the simulated and observed flows at Minot begin on April 1st of 2006, 2007, and 2008 as a result of the assumed water supply releases made from Lake Darling Reservoir for the Eaton irrigation district and the J. Clark Salyer National Wildlife Refuge structures. In 2006, Lake Darling releases more volume as a result of the downstream water use rule than what was observed and this difference was carried forward in the model. In 2008, the releases from Lake Darling are less than the observed, because they are limited by the assumed release rule for the downstream water use requirements.

During 2009, the model closely matches the observed peak discharge, volume, and timing of the spring flood event. *Table 59* shows that the simulated volume and observed volume and daily peak flow are nearly identical. *Figure 40* indicates that the both observed and modeled flows exceeded the maximum downstream flow at Minot. The maximum flow limit was exceeded at Minot because flow contributions from the Des Lacs River.

After the spring flood event receded, the simulated discharge at Minot was generally higher than the observed discharge. A review of the release decision report for the Lake Darling Reservoir during the May through September 2009 period indicates that Lake Darling Reservoir reached its conservation pool (guide curve, 1597.0 ft; 486.77 m) elevation. As a result, when the simulated pool elevation was equal to the guide curve elevation the Lake Darling Reservoir model released as much water as required to maintain this elevation, while in reality the reservoir remained below 486.77 m (1597 ft) and thus less water was released.

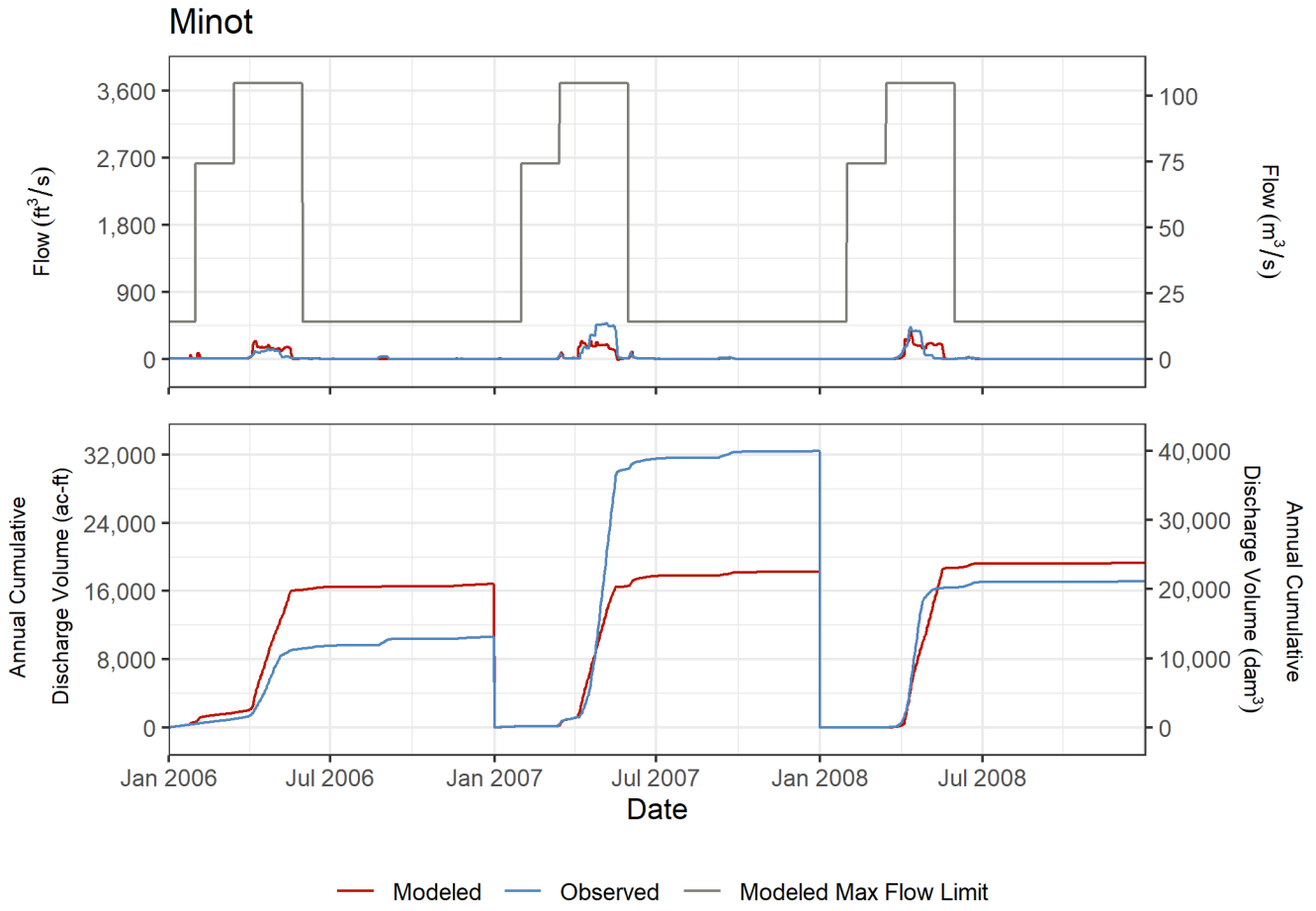


Figure 39 Minot, ND simulated and observed discharge, cumulative annual discharge volume, and maximum flow limit 2006-2008

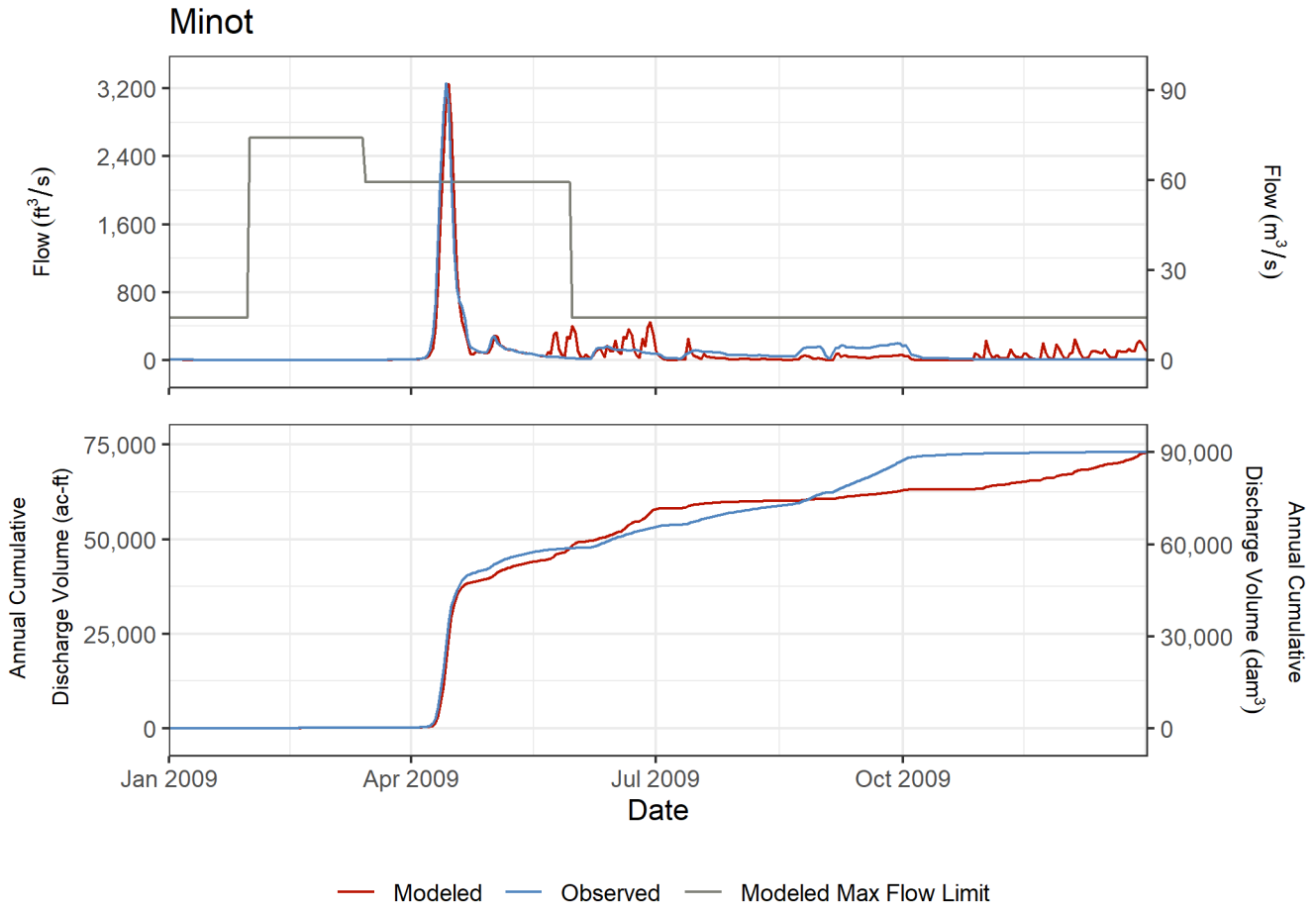


Figure 40 Minot, ND simulated and observed discharge, cumulative annual discharge volume, and maximum flow limit 2009

At the downstream locations of Bantry (***Figure 41***) and Westhope (***Figure 42***), the effects of the Souris River Project Reservoirs become less apparent as tributary and local flow contributions increase. The simulated results for each of these sites closely matches the observed results. Table 59 shows that the differences between the simulated and observed discharge volumes decreases when looking at downstream model results compared to upstream model results. This indicates that the model is reasonably simulating conditions in the watershed.

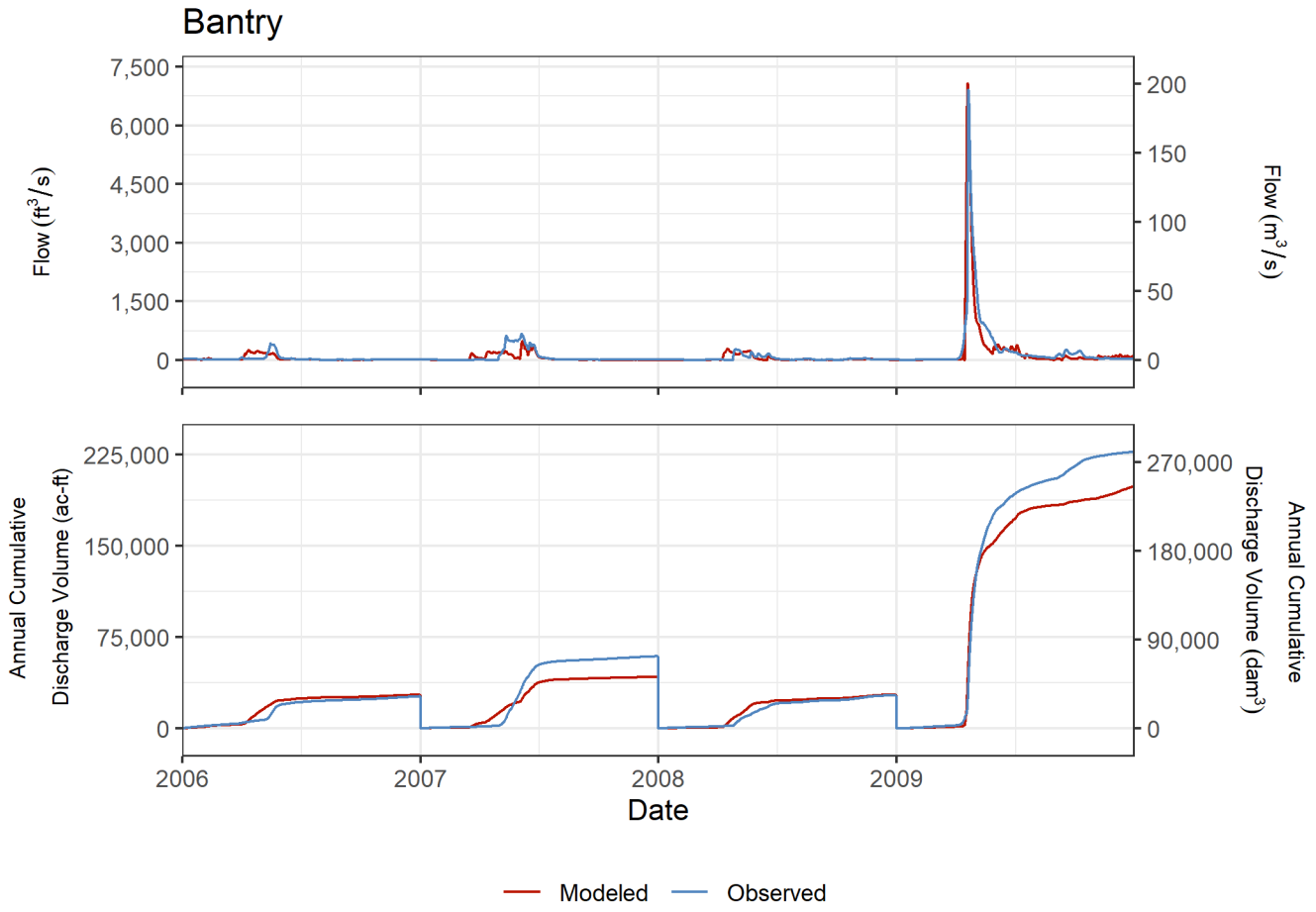


Figure 41 Bantry, ND simulated and observed discharge, cumulative annual discharge volume, and maximum flow limit 2006-2009

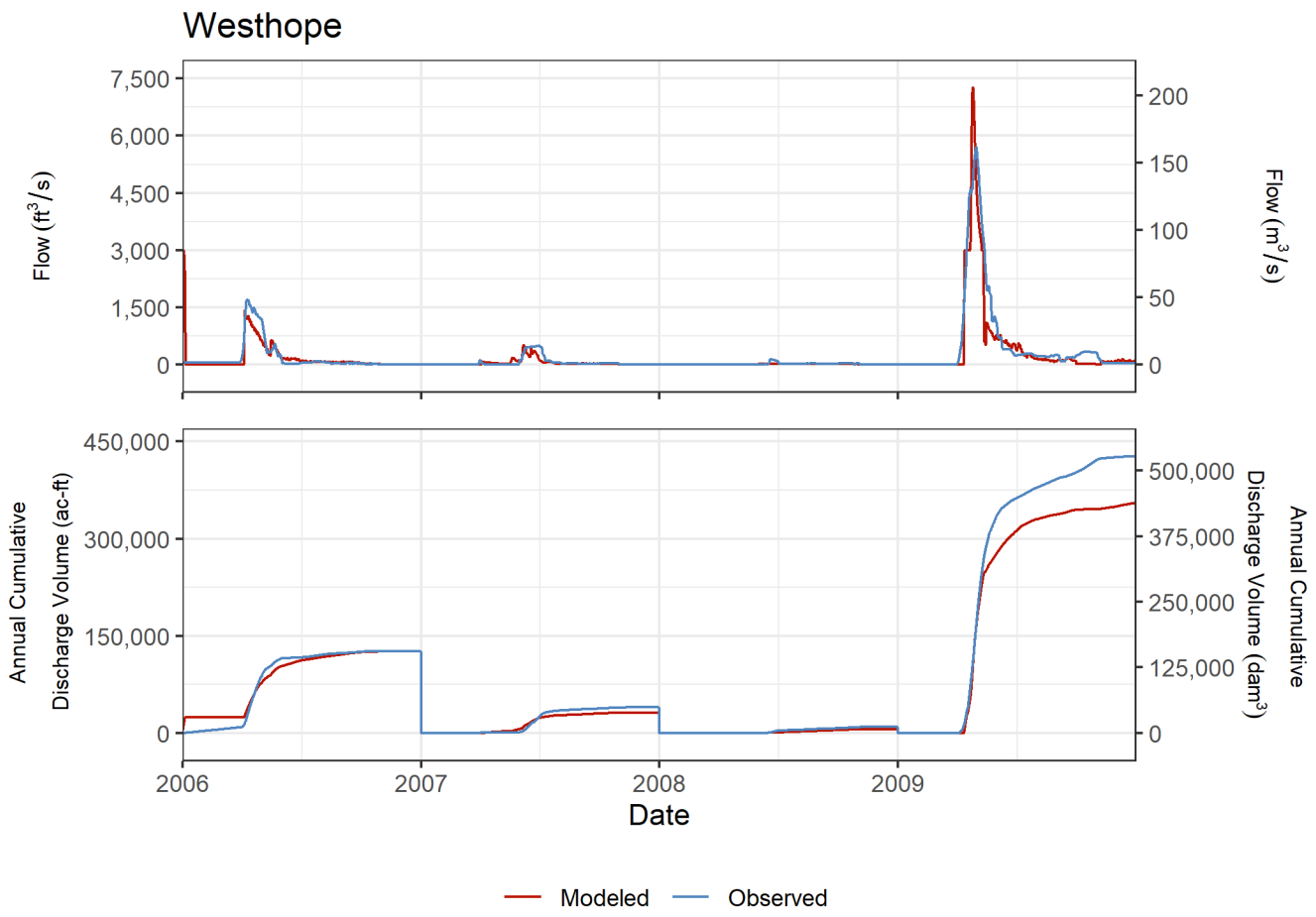


Figure 42 Westhope, ND simulated and observed discharge, cumulative annual discharge volume, and maximum flow limit 2006-2009

5.2 Flood Operations Verification 2001, 2011 & 2013

5.2.1 Flood Verification: Rafferty Reservoir

A summary of the percent difference between the simulated and observed annual discharge volumes at Rafferty Reservoir is shown in Table 60 below. Figure 43, Figure 44, and Figure 45 show the observed versus modeled discharges for the 2001, 2011, and 2013 flood events, respectively. The reservoir model accurately represents the release volumes and pool elevations at Rafferty Reservoir during flood years. The largest difference between the simulated and observed annual discharge volumes is less than 15%. A discussion of each of the verification events is included below.

Table 60 Flood operations verification for 2001, 2011, and 2013: Rafferty Reservoir

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume	Simulated Peak Daily Flow, ft^3/s (m^3/s)	Observed Peak Daily Flow, ft^3/s (m^3/s)	Percent Change Peak Flow
2001	131,875 (162,602)	131,372 (161,981)	504 (621)	0	1,972 (55.84)	1,624 (46.01)	21
2011	812,682 (1,002,037)	945,977 (1,166,389)	-133,295 (-164,353)	-14	17,428 (493.56)	19,211 (544.06)	-9
2013	136,432 (168,220)	141,807 (174,848)	-5,375 (-6,628)	-4	653 (18.49)	1,575 (44.61)	-59

The simulated and observed pool elevations track closely throughout the 2001 calendar year. Figure 43 shows the model results and observed data for the 2001 event. It should be noted that Rafferty Reservoir was operated somewhat differently in 2001 due to oil wells that needed to be flood proofed. In early March when the simulated pool elevation is drawndown lower than what occurred in the reality. The model uses observed data in its forecasts to determine if the reservoir needs an additional drawdown and how much the drawdown should be. Since the model knows how large the inflow hydrograph will be, it draws down the reservoir enough to accommodate the runoff volume. In reality, operators have to make drawdown decisions based on estimated forecasts.

The observed pool elevation returns to the guide curve elevation in early May and the simulated pool elevation returns to the guide curve in early June. The simulated pool elevation remains higher than the observed pool elevation for the remainder of the year. This is because ResSim attempts to keep the pool at FSL. In reality, operators allowed the pool to fall slightly below FSL. Overall, the differences in elevation between the simulated and observed pool are small.

The simulated and observed releases track each other well during the event after March 15th. The simulated peak daily release is 1,972 ft^3/s (55.84 m^3/s) and the observed peak daily release is 1,624 ft^3/s (46 m^3/s), which is a difference of 21%. This difference is because of operational guidelines specified in the model, which limit releases from the reservoir to prevent flow at Estevan from exceeding the maximum flow limits. The largest difference between the simulated

and observed releases occurs during the extended drawdown period from February 1st to March 15th. During this time, the model attempts to follow the computed guide curve and reach the target drawdown elevation which was lower than what operators actually targeted. This results in the model making higher releases during the extended drawdown period than what was observed.

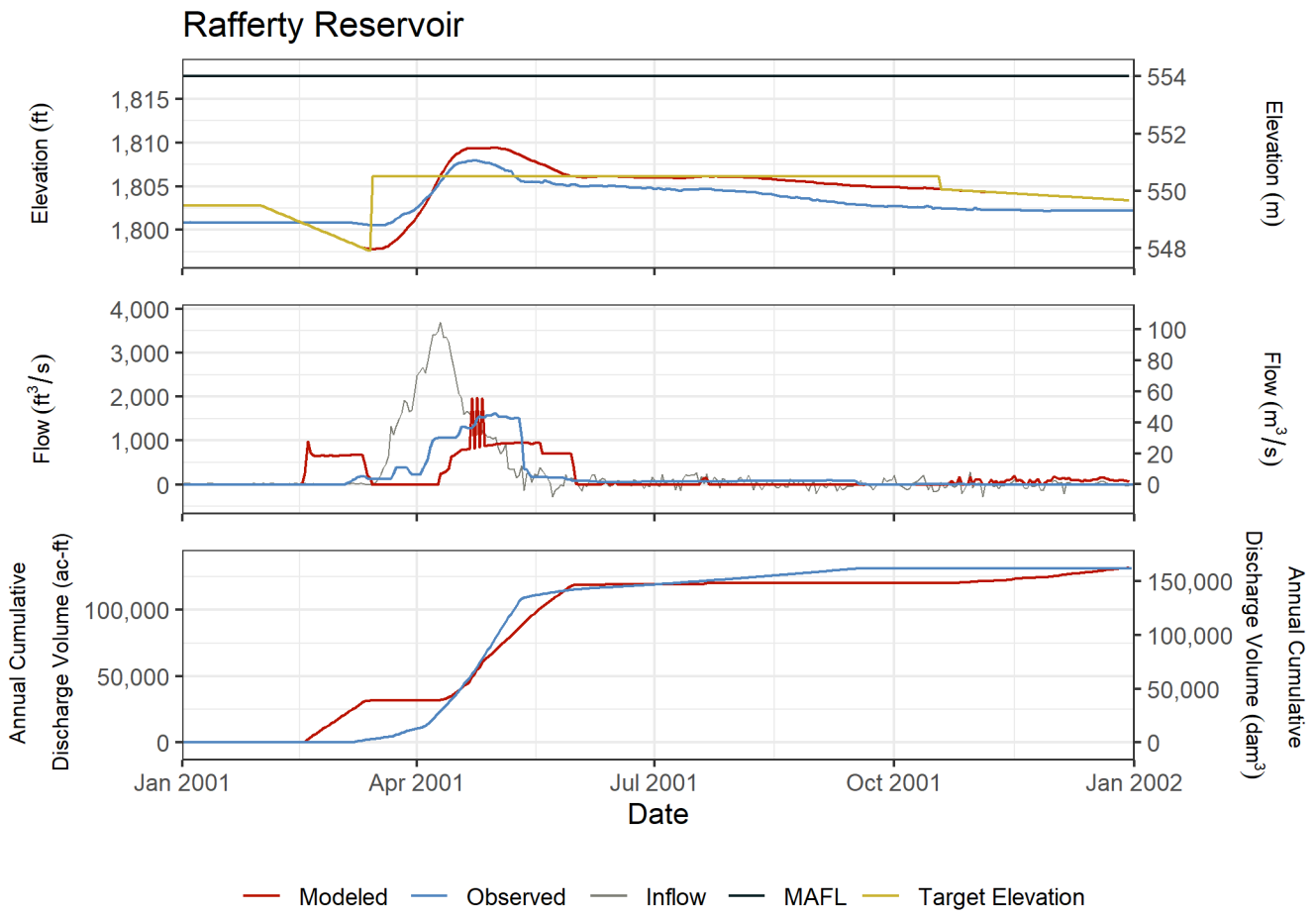


Figure 43 Rafferty Reservoir simulated and observed pool level, discharge, and cumulative annual discharge volume to the Souris River from 2001

The simulated pool elevation matches the observed closely during the 2011 event with several small differences. The model attempts to draw the reservoir down further than it was in reality, this results in greater releases during the spring drawdown period. Additionally, the ResSim model is setup to achieve spring drawdown by March 15th. In reality, operators have until the onset of the spring melt to fulfil the drawdown objective. This is why the simulated pool elevations reach the target drawdown elevation before what was observed. This explains why the model makes larger releases than what was observed before March 15th and smaller releases than what was observed after March 15th. After the peak elevation was reached in 2011, the observed pool elevation was brought down to the full supply target more quickly than what was simulated. The model stays at a higher elevation because it enforces the downstream maximum flow constraint at Estevan when the pool is below the MAFL of 554.00 m (1817.59 ft). During the runoff event, the simulated pool elevation and release closely tracks what occurred in reality. The simulated peak daily discharge is within 10% of the observed peak daily discharge. At the end of the year, the releases match closely, but the simulated pool elevation remains higher than the observed pool because the model attempts to follow the guide curve. In reality, Rafferty Reservoir was allowed to fall below the guide curve elevation. Results for the 2011 event are shown in ***Figure 44***.

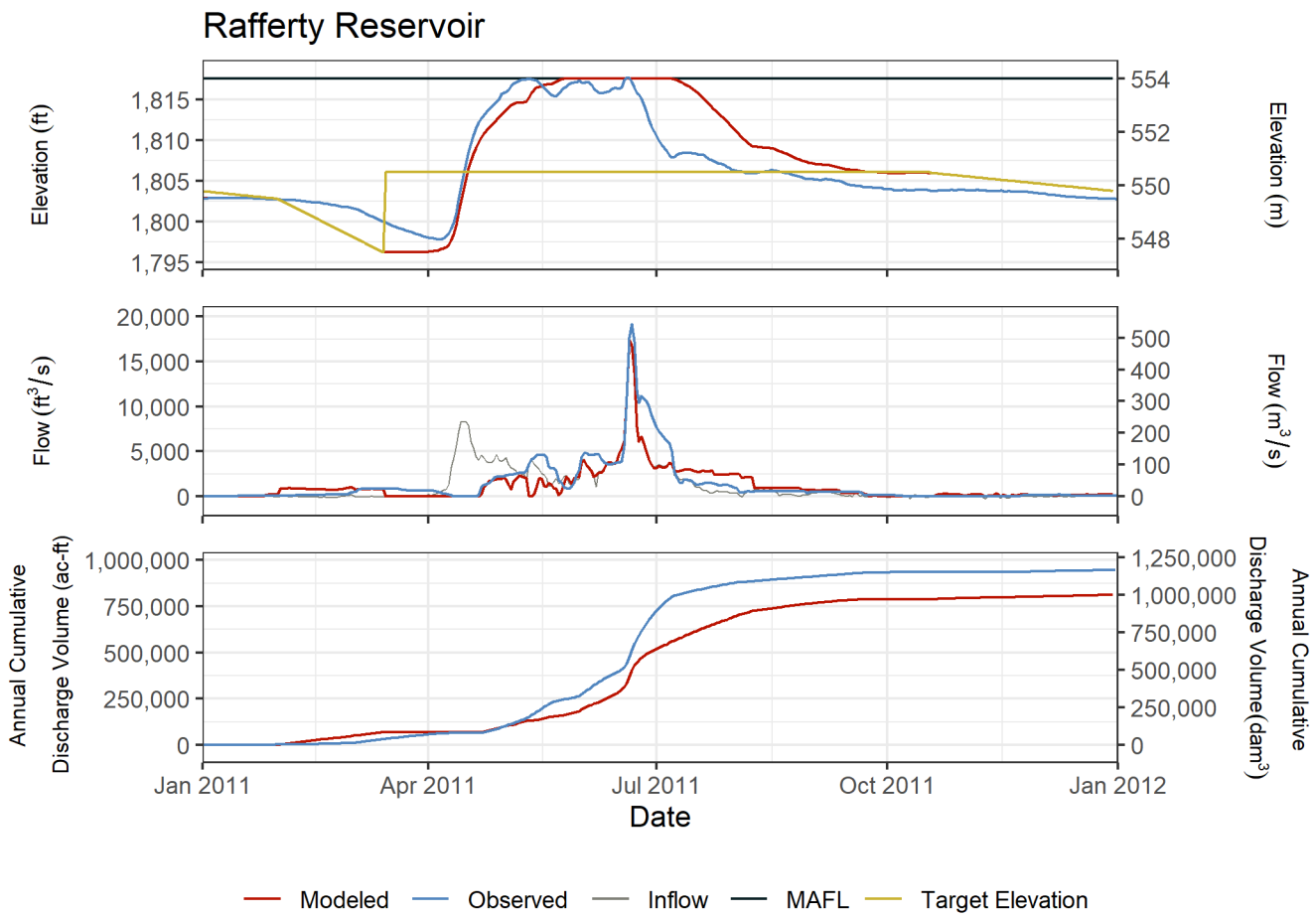


Figure 44 Rafferty Reservoir simulated and observed pool level, discharge, and cumulative annual discharge volume to the Souris River from 2011

During the 2013 flood event the simulated and observed pool elevations nearly match for the entire year except during the extended drawdown period between February 1st and March 15th. In reality, operators do not have to reach the extended drawdown elevation by March 15th. Because the model assumes it needs to be drawndown earlier than it was in reality, it makes larger releases during the extended drawdown period than what was observed in reality, resulting in differences between the simulated and observed elevation and discharge. After the event passes, the simulated and observed pool elevations match each other well, as do the simulated and observed releases. The difference between the simulated and observed volumes is nearly zero by approximately May of the calendar year. Results for the 2013 event are shown in Figure 45.

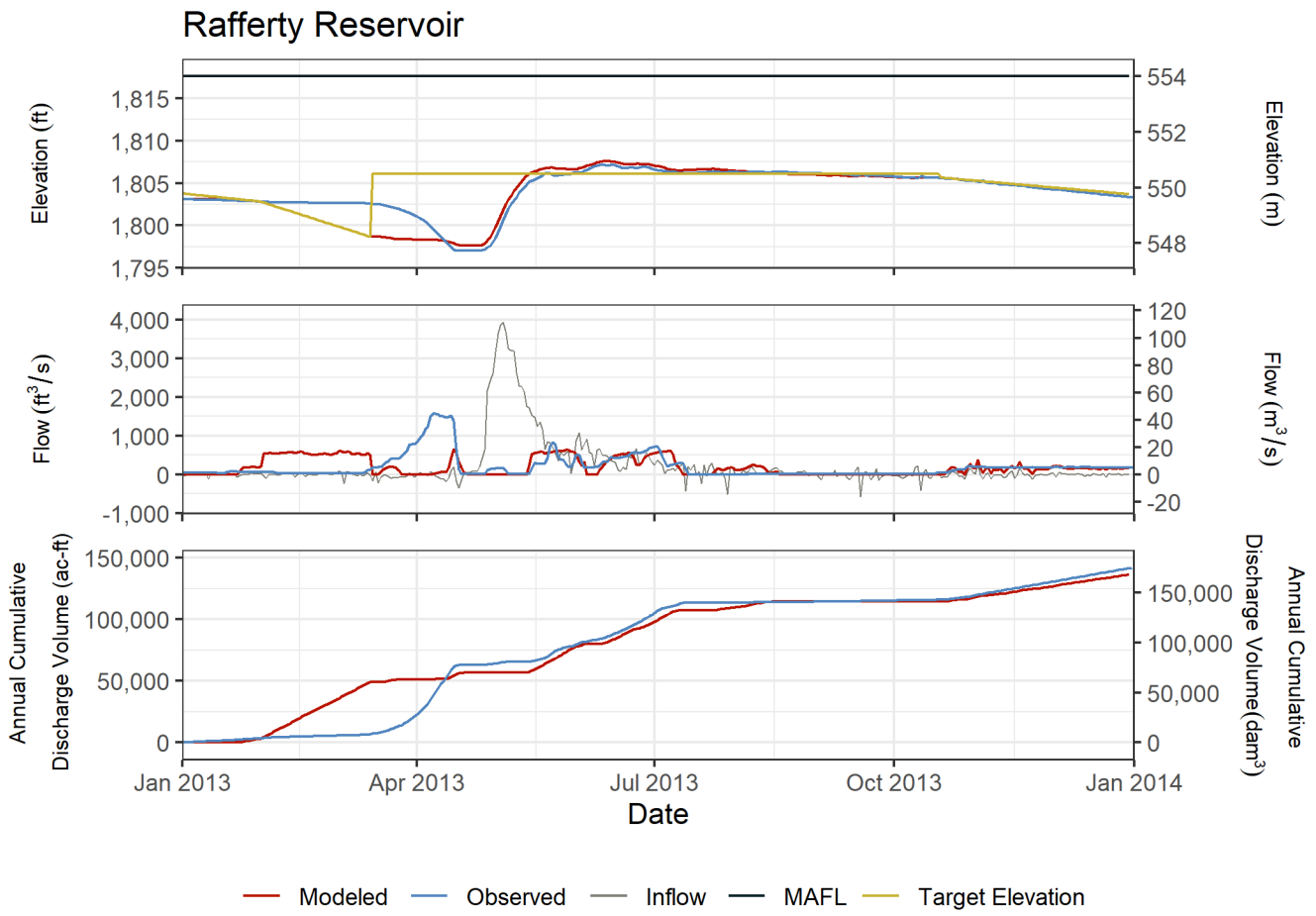


Figure 45 Rafferty Reservoir simulated and observed pool level, discharge, and cumulative annual discharge volume to the Souris River from 2013

5.2.2 Flood Verification: Boundary Reservoir

Figure 46 through *Figure 48* show simulated and observed pool elevations at Boundary Reservoir and discharges to Long Creek for the 2001, 2011, and 2013 events, respectively. A summary table comparing the simulated and observed annual release volume from Boundary Reservoir is shown in *Table 61*. The large percent difference between the simulated and observed volumes likely stems from assumptions made related to water usages at Boundary Reservoir and differences in actual and modeled diversion operation. Water at Boundary Reservoir is used by SaskPower and the City of Estevan. The exact water use is not recorded and is variable from year-to-year; therefore, it is difficult to model.

Table 61 Flood operations verification for 2001, 2011, and 2013: Boundary Reservoir

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume	Simulated Peak Daily Flow, ft^3/s (m^3/s)	Observed Peak Daily Flow, ft^3/s (m^3/s)	Percent Change Peak Flow
2001	12,745 (15,715)	23,771 (29,310)	-11,026 (-13,595)	-46	796 (22.55)	367 (10.39)	117
2011	362,728 (447,244)	255,194 (314,655)	107,534 (132,589)	42	9,517 (269.52)	9,005 (255.03)	6
2013	51,420 (63,401)	52,729 (65,014)	-1,308 (-1,613)	-2	2,575 (72.93)	1,713 (48.51)	50

The simulated and observed results for Boundary Reservoir during the 2001, 2011, and 2013 events are shown in *Figure 46*, *Figure 47*, and *Figure 48*, respectively. The simulated pool elevations generally match the observed elevations well after March 15th. Prior to this date, there are differences between the simulated and observed elevations due to differences in when the spring drawdown target is reached. The modeled elevation of Boundary Reservoir often exceeds the observed elevation because it is a small reservoir and small changes in inflow or water use can result in large discrepancies in pool elevation.

In 2001, Boundary Reservoir was drawndown farther based on real time forecasts than an approximation of reservoir inflows based on observed discharge would necessitate. Differences in releases and elevations prior to the onset of the spring melt are caused by this difference in drawdown elevation. Differences in releases throughout the event can be attributed to the models attempts to hold the pool to FSL versus the real time operator's tendency to hold the pool to a slightly lower elevation.

In 2011, the model targets the maximum drawdown elevation at Boundary Reservoir (557.78 m, 1830 ft) by 15 March. The observed drawdown target was slightly higher: 559.0 m (1834 ft) and operators did not reach this elevation until April. This caused minor differences between the observed releases and the simulated releases, but overall the modeled releases closely match what occurred in reality.

Figure 47 shows that the simulated releases match the observed releases closely with respect to timing and magnitude. The difference between the maximum simulated and observed mean daily release is 6%.

The main differences between the simulated and observed results at Boundary Reservoir in 2013 are driven by the differences in spring drawdown target. Figure 48 shows that the model estimated a drawdown would not be needed for the 2013 runoff event. In 2013 operators lowered Boundary Reservoir to its maximum drawdown elevation. This was done primarily to provide for a conservative drawdown to preemptively prevent conditions similar to those that occurred in 2011 from materializing.

Figure 49 through show the simulated results for the Boundary Diversion Channel. In 2001 the simulated diversion releases matches the observed releases reasonably well (Figure 49). In 2011, the simulated and observed peak discharge through the diversion channel match well, but observed releases occurring later in the year did not occur in the model. The diversion channel results in Figure 51 for the 2013 event closely matches the observed peak daily discharge and annual flow volume through the diversion channel.

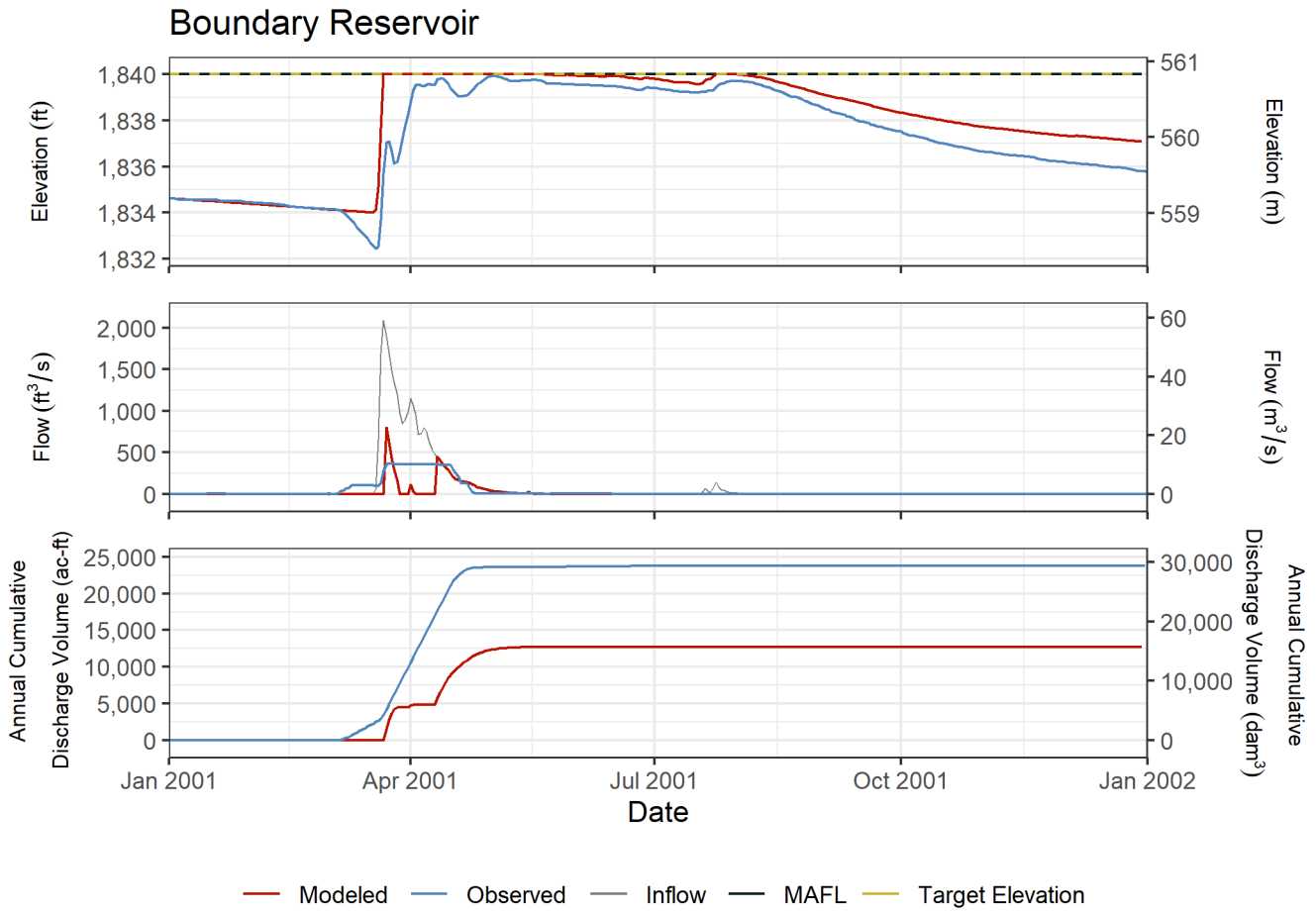


Figure 46 Boundary Reservoir simulated and observed pool level, discharge, and cumulative annual discharge volume to Long Creek from 2001

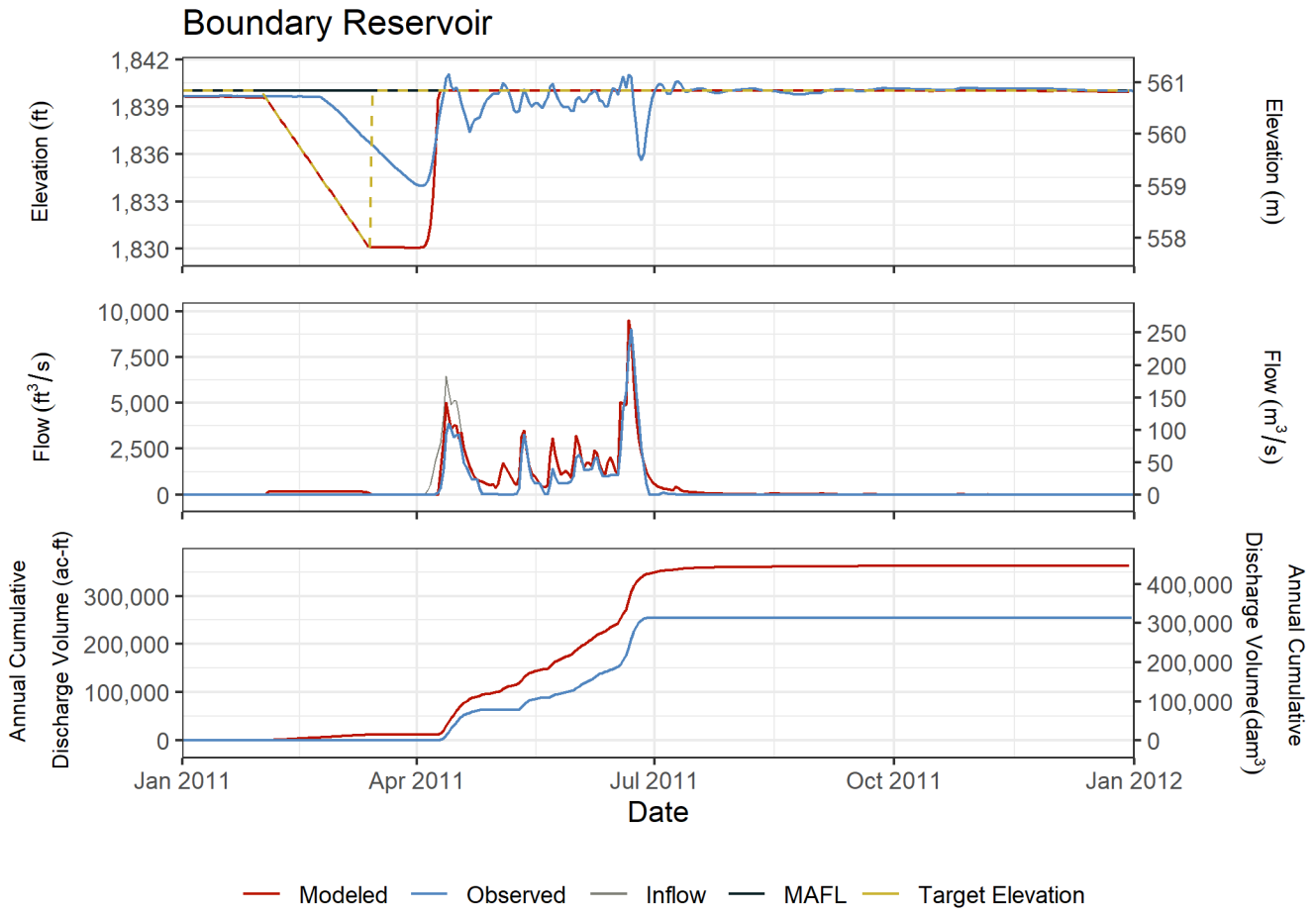


Figure 47 Boundary Reservoir simulated and observed pool level, discharge, and cumulative annual discharge volume to Long Creek from 2011

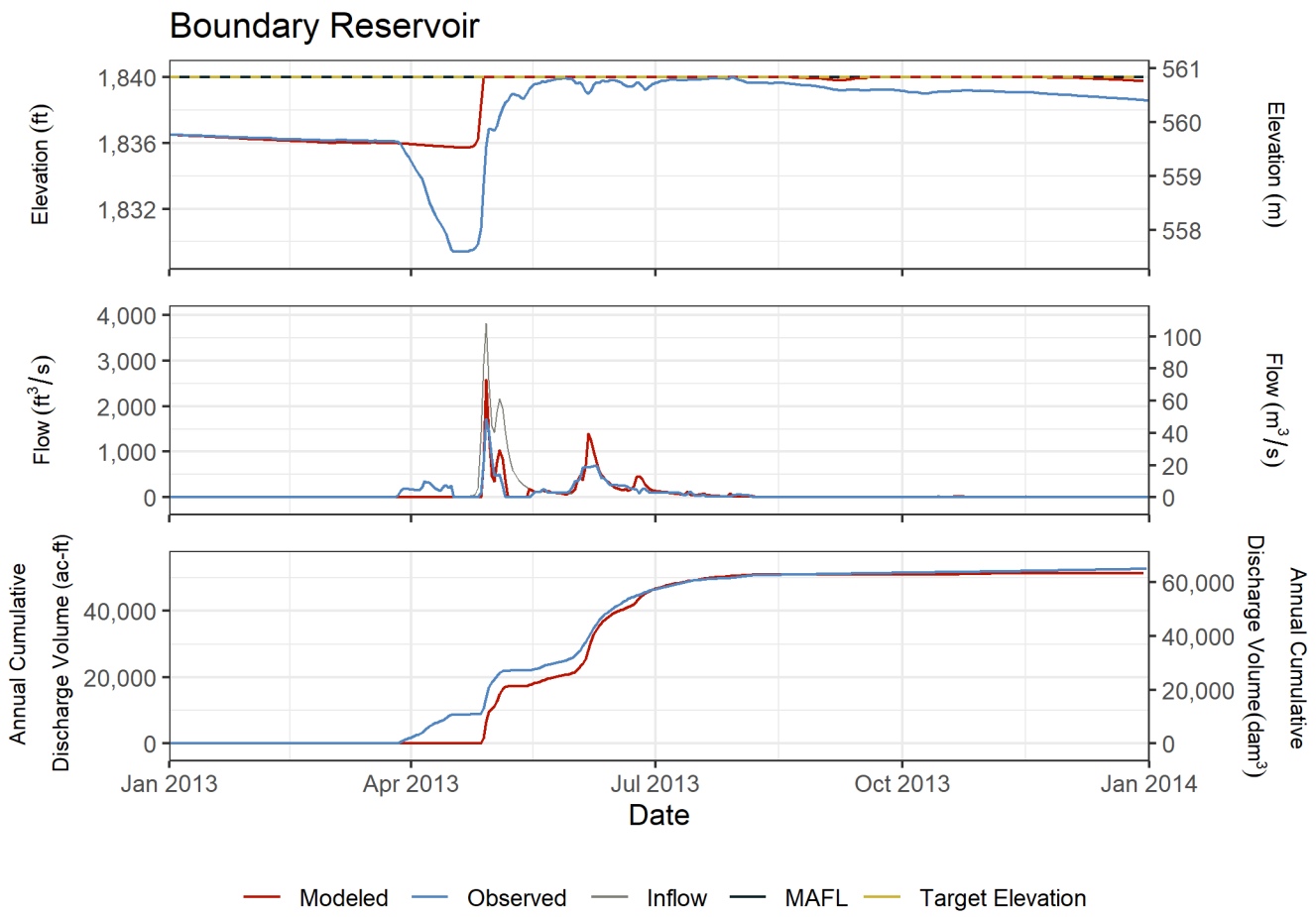


Figure 48 Boundary Reservoir simulated and observed pool level, discharge, and cumulative annual discharge volume to Long Creek from 2013

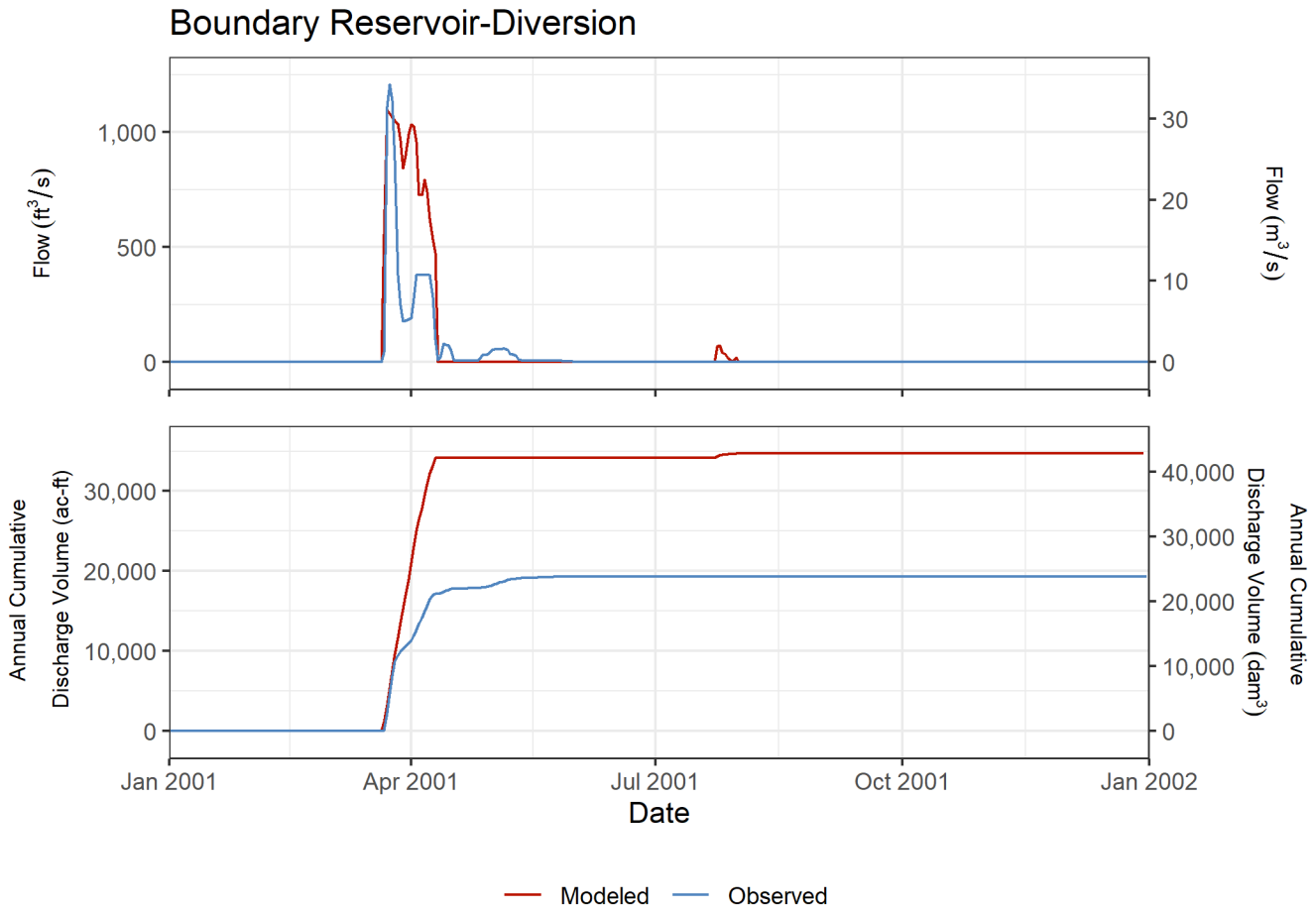


Figure 49 Boundary Reservoir diversion discharge, and cumulative annual discharge volume to Rafferty Reservoir from 2001

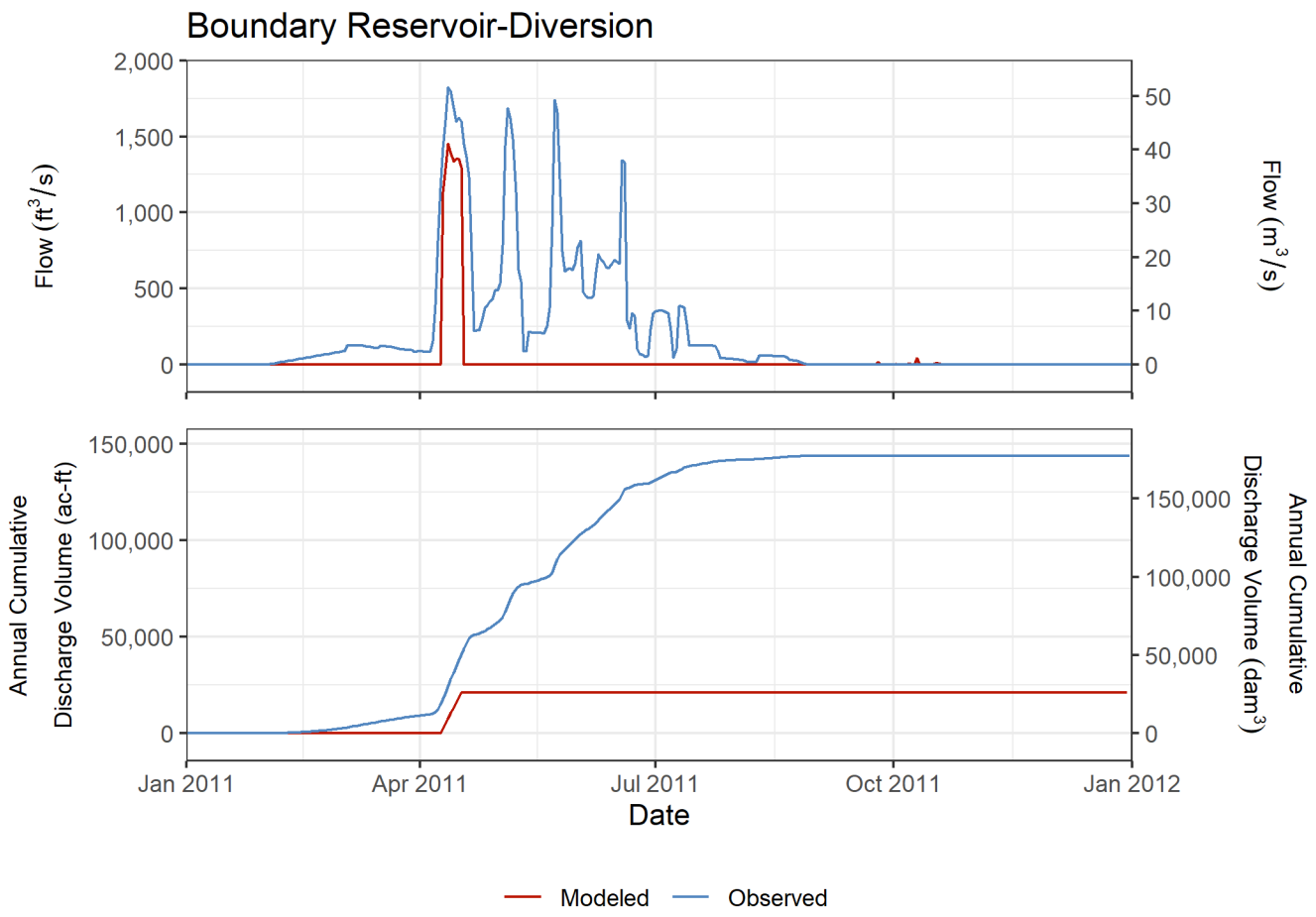


Figure 50 Boundary Reservoir diversion simulated and observed pool level, discharge, and cumulative annual discharge volume to Rafferty Reservoir from 2011

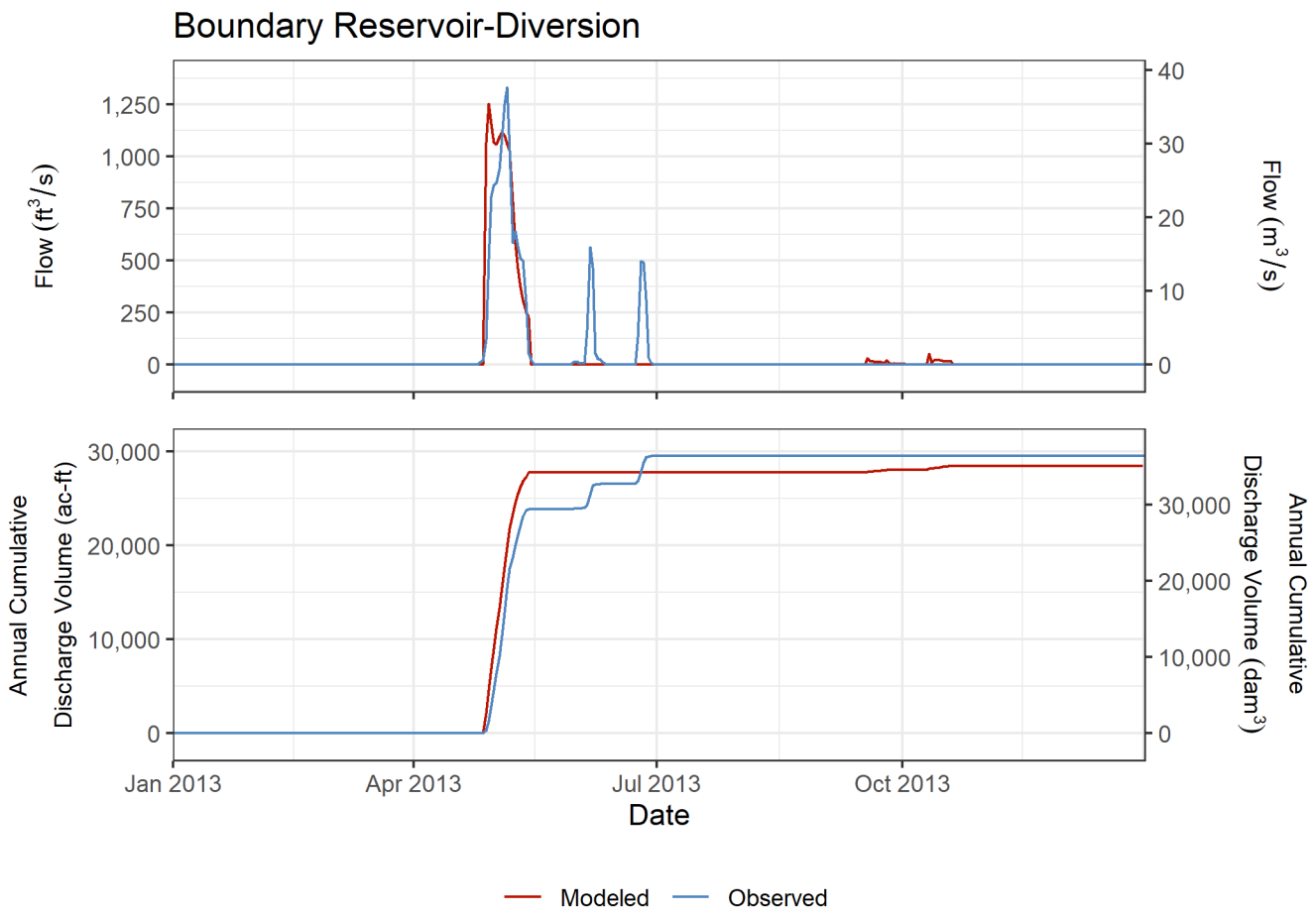


Figure 51 Boundary Reservoir diversion simulated and observed pool level, discharge, and cumulative annual discharge volume to Rafferty Reservoir from 2013

5.2.3 Flood Verification: Grant Devine Reservoir

Figure 52, *Figure 53*, and *Figure 54* show the simulated versus observed results for the 2001, 2011, and 2013 events, respectively. The simulated and observed results match closely to the volume of discharge and the daily peak discharge at Grant Devine Lake. Table 62 shows that the largest difference in annual flood volume between the model and the observed data is 4%. The model also reasonably simulates the peak daily discharge for the calendar year also shown in Table 62.

Table 62 Flood operations verification for 2001, 2011, and 2013: Grant Devine Lake

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume	Simulated Peak Daily Flow, ft^3/s (m^3/s)	Observed Peak Daily Flow, ft^3/s (m^3/s)	Percent Change Peak Flow
2001	58,916 (72,643)	61,650 (76,015)	-2,734 (-3,371)	-4	706 (19.99)	724 (20.50)	-2
2011	303,984 (374,813)	308,248 (380,070)	-4,264 (-5,258)	-1	3,502 (99.18)	2,348 (66.51)	49
2013	49,442 (60,962)	50,989 (62,869)	-1,547 (-1,907)	-3	497 (14.08)	667 (18.89)	-26

The biggest differences between the simulated and observed results occur during the extended drawdown period from February 1st through March 15th. For example, in 2001 and 2013 the model determined that the reservoir would need to be drawndown lower than they were in reality. The extended drawdown end date of March 15th is also earlier than date the final drawdown target was reached historically. This difference in the drawdown target elevation and timing results in the model making different releases compared to what was observed.

After March 15th, the simulated and observed pool elevations closely match each other. Releases after March 15th also generally match the volume of releases made in reality. Despite there being a 49% difference in peak release in 2011, respectively, release magnitudes are within the same order of magnitude for observed versus modeled conditions.

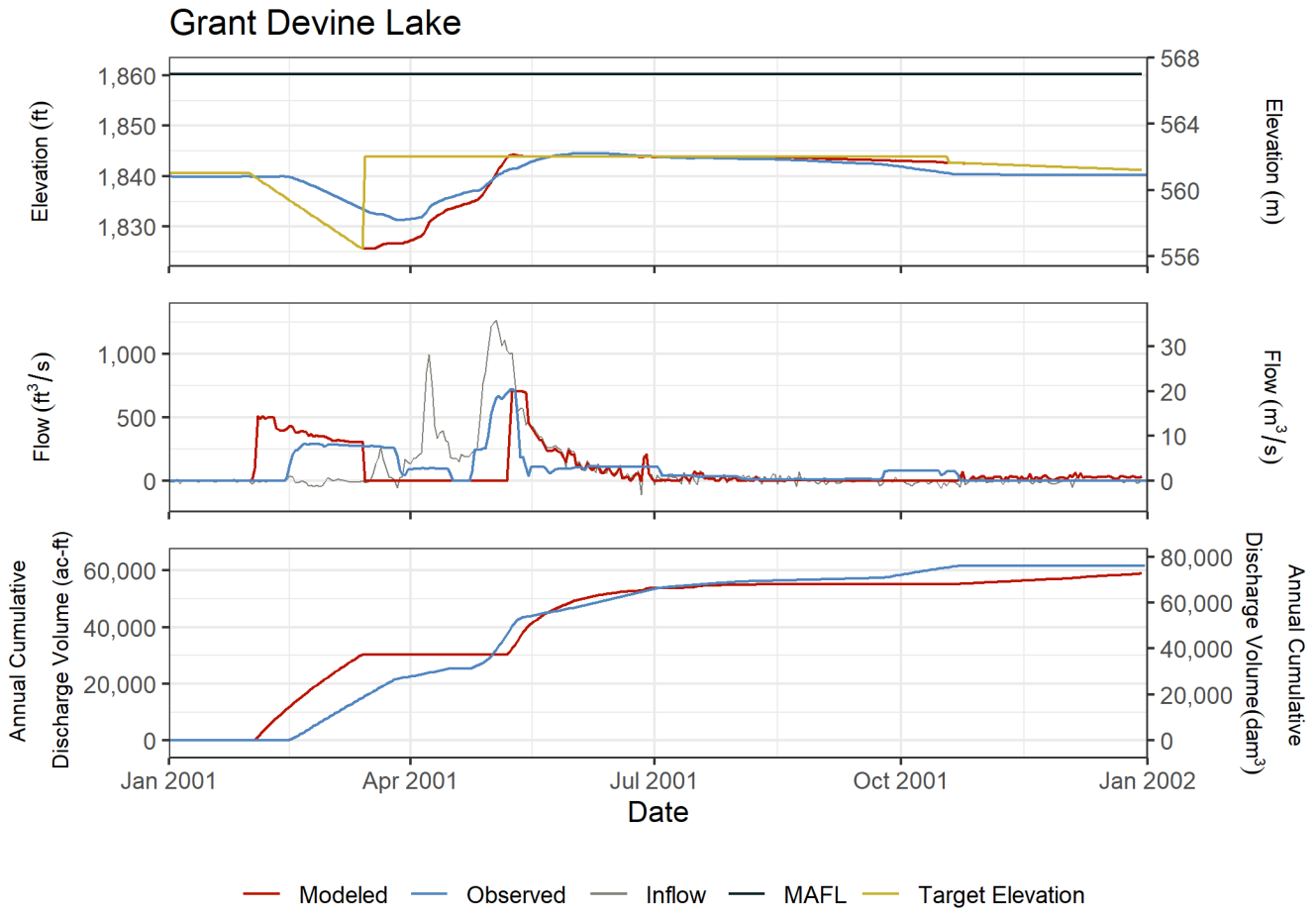


Figure 52 Grant Devine Lake simulated and observed pool level, discharge, and cumulative annual discharge volume from 2001

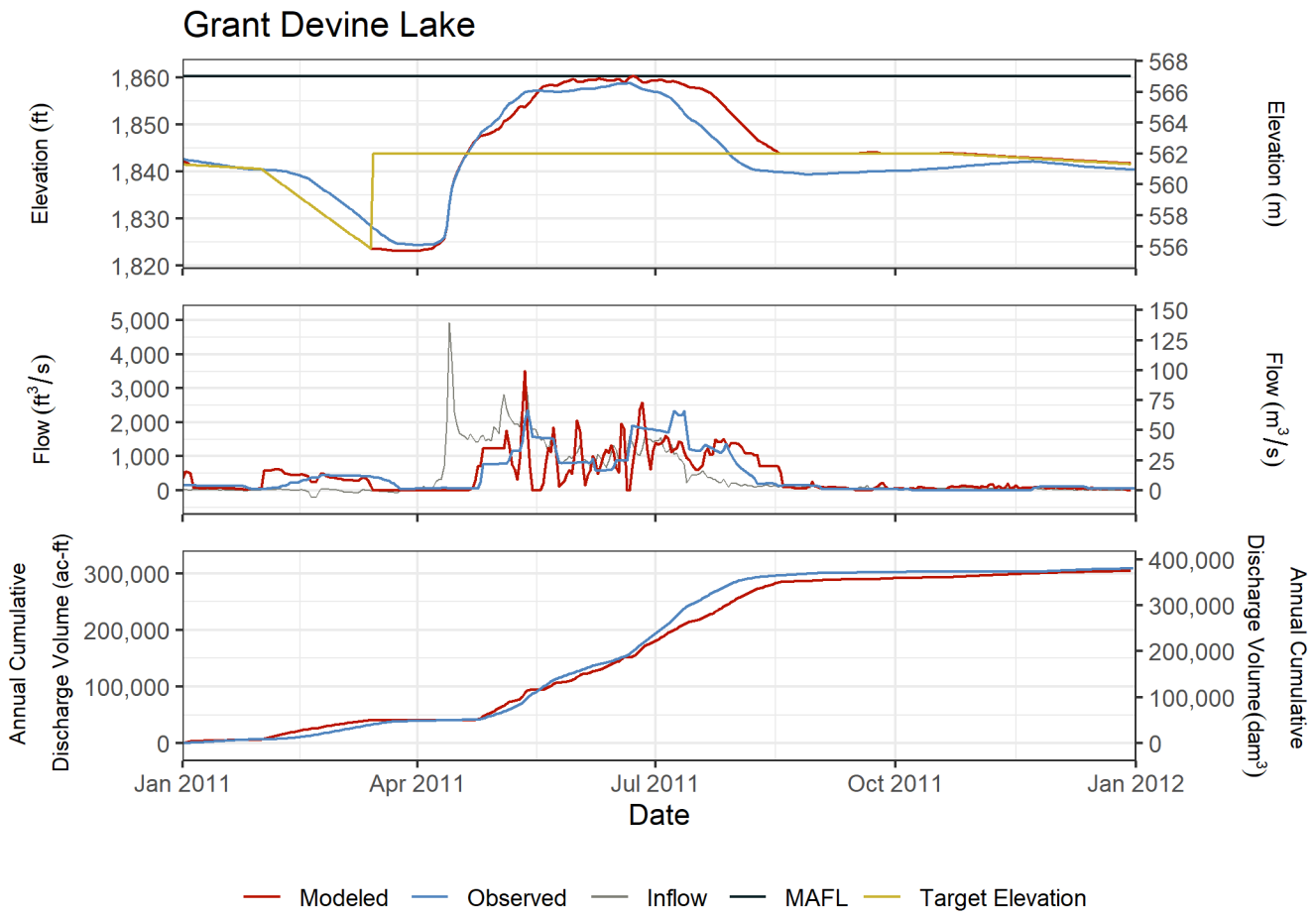


Figure 53 Grant Devine Lake simulated and observed pool level, discharge, and cumulative annual discharge volume from 2011

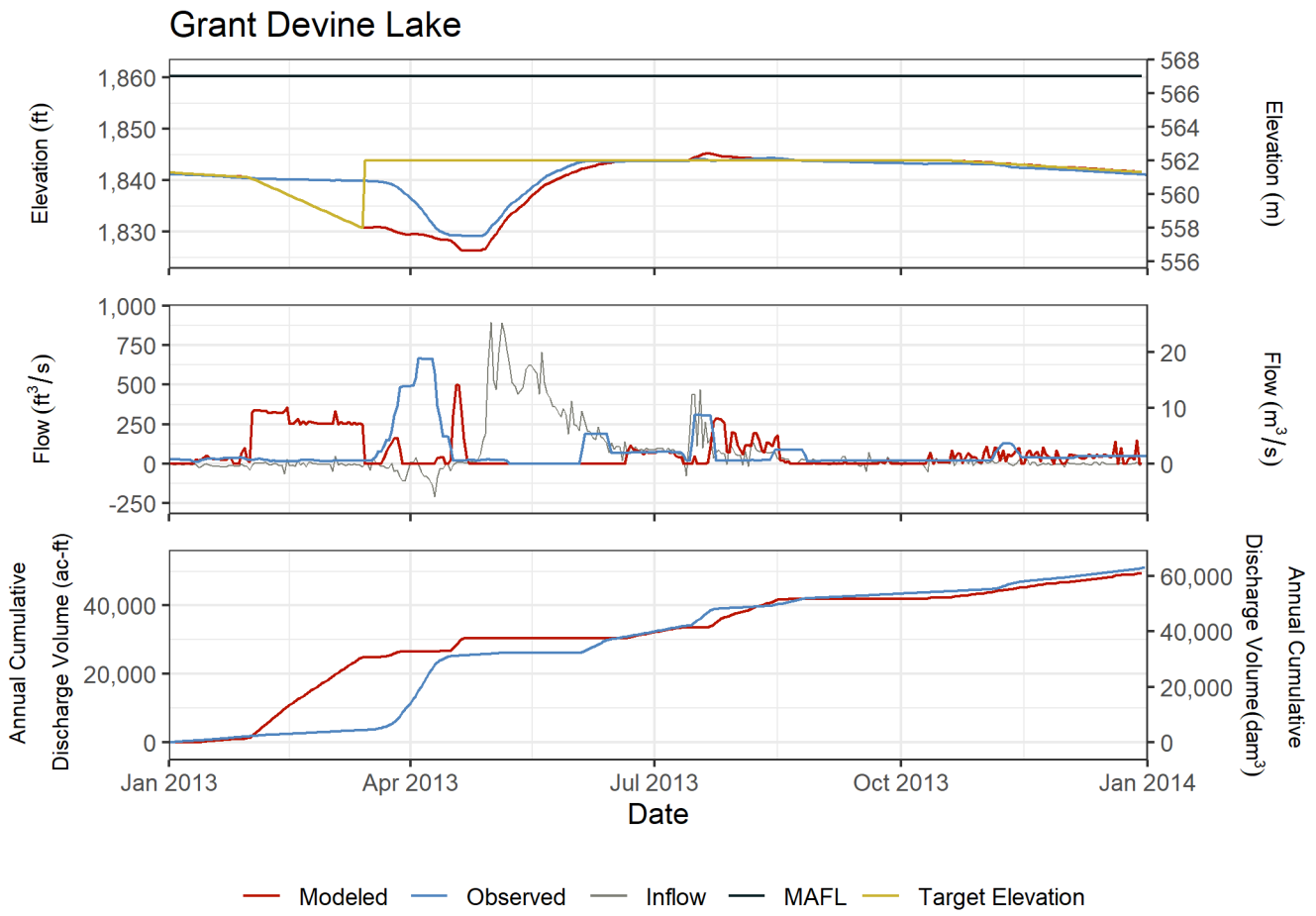


Figure 54 Grant Devine Lake simulated and observed pool level, discharge, and cumulative annual discharge volume from 2013

5.2.4 Flood Verification: Lake Darling Reservoir

Figure 55, *Figure 56*, and *Figure 57* show a comparison of observed versus simulated reservoir pool elevations and reservoir outflows for Lake Darling during the 2001, 2011, and 2013 events. Table 63 shows the percent difference between the simulated and observed annual discharge volume. The largest percent difference between the simulated and observed annual discharge volume is -4 %, which shows that the model closely replicates the total volume discharged through the reservoir. The plots in *Figure 55*, *Figure 56*, and *Figure 57* also show that the timing of the volumetric releases made by the model closely matches what occurred in reality.

Table 63 Flood operations verification for 2001, 2011, and 2013: Lake Darling

Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam^3)	Difference, acre-ft (dam^3)	Percent Change Volume	Simulated Peak Daily Flow, ft^3/s (m^3/s)	Observed Peak Daily Flow, ft^3/s (m^3/s)	Percent Change Peak Flow
2001	237,829 (293,243)	247,957 (305,731)	-10,128 (-12,488)	-4	2,637 (74.68)	2,210 (62.59)	19
2011	1,693,294 (2,087,831)	1,740,796 (2,146,402)	-47,502 (-58,571)	-3	26,586 (752.91)	26,000 (736.32)	2
2013	299,373 (369,127)	308,334 (380,176)	-8,961 (-11,049)	-3	2,687 (76.09n)	2,760 (78.16)	-3

Figure 55 shows the simulated results and observed data for the 2001 event. The simulated and observed pool elevations generally match. The model follows the observed drawdown curve and reaches the target elevation similarly to what occurred historically. There are notable differences between the simulated and observed releases. During February and March of 2001, the model makes much larger releases than what was observed. This can primarily be attributed to the differences between simulated and observed releases being made from the upstream reservoirs.

The simulated releases at Lake Darling during the 2001 and 2013 events oscillate. The reason for the oscillations is driven by the guide curve logic in the model. During the months of April through August, the model strictly maintains its target pool elevation (guide curve), while in real time operators allow for slight deviations from the guide curve. This flexibility prevents the stark oscillations in releases.

The simulated spring drawdown target reached prior to the 2011 spring event was lower than the pool elevation actually reached prior to the 2011 melt. Similarly to how Rafferty and Grant Devine Reservoirs were operated in 2011, operators released flows in excess of the downstream constraint at Minot until Lake Darling's pool fell to its FSL. The model more strictly adheres to downstream restraints. Consequently, the simulated pool remains near the top of the flood control pool longer than the observed pool during 2011.

In 2013, operators preemptively drew down the reservoir further than the observed flow contributions to Lake Darling would have necessitated. Consequently, the modeled pool remains higher prior to the event then the observed pool. USACE St. Paul District Water Management

also indicated that part of the reason for drawing Lake Darling down so low in 2013 was to be conservative to prevent conditions similar to the 2011 event from materializing.

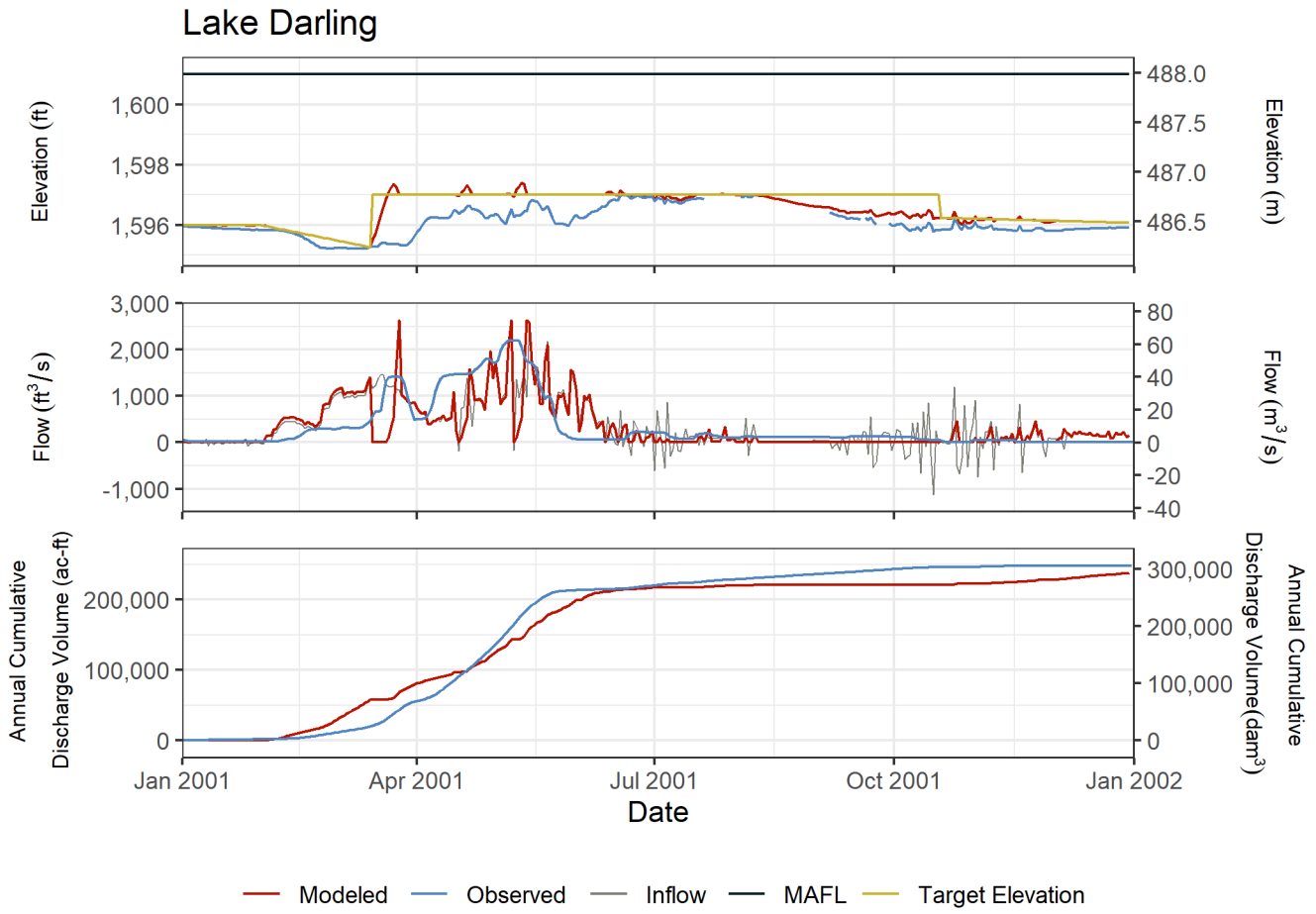


Figure 55 Lake Darling simulated and observed pool level, discharge, and cumulative annual discharge volume from 2001

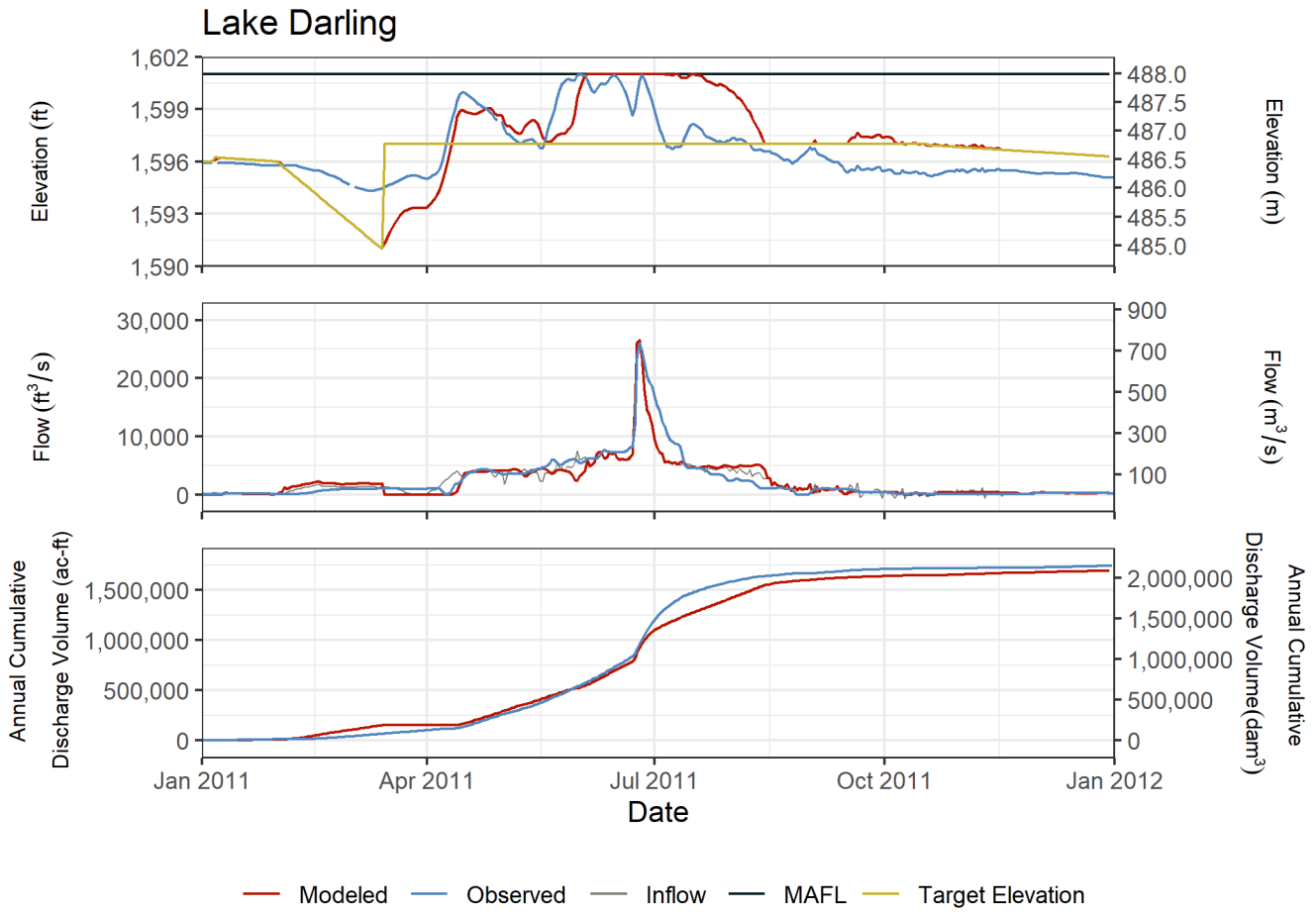


Figure 56 Lake Darling simulated and observed pool level, discharge, and cumulative annual discharge volume from 2011

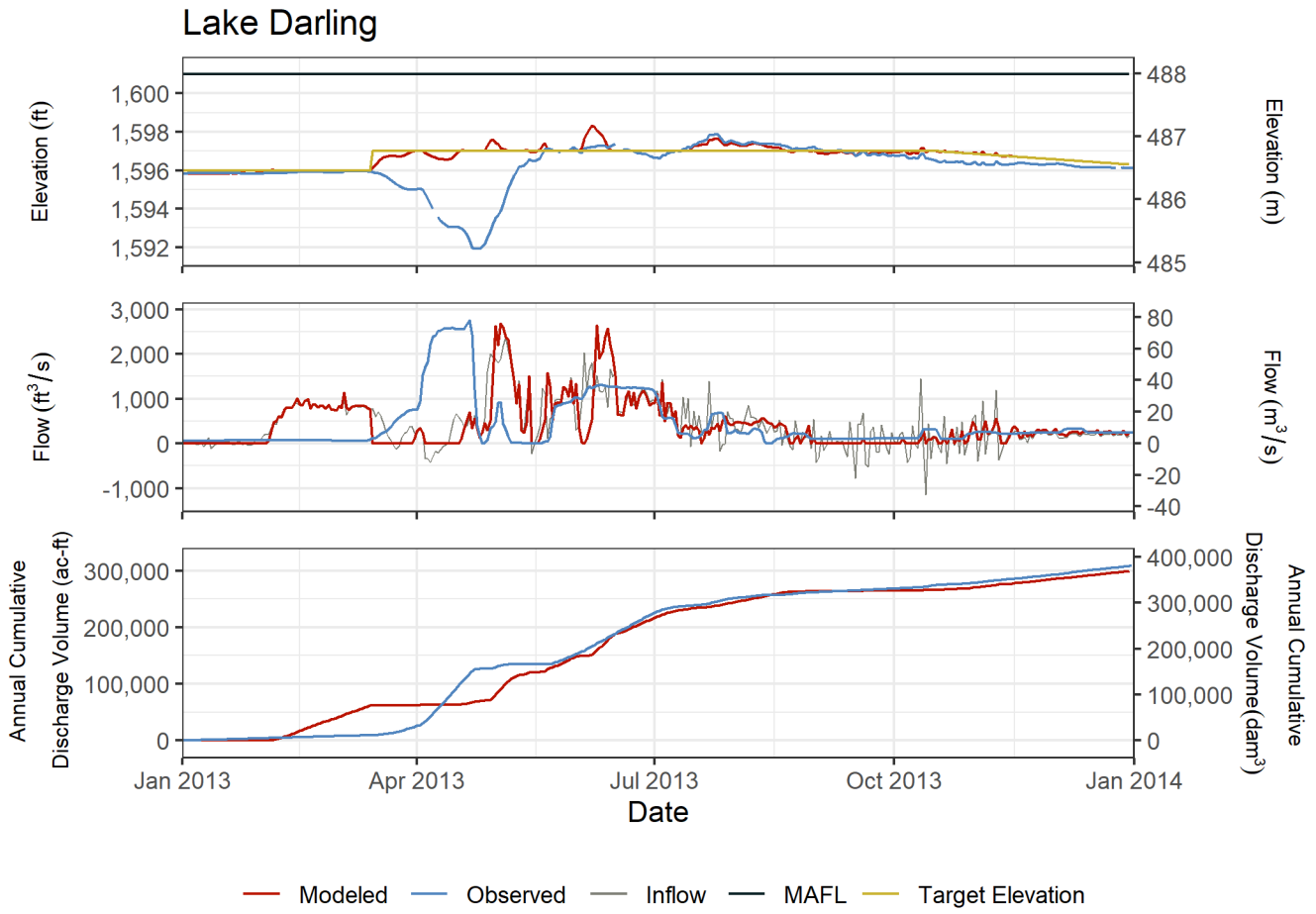


Figure 57 Lake Darling simulated and observed pool level, discharge, and cumulative annual discharge volume from 2013

5.2.5 *Verification at Downstream Control Points*

Table 64 shows a comparison of the simulated and observed annual discharge volume and the simulated and observed daily peak discharge for Estevan, Sherwood, Minot, and Bantry. These locations are a subset of locations on the main stem of the Souris River and were selected for comparison because they collectively represent flood control, water supply, and agricultural targets of interest in the watershed. The model performs well in estimating the volume of the hydrograph for each of these sites. The largest percent difference between the simulated and observed annual volume is less than 8%. The model also does a reasonable job of estimating the peak daily discharge for each of the sites. The largest difference between a simulated and observed peak at any of the sites is less than 30%. In general it appears that during high flow events, the model tends to slightly underestimate the annual discharge volume and annual peak discharge when compared to the observed data. Hydrographs and cumulative volume curves are presented in Figure 58 to Figure 61 for the 2011 event of record at all sites along the mainstem of the Souris River.

Table 64 Simulated vs. observed volume and discharge at key control points during select flood years

Site	Year	Simulated Annual Volume, acre-ft (dam^3)	Observed Annual Volume, acre-ft (dam3)	Percent Change Volume	Simulated Peak Daily Flow, ft^3/s (m^3/s)	Observed Peak Daily Flow, ft^3/s (m^3/s)	Percent Change Flow
Estevan	2001	144,621 (178,317)	155,143 (191,291)	-7	1,791 (51)	1,627 (46)	30
	2011	1,175,410 (1,449,280)	1,201,171 (1,481,044)	-2	24,458 (693)	27,051 (766)	-3
	2013	187,852 (231,621)	194,536 (239,862)	-3	2,703 (77)	1,899 (54)	36
Sherwood	2001	246,383 (303,790)	253,486 (312,548)	-3	3,039 (86)	2,200 (62)	-29
	2011	1,621,675 (1,999,525)	1,655,941 (2,041,775)	-2	2,284 (65)	28,800 (816)	-9
	2013	286,397 (353,127)	294,649 (363,302)	-3	27,448 (777)	2,320 (66)	-2
Minot	2001	238,489 (294,057)	250,820 (309,261)	-5	2,351 (67)	2,060 (58)	14
	2011	1,930,747 (2,380,611)	1,980,588 (2,442,065)	-3	28,531 (808)	26,500 (750)	8
	2013	404,714 (499,012)	412,169 (508,204)	-2	3,132 (89)	3,810 (108)	-18
Bantry	2001	304,459 (375,399)	322,190 (397,260)	-6	1,873 (53)	2,260 (64)	-17
	2011	2,306,908 (2,844,417)	2,406,614 (2,967,355)	-4	25,444 (721)	29,100 (824)	-13
	2013	622,473 (767,510)	649,056 (800,286)	-4	5,476 (155)	6,180 (175)	-11

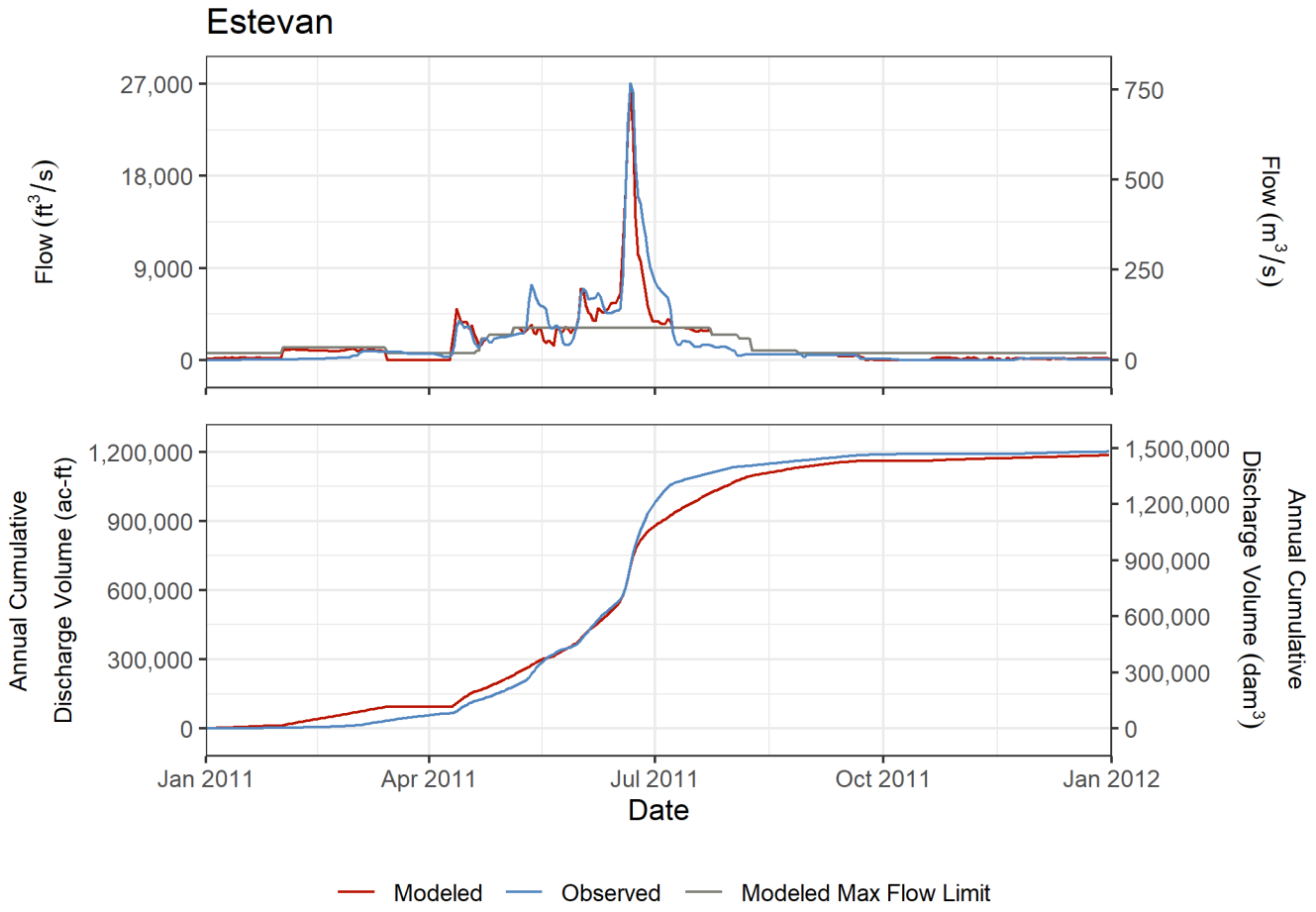


Figure 58 Souris River at Estevan, SK 2011 flood event simulation results

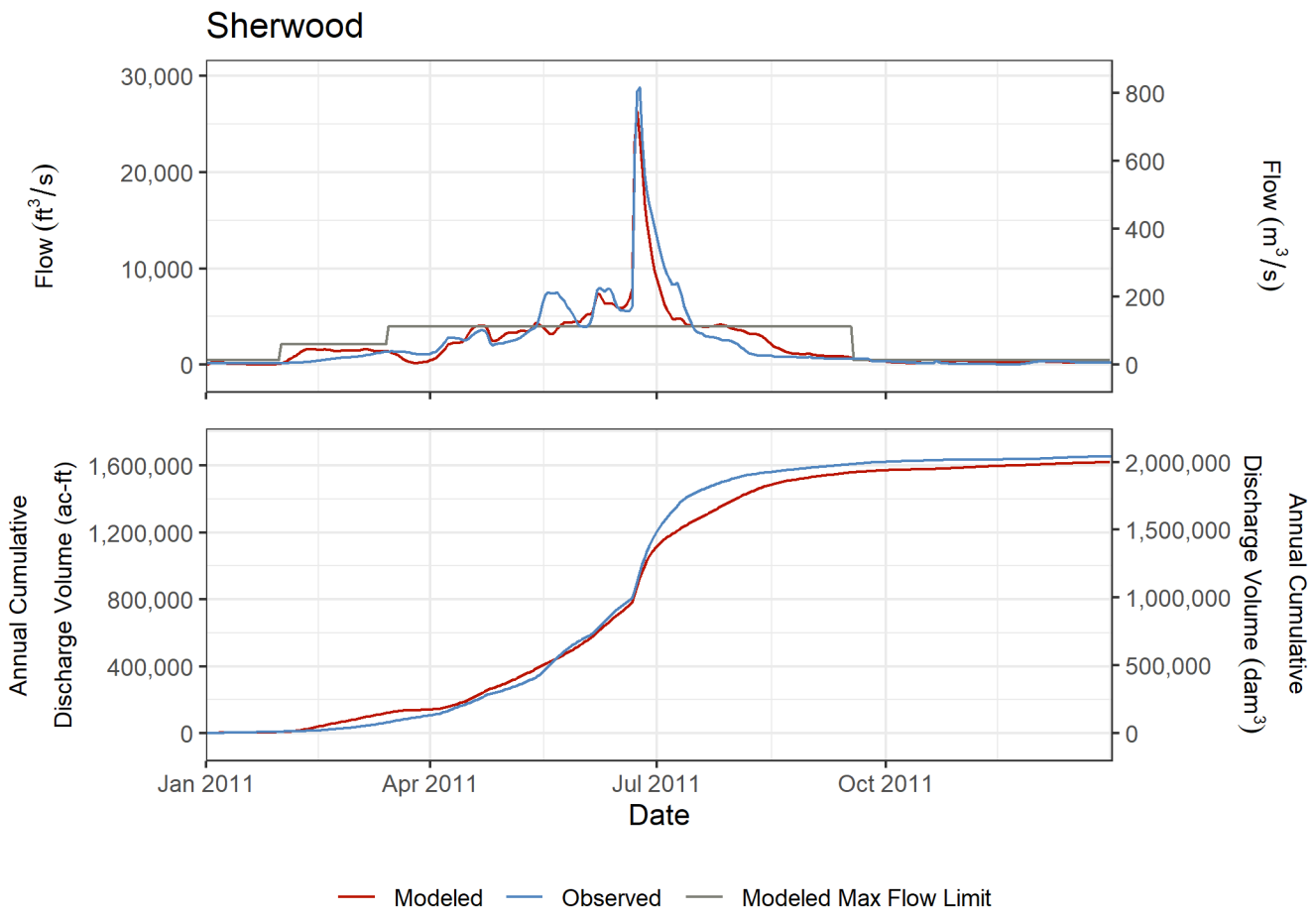


Figure 59 Souris River at Sherwood, ND 2011 flood event simulation results

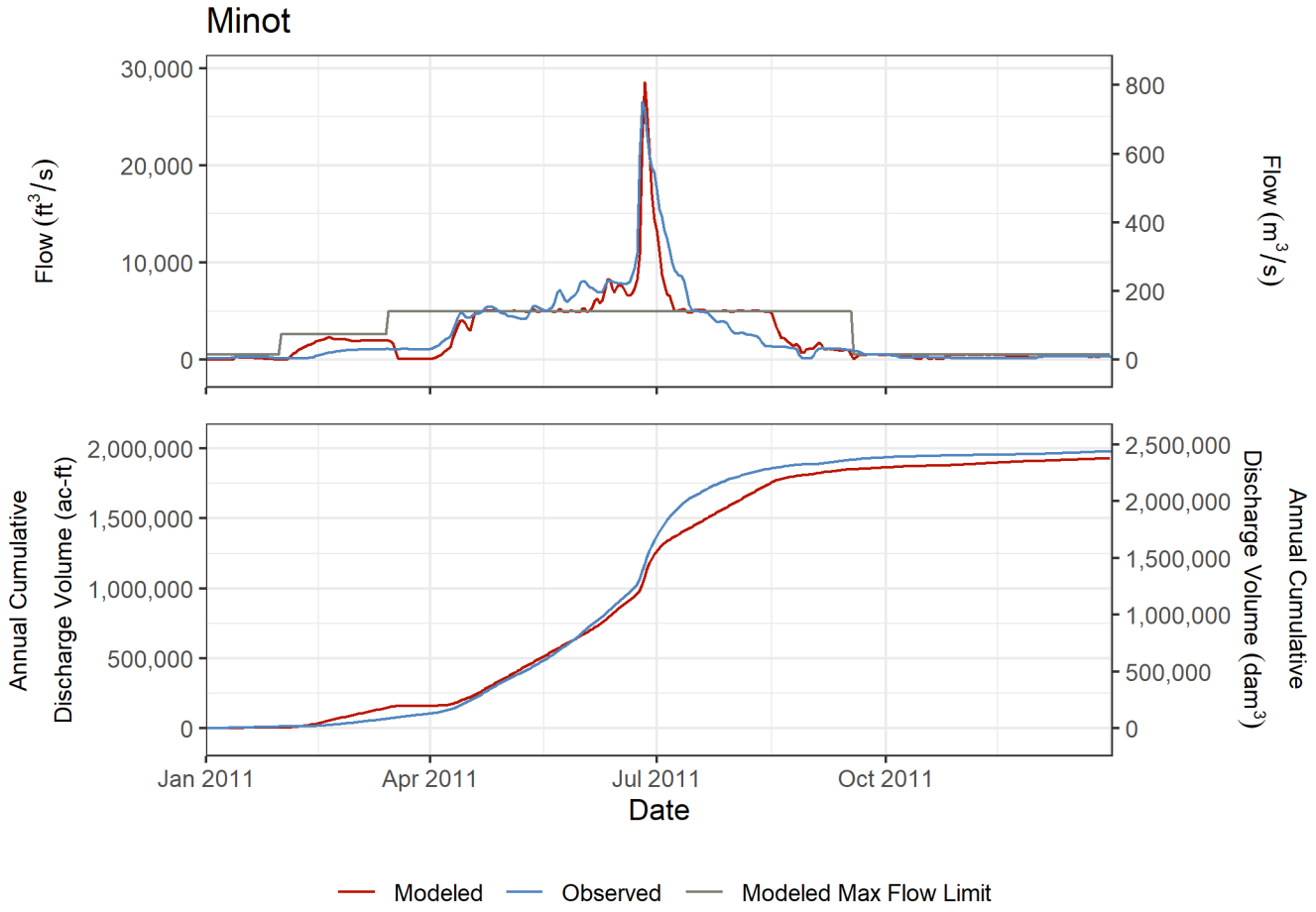


Figure 60 Souris River at Minot, ND 2011 flood event simulation results

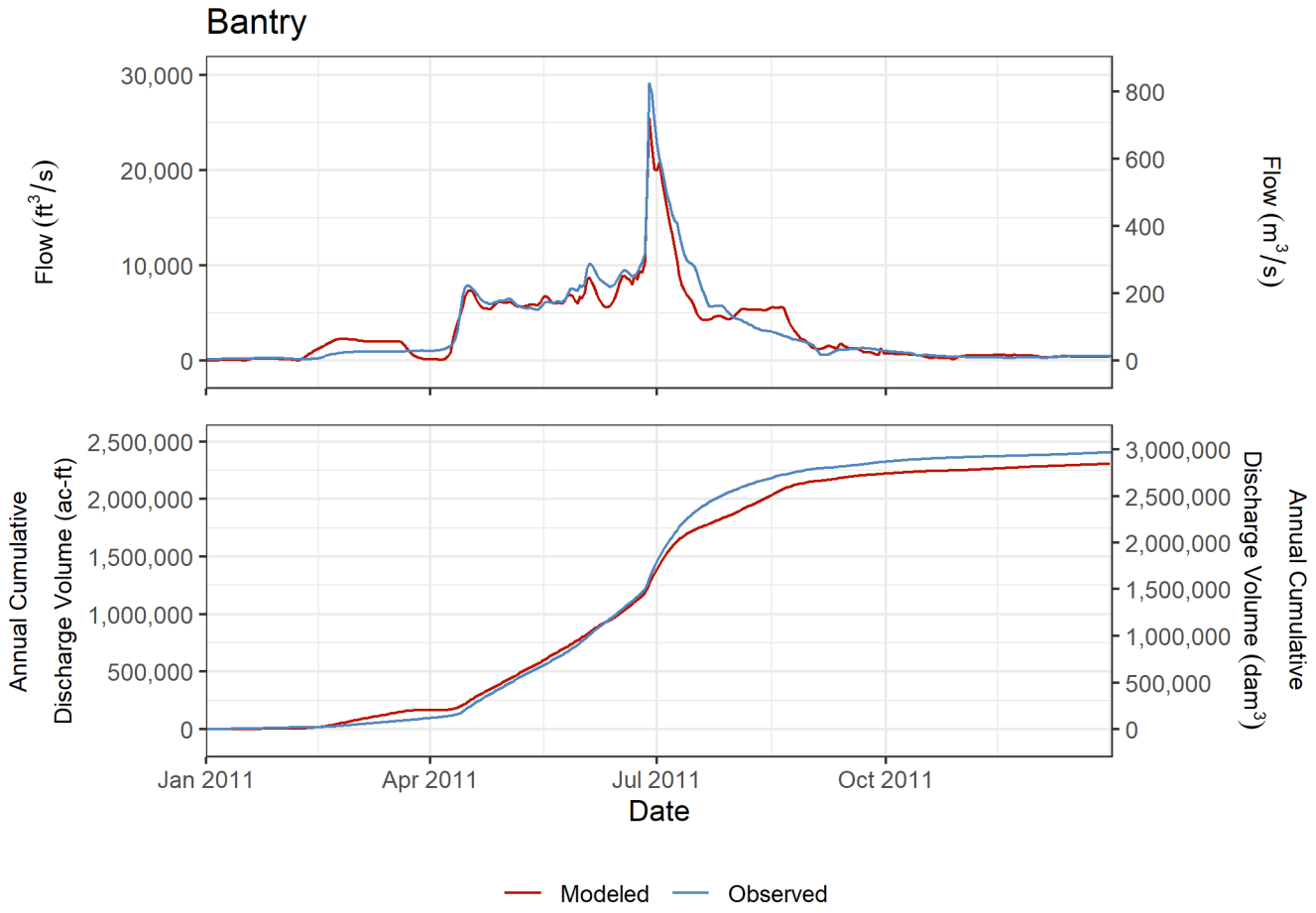


Figure 61 Souris River at Bantry, ND 2011 flood event simulation results

5.3 1998-2017 Continuous Simulation Verification Period

The 1998-2017 period of record was selected to assess the ability of the model to replicate operations overtime because this period encompasses the time when all four major Souris River Project reservoirs were operational. Due to ongoing litigation, Grant Devine Reservoir only filled to its full supply pool in 1999 (WSA, 2018). Thus for this analysis, the portion of the period of record assumed to be most representative of present day operations is from 1998 through 2017.

Table 65 provides a quantitative summary comparing modeled versus observed results for each of the reservoirs that make up the Souris River Project. Events are categorized as high, moderate and low flow events. Events that trigger spring flood operations in the model are classified as high flow events. One exception to this criteria is the 2015 flood event which did not trigger a flood status in the ResSim model. The volume of the 2015 event was greater than the volume of the 2017 event which did trigger spring flood operations in the model, therefore, the 2017 event was included as a high flow event rather than a moderate flow event. Moderate flow events are defined as events where a flood has not been triggered in the model and the June 1st natural flow volume at Sherwood is greater than 50,000 dam^3 (40,500 acre-feet) (the threshold used in *Annex B* to determine the apportionment calculations). Low flow years are years in which the June 1st natural flow volume at Sherwood Crossing is less than 50,000 dam^3 (40,500 acre-feet).

Modeled releases from Rafferty Reservoir to the Souris River (i.e. not including the Rafferty Pipeline) reasonably replicate observed releases for all the high flow events (difference in annual volume is < 30%). Operations during moderate and low flows at Rafferty are reasonably replicated for the majority of events. Boundary Reservoir's modeled releases to the Souris River (i.e. not including releases to Rafferty Reservoir via the Boundary Diversion) are similar to observed annual release volumes for both the high and low flow regimes. Errors are apparent in model results for more moderate events, likely due to uncertainty related to water supplies loses. Modeled releases from Grant Devine Reservoir are able to replicate observed annual volumes reasonably well for the majority of events across all three flow regimes. Lake Darling's modeled releases are consistent with observed annual volumes for both the high and moderate flow regimes. However, Lake Darling's modeled outflows during low flow years deviate considerably from observed outflows. This is likely due to uncertainty associated with Lake Darling's water supply releases for Eaton Irrigation and J. Clark Salyer.

Table 65 provides a summary of simulated versus observed annual flow volume for each reservoir sorted by the flow regimes discussed in the previous paragraphs. ***Table 66*** and ***Table 67*** summarize the total annual volume and average flow volume, respectively, for each flow regime. ***Table 66*** shows that the model is generally able to match the observed volumes for each reservoir within approximately 10 percent during high and moderate flow conditions. The exception is noted at Boundary Reservoir where the percent difference is higher.

Table 68 summarizes the average flow volume for each reservoir by flow regime. The results from the table show that under low flow conditions, there is a bias in the model which causes the Canadian reservoirs to release more than what was observed. The Canadian project reservoirs simulated releases average 3,684 dam^3 (2,987 acre-feet) more under low flow conditions than

what is indicated by the observed data. This bias is likely caused by the negative local flows in between Grant Devine and Sherwood. These negative local flows can impact the releases need to enforce the 0.11 m^3/s (4 ft^3/s) minimum flow rule at Sherwood. For example, if a negative local flow at Sherwood of 2.83 m^3/s (100 ft^3/s) occurs, the model would try to release something substantially greater than 2.83 m^3/s (100 ft^3/s) several days prior to account for travel time and attenuation. These over deliveries likely add up over time. This indicates a potential bias in the model which is a limitation and is discussed in Section 6.

Table 65 Simulated vs. observed percent difference in discharge and volume by flow regime

POS	Flow regime criteria			Rafferty Releases to Souris River			Boundary Releases to Souris River			Grant Devine Releases			Lake Darling Releases		
Year	ResSim Flood Status 1 = flood 0 = non-flood (a_fld_status)	June 1st Natural Flow Volume at Sherwood, ac-ft (*dam³*)	Flow Regime	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Percent Difference (%)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Percent Difference (%)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Percent Difference (%)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Percent Difference (%)
2011	1	705,448	1- High Flow	823,018	945,738	-13.0	363,007	255,130	42.3	301,335	308,445	-2.3	1,708,394	1,740,837	-1.9
		(870,171)		*(1,015,194)*	*(1,166,570)*		*(447,770)*	*(314,703)*		*(371,697)*	*(380,467)*		*(2,107,307)*	*(2,147,326)*	
1999	1	251,708	1- High Flow	132,049	193,165	-31.6	39,722	7,354	>100	6,329	14,703	-57.0	282,644	319,504	-11.5
		(310,482)		*(162,883)*	*(238,269)*		*(48,997)*	*(9,071)*		*(7,807)*	*(18,136)*		*(348,642)*	*(394,109)*	
2001	1	251,297	1- High Flow	152,868	131,339	16.4	13,944	23,766	-41.3	61,701	61,635	0.1	263,993	247,894	6.5
		(309,975)		*(188,563)*	*(162,007)*		*(17,200)*	*(29,315)*		*(76,108)*	*(76,027)*		*(325,636)*	*(305,778)*	
2013	1	177,886	1- High Flow	136,558	141,863	-3.7	51,661	52,716	-2.0	49,543	51,033	-2.9	303,785	308,732	-1.6
		(219,423)		*(168,445)*	*(174,988)*		*(63,724)*	*(65,025)*		*(61,111)*	*(62,949)*		*(374,719)*	*(380,822)*	
2015	0	168,554	1- High Flow	70,383	58,347	20.6	8,163	14,988	-45.5	72,911	73,854	-1.3	187,757	182,112	3.1
		(207,911)		*(86,818)*	*(71,971)*		*(10,069)*	*(18,488)*		*(89,936)*	*(91,099)*		*(231,599)*	*(224,636)*	
2017	1	149,306	1- High Flow	13,566	20,909	-35.1	8,638	48	>100	30,182	30,657	-1.5	112,569	116,734	-3.6
		(184,169)		*(16,734)*	*(25,791)*		*(10,655)*	*(59)*		*(37,230)*	*(37,815)*		*(138,854)*	*(143,992)*	
2009	1	145,440	2 - Moderate Flow	21,361	32,031	-33.3	10,786	9,897	9.0	16,328	8,614	89.6	25,054	22,946	9.2
		(179,401)		*(26,349)*	*(39,510)*		*(13,305)*	*(12,208)*		*(20,141)*	*(10,625)*		*(30,904)*	*(28,304)*	
2014	0	107,660	2 - Moderate Flow	33,534	47,848	-29.9	2,023	7,891	-74.4	130,979	130,967	0.0	235,994	258,035	-8.5
		(132,799)		*(41,364)*	*(59,021)*		*(2,495)*	*(9,734)*		*(161,563)*	*(161,548)*		*(291,099)*	*(318,287)*	
2005	0	91,438	2 - Moderate Flow	10,027	5,976	67.8	0	534	NA	26,357	33,114	-20.4	83,342	79,204	5.2
		(112,789)		*(12,368)*	*(7,371)*		*()*	*(659)*		*(32,511)*	*(40,846)*		*(102,803)*	*(97,698)*	
2003	0	68,734	2 - Moderate Flow	38	492	-92.3	0	425	NA	15,609	13,374	16.7	22,636	17,206	31.6
		(84,784)		*(47)*	*(607)*		*()*	*(524)*		*(19,254)*	*(16,497)*		*(27,922)*	*(21,224)*	
2012	0	64,160	2 - Moderate Flow	17,897	6,082	>100	90	1,188	-92.4	33,605	30,226	11.2	61,089	36,489	67.4
		(79,142)		*(22,076)*	*(7,502)*		*(111)*	*(1,465)*		*(41,452)*	*(37,284)*		*(75,353)*	*(45,009)*	
2010	0	31,353	3 - Low Flow	43,122	43,351	-0.5	2,874	86	>100	24,055	22,943	4.8	84,345	82,076	2.8
		(38,675)		*(53,191)*	*(53,474)*		*(3,545)*	*(106)*		*(29,672)*	*(28,300)*		*(104,040)*	*(101,241)*	
2007	0	26,500	3 - Low Flow	519	959	-45.9	0	264	NA	11,933	10,507	13.6	13,840	29,013	-52.3
		(32,688)		*(640)*	*(1,183)*		*()*	*(326)*		*(14,719)*	*(12,960)*		*(17,072)*	*(35,788)*	
1998	0	24,924	3 - Low Flow	13	2,920	-99.6	0	392	NA	6,403	95	>100	12,289	8,272	48.6
		(30,744)		*(16)*	*(3,602)*		*()*	*(484)*		*(7,898)*	*(117)*		*(15,159)*	*(10,204)*	
2004	0	17,839	3 - Low Flow	8	82	-90.2	0	491	NA	8,529	3,889	>100	28,231	28,350	-0.4
		(22,004)		*(10)*	*(101)*		*()*	*(606)*		*(10,521)*	*(4,797)*		*(34,823)*	*(34,970)*	
2006	0	16,445	3 - Low Flow	5,127	599	>100	0	174	NA	4,843	4,726	2.5	23,952	8,013	>100
		(20,285)		*(6,324)*	*(739)*		*()*	*(215)*		*(5,974)*	*(5,830)*		*(29,545)*	*(9,884)*	
2016	0	16,353	3 - Low Flow	7,396	7,501	-1.4	0	420	NA	9,597	7,962	20.5	23,982	19,299	24.3
		(20,172)		*(9,123)*	*(9,252)*		*()*	*(518)*		*(11,838)*	*(9,821)*		*(29,582)*	*(23,805)*	
2008	0	13,041	3 - Low Flow	15	143	-89.5	0	111	NA	783	5,992	-86.9	17,477	15,449	13.1
		(16,086)		*(19)*	*(176)*		*()*	*(137)*		*(966)*	*(7,391)*		*(21,558)*	*(19,056)*	
2002	0	12,333	3 - Low Flow	6,708	51	>100	0	181	NA	4,475	4,238	5.6	18,635	4,164	>100
		(15,213)		*(8,274)*	*(63)*		*()*	*(223)*		*(5,520)*	*(5,228)*		*(22,986)*	*(5,136)*	
2000	0	9,260	3 - Low Flow	9,469	68	>100	0	217	NA	5,478	6,104	-10.3	27,091	7,196	>100
		(11,422)		*(11,680)*	*(84)*		*()*	*(268)*		*(6,757)*	*(7,529)*		*(33,417)*	*(8,876)*	
Color Key to Table:						**Simulated value > observed value**						**Simulated value < observed value**			

Table 66 Comparison of simulated and observed total flow volume by flow regime

Comparison of Simulated and Observed Total Flow Volume by Flow Regime												
	Rafferty Releases to Souris River			Boundary Releases to Souris River			Grant Devine			Lake Darling		
Flow Regime	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Percent Difference From Observed (%)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Percent Difference From Observed (%)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Percent Difference From Observed (%)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Percent Difference From Observed (%)
High Flow Events Total Volume	1,328,442	1,491,361	-10.9	485,135	354,002	37.0	522,001	540,327	-3.4	2,859,142	2,915,813	-1.9
	(1,638,636)	*(1,839,597)*		*(598,415)*	*(436,662)*		*(643,889)*	*(666,494)*		*(3,526,757)*	*(3,596,661)*	
Moderate Flow Events Total Volume	82,857	92,429	-10.4	12,899	19,935	-35.3	222,878	216,295	3.0	428,115	413,880	3.4
	(102,204)	*(114,011)*		*(15,911)*	*(24,590)*		*(274,920)*	*(266,800)*		*(528,081)*	*(510,522)*	
Low Flow Events Total Volume	72,377	55,674	30.0	2,874	2,336	23.0	76,096	66,456	14.5	249,842	201,832	23.8
	(89,277)	*(68,674)*		*(3,545)*	*(2,881)*		*(93,865)*	*(81,974)*		*(308,181)*	*(248,960)*	
A negative percent difference indicates that the modeled results is less than the observed. A positive percent difference indicates that the modeled value is greater than the observed												

Table 67 Comparison of simulated and observed average volumes by flow regime

Comparison of Simulated and Observed Average Flow Volume by Flow Regime												
	Rafferty Releases to Souris River			Boundary Releases to Souris River			Grant Devine			Lake Darling		
Flow Regime	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Difference, Sim-Obs ac-ft (*dam³*)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Difference, Sim-Obs ac-ft (*dam³*)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Difference, Sim-Obs ac-ft (*dam³*)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Difference, Sim-Obs ac-ft (*dam³*)
Avg. High Volume	221,407	248,560	-27,153	80,856	59,000	21,856	87,000	90,055	-3,054	476,524	485,969	-9,445
	(273,106)	*(306,599)*	*(-33,493)*	*(99,736)*	*(72,777)*	*(26,959)*	*(107,315)*	*(111,082)*	*(-3,768)*	*(587,793)*	*(599,443)*	*(-11,651)*
Avg. Moderate Volume	16,571	18,486	-1,914	2,580	3,987	-1,407	44,576	43,259	1,317	85,623	82,776	2,847
	(20,441)	*(22,802)*	*(-2,361)*	*(3,182)*	*(4,918)*	*(-1,736)*	*(54,984)*	*(53,360)*	*(1,624)*	*(105,616)*	*(102,104)*	*(3,512)*
Avg. Low Volume	8,042	6,186	1,856	319	260	60	8,455	7,384	1,071	27,760	22,426	5,334
	(9,920)	*(7,630)*	*(2,289)*	*(394)*	*(320)*	*(74)*	*(10,429)*	*(9,108)*	*(1,321)*	*(34,242)*	*(27,662)*	*(6,580)*

Table 68 Summary of comparison between simulated and observed average flow volume for the Canadian project reservoirs

Comparison of Simulated and Observed Average Flow Volume by Flow Regime - Canadian Reservoirs			
All Canadian Reservoirs (Rafferty, Boundary, Grand Devine)	Simulated Annual Discharge Volume, ac-ft (*dam³*)	Observed Annual Discharge Volume, ac-ft (*dam³*)	Difference, Sim-Obs ac-ft (*dam³*)
Avg. High Volume	389,263	397,615	-8,352
	(480,157)	*(490,459)*	*(-10,302)*
Avg. Moderate Volume	63,727	65,732	-2,005
	(78,607)	*(81,080)*	*(-2,473)*
Avg Low Flow Volume	16,816	13,830	2,987
	(20,743)	*(17,059)*	*(3,684)*

5.3.1 Verification: Rafferty Reservoir

Figure 62 and Figure 63 show observed and simulated daily pool elevation, daily outflow, and the annual cumulative volume for Rafferty Reservoir and the Rafferty Pipeline, respectively. *Figure 62* shows the 10-day average, flows and volumes shown use a log scale, and values below 0.03 m^3/s (1 ft^3/s) or 1.23 dam^3 (1 acre-feet) are not shown for clarity. The observed pool elevation during 1998 through 2001 is lower than the simulated elevation because the reservoir was being held to a lower elevation to allow oil wells to be decommissioned or flood proofed (WSA, 2018). The Rafferty Pipeline is generally operated in the model when observed operation occurred. The simulated, cumulative, annual volumes compare well with the observed volumes.

Differences between the simulated and observed pool elevations at Rafferty Reservoir begin in 2010 prior to the spring runoff event of 2011. The differences are primarily due to how the reservoir is modeled compared to how it is operated. The ResSim model attempts to reach the normal drawdown elevation by February 1st. In practice, the reservoir was operated so that the normal drawdown elevation was achieved by the end of September 2010.

The model allows for an extended drawdown between February 1st and March 15th of each calendar year to accommodate excess runoff as the result of a spring flood. The end date of March 15th was a modeling decision to ensure that all reservoirs reach their final drawdown elevation in time to capture the spring runoff event. In practice, operators are not constrained by this date and can reach the extended drawdown at a date earlier or later in the year than March 15th. Differences in the extended drawdown target date result in differences in the model in 1999, 2001, 2011, 2013, and 2015.

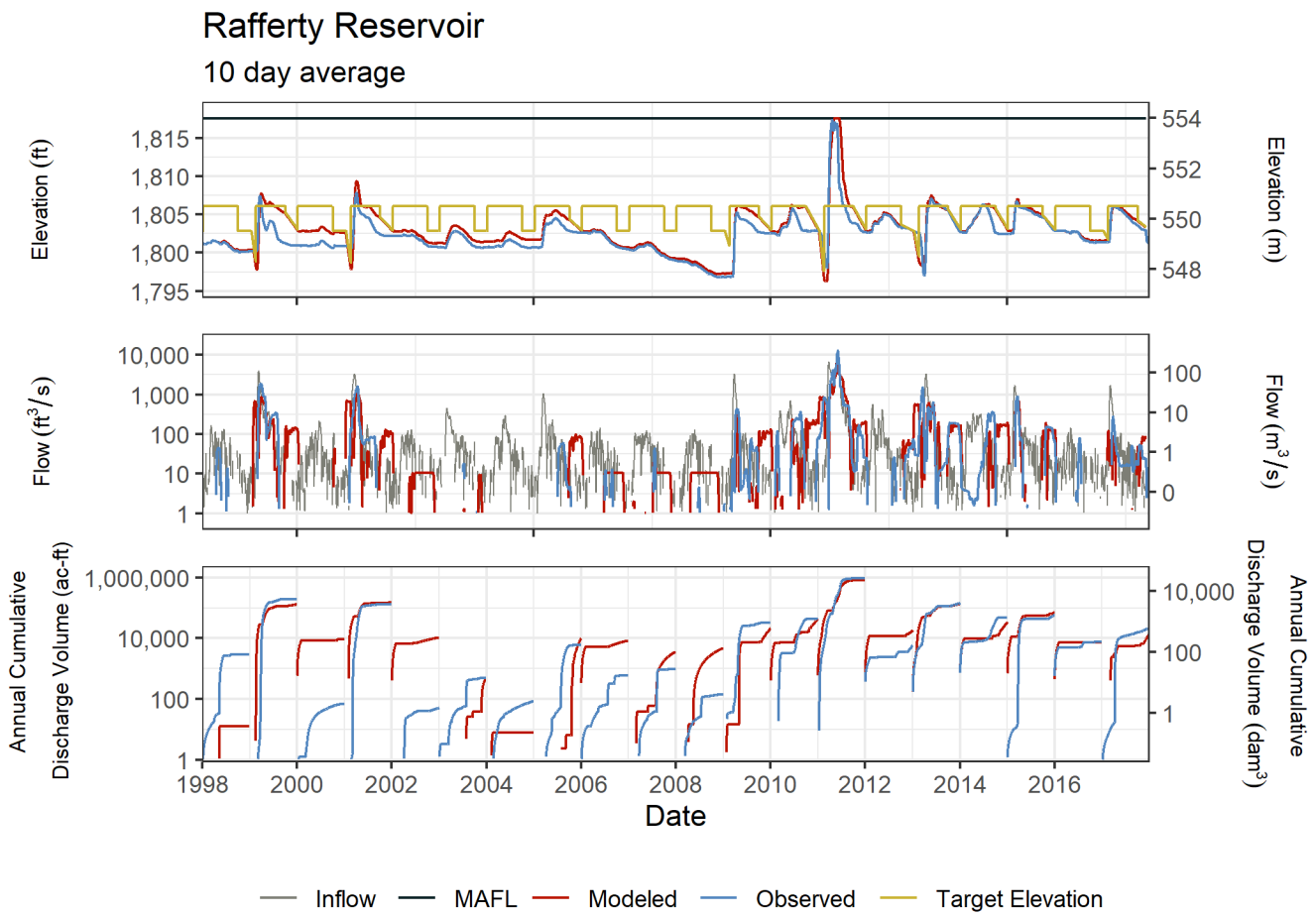


Figure 62 Rafferty Reservoir 10-day average simulated and observed pool level, discharge, and annual, cumulative discharge volume to the Souris River from 1998-2017

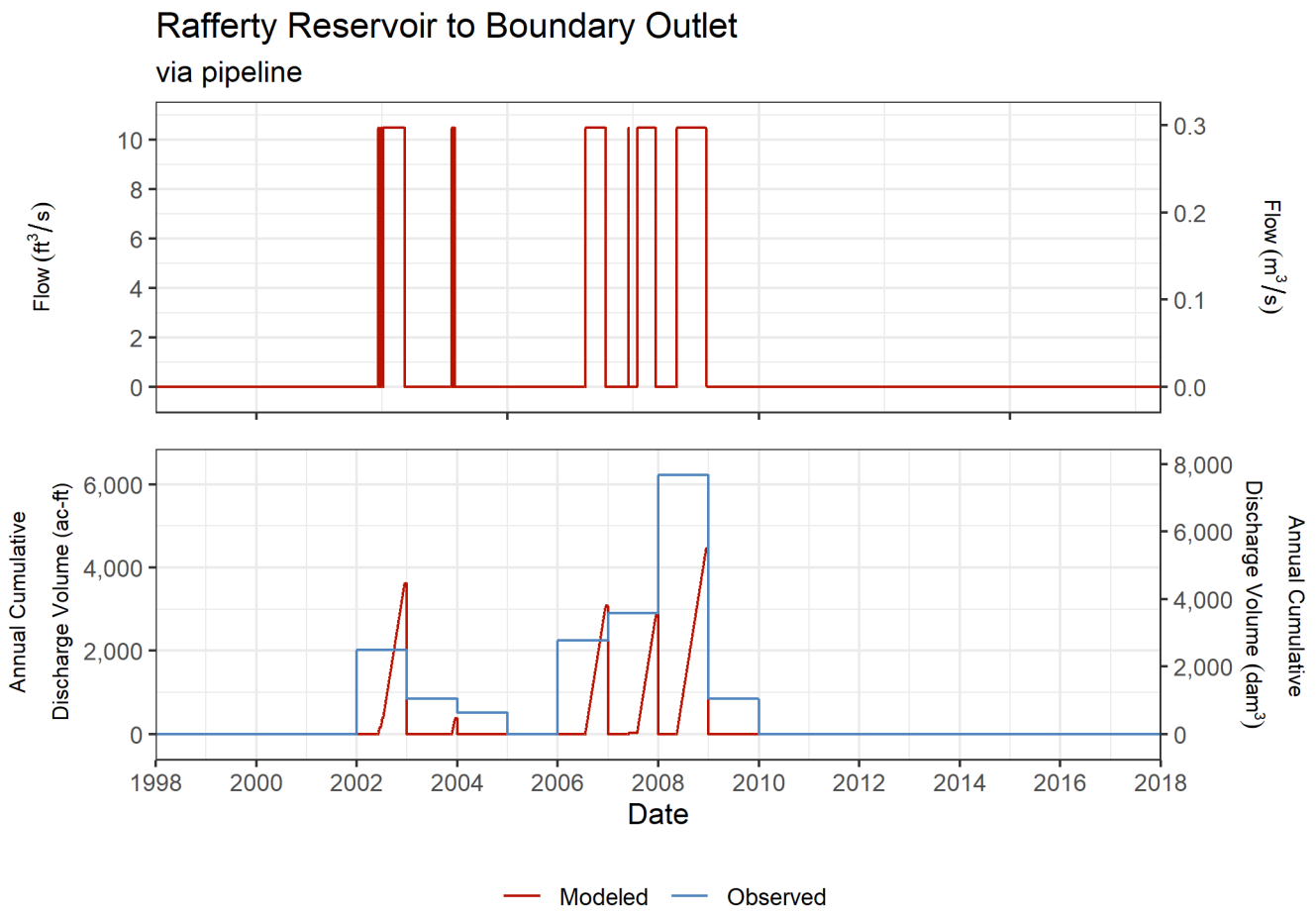


Figure 63 Rafferty Reservoir discharge and annual, cumulative discharge volume to Boundary Reservoir via the pipeline from 1998-2017

5.3.2 Verification: Boundary Reservoir

Figure 64 shows simulated and observed pool elevations at Boundary Reservoir and observed and simulated discharges from Boundary Reservoir to Long Creek. Figure 65 shows discharges to Rafferty Reservoir, respectively. Figure 64 shows the 10-day average, flows and volumes shown use a log scale, and values below 0.03 m^3/s (1 ft^3/s) or 1.23 dam^3 (1 acre-feet) are not shown for clarity. The simulated pool matches the observed pool fairly well.

The modeled elevation of Boundary Reservoir frequently exceeds the observed elevation because it is a small reservoir and small changes in inflow or water use can result in large discrepancies in pool elevation. Actual water usages are not recorded, so it is difficult to accurately model water supply loses.

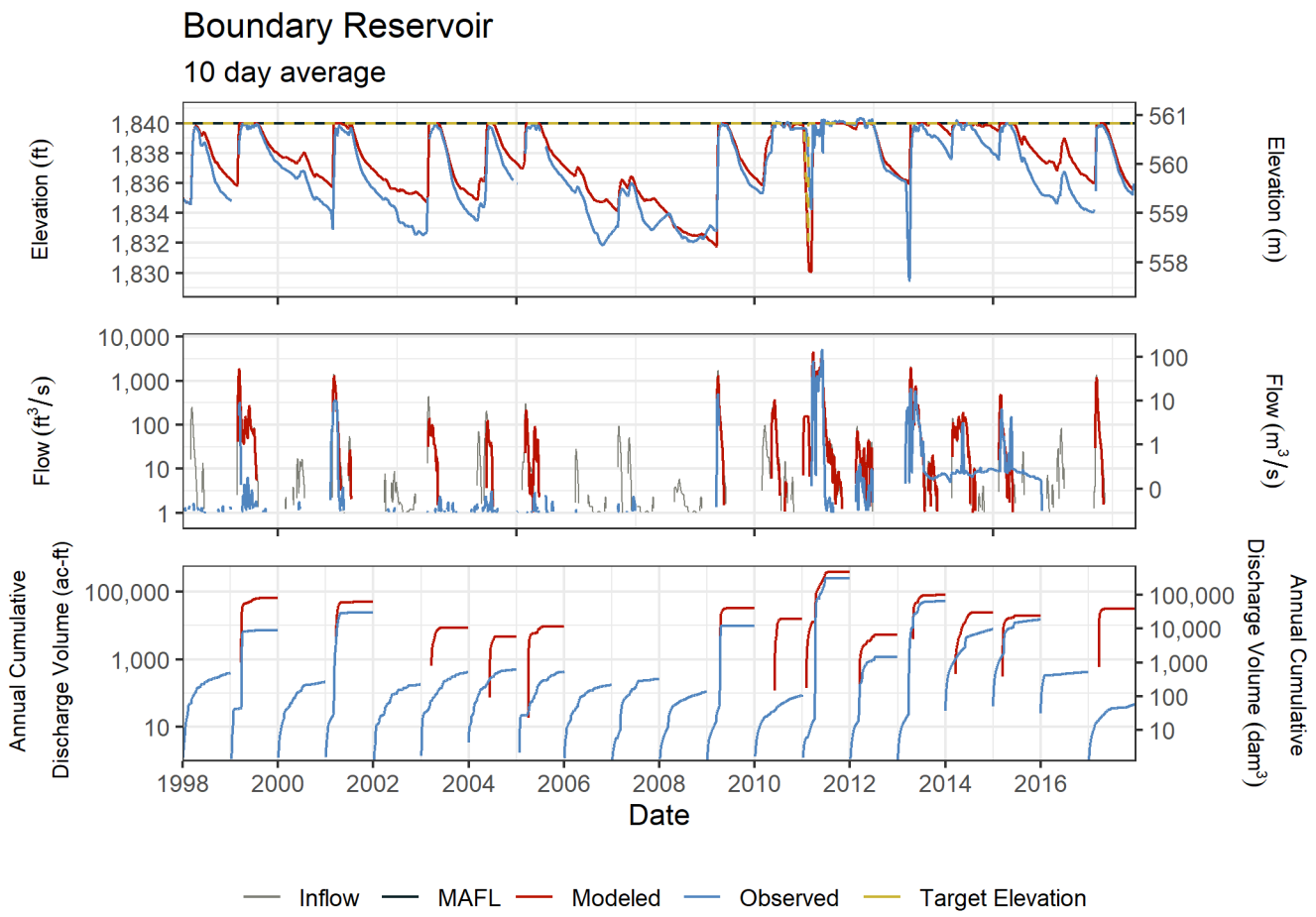


Figure 64 Boundary Reservoir 10-day average simulated and observed pool level, discharge, and annual, cumulative discharge volume to Long Creek from 1998-2017

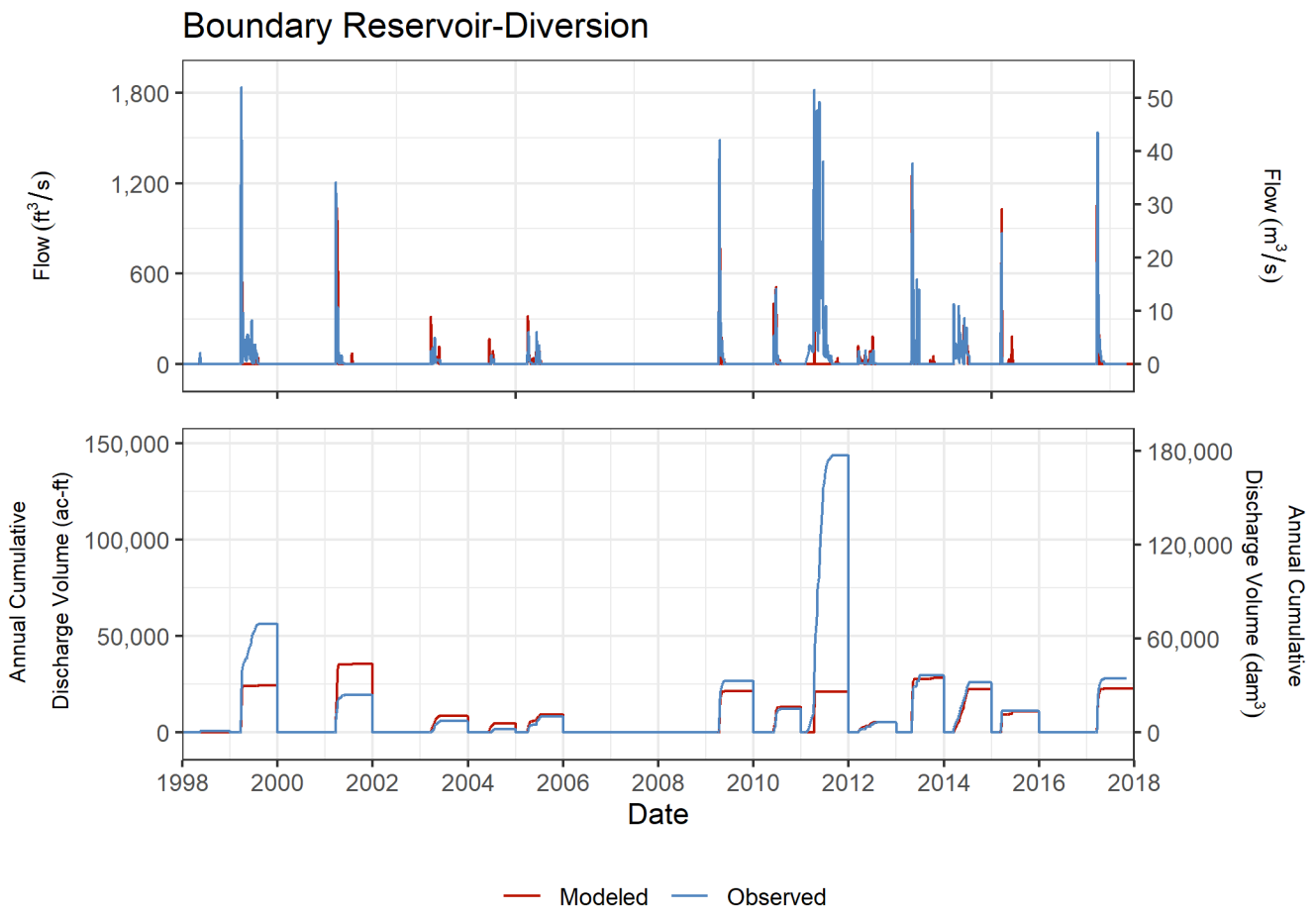


Figure 65 Boundary Reservoir simulated and observed pool level, discharge, and annual, cumulative discharge volume to Rafferty Reservoir from 1998-2017

5.3.3 Verification: Grant Devine Lake

Figure 66 shows a comparison of observed versus simulated reservoir pool elevations and reservoir outflows for Grant Devine Lake. *Figure 66* shows the 10-day average, flows and volumes shown use a log scale, and values below 0.03 m^3/s (1 ft^3/s) or 1.23 dam^3 (1 acre-feet) are not shown for clarity. The simulated drawdowns preceding spring flood operation, match the observed drawdowns well. There are small differences in the timing of the drawdown in 2011 and 2013 which lead to slightly different releases from the reservoir. Similarly to how Rafferty Reservoir was operated in 2011, operators released flows in excess of the downstream constraint at Sherwood until Grant Devine's pool reached its FSL. Consequently, the simulated pool remains near the top of the flood control pool longer than the observed pool during the 2011 event.

During the 2014 rain event, the model makes use of available flood storage, while in real time operators did not allow the pool to rise as far above its FSL (summertime conservation pool elevation). This difference between modeled and observed reservoir operations is due to the maximum downstream flow rules adopted as part of this study. The rules limit the modeled releases from the reservoir lower than what was observed. There are differences between modeled and observed summer operations because *Annex A* does not contain detailed guidelines for operating the reservoirs in response to summer flooding. Overall, the simulated results at Grant Devine closely match the observed data.

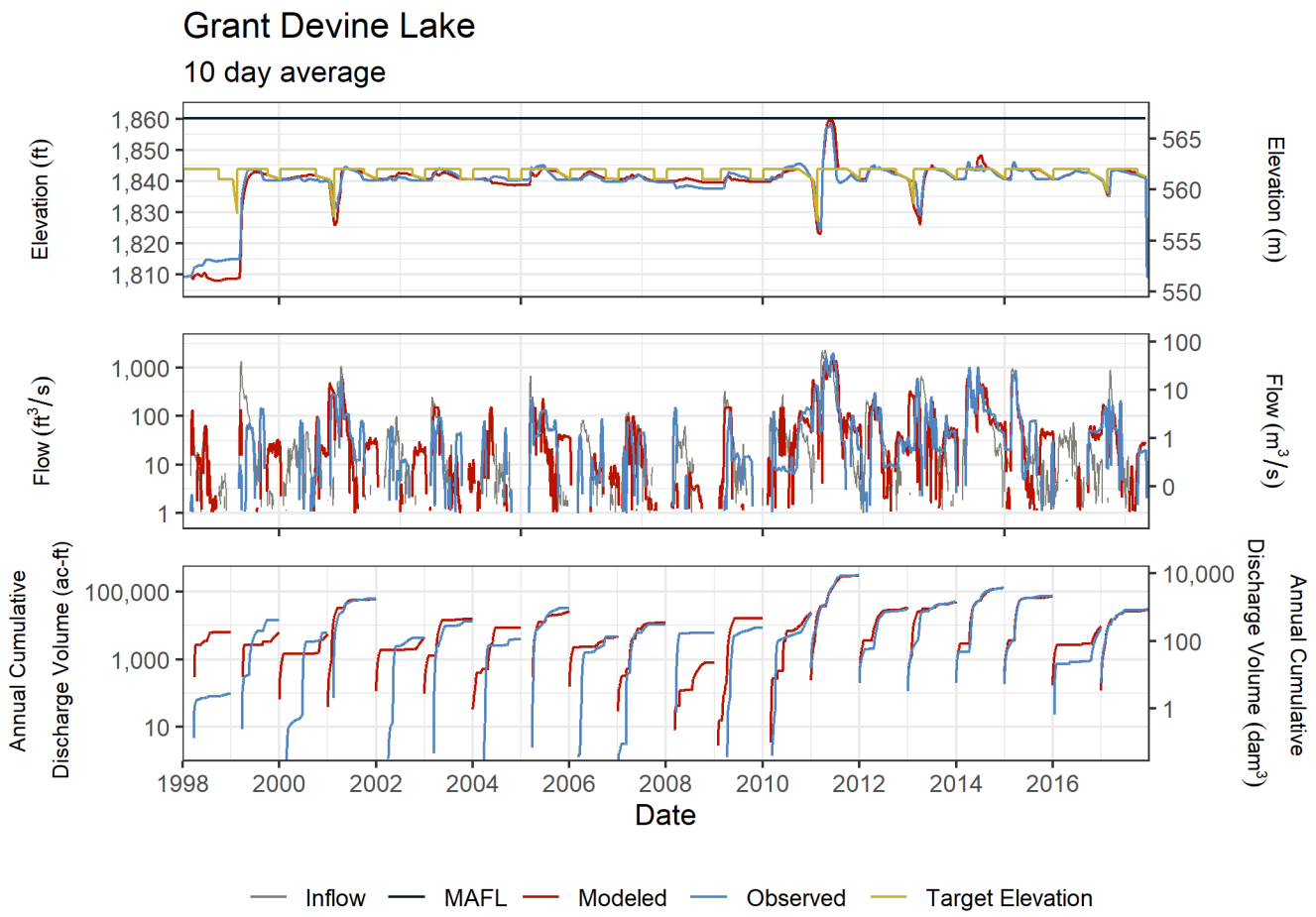


Figure 66 Grant Devine Lake 10-day average simulated and observed pool level, discharge, and annual, cumulative discharge volume from 1998-2017

5.3.4 Verification: Lake Darling

Figure 67 shows a comparison of observed versus simulated reservoir pool elevations and reservoir outflows for Lake Darling for the 1998 through 2017 period of record. Note that *Figure 67* shows the 10-day average, flows and volumes shown use a log scale, and values below 0.03 m^3/s (1 ft^3/s) or 1.23 dam^3 (1 acre-feet) are not shown for clarity. The simulated pool elevation tracks the observed pool elevation closely during the simulation period. Two noticeable differences between the simulated and observed results occur during the drawdown period in 2013 and 2017. In 2013, the observed pool elevation was drawndown prior to spring runoff as a result of the spring flood forecast. The model does not draw down the pool prior to the 2013 event. A similar scenario occurs in 2017. In real time, flood forecasts have a lot of uncertainty associated with them which can make it difficult to accurately estimate how much to draw the reservoir down to accommodate spring runoff. The ResSim model uses observed flow when making drawdown decisions which reduces some of this uncertainty. This is why in 2013 and 2017 the model did not draw the reservoir down as low as operators did in practice.

Figure 68 shows an example of how the ResSim model at Lake Darling responds to a summer rainfall driven event in 2014. A rainfall event occurred in June 2014 which forced the reservoir to exceed its normal summer pool elevation of 486.77 m (1597 ft). During this event, the model tried to prevent the reservoir pool elevation from rising above the summer top of flood control elevation of 487.07 m (1598 ft), but releases were limited by the rate of change rules. The simulated pool elevation matches the observed elevation fairly well, but the simulated peak discharge of 109 m^3/s (3,860 ft^3/s) was larger than the observed discharge peak of 57 m^3/s (2000 ft^3/s). Guidance for summer operation is unclear; however, in the instance, the model generally match the observed operations.

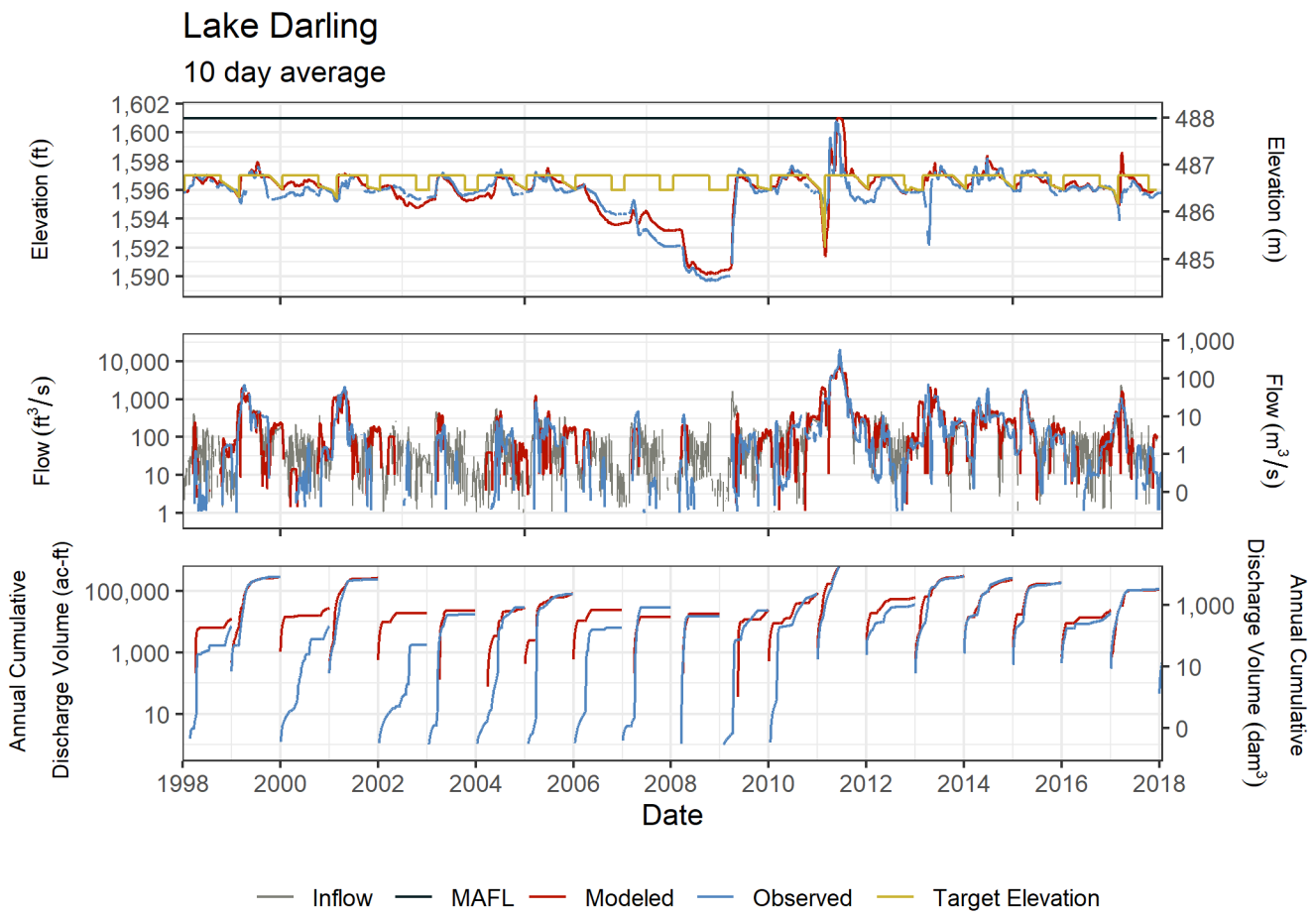


Figure 67 Lake Darling 10-day average simulated and observed pool level, discharge, and annual, cumulative discharge volume from 1998-2017

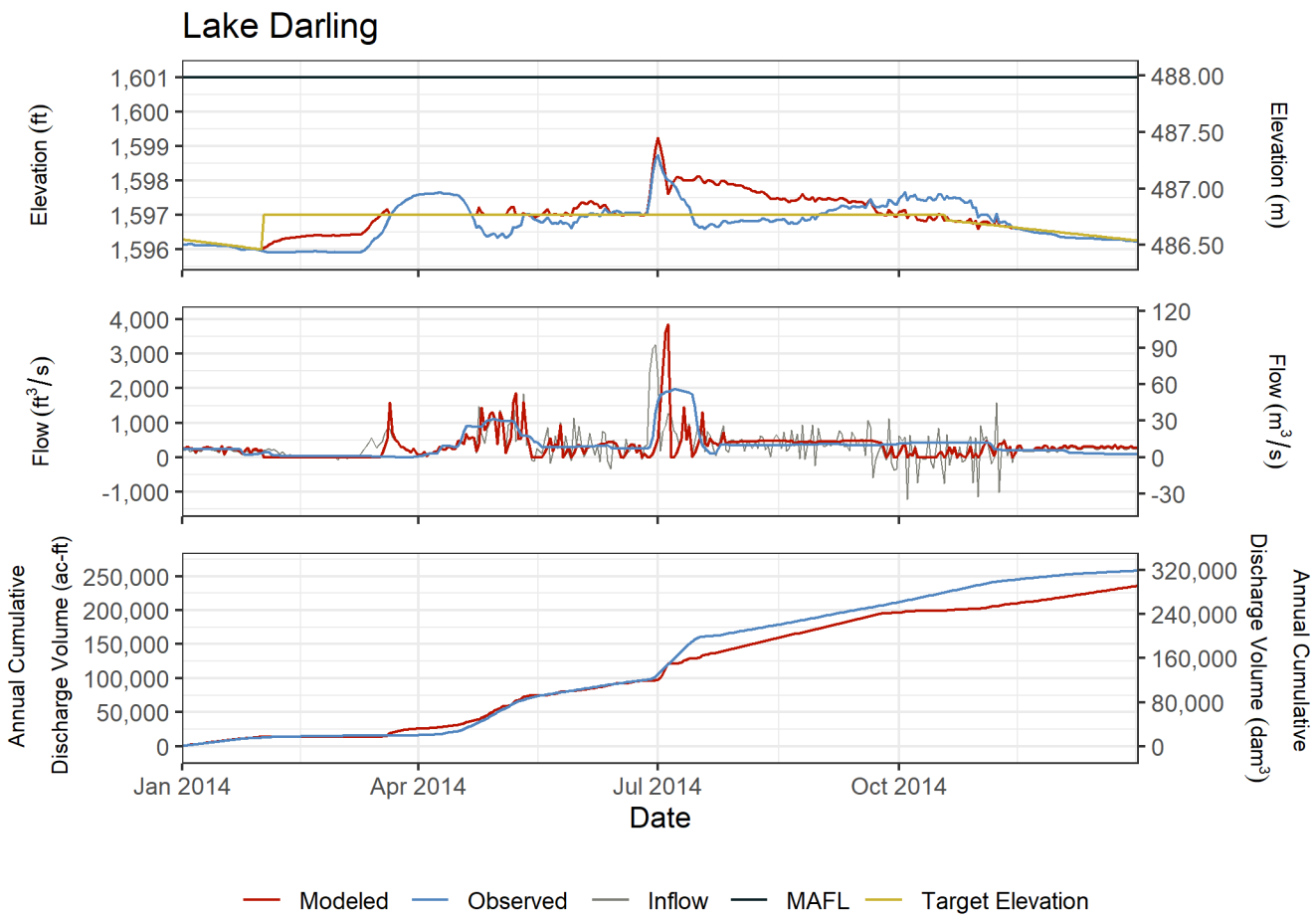


Figure 68 Lake Darling simulated and observed pool level, discharge, and annual, cumulative discharge volume 2014 rain event

5.4 Determination of Flood Years

The inputs generated as part of the 2013 and 2018 reconstructed hydrology (HH1) efforts were used to model the historical period of record from 1930 through 2017. During this time period the model identified 21 total flood years where spring flood operations, as defined in *Annex A,* were triggered in ResSim. A flood is triggered when the simulated unregulated 30-day maximum flow volume at Sherwood Crossing is greater than 216,110 dam^3 (175,200 acre-feet) or if the local 30-day flow volume at Sherwood Crossing is greater than 37,000 dam^3 (30,000 acre-feet).

The 21 years identified as flood years by the model are listed in ***Table 69***. *Annex A* estimates that the flood operating plan would have been used approximately six times between 1930 and 1988 (1969, 1976, 1975, 1979 and 1982). The HH6 ResSim model indicates that the operating plan would have been used a total of 13 times during this same period.

Between 1998 and 2017, the model initiates flood operations six times, while the ISRB initiated flood operations five times. 1999 was identified as a flood year by the model, but not by the ISRB. The model did not initially recognize the 2009 flood event because the observed natural flow volume at Sherwood was just shy of the flood threshold. A special trigger was added to the state variable script to force the model to identify the 2009 event as a flood year.

Some small differences can be expected as forecasts are used operationally to declare flood events whereas the model benefits from perfect foresight.

Table 69 Flood years determined by ResSim Model.

Flood Years		
1943	1974	1997
1948	1975	1999
1951	1976	2001
1955	1979	2009
1960	1982	2011
1969	1983	2013
1972	1996	2017

5.5 Apportionment

Evaluating the model's capability to capture the apportionment of flows between Canada and the United States is assessed by comparing the annual natural flow volume at Sherwood, the apportionment target ratio, and the annual surplus or deficit predicted by the model with those values as calculated by the ISRB. A quantitative comparison of the natural flow volume, regulated volume, and surplus volume at Sherwood Crossing is shown in ***Table 70***.

The apportionment target is driven by the cumulative, annual, natural flow volume calculation at Sherwood Crossing and the Lake Darling pool elevation. The computation used by the ISRB to calculate the natural flow volume at Sherwood is complex. The model uses a simplified version of this calculation defined in Section 4.3.1. ***Figure 69*** shows the comparison of the ISRB

calculated, Sherwood natural flow volume to the Sherwood natural flow volume calculated within the ResSim model. The natural flow record defined by the model compares well with the natural flow record derived using the ISRB calculation. ***Figure 69*** also includes the recorded, regulated volume at Sherwood and the simulated, regulated volume at Sherwood. The model results compare well with the simulated data.

In addition to displaying the natural and regulated flow records at Sherwood, ***Figure 69***, shows the annual ISRB determined apportionment ratio compared to the simulated, apportionment ratio. The observed apportionment ratio is represented in the plots below as a constant time series dataset for the entire year equivalent to the post-June 1st apportionment ratio. The year-end modeled apportionment split matches the ISRB determined apportionment split. It is important to note that in the year 2000, the ISRB used a different apportionment criteria because *Annex B* was not yet amended (Canada and USA, 2000).

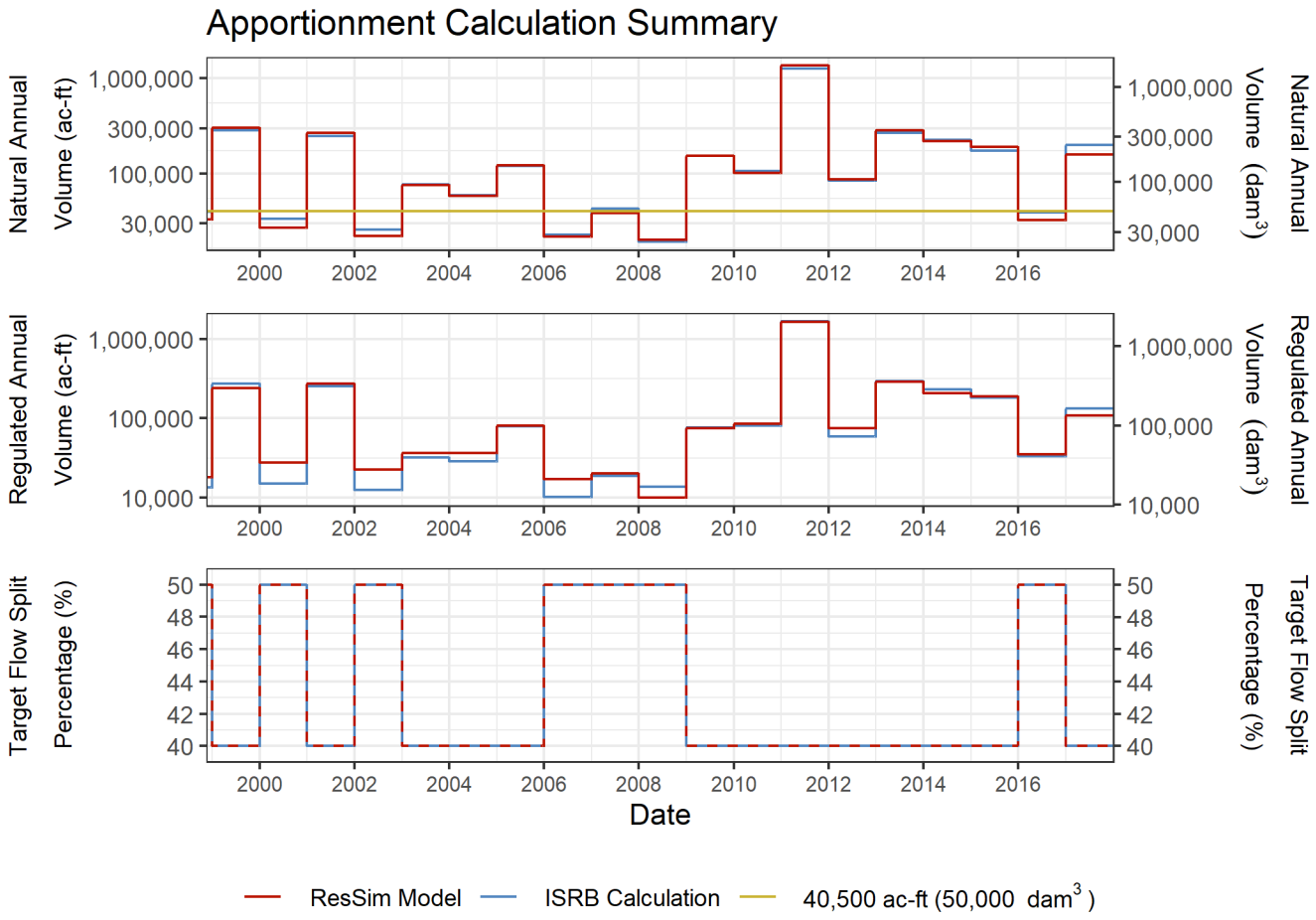


Figure 69 Comparison of the modeled and ISRB calculated annual natural Sherwood volume, the regulated annual Sherwood volume, and apportionment split

Table 70 shows a comparison of the simulated and observed ISRB apportionment volume estimates for the natural volume, regulated volume, and surplus volume at Sherwood Crossing. The modeled results tend to produce higher volumes when compared to the observed results. For the 2000 through 2017 the model accurately estimates the natural flow volume and the regulated flow volume at Sherwood Crossing. On average, the model is in very good agreement with the ISRB calculated natural volume, regulated volume, and year end surplus. The largest difference is the year end surplus during flood years where the model simulates a 14% higher surplus; however, during flood years, the surplus has no impact on operations.

Table 70 Apportionment Volume Comparison at Sherwood Crossing

Calendar Year	Flood Status	Natural Volume			Regulated Volume			Surplus Volume		
		Simulated, ac-ft (dam3)	ISRB, ac-ft (dam³)	Percent Difference	Simulated, ac-ft (dam3)	ISRB, ac-ft (dam³)	Percent Difference	Simulated, ac-ft (dam3)	ISRB, ac-ft (dam³)	Percent Difference
2000	Non-flood	27,027 (33,325)	33,466 (41,264)	-19%	27,730 (34,191)	15,079 (18,593)	84%	14,988 (18,480)	-365 (-450)	-4208%
2001	Flood	269,708 (332,549)	248,735 (306,690)	8%	270,906 (334,027)	253,753 (312,878)	7%	163,956 (202,157)	155,227 (191,395)	6%
2002	Non-flood	22,207 (27,381)	25,829 (31,848)	-14%	22,538 (27,789)	12,566 (15,494)	79%	13,448 (16,581)	940 (1,160)	1330%
2003	Non-flood	76,005 (93,714)	76,592 (94,438)	-1%	36,442 (44,933)	32,023 (39,485)	14%	7,558 (9,319)	2,813 (3,469)	169%
2004	Non-flood	57,926 (71,423)	59,198 (72,991)	-2%	36,555 (45,072)	28,537 (35,186)	28%	14,089 (17,371)	6,429 (7,927)	119%
2005	Non-flood	122,542 (151,094)	120,731 (148,862)	1%	81,524 (100,519)	78,631 (96,952)	4%	32,884 (40,546)	32,153 (39,645)	2%
2006	Non-flood	21,727 (26,789)	22,773 (28,079)	-5%	17,250 (21,269)	10,215 (12,595)	69%	9,100 (11,221)	276 (340)	3202%
2007	Non-flood	38,612 (47,609)	42,778 (52,745)	-10%	20,199 (24,906)	18,646 (22,991)	8%	3,280 (4,044)	-1,437 (-1,772)	-328%
2008	Non-flood	20,170 (24,869)	19,215 (23,692)	5%	10,030 (12,367)	13,725 (16,923)	-27%	2,554 (3,149)	5,286 (6,517)	-52%
2009	Flood	154,738 (190,792)	152,926 (188,558)	1%	75,442 (93,020)	76,137 (93,877)	-1%	15,235 (18,784)	16,436 (20,265)	-7%
2010	Non-flood	101,848 (125,578)	107,018 (131,953)	-5%	84,693 (104,426)	80,684 (99,483)	5%	43,954 (54,195)	39,600 (48,827)	11%
2011	Flood	1,356,690 (1,672,799)	1,274,517 (1,571,480)	6%	1,632,824 (2,013,271)	1,656,414 (2,042,359)	-1%	1,090,148 (1,344,152)	1,148,497 (1,416,096)	-5%
2012	Non-flood	86,683 (106,880)	83,897 (103,445)	3%	75,489 (93,078)	59,051 (72,810)	28%	42,474 (52,370)	27,025 (33,322)	57%
2013	Flood	284,449 (350,725)	268,706 (331,314)	6%	287,269 (354,203)	295,084 (363,839)	-3%	174,684 (215,385)	189,386 (233,513)	-8%
2014	Non-flood	220,314 (271,647)	226,055 (278,726)	-3%	206,834 (255,026)	229,801 (283,344)	-10%	118,708 (146,368)	141,061 (173,928)	-16%
2015	Non-flood	190,274 (234,607)	173,312 (213,693)	10%	189,251 (233,347)	182,233 (224,693)	4%	114,761 (141,501)	114,623 (141,330)	0%
2016	Non-flood	32,732 (40,358)	38,853 (47,906)	-16%	35,100 (43,278)	33,475 (41,275)	5%	19,457 (23,991)	15,532 (19,152)	25%
2017	Flood	158,826 (195,833)	198,692 (244,987)	-20%	108,550 (133,842)	133,576 (164,699)	-19%	46,854 (57,771)	56,091 (69,160)	-16%
Average % Difference (All Years):				**2%**	**Average % Difference (All):**		**0%**	**Average % Difference (All):**		**-1%**
Average % Difference (Non-Flood Years):				**4%**	**Average % Difference (Non-Flood):**		**-2%**	**Average % Difference (Non-Flood):**		**-5%**
Average % Difference (Flood Years):				**-1%**	**Average % Difference (Flood):**		**6%**	**Average % Difference (Flood):**		**14%**

Simulated value > observed value

Simulated value < observed value

6 Summary of Model Limitations

A summary of identified limitations within the Plan of Study ResSim model is included below. As the study progresses and resources become available these issues offer opportunities for model improvement.

Minimum Flow Requirements with Datasets that include Negative Flow. The summary of results presented in Section 5.3 noted that under low flow conditions the Canadian project reservoirs tend to have higher releases on average than what the observed dataset indicates, likely due to the 4 ft^3/s (0.11 m^3/s) minimum flow rule coupled with negative flows in the HH1 dataset. The model is not well suited for alternatives evaluating instream flow requirements when using a dataset with negative flows (e.g. HH1). It is recommended that an input dataset without negatives (e.g. HH6 or HH4) is used to evaluate alternatives that may be dependent on instream flow requirements.

Channel Seepage Losses or Gains. The ResSim model should be modified to account for seepage loss or gains due to baseflow when using an input dataset that is not HH1. The HH1 dataset was derived using reverse routing and any gains or losses are implicit within the dataset. Loss rates should be considered when using other datasets to evaluate low flow conditions. Baseflow gains may not be as impactful because they would typically occur in wet conditions.

Spring Drawdown Targets. Spring drawdown targets for Rafferty, Boundary and Grant Devine Reservoirs are based a forecasted 90 day, 90 percent inflow volume. Because historic forecasts are unavailable for 1930-2008 a reduction factor of 0.5 is applied to historically based inflows to make them representative of the forecasted 90 day, 90 percent inflow volumes. As the HH10, Forecasting Assessment task progresses, improvements to this inflow reduction factor could be incorporated into the ResSim model logic.

J. Clark National Wildlife Refuge Structures. Although some information is available for the J. Clark NWR structures, the data informing operations of these structures is not easily captured in timeseries dataset (e.g. cattail growth, habitat suitability) and operation discursion is typically used. Because of the variability of operation that is driven by data that is not digestible or available in a timeseries format, these structures cannot be modeled in detail.

Distribution & Magnitude of Apportionment Releases. The timing and magnitude of releases made to meet apportionment requirements are highly discretionary. Further analysis could be carried out to better define how apportionment releases are made. The model currently only accurately captures cumulative, annual apportionment releases, but is unable to replicate the magnitude and distribution of day-to-day releases made to meet apportionment. However the distribution and magnitude of the apportionment releases aren't nearly as critical as the cumulative volume, which the model seems to do well.

Eaton Irrigation District. There is little information about water use for the Eaton Irrigation District. Currently the Eaton Irrigation District contacts Lake Darling in April if water levels at Eaton are too low for their intake gate. Darling then releases more water in order for the Eaton project to fill. The NDSWC estimates that it takes about 15,418.5 dam^3 (12,500 acre-feet) to fill

the irrigation system. This information is currently, what the ResSim modeling assumptions are based on, if additional information is obtained on how water is used for the Eaton Irrigation District, this can be incorporated into the model to more accurately simulate water supply releases from Lake Darling. Losses from the Eaton Irrigation District are implicit within the HH1 dataset and a loss rate should be added during model runs that use other datasets.

ResSim Software Limitations. The USACE HEC has identified HEC-ResSim software issues with its "If Block" functionality. As a consequence, issues have been identified with the "If Block" based gate switch rules at Rafferty Reservoir and Grant Devine Lake. At times, ResSim erroneously ignores rules which are placed below the "If Blocks" in ResSim. This requires that the "If Blocks" be placed as the lowest priority rules. This can result in releases beyond what is operationally possible at low pool levels because of a higher priority minimum release rule. This was partially remediated by modifying, higher priority downstream release rules to make them dependent on model variables, rather than state variables. An additional software driven model limitation relates to how rate of change rules are modeled within ResSim. It appears that when rate of change rules are applied the reservoirs stop discharging a few days before reaching the drawdown target. This has been confirmed as a limitation by HEC and has negligible effect on the results.

7 Model Change Log

Improvements to the model have been ongoing throughout the study. Many of the improvements make release decision logic more robust and applicable over a wider variety of inflow scenarios. The description of the model and results presented in this document are representative of the model as of June 30, 2020. A list of improvements since the initial baseline model date of April 2019 are summarized in this section.

7.1 Improvements Made during or before Phase 3.5 Alternative Developments (October 2019)

- Estevan and Grant Devine Downstream Constraints
    - The Saskatchewan WSA provided updated maximum flow constraints at Estevan, Saskatchewan and just downstream of Grant Devine Lake.
- Downstream flow Constraints at Boundary Reservoir
    - After consulting with the ResSim program developers, it was determined that downstream rules applied to Boundary Reservoir were causing undesired behavior and overly-constraining the model. The downstream constraints were removed and did not have any significant impact to the model results.

7.2 Improvements Made During or before Phase 4 Alternative Developments (April 2020)

- Rate of Change Rules
    - Rate of increase and decrease rules were added to create more realistic releases and reduce the likelihood of oscillations in releases. A limitation of the rate of change rules is the reservoirs stop discharging a few days before achieving full drawdown. This software issue has little impact on the results.

- Zone Transition Rules
    - While developing the Phase 4 models, the modeling team noticed that ResSim would occasionally cut releases from Rafferty, Grant Devine, and Lake Darling to unrealistically low outflow rates, (e.g. <100 ft^3/s or 2.8 m^3/s), during extreme events like the 2011 flood, effectively negating the intended operations. The modeling team determined that this occurred only in events where it was possible for a reservoir's pool to rise above its Maximum Allowable Flood Level (MAFL)/ Top of Flood Control pool. There was no continuity between the rules defined within the MAFL zone and the subsequent "Top of Dam Zone." Because of the inconsistency in the rule sets across the zone boundary, the reservoir model has difficulty determining what flows to release at pool elevations near or at MAFL. To mitigate this issue, the modeling team added an IF statement to each reservoir's "Top of Dam" zone titled "Within 0.5 ft MAFL." Each IF statement states that if a reservoir's pool is within 0.15 m (0.5 ft) of its MAFL, then it must release 102% of inflow.
- Increase Compute Passes
    - During Phase 4 modeling, preliminary results showed subtle discrepancies between some of the simulations run that could not be explained by the differences between the alternatives being modeled. This was not a concern for most years within the simulations. However, there were a handful of years where more significant differences between results were apparent. The modeling team consulted with the developer of ResSim to troubleshoot the issue, and it was determined that these discrepancies could be remediated by increasing the number of computational passes ResSim applies before reporting simulation results. To address the issue, the minimum number of computational passes, or iterations, for each simulation was increased from three to six.

7.3 Improvements addressing Plan of Study Board Comments (June 2020)

- Further simplification at Boundary Reservoir
    - The minimum discharge rule at Boundary Reservoir was developed to force the reservoir to release when inflow was forecasted and the pool elevation was below FSL. This rule no longer was relevant because of the simplified modeling approach to Boundary Reservoir.
    - The "Above FSL" zone was removed at Boundary Reservoir. The zone was initially created to prevent the reservoir from rising than .3048 m (1 ft) above FSL. This is no longer necessary because the downstream constraints were removed from Boundary Reservoir.
- Natural Flow Calculation at Sherwood
    - The natural flow calculation at Sherwood originally used the unregulated, routed flow as calculated by ResSim. Negative flows cannot be routed and are converted

to zero before routing by ResSim which resulted in consistent over-estimation of the natural flow using this method. The model was improved by using the cumulative total of all local inflows above Sherwood in its estimated natural flow calculation. This method was checked with some Phase 5 alternatives to make sure it will work as expected with the apportionment shift alternatives; however, it was not incorporated into Phase 5.

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