APPENDIX A-2: IMPACT OF NEGATIVE FLOWS ON ALTERNATIVE EVALUATION

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To: International Souris River Study Board
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Subject: Negative Inflow and Local Flow Impacts to the HH6 HEC-ResSim Model

Negative Input Flow Values and HEC-ResSim

Input flow time series information is required at all the upstream most junction elements in the ResSim model in order to perform a simulation. Additionally, local flow information is added at junctions and elements throughout the model to represent the flow contributions from intervening drainage areas in the watershed. For reservoirs, inflows are often developed using a reverse routing computation procedure to estimate the inflow based on observed changes in pool elevation (changes in volume) and observed outflows. For model elements which receive local flows, local flows are often estimated using the holdout hydrograph computation procedure. The holdout hydrograph calculation 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. 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 local flow computations rely on a coarse mass balance approach and thus the resulting flow record will include any errors in observed data and the cumulative effect of any losses or gains that were not explicitly accounted for in the calculation. Negative values are also artifacts from the somewhat coarse accuracy of hydrologic routing methods. When the cumulative impact of net losses not directly accounted for is greater than the amount of runoff which reaches the reservoir or an element in the model this results in a negative computed flow. The negative flows need to be carried forward and applied because they satisfy conservation of mass; however, there are cases where they cannot be handled correctly by the ResSim model and are ignored. This results in a violation of the conservation of mass within the ResSim model network.

Negative inflow to reservoir elements in this model are not an issue because the conservation of mass is maintained when flows are routed through the reservoir even if the inflow records contain negative values. The reservoir element has enough volume to compensate for negative inflows to the reservoir. Conservation of mass can be an issue in the reservoir network for routing reaches which use any routing method other than null routing and for the unregulated records computed by ResSim during a simulation. Negative flows which are routed through non-null routing reaches are set to zero during the routing operation carried out by ResSim. 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 than it would have if the negative flow values were maintained.

The amount of negative flow volume zeroed out of the reservoir network depends on the magnitude of negative flows in the input flow records and the magnitude of flow being routed through the reservoir system. Local flow records which are added to the system are typically added at network junction elements. Before the local flow is routed downstream, it is added to the flow from the upstream routing reach entering the same junction to compute the total flow at the junction. When the flow from the upstream routing reach for a specified time step is greater than the negative flows from the local flow record for that same time step, the net result is a positive flow value at the junction. Mass is maintained under these conditions. When the magnitude of the negative local flow for a time step is greater than the positive flow magnitude from the upstream reach for that same time step, the result is a negative flow for that time step at the junction. When the negative flows computed for the junction are routed through a non-null routing reach below the junction, the negatives are zeroed out and negative volume is not accounted for in the system. The model overestimates volume in these cases.

An example of how negative flows are zeroed out is illustrated in Table 1 and Figure 1 below. Flows at the inlet of the Glen Ewen to Sherwood routing reach (Column 2, Table 1) are routed to the Sherwood junction in the model and combined with the local flow inputs for Sherwood (column 3, Table 1). The routed flows upstream of the Sherwood junction (column 2, Table 1) are combined with the local flows at Sherwood (column 3, Table 1) to determine the total flow at the Sherwood junction (column 4, Table 1). 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 1. 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 1) and negative flow volume is lost from the system.

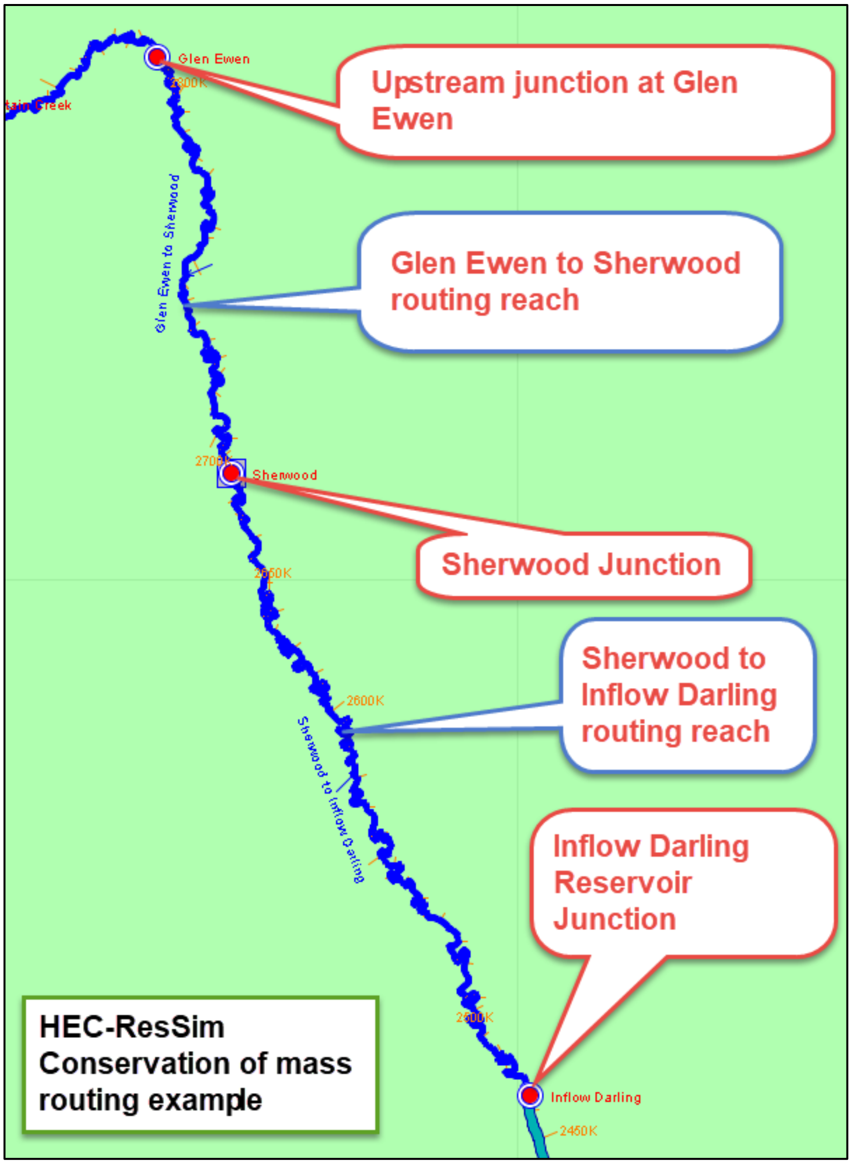

Figure 1 Negative flow routing example

Table 1 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	Local flows computed for the Sherwood junction	Total flow at the Sherwood junction from the upstream routing reach and local flow inputs (4) = (2) + (3)	Flow routed through the routing reach downstream of Sherwood
16 Apr 13, 24:00	32.95	-18.94	14.01	3.36
17 Apr 13, 24:00	42.95	-9.09	33.86	12.74
18 Apr 13, 24:00	41.77	-17.27	24.51	28.85
19 Apr 13, 24:00	42.16	-91.34	-49.18	21.68
20 Apr 13, 24:00	63.94	-196.51	-132.57	0.00
21 Apr 13, 24:00	106.01	-211.37	-105.36	0.00
22 Apr 13, 24:00	143.59	-180.92	-37.34	0.00
23 Apr 13, 24:00	157.77	-128.44	29.33	0.00
24 Apr 13, 24:00	149.25	-66.52	82.74	15.45

Understanding how mass is not conserved in the model is important for interpreting results from the model. A sensitivity analysis was performed for the Sherwood and Minot junction elements 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. The sensitivity analysis events selected were 1976 (a high flow event), 1978 (an average magnitude event), 2003 (a low flow event), and 2011 (a high flow event). A range of event magnitudes were selected to show the effect that flow in the system has on the amount of volume lost.

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 which apply non-null routing between the Canadian Reservoirs and Minot. Note that negative flows are accounted for when the model applies null or direct routing. Consequently, the total flow records at junctions upstream of Sherwood and Minot which are directly above non-null routing reaches were selected to approximate the volume of negative flow lost from the system as it was routed through the non-null routing reach. The junctions selected to approximate the total unaccounted for negative flow volume by the time it reaches Sherwood and Minot are outlined below.

- Negative Flow Records Upstream of Sherwood accounted for in sensitivity analysis:
    - Estevan junction
    - Roche Percee junction
    - Oxbow junction
    - Glen Ewen junction

- Negative flow records upstream of Minot accounted for in sensitivity analysis:
    - Estevan junction
    - Roche Percee junction
    - Oxbow junction
    - Glen Ewen junction
    - Sherwood junction
    - Foxholm Des Lacs junction
    - Des Lacs Confluence junction

The remaining, total negative flow volume not offset by the upstream flow contribution at the upstream node of each non-null routing reach is assumed to be equivalent to be the unaccounted for, negative flow volume. These values are summed up for all the junctions listed above. Note that this approximation of the negative flow volume using null routing ignores lag and attenuation that occurs as a result of routing from upstream to downstream.

The sensitivity analysis was performed for Sherwood and Minot using 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. Only the negative flows were summed up for the junctions noted in the bullet point lists above and the total volume lost for the calendar sensitivity period in 1976, 1978, 2003, and 2011 was determined.

The results for the regulated and unregulated sensitivity analysis at Sherwood are shown in Table 2 and Table 3 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.

In the regulated case, the estimated percent error in volume is extremely low for the high flow events and is not substantial for the average and low flow events. This shows that during a high flow event, the negative flow volume is maintained in the system. During low and average flow events, a small amount of volume is lost from the system which is unlikely to have a significant impact on results for the regulated case.

Table 2 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)[1]	[4] Total Simulated Volume Available in ResSim Model at Sherwood (ac-ft)	[5] Estimated Volume at Sherwood Had Negative Flow Volumes Been Maintained (Not Zeroed Out) In ResSim Model (ac-ft)	[6] Estimated Percent Error in Volume (%)
1976	High flow year	-388.5	596,592.7	596,204.2	0.07
1978	Average year	-1,528.7	50,358.9	48,830.2	3.13
2003	Low flow year	-1.7	36,591.9	36,590.2	0.00
2011	High flow year	0.0	1,706,245.0	1,706,245.0	0.00

[1]Estimate of zeroed out negative inflow volume does not account for attenuation and lag

For the unregulated case, the amount of volume lost during the high and average flow years is not significant and would not impact the results of the model in a significant way. During the low flow event, the missing volume represents a 15% difference in the overall volume of the model at Sherwood. This indicates that model results are not significantly impacted when there is an average or high flow event simulated, but that the apportionment calculation could be impacted during low flow events. The apportionment may overestimate how much water would have reached Sherwood during the unregulated condition, especially during low flow events.

Table 3 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)[1]	[4] Total Simulated Volume Available in ResSim Model at Sherwood (ac-ft)	[5] Estimated Volume at Sherwood Had Negative Flow Volumes Been Maintained (Not Zeroed Out) In ResSim Model (ac-ft)	[6] Estimated Percent Error in Volume (%)
1976	High flow year	-8,352.0	647,360.6	639,008.6	1.31
1978	Average flow year	-2,018.8	120,402.6	118,383.9	1.71
2003	Low flow year	-12,268.3	92,790.7	80,522.4	15.24
2011	High flow year	-9,368.9	1,740,582.5	1,731,213.6	0.54

[1]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 4 and Table 5 below. In each case and in each table, 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.

In 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 larger than either of the high flow scenarios or the low flow scenario, but overall the model still closely estimates the volume in the system. Collectively, the results from this sensitivity test show that omitting negative volume from the system as a result of the routing reaches zeroing out negative values has little impact for the regulated case. The regulated case typically has enough volume to closely preserve conservation of mass even though some negative volume in the system is not accounted for.

Table 4 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)[1]**	**[4] Total Simulated Volume Available in ResSim Model at Minot (ac-ft)**	**[5] Estimated Volume at Minot Had Negative Flow Volumes Been Maintained (Not Zeroed Out) In ResSim Model (ac-ft)**	**[6] Estimated Percent Error in Volume (%)**
1976	High flow year	-867.3	731,068.4	730,201.1	0.12
1978	Average year	-3,350.2	38,975.5	35,625.4	9.40
2003	Low flow year	-606.5	28,534.9	27,928.4	2.17
2011	High flow year	0.0	2,021,162.5	2,021,162.5	0.00

[1]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. This indicates that model results are not impacted when there is an average or high flow event being simulated.

Table 5 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)[1]**	**[4] Total Simulated Volume Available in ResSim Model at Minot (ac-ft)**	**[5] Estimated Volume at Minot Had Negative Flow Volumes Been Maintained (Not Zeroed Out) In ResSim Model (ac-ft)**	**[6] Estimated Percent Error in Volume (%)**
1976	High flow year	-8,462.7	819,954.6	811,491.9	1.04
1978	Average flow year	-2,201.8	166,763.2	164,561.5	1.34
2003	Low flow year	-12,318.4	138,710.8	126,392.5	9.75
2011	High flow year	-9,368.9	2,073,001.0	2,063,632.1	0.45

[1]Estimate of zeroed out negative inflow volume does not account for attenuation and lag

<u>Negative Flow Impact to Model Results</u>

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. This would directly affect how the model carries out the apportionment calculation because apportionment releases are reliant on the determination of the unregulated record at Sherwood. The effect on the apportionment estimate is that the modeled volumes will be higher than they should be because negative flow volume is not accounted for in the system. This is illustrated by comparing the official ISRB apportionment estimates to the values computed by ResSim for the 1998-2017 period of record in Figure 2. The period of record was selected to be consistent with current operating rules and reflects the period after Rafferty Reservoir was filled. As Figure 2 shows, the ResSim apportionment volume is on average 14% greater than the official ISRB estimate. This is likely because negative flow volume is zeroed out by the model which would reduce the ResSim simulated apportionment values if it were counted.

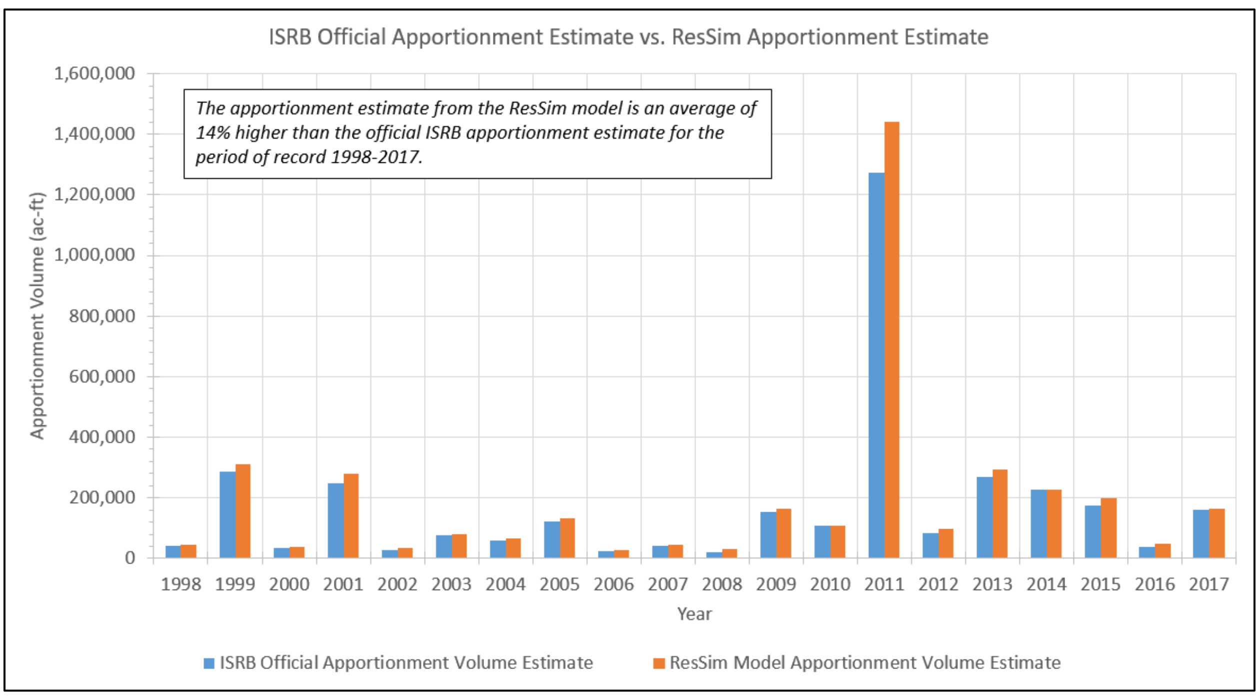

Figure 2 Comparison of official ISRB apportionment estimates to ResSim apportionment estimates for 1998-2017

Conclusion

The Souris River Plan of Study ResSim model will be used to compare alternatives of how to manage the many reservoirs in the Souris River basin. Since the model is primarily being used as a comparative tool, it is not anticipated that the lost negative flow volume will impact how alternatives are ranked because the impact of zeroing out the negative flow volumes should be consistent from alternative to alternative simulation.

References

USACE, 2013. *Regional and Reconstructed Hydrology of the Souris River.* Prepared by USACE St. Paul District.