Appendix F

WMOP Truckee River Hourly River Model Time Lag Routing

WMOP TRUCKEE RIVER HOURLY RIVER MODEL TIME LAG ROUTING

Truckee Basin Water Management Options Pilot, Memorandum of Agreement, Task 4: Model and Dataset Development

2021 Hydrologic Engineering Analysis Tasks, Task F.2: "TR Hourly River Model Development"

Abstract

As part of the hourly flood control model being developed, routing parameters for the reaches in the Truckee River basin were developed to simulate attenuation and lag time along the course of the river.

To: Truckee Basin Water Management Operations Pilot Technical Team

By: Kyler Olsen
Caleb Erkman, PE
Todd Vandegrift, PE

DATE: November 8, 2021

RE: Hourly Model Routing

On Behalf of TMWA

Precision Water Resource Engineering
720.261.7007 www.precisionwre.com
3401 County Road 16 ● Loveland, CO ● 80537

1 INTRODUCTION

The 2021 Hydrologic Engineering Analysis Tasks (HEAT) describes the work that will be completed as part of the larger Truckee Basin Water Management Options Pilot (WMOP) Study (United States Bureau of Reclamation, Lahontan Basin Area Office, 2021). The Model and Dataset Development and Technical Analyses tasks described in the Truckee Basin WMOP Memorandum of Agreement (MOA) are described in detail, renamed, reordered, and condensed in the HEAT. Task F.2 of the HEAT prescribes development of an hourly RiverWare model known as the "TR Hourly River Model". Per the MOA and HEAT, the Pyramid Lake Paiute Tribe (PLPT) has agreed to calculate local inflows while Truckee Meadows Water Authority has agreed to develop the TR Hourly River Model which includes composition of this report. In order to accurately calculate historical local inflows, reach routing parameters are needed. PWRE has been tasked with developing these routing parameters to facilitate further progress with local inflow calculation and for use in the TR Hourly River Model. A schematic of the TR Hourly River Model is shown in Figure 1.

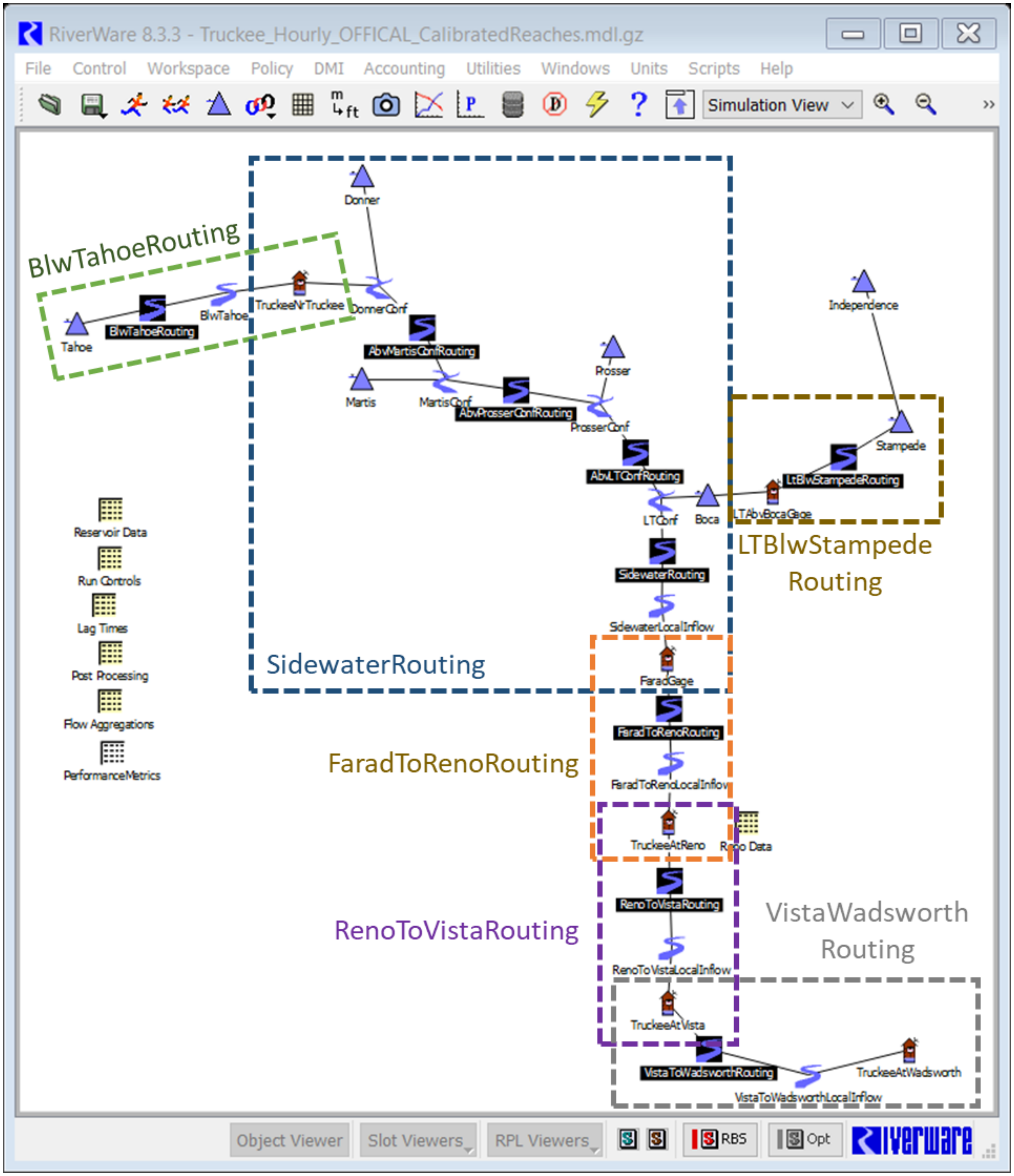


Figure 1: TR Hourly River Model Schematic with routing reach highlighted and calibration subbasins emphasized.

2 PURPOSE

The Truckee River Basin has multiple streamflow gage stations with appreciable record length. However, additional data are needed to more accurately simulate flood effects, as a large part of flood event inflows comes from ungaged inflows to the Truckee River between gages. In RiverWare, this ungaged inflow is called local inflow and is calculated from the difference in the routed upstream and downstream recorded flows. However, these calculations can be unclear if flow changes in the downstream gage are caused by changes in the upstream gage or changes in the local inflow. River reach routing is a way of approximating the flow changes at the downstream gage that result from flow changes upstream. With appropriate river routing, a more accurate calculation of local inflows can be achieved, and reservoirs releases can be re-simulated to evaluate changes to flood operational policy.

Reach routing aims to describe the inflow, outflow and storage aspects of a river section as river stage and velocities increase, decrease, or remain the same over time. Reach routing is developed under the principle of conservation of mass and allows for distribution of mass over different timesteps of a model (United States Division of Agriculture (USDA), Natural Resource Conservation Service (NRCS), 2014). Since this happens on a relatively short time scale (hours typically), reach routing is needed in models where lag time effects will be seen between model time steps, as in this study.

3 METHODOLOGY

3.1 ROUTING METHOD

Muskingum Routing is the routing method that has been used for previous models of this region therefore it was selected for use in this model (United States Army Corps of Engineers (USACE), Hydrologic Engineering Center (HEC), September 2020). Muskingum routing was used over Muskingum-Cunge methods due to data limitations at the time of analysis. When the routing method was selected, only ResSIM data was available, therefore routing method selection criteria was dependent on USACE acceptability while minimizing alterations necessary to the ResSIM model. Muskingum routing in RiverWare consists of three variables: K, a lag time in hours, X, a variable describing attenuation in the river, and the number of segments, which is used by RiverWare to further discretize the reach. Each reach segment of the reach is given the same designated K and X value, and the set of segments is then solved for each model timestep. Each of these values may be calibration parameters (USACE, HEC, 2021). Because documentation of prior calibration was not available and because of slight application differences between Hydrologic Engineering Center (HEC) products (including Hydrologic Modeling System (HMS) and Reservoir System Simulation (ResSim)) and RiverWare applications of Muskingum routing, calibration of routing parameters for the TR Hourly River Model was deemed necessary (Center for Advanced Decision Support for Water and Environmental Systems (CADSWES), 2021).

3.2 CALIBRATION AND VALIDATION OVERVIEW

Calibration is a process that fine tunes a model to make better predictions by using previously observed data and comparing to model outputs. Validation is a similar process, but instead of adjusting calibration parameters, the difference between modeled and observed data is used to evaluate how well the calibrated model represents events that were not used in the calibration process.

The following were required to carry out calibration and validation of routing reach parameters for this setting: a working RiverWare model of the watershed broken into segments with routing reach objects containing the Muskingum routing parameters, flow data for various events to run through the model, and a model performance metric. Additional information that aided the process was an initial estimate of calibration parameters, constraints on calibration parameters, automation of routing reach parameter selection and model runs, and visualization of results. The following paragraphs describe the data, inputs, and tools used to perform routing parameter calibration for this model.

4 CALIBRATION AND VALIDATION EVENT DATA

The purpose of this calibration process is to represent how changes in flow process down the basin. To meet this purpose the ideal calibration and validation events needed to be carefully selected to meet the following objectives:

1. Contain a variety of flows for each stream gage in question
2. Show changing flows for each stream gage in question
3. Be in periods where the downstream gage flow is predominately the summation of upstream gage flows (e.g. local inflows are small or at least relatively constant.)

Unfortunately, in the Truckee Basin reservoir releases seldom occur to optimally meet these objectives. For example, when river flows are high reservoir releases are reduced to conserve water and/or reduce flooding. Flood stage flows are generally produced by high local inflows downstream of the reservoirs making it difficult to distinguish when changes in flow are occurring from changes in upstream releases or changes in local inflows making it not feasible to use any events where floods occurred. Because of these challenges sub-optimum events had to be chosen. At times, the calibration metrics were poor because the best events that were identified contained significant and variable local inflows such as during the runoff. Tables in this section describe the dates which correspond with validation and calibration events. Three event date ranges are specified for each routing reach. The calibration event date range are shown in Table 1 and the validation event date ranges are shown in Table 3. The range of flows observable at each calibration event for all reaches are shown in

Table 2 while the validation event flow ranges are shown in Table 4. Upstream and downstream gages at relevant reaches are specified in Table 6 and illustrated in Figure 1.

Table 1: Calibration events used for each reach

Routing Reach Name	Calibration Event Dates		
	Event 1	**Event 2**	**Event 3**
BlwTahoeRouting	1/20-2/6/99	12/1-12/30/17	8/21-10/19/19
SidewaterRouting	3/16-5/24/19	6/23-8/31/17	7/11-9/29/19
LTBlwStampedeRouting	3/16-5/24/17	4/16-6/24/19	11/16-12/12/17
FaradtoRenoRouting	3/16-5/24/17	4/16-6/24/19	11/16-12/12/17
RenoToVistaRouting	3/16-5/24/17	4/16-6/24/19	11/16-12/12/17
VistaToWadsworthRouting	3/16-5/24/17	4/16-6/24/19	11/16-12/12/17

Table 2: Flow range present in each calibration event

Routing Reach Name	**Calibration Event Downstream Gage Flow Range (cfs)**		
	Event 1	**Event 2**	**Event 3**
BlwTahoeRouting	200-1,000	100-1,200	100-300
LTBlwStampedeRouting	400-1,500	300-1,300	100-700
SidewaterRouting	1,600-4,600	600-3,100	500-700
FaradtoRenoRouting	2,500-6,600	1,400-4,400	600-2,500
RenoToVistaRouting	1,700-5,100	400-3,400	600-3,000
VistaToWadsworthRouting	1,700-5,100	400-3,400	600-2,900

Table 3: Validation event used for each reach

Routing Reach Name	**Validation Event Dates**		
	Event 1	**Event 2**	**Event 3**
BlwTahoeRouting	3/25-4/16/18	6/25-7/4/06	9/5-9/25/20
SidewaterRouting	4/11-6/9/18	11/16-12/12/17	6/19-9/29/16
LTBlwStampedeRouting	2/1-2/28/17	4/11-6/9/18	4/3-7/3/06
FaradtoRenoRouting	2/1-2/28/17	4/11-6/9/18	4/3-7/3/06
RenoToVistaRouting	2/1-2/28/17	4/11-6/9/18	4/3-7/3/06
VistaToWadsworthRouting	2/1-2/28/17	4/11-6/9/18	4/3-7/3/06

Table 4: Flow range present for each validation event

Routing Reach Name	**Validation Event Downstream Gage Flow Range (cfs)**		
	Event 1	**Event 2**	**Event 3**
BlwTahoeRouting	900-2,600	300-1,900	100-400
LTBlwStampedeRouting	0-700	0-1,200	100-1,300
SidewaterRouting	500-4,900	800-2,400	100-600
FaradtoRenoRouting	500-10,200	300-4,900	800-4,100
RenoToVistaRouting	700-9,700	500-5,200	100-400
VistaToWadsworthRouting	600-11,000	400-5,000	100-300

4.1 DATA ACQUISITION

The HEAT requires three separate calibration and three additional validation events. Six events were selected throughout the model study period for each routing reach with the objective of finding a wide range of reservoir release and river flow values while minimizing variability of local inflows. This was done because high variations in local inflows mask the effects of reach routing, which undermines the calibration process. A high, mid-range, and low flow event were selected for both calibration and validation events to evaluate routing parameters over a larger range of flow conditions. Time periods containing the highest flows on record we excluded because they did not meet the criteria of stable or quantified local inflows. Table 1, Table 2, Table 3 and Table 4 summarize event dates and flow ranges used for the calibration and validation of each reach.

Once events were selected, raw streamflow data was gathered from USGS and TROA Information System (TIS) databases (U.S. Geological Survey (USGS), 2021), (Truckee River Operating Agreement (TROA), 2021). A summary of the source of data for each streamflow gage is summarized in Table 5. All data gathered was instantaneous flow data and one hour average flow was computed for use in the model to match the timestep. This data was then compiled and formatted in Excel workbooks for RiverWare Input Data Management Interface (DMI) reference. Any missing data points were estimated from available daily data and nearby gage stations. All corrections to dataset are summarized in Appendix A: Dataset Corrections.

Table 5. Data Source by Streamflow Gage

Streamflow Gage	Data Source:
Truckee at Tahoe	USGS
Truckee near Truckee	USGS
Donner Creek	USGS
Prosser Creek	USGS
Martis Creek	TIS
Independence Creek	USGS
Stampede Outflow	TIS
Little Truckee above Boca	USGS
Little Truckee below Boca	USGS
Truckee at Farad	USGS
Truckee at Reno	USGS
Truckee at Vista	USGS
Truckee at Wadsworth	USGS

4.2 CALIBRATION AND VALIDATION

A RiverWare model of the Truckee River watershed was developed with the basin broken down into several segments based on streamflow gage location. The schematic of the RiverWare model is shown in Figure 1. This model was derived from the model developed for the larger project and adapted for calibration and validation use. It should be noted that all river reaches between the Truckee Near Truckee and Truckee at Farad gages were calibrated as a single reach due to lack in intervening gages on the Truckee River. See the blue "SidewaterRouting" box in Figure 1. Hereafter, these will be referenced as the SidewaterRouting and discussed as a single reach for the purposes of this report. Reach routing parameters will remain separate for each sub-reach. See Table 6 for reach routing segments and gages used to calibrate each segment.

Table 6. RiverWare Hourly Model Routing Reaches

RiverWare Hourly Model Lag Reaches		
RiverWareRoutingReach	**Upstream Gage**	**Downstream Gage**
BlwTahoeRouting	Truckee River at Tahoe	Truckee Near Truckee
AbvMartisConfRouting	Truckee Near Truckee	n/a
AbvProsserConfRouting	n/a	n/a
AvbLTConfRouting	n/a	n/a
SidewaterRouting	n/a	Truckee at Farad
LtBlwStampedeRouting	Stampede Outflow	Little Truckee above Boca
FaradtoRenoRouting	Truckee at Farad	Truckee at Reno
RenoToVistaRouting	Truckee at Reno	Truckee at Vista
VistaToWadsworthRouting	Truckee at Vista	Truckee at Wadsworth

Upstream gage outflow was used as input to the reach routing objects in the model, and routing reach outflow was compared to the downstream gage outflow. Initial routing parameter estimates were taken from the USACE flood control model (Final Report for the Truckee River Watershed, 2020). Parameter constraints were developed by selecting reasonable physical properties of each reach, including reach length, flow velocity, etc. It is important to note that the reach divisions in the TR Hourly model are not the same as those within the TROA Accounting and Operations model which is divided into a few additional reaches. A summary of constraints and initial parameters can be seen in Table 8.

Nash-Sutcliffe Efficiency (NSE) was selected as the calibration metric for hydrologic model analysis. In this case, the NSE metric was normalized using the equation below to compute the Normalized Nash-Sutcliffe Efficiency (NNSE). The normalization reduces the range of the metric from between -∞ and 1 to 0 and 1 for improved use in an automated application. A RiverWare function calculated the NNSE for each of the 3 calibration events and then averaged the value for a final NNSE for the RiverWare MRM run.

$$NNSE = \frac{1}{2 - NSE}$$

The accepted ranges of the NSE specified by (Mariasi, et al., 2007) were adapted to the NNSE statistic in Table 7.

Table 7: Accepted NSE and NNSE ranges

	NSE	NNSE
Very Good	0.75 – 1.00	0.8 – 1.00
Good	0.65 - 0.75	0.74 - 0.80
Satisfactory	0.50 - 0.65	0.67 - 0.74
Unsatisfactory	< 0.50	0.50 - 0.67

Table 8. Calibration Initial Parameters and Ranges

Calibration Parameter Ranges												
RiverWare Routing Reach Name	**K Range**			**X Range**			**Segments**			**Distance (mi)**	**Reach Elev. Drop (ft)**	**Elev. Drop (ft/mile)**
	Min	**Init.**	**Max**	**Min**	**Init.**	**Max**	**Min**	**Init.**	**Max**			
BlwTahoeRouting	2.8	4.0	22.4	0	0.2	0.5	2	4	6	12.5	350	28.0
AbvMartisConfRouting	2.6	1.0	20.8	0	0.3	0.5	1	1	3	7.7	200	26.0
AbvProsserConfRouting	3.0	1.0	24.0	0	0.3	0.5	1	1	3	3.0	90	30.0
AvbLTConfRouting	2.6	1.0	20.8	0	0.3	0.5	1	1	3	2.5	65	26.0
SidewaterRouting	1.4	1.0	11.3	0	0.4	0.5	1	1	3	8.5	120	14.1
LtBlwStampedeRouting	3.6	1.0	28.8	0	0.4	0.5	1	1	3	9.3	335	36.0
FaradtoRenoRouting	2.4	1.0	18.9	0	0.4	0.5	1	1	3	22.0	520	23.6
RenoToVistaRouting	1.3	1.0	10.0	0	0.3	0.5	1	1	3	6.0	75	12.5
VistaToWadsworthRouting	1.0	1.0	8.0	0	0.3	0.5	1	1	3	30.0	300	10.0
	Max vel. (mph):		10	0 = max attenuation			Round to integer					
	Min vel. (mph):		1.25	0.5 = no attenuation			+/-	2	seg.			

To automate and improve the calibration process, a Multi-Objective Evolutionary Algorithm (MOEA) controller interface was built to run calibration of reach routing parameters over many runs on the objective of improved reach NNSE between downstream gage flow and routed flow. This MOEA controller utilized the Borg MOEA (Reed, 2013) as implemented within the Borg-RiverWare wrapper (Center for Advanced Decision Support for Water and Environmental Systems, 2021). The MOEA analysis is an evolutionary method that uses random mutation in an original population of input variables to vary the input parameters. The result of these inputs is then evaluated against a target, and the input values that arrive at a solution closer to the target are used to create a new "generation" of input values. The target in this case was to approximate a NNSE value of 1 (optimum), and the algorithm will focus the population toward this goal and select the optimum input parameters as the pareto point (optimum solution). This process allowed for efficient computation across a large array of parameter set analyses. Calibration parameters, constraints, and metrics were input to the Borg MOEA controller. Table 9 shows an example of the MOEA objectives and decision variables for the BlwTahoeRouting reach. The decision variables were updated for the calibration of each individual routing reach. The MOEA was allowed 500 evaluations and began with a population of 10 randomly selected input parameters.

Table 9. Example MOEA input information

Example MOEA Input Information			
Objective:	**Decision Variables**	**Min**	**Max**
BlwTahoeNNSE	BlwTahoe Muskingum K	2.8	22.4
	BlwTahoe Muskingum X	0	0.5
	BlwTahoe Number of Segments	2	6

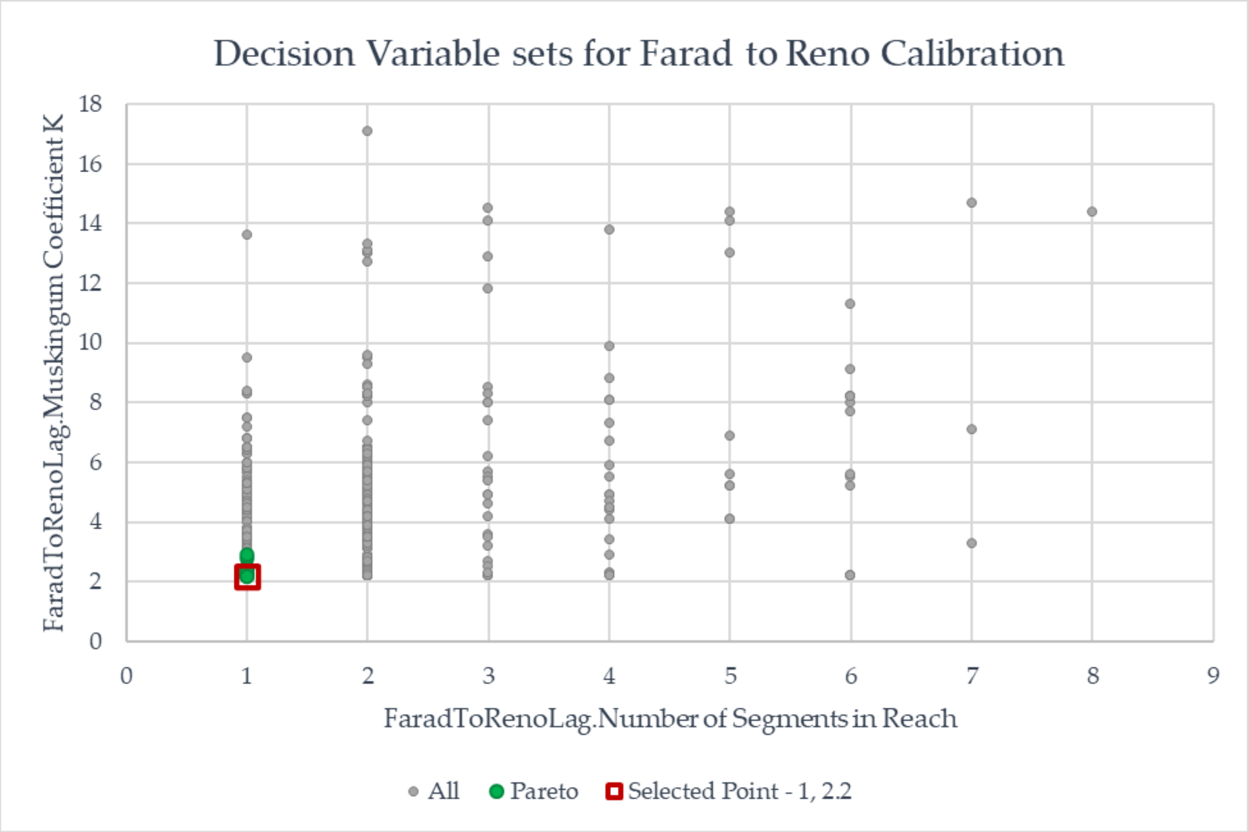


Figure 2. Example of Decision Variable sets analyzed by the Borg- RiverWare MOEA

Each reach was individually calibrated through the MOEA process and optimal routing parameters were recorded. These MOEA parameters were input to RiverWare and used during a Multiple Run Management (MRM) run of the three calibration events to export results for each event via Excel Output DMI. A spreadsheet tool was used for visual verification of MOEA calibration results and model routing performance (see example in Figure 2). Each set of parameters was then visually verified for errors. In some instances, the MOEA calibration process was not effective over multiple efforts due to complications with events, local inflows, and lack of additional gage station records. These reaches were manually calibrated through trial and error for a visual best fit. It should be noted that the differences of NNSE for the MOEA and manual calibration efforts were minimal because of high amounts of variability in the local inflows controlled the NNSE value. A summary of calibration methods for each reach is included below in Table 10.

Table 10. Hourly model Muskingum routing calibration methods

Hourly Model Calibration Methods	
RiverWare Routing Reach	**Notes:**
BlwTahoeRouting	**MOEA calibrated, fine-tuned manually (K=1.5 and X=.27 performs better on the higher flow events)**
AbvMartisConfRouting	**Manually calibrated simultaneously because only the Farad Gage is available for comparison. MOEA calibration pushed the routing reach outflow too far forward in time to match observed flow.**
AbvProsserConfRouting	
LtBlwStampedeRouting	
AbvLTConfRouting	
SidewaterRouting	
FaradtoRenoRouting	**MOEA calibrated**
RenoToVistaRouting	**MOEA calibrated**
VistaToWadsworthRouting	**MOEA calibrated, fine-tuned manually (adjusted lag time number of segments to fit to diurnals)**

Figure 3 shows the MOEA calibrated version of the Sidewater Calibration event. Note that the routed upstream flow is much smoother than the Farad Gage flow and that the peak that occurred on April 9th is much less pronounced in the with the Routed Upstream Flow. These reaches were manually adjusted to improve the calibration and replicate some of the important features of the hydrograph as shown in Figure 4. Since several routing parameter combinations resulted in the very similar NNSE values with results that were not visually satisfactory manual adjustment was necessary.

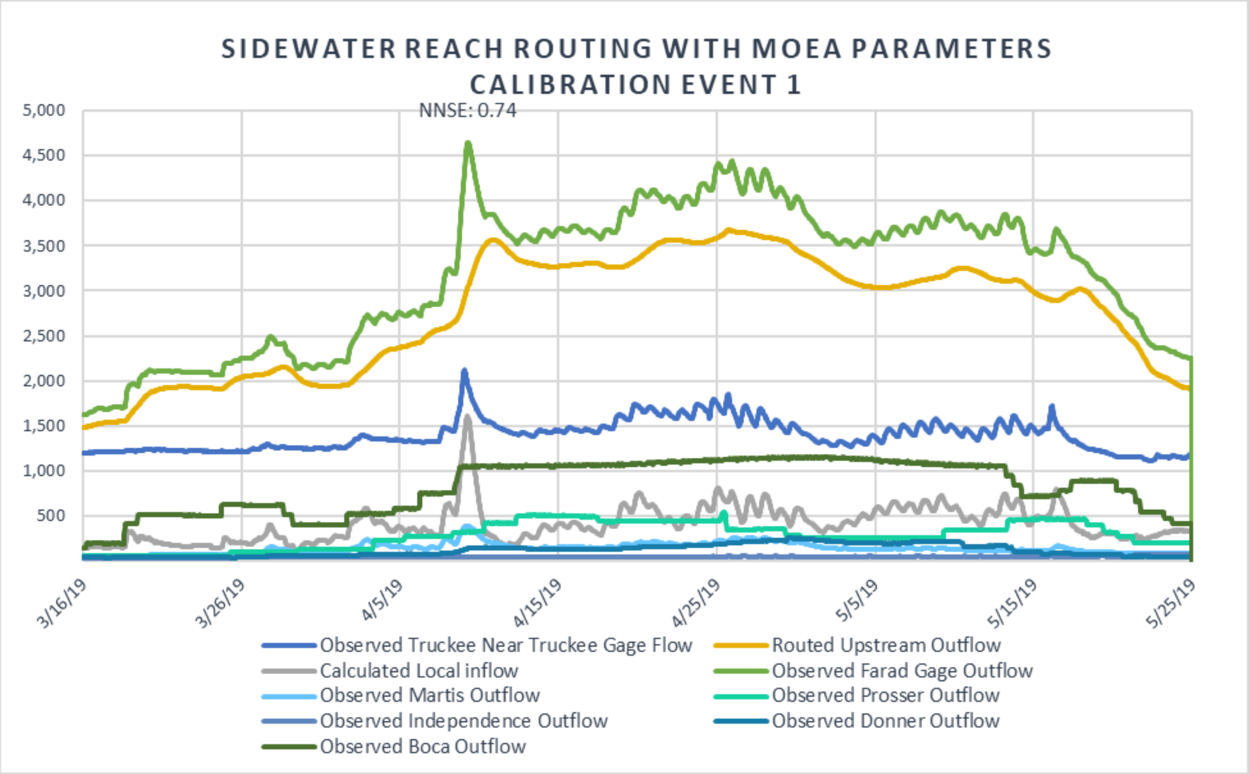


Figure 3: Sidewater Reach Routing from MOEA Calibration

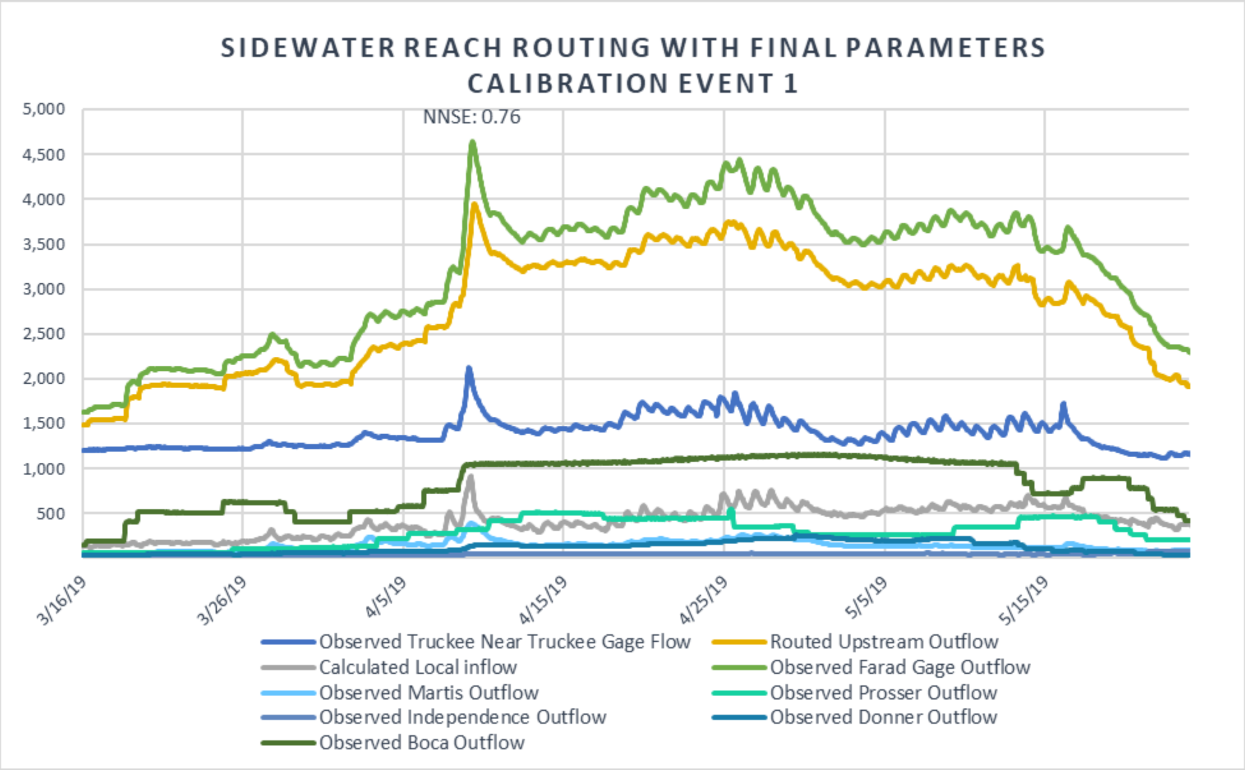


Figure 4: Sidewater Reach Routing Calibration after manual adjustment to have a better visual fit but lower NNSE

Satisfactory routing parameters were recorded and then each validation event was run with the TR Hourly River model to determine the validation event NNSE value for each reach, routing parameter set, and event combination. Individual plots of the calibration and validation events for each reach can be found in Appendix B: Routing Performance Plots. These NNSE values for each reach were recorded and averaged over the three events for a final NNSE for each reach as a metric of routing parameter accuracy and a tabulated in Table 13. MOEA analysis was unsatisfactory on the LtBlwStampedeRouting reach since this reach is short, and its corresponding gage is a small distance down the reach. Although the MOEA failure on this reach was surprising, it is explained by issues of data availability and short reach length. Final calibration parameters, performance metrics, and plots are discussed in the following section.

4.3 RESULTS AND DISCUSSION

Final reach routing parameters and performance metric values were recorded, and plots were generated to illustrate the effects of the routing. An example routing plot can be seen below in Figure 5 which shows the calibrated routing for the BlwTahoeRouting reach. A compilation of plots for each reach and event routed with the final parameters can be found in Appendix B. Final calibrated parameters are included in Appendix C: NNSE Calculations.

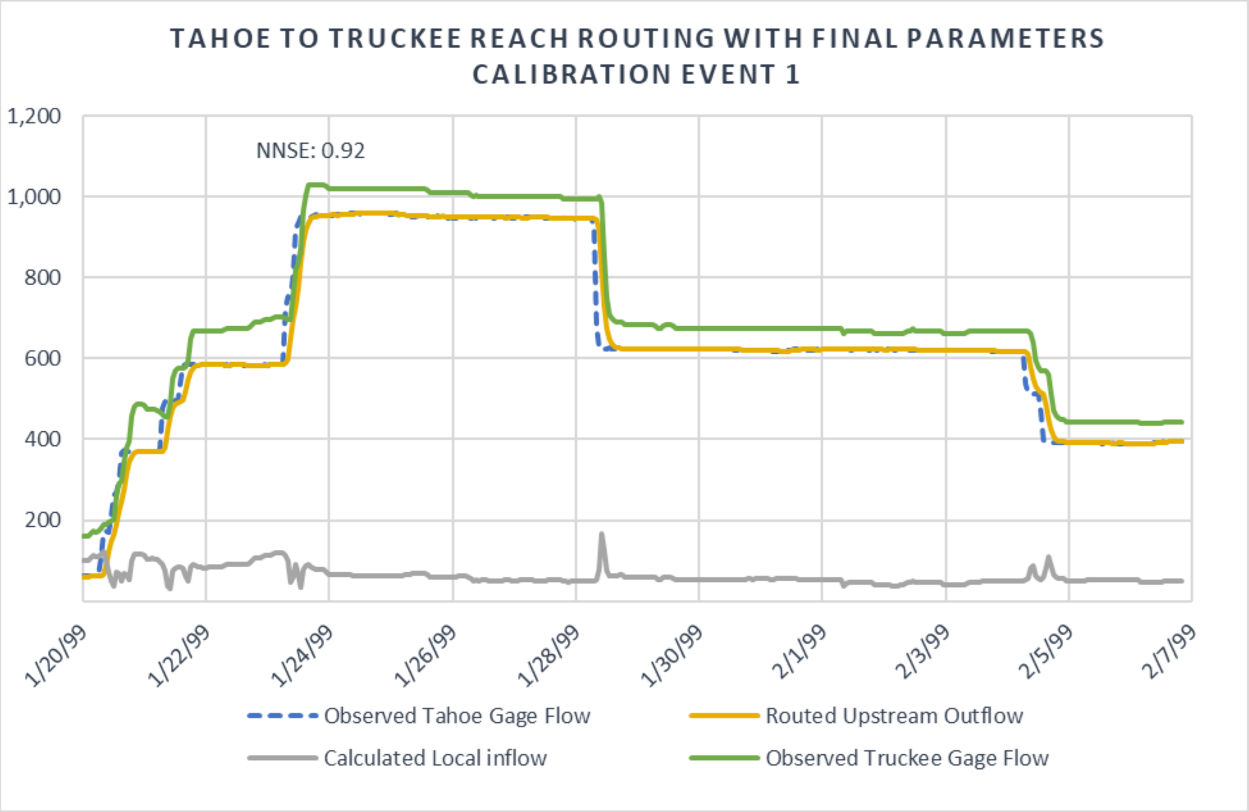


Figure 5: Example Routing Plot

The final calibrated Muskingum Routing parameters are summarized in Table 11. The BlwTahoe, FaradToReno, RenoToVista and VistaToWadsworth reaches all exceeded the “Very Good” threshold for the NNSE (Table 7) for both the average calibration and validation. The LTBlwStampede reach scored in the “Good” range for both the calibration and validation. The sidewater optimization group encompassing the AbvMartisConf, AbvProsserConf, AbvLTConf and Sidewater reaches scored in the Unsatisfactory range for the calibration events but scored in the “Very Good” range for the validation events. As shown in Appendix B: Sidewater Reach Routing the low score for the calibration events is predominately caused by Calibration Event 3 which scored only 0.18 while Calibration event 1 and 2 scored 0.76 and 0.79, respectively. Review of Calibration Event 3 for the Sidewater reach shows that the Routed Upstream Outflow matches the patter in the Observed Farad Gage rather well especially in the reduction in flow that occurred the first days in September 2019 and the spike in flows occurring around September 18th. Thus, the low NNSE score seems to be caused by the local inflow being a significant portion of the flow reaching the Farad Gage and not by poor routing parameters.

Table 11. Final Calibrated Hourly Model Muskingum Routing Parameters

Final RiverWare Hourly Model Muskingum Routing Parameters					
RiverWare Routing Reach	K	X	Num. of Segments	Calibration NNSE	Validation NNSE
BlwTahoeRouting	1.5	0.27	2	**0.96**	**0.88**
AbvMartisConfRouting	1.3	0.25	1	**0.58**	**0.82**
AbvProsserConfRouting	0.6	0.3	1		
AbvLTConfRouting	1.5	0.2	2		
SidewaterRouting	1.6	0.4	2		
LtBlwStampedeRouting	0.6	0.25	1	**0.74**	**0.76**
FaradtoRenoRouting	2.2	0.35	1	**0.93**	**0.91**
RenoToVistaRouting	1.5	0.07	1	**0.91**	**0.92**
VistaToWadsworthRouting	3.5	0.15	2	**0.96**	**0.98**

It was noted that some routing error was introduced due to the tendency of the MOEA to shift reach routing parameters toward slightly larger K and smaller X values. This occurred because the downstream flow typically includes local inflows which cause a vertical shift seen in the graphs. In order to more closely approximate the NNSE target value, the MOEA selects a slightly longer lag time and slightly higher attenuation to reduce the space between the lines which scores closer to the target value. The true cause of the gap is local inflows, not the reach routing. This slight error can be seen in the generated plots and required manual adjustment of parameters in some reaches, and manual calibration for other reaches.

Selection of calibration events also played a big part in arriving at accurate parameters. Some time periods have higher variability of local inflows which decrease the ability of the performance metric to capture the effect of different routing parameters on the model. In other words, high, variable, and unknown local inflows make it difficult to decipher whether changes in downstream flows are in fact due to changes in the upstream flow or are instead due to local inflows entering the river within the reach over which routing is being performed. Other time periods have spotty streamflow record data that would require higher amounts of data filling and estimation. Unfortunately, operations in the Truckee River seldom dictate large releases when flows local inflows are low and steady which limited the sets of potential calibration events in the very high flows.

Although these various challenges affect the final routing parameters, the overall effect is not significant enough to override the intrinsic estimations of the Muskingum routing parameters and other sources of error embedded in the dataset such as measurement precision, missing data, etc. This is illustrated by the average NNSE scored being rated at either Good or Very Good in the Validation events for all reaches.

5 CONCLUSION

In preparation to calculate local inflows for the time period of study, a routing method for the Truckee River was developed, calibrated, and validated. A RiverWare model was developed and divided into segments with routing reaches containing Muskingum routing parameters. These parameters were calibrated and validated using six hydrologic events that occurred during the period of study. An MOEA analysis was used to calibrate parameters, using normalized NNSE as a model performance metric and the resulting routing parameters are summarized in Table 11. MOEA results were visually reviewed and adjusted where limitations in the performance metric promoted model deviation from observed data. The calibrated routing parameters were then used to rout three independent validation events for each reach and the average NNSE for each reach was rated at either Good or Very Good (Table 7 and Table 11). An estimation of routing parameter performance over larger flow events gives confidence in utilizing routing parameters moving forward. Calibrated reach routing parameters should be used by PLPT to calculate hourly local inflows as necessary for the study so that the computed inflows will be consistent with the routing assumptions of the TR Hourly Model which will be used to evaluate proposed changes to flood operations policy.

6 REFERENCES

Center for Advanced Decision Support for Water and Environmental Systems (CADSWES). (2021, January 1). *RiverWare User's Guides*. Retrieved from Routing Parameters: https://www.riverware.org/HelpSystem/index.html#page/Objects/reachObject.24.20.html

Center for Advanced Decision Support for Water and Environmental Systems. (2021). Borg-RiverWare version 8.2 User Guide. Boulder, CO, USA.

(2020). *Final Report for the Truckee River Watershed.* U.S. Army Corps of Engineers, Corps Water Management System.

Mariasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model Evaluation Guidelines for Wystematic Quantification of Accuracy in Watershed Simulations. *2007 American Society of Agircultural and Biological Engineers, 50*(3). Retrieved from https://swat.tamu.edu/media/1312/moriasimodeleval.pdf

Reed, D. H. (2013). *BorgMOEA*. Retrieved from http://borgmoea.org/#main

Truckee River Operating Agreement (TROA). (2021). *TROA Information System*. Retrieved from https://www.troa.net/tis/

U.S. Geological Survey (USGS). (2021). *National Water Information System: Web Interface*. Retrieved from Historical Observations: https://waterdata.usgs.gov/nwis/sw

United States Army Corps of Engineers (USACE), Hydrologic Engineering Center (HEC). (September 2020). *Corps Water Management System (CWMS) Final Report for the Truckee River Watershed.*

United States Bureau of Reclamation, Lahontan Basin Area Office. (2021). 2021 Hydrologic Enginerring Analysis Tasks Report. Carson City, NV.

United States Division of Agriculture (USDA), Natural Resource Conservation Service (NRCS). (2014, April). National Engineering Handbook. *Chapter 17: Flood Routing*.

USACE, HEC. (2021, June 9). Hydrologic Modeling System HEC-HMS User's Manual.

7 APPENDIX A: DATASET CORRECTIONS

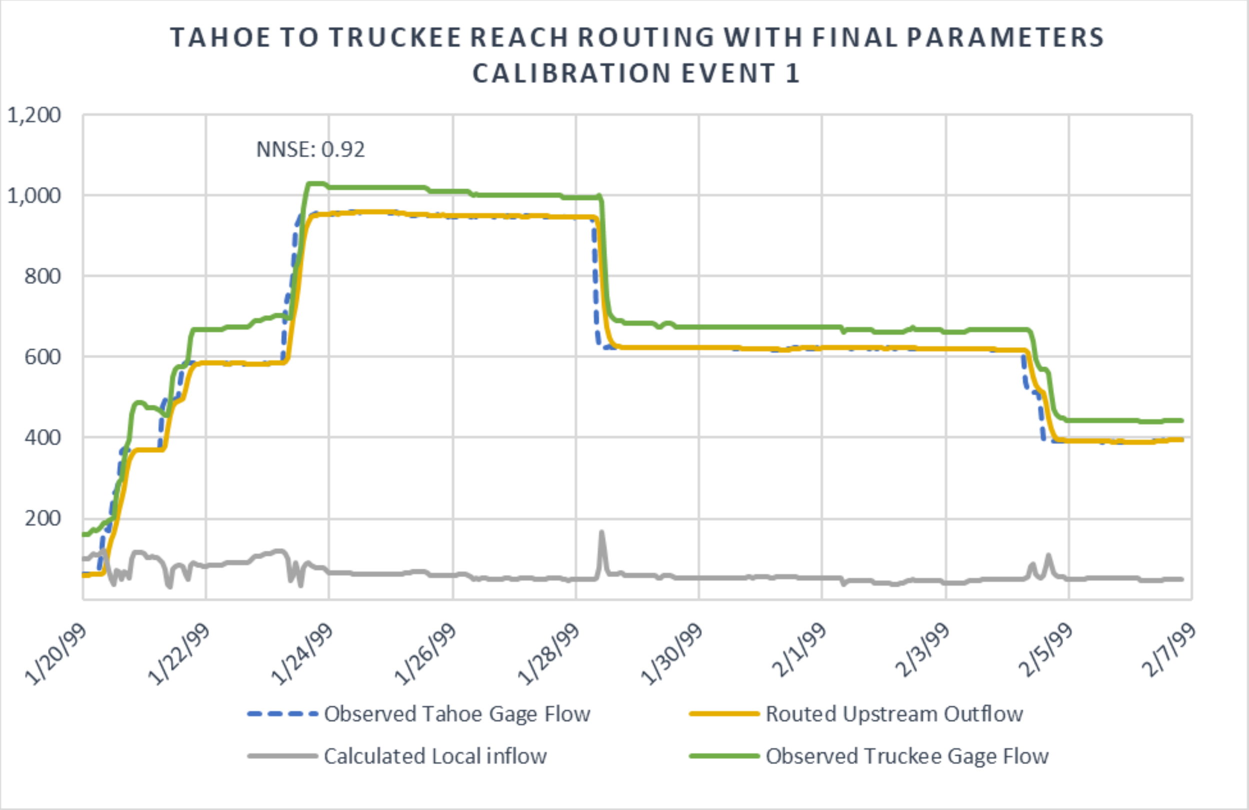
This table includes a summary of all corrections made to the flow data used in the calibration and validation analysis by gage station, date, and event. It also describes the fill method for estimating missing readings.

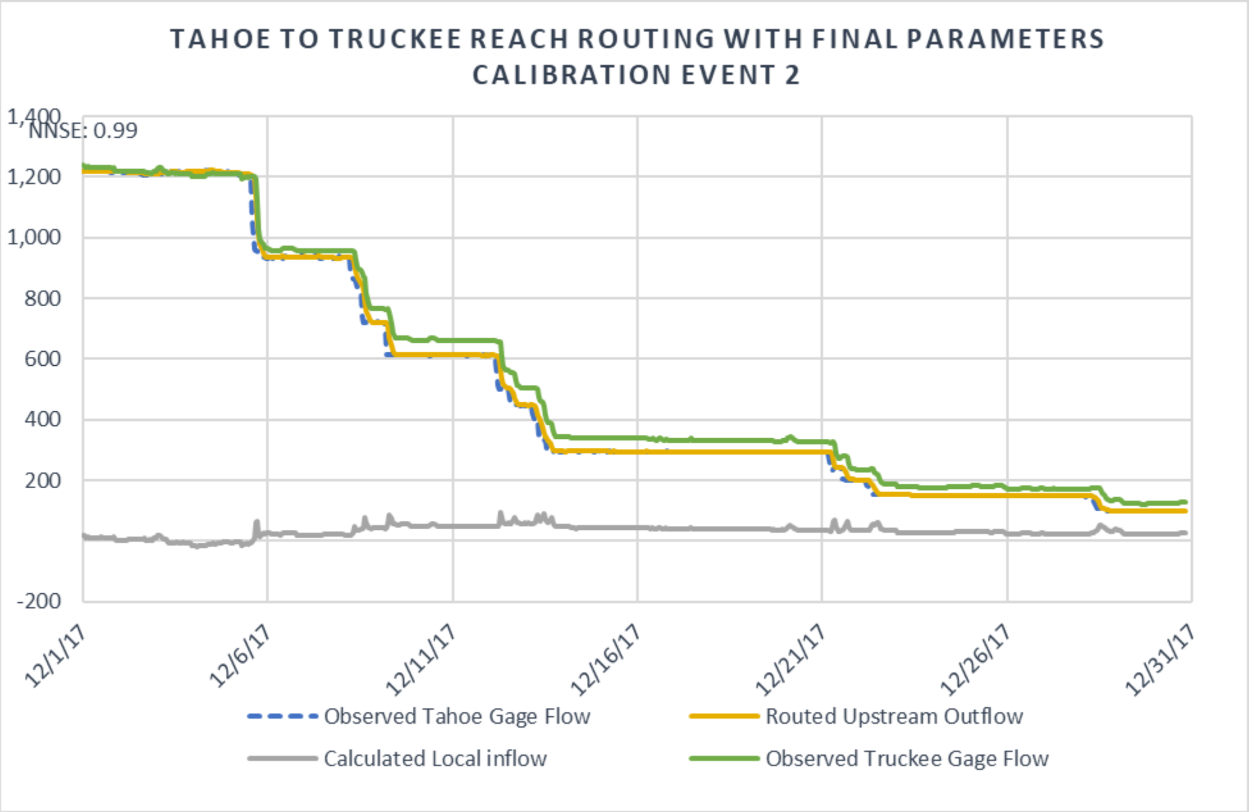
Event	Date:	Gage Station:	Fill Method:
Tahoe Val. 2	6/28/2006 0:00-23:00	Truckee at Tahoe	Estimated from documented release changes
Sidewater Cal. 2	6/28/2017 11:00	Stampede	Estimated from previous timestep
Sidewater Cal. 2	7/10/2017 12:00 - 7/14/2017 6:00	Martis	Estimated from daily data
Sidewater Cal. 2	7/14/2017 12:00 - 7/19/2017 12:00	Stampede	Estimated from daily data
Sidewater Cal. 2	7/19/2017 14:00	Prosser	Averaged from timesteps before and after
Sidewater Cal. 2	8/11/2017 10:00, 8/21/2017 22:00	Martis	Averaged from timesteps before and after
Sidewater Cal. 2	8/22/2017 12:00, 8/23/2017 6:00	Martis	Averaged from timesteps before and after
Sidewater Cal. 3	8/9/2019 11:00-13:00	Martis	Averaged from timesteps before and after
Sidewater Cal. 3	8/26/2019 9:00 - 9/5/2019 8:00	Stampede	Estimated from daily data
Sidewater Cal. 3	8/29/2019 13:00	Martis	Averaged from timesteps before and after
Sidewater Val. 1	5/23/2018 2:00	Martis	Averaged from timesteps before and after
Sidewater Val. 2	11/23/2017 11:00:00 - 11/27/2017 13:00	Martis	Estimated from daily data
Sidewater Val. 3	6/19/2016 0:00 - 7/3/2016 23:00	Martis	Estimated from daily data
Sidewater Val. 3	6/19/2016 0:00 - 7/2/2016 22:00	Stampede	Estimated from daily data
Sidewater Val. 3	7/26/2016 10:00, 8/15/2016 17:00	Martis	Averaged from timesteps before and after
Sidewater Val. 3	9/14/2016 14:00, 9/15/2016 13:00	Martis	Averaged from timesteps before and after
Sidewater Val. 3	9/25/2016 6:00	Martis	Averaged from timesteps before and after
Sidewater Val. 3	9/29/2016 23:00 - 9/30/2016 23:00	Prosser	Estimated from daily data
Farad Cal. 1	3/22/2017 12:00 - 14:00	Truckee at Farad	Averaged from timesteps before and after
Farad Val. 3	6/13/2006 23:00 - 6/15/2006 22:00	Truckee at Farad	Estimated from daily data

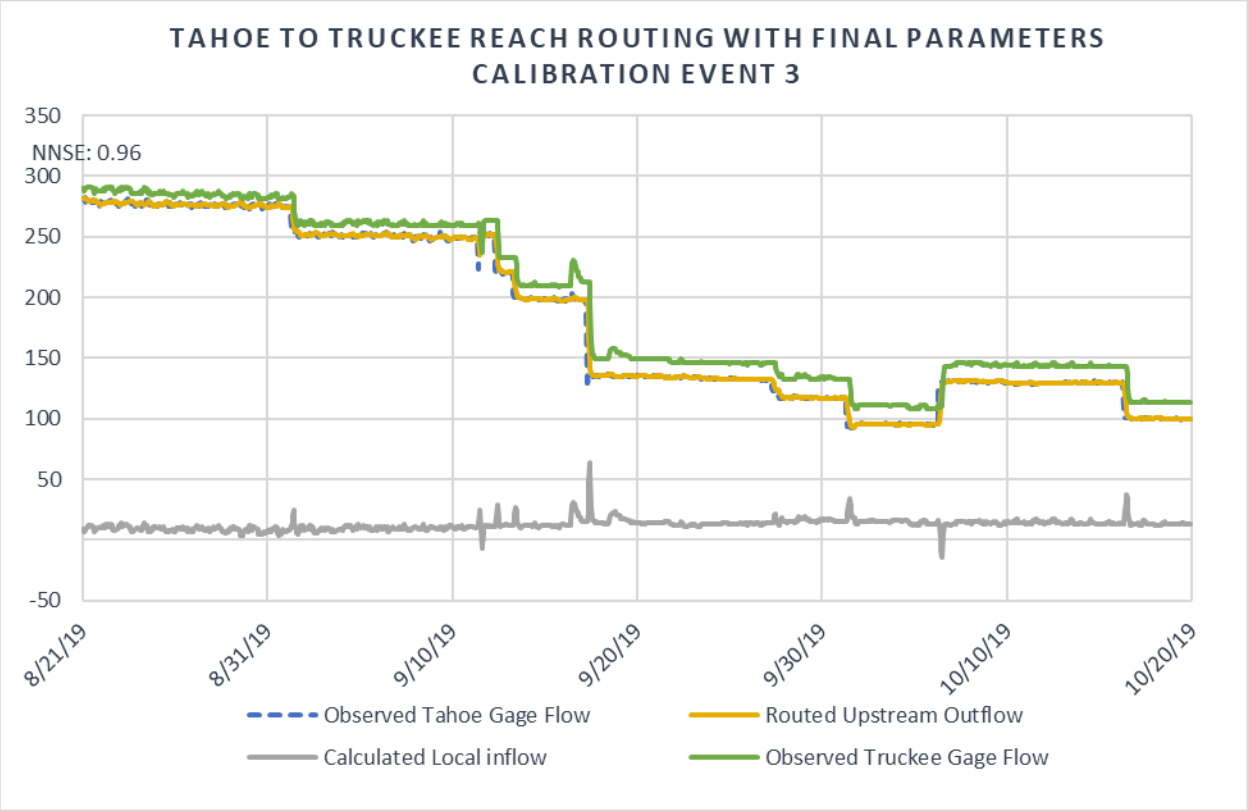
8 APPENDIX B: ROUTING PERFORMANCE PLOTS

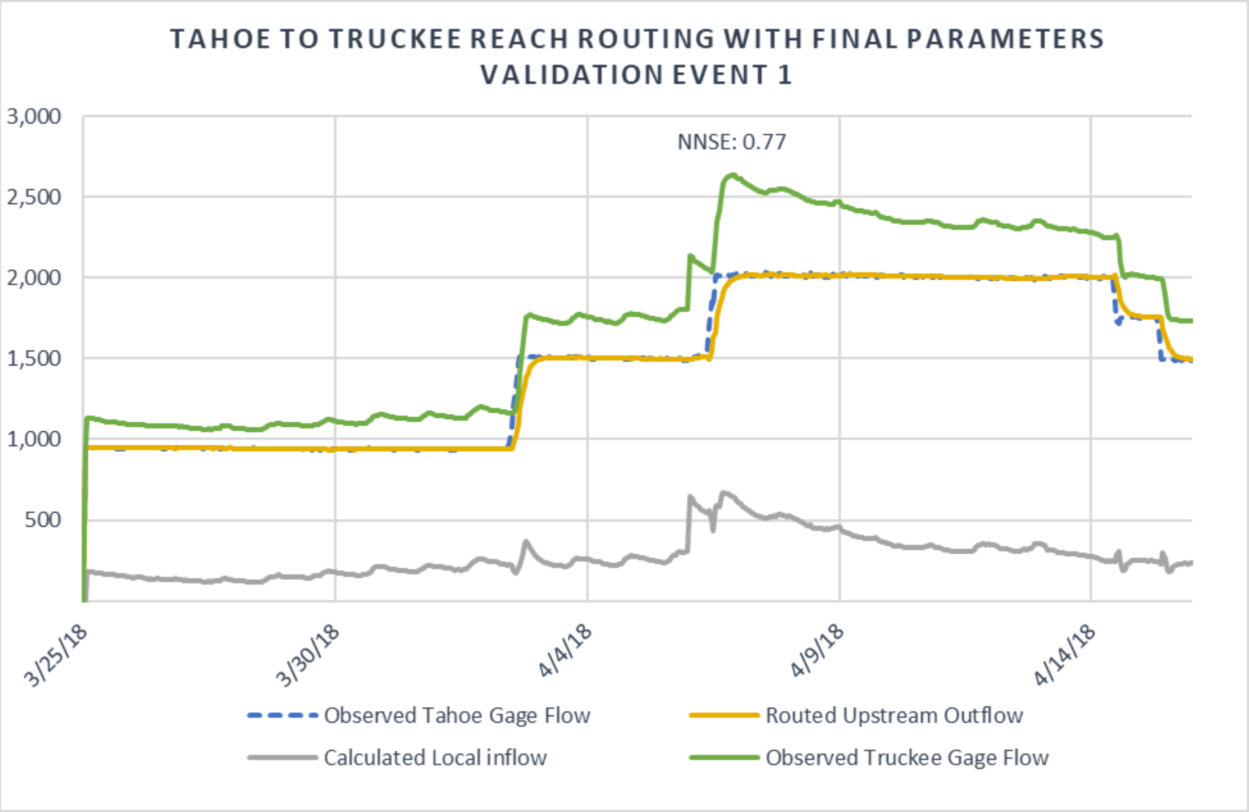
The following plots show the routing performance for each routing reach for all calibration and validation events. The blue line represents the observed upstream gage flow, the green line represents the observed downstream gage flow, the yellow line represents the routed flow using the final Muskingum routing parameters and the gray line shows the calculated local inflows. In the Sidewater plots, only the intermediate reservoir outflows are shown to reduce plot noise, although individual routing reaches between the outflows of each reservoir were included in the model.

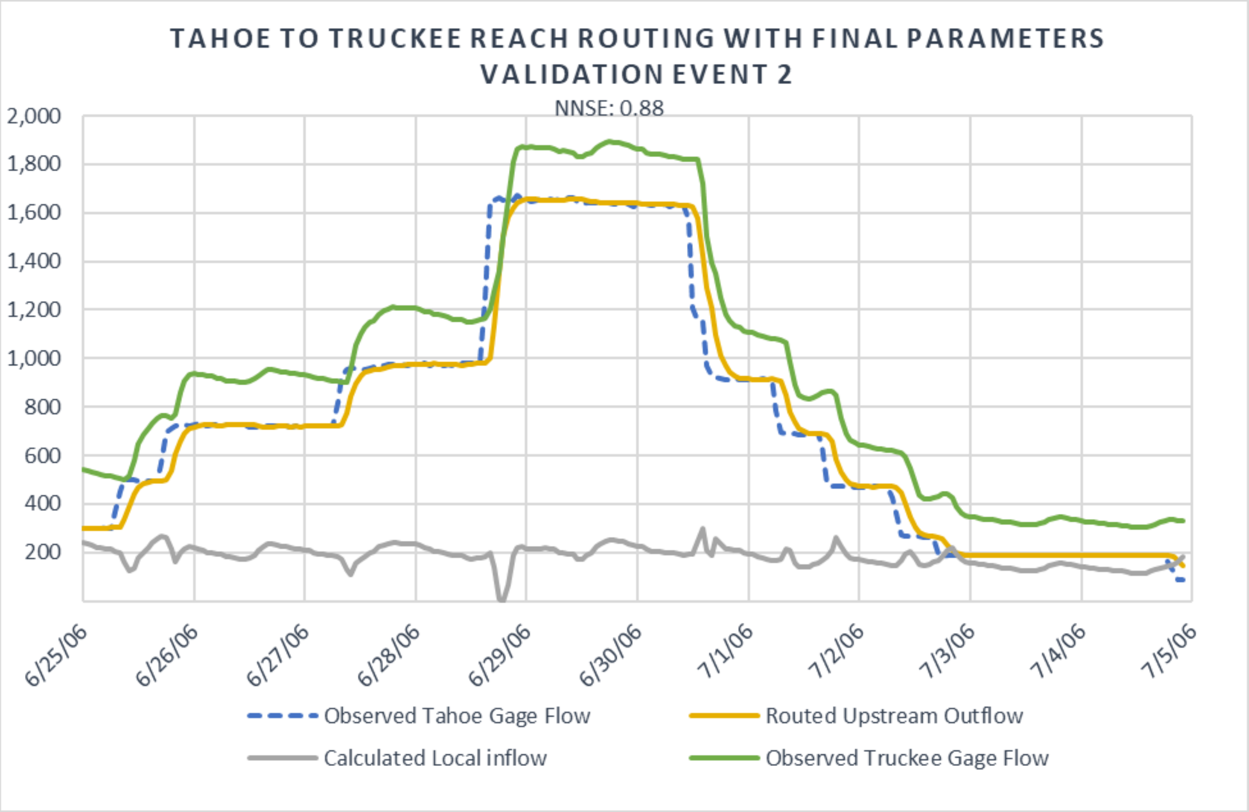
8.1 TAHOE TO TRUCKEE REACH ROUTING

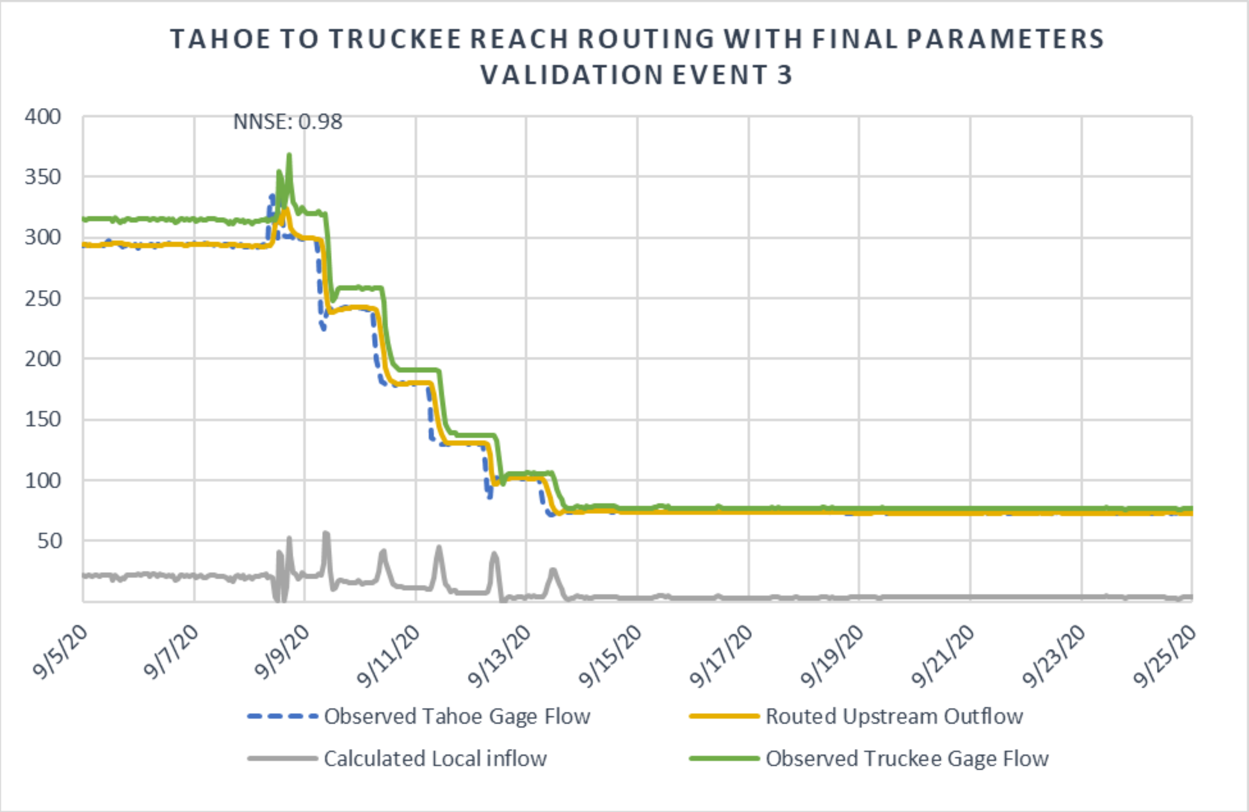



TAHOE TO TRUCKEE REACH ROUTING WITH FINAL PARAMETERS CALIBRATION EVENT 2

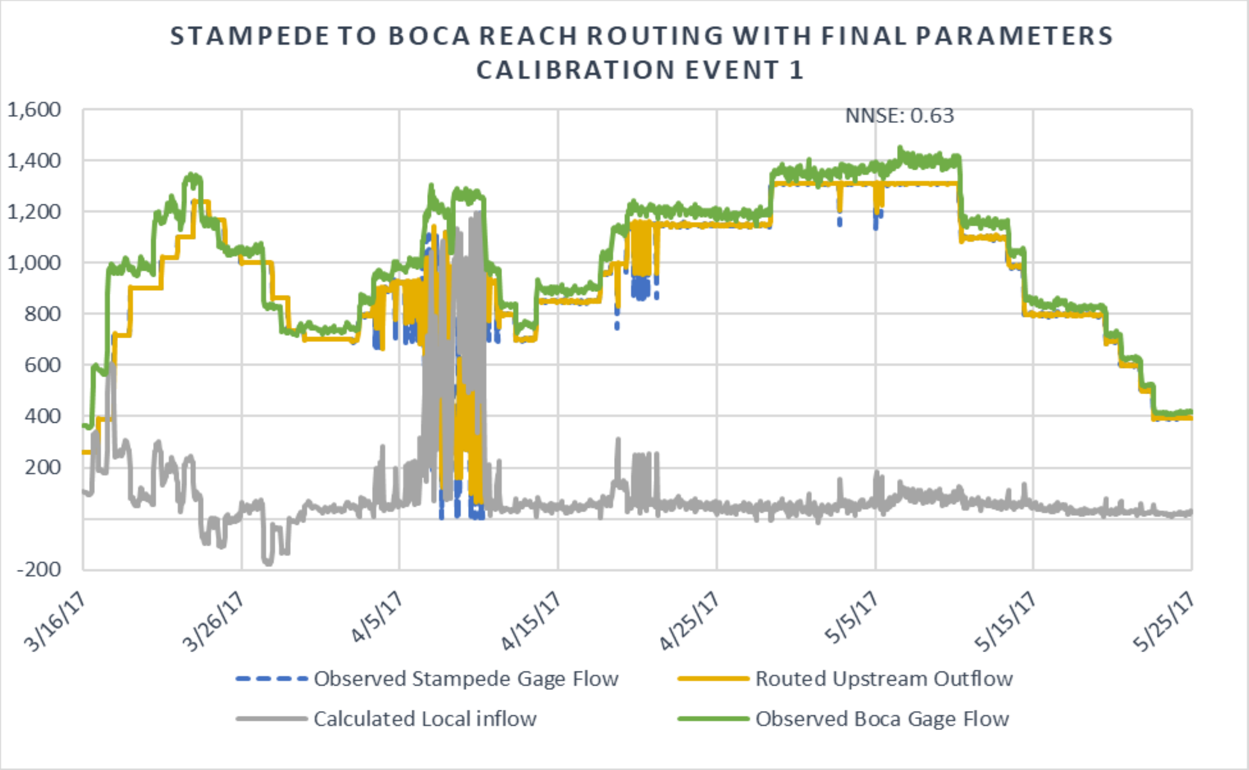

TAHOE TO TRUCKEE REACH ROUTING WITH FINAL PARAMETERS CALIBRATION EVENT 3

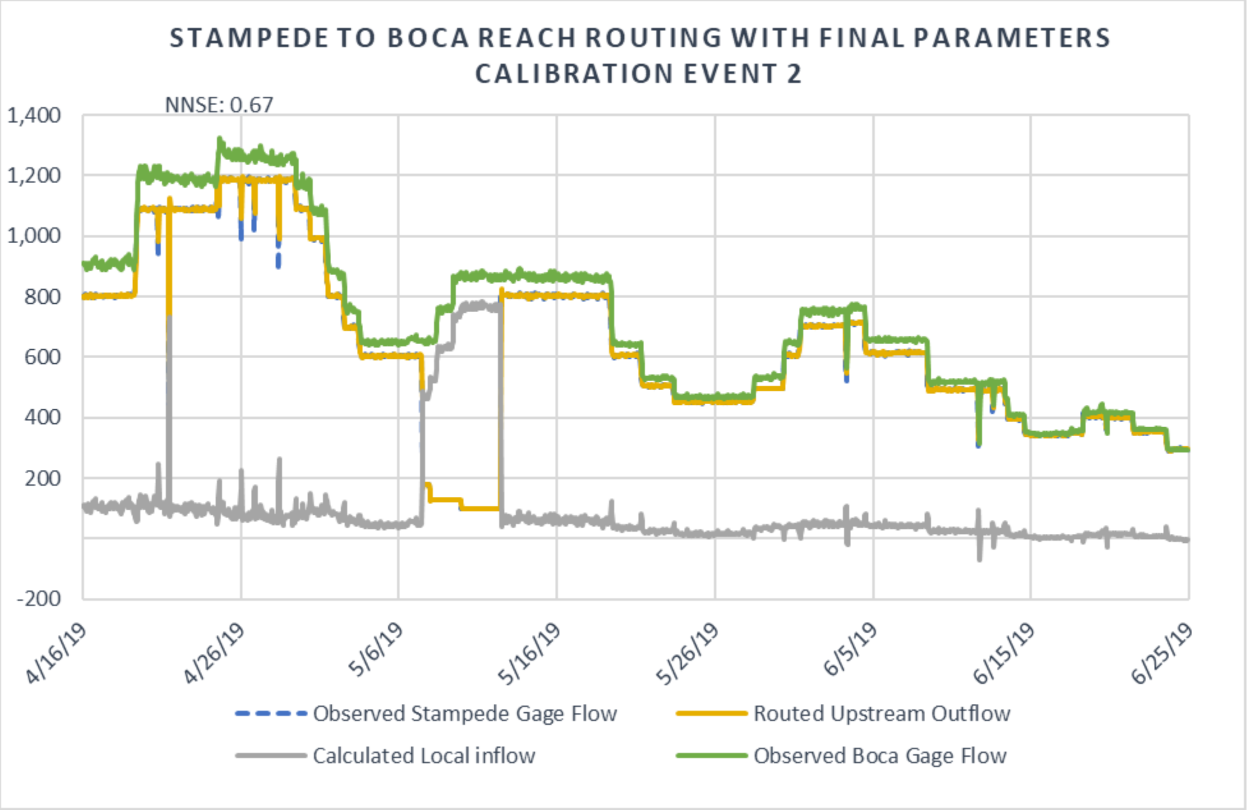

TAHOE TO TRUCKEE REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 1
NNSE: 0.77
3,000
2,500
2,000
1,500
1,000
500
3/25/18
3/30/18
4/4/18
4/9/18
4/14/18
Observed Tahoe Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Truckee Gage Flow

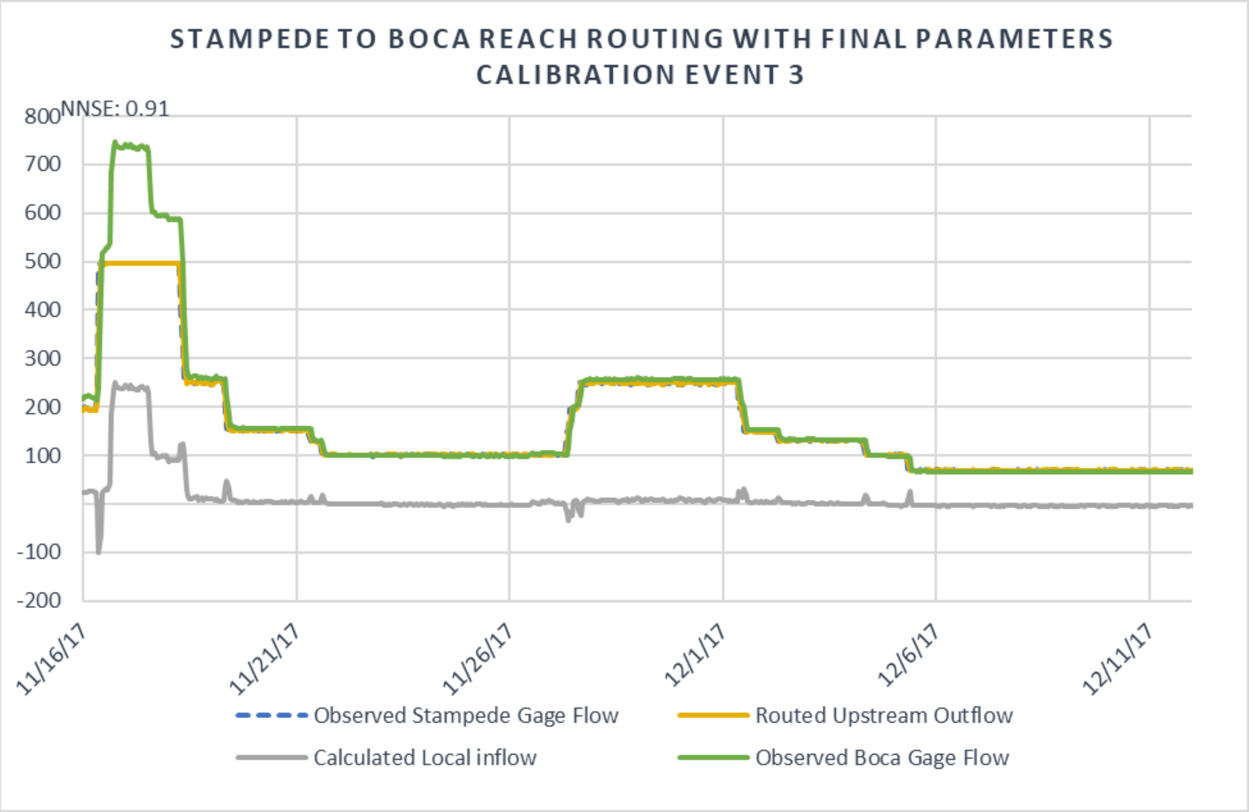

TAHOE TO TRUCKEE REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 2
NNSE: 0.88
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
6/25/06
6/26/06
6/27/06
6/28/06
6/29/06
6/30/06
7/1/06
7/2/06
7/3/06
7/4/06
7/5/06
Observed Tahoe Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Truckee Gage Flow

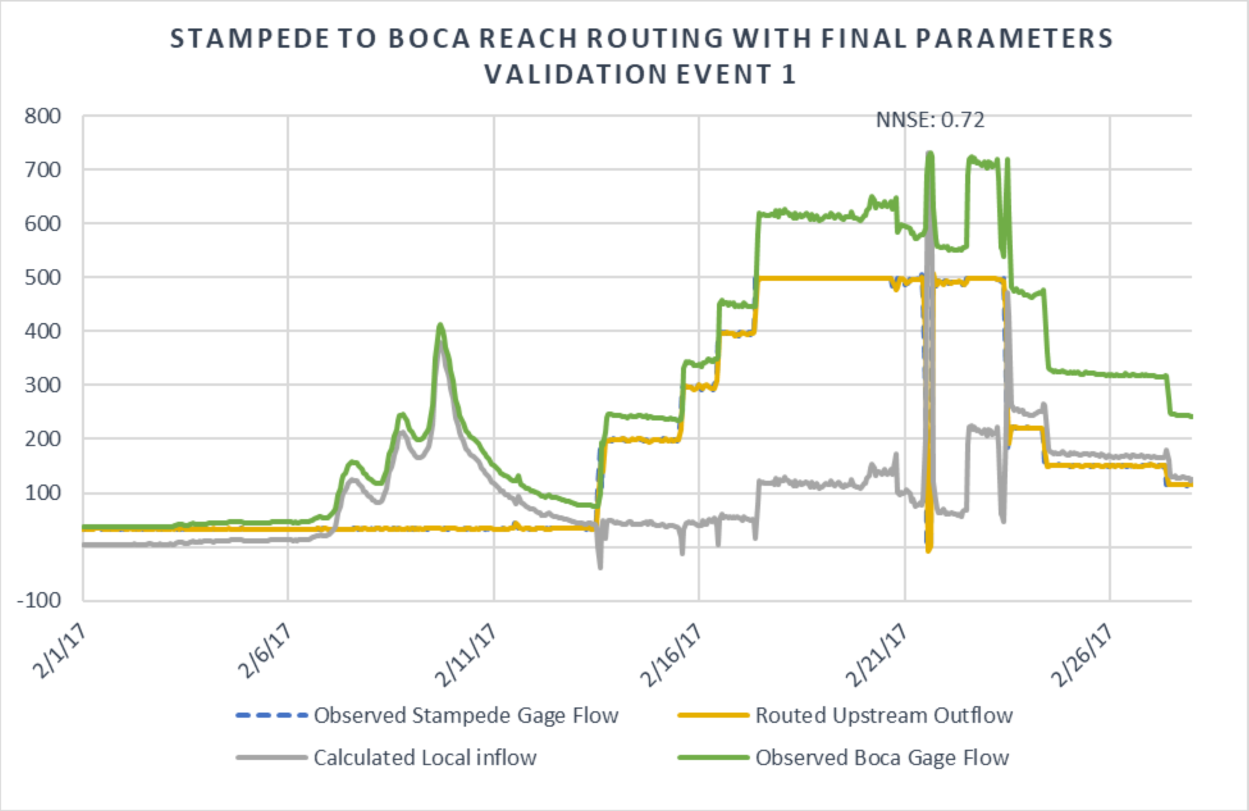

TAHOE TO TRUCKEE REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 3
NNSE: 0.98
400
350
300
250
200
150
100
50
9/5/20
9/7/20
9/9/20
9/11/20
9/13/20
9/15/20
9/17/20
9/19/20
9/21/20
9/23/20
9/25/20
Observed Tahoe Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Truckee Gage Flow

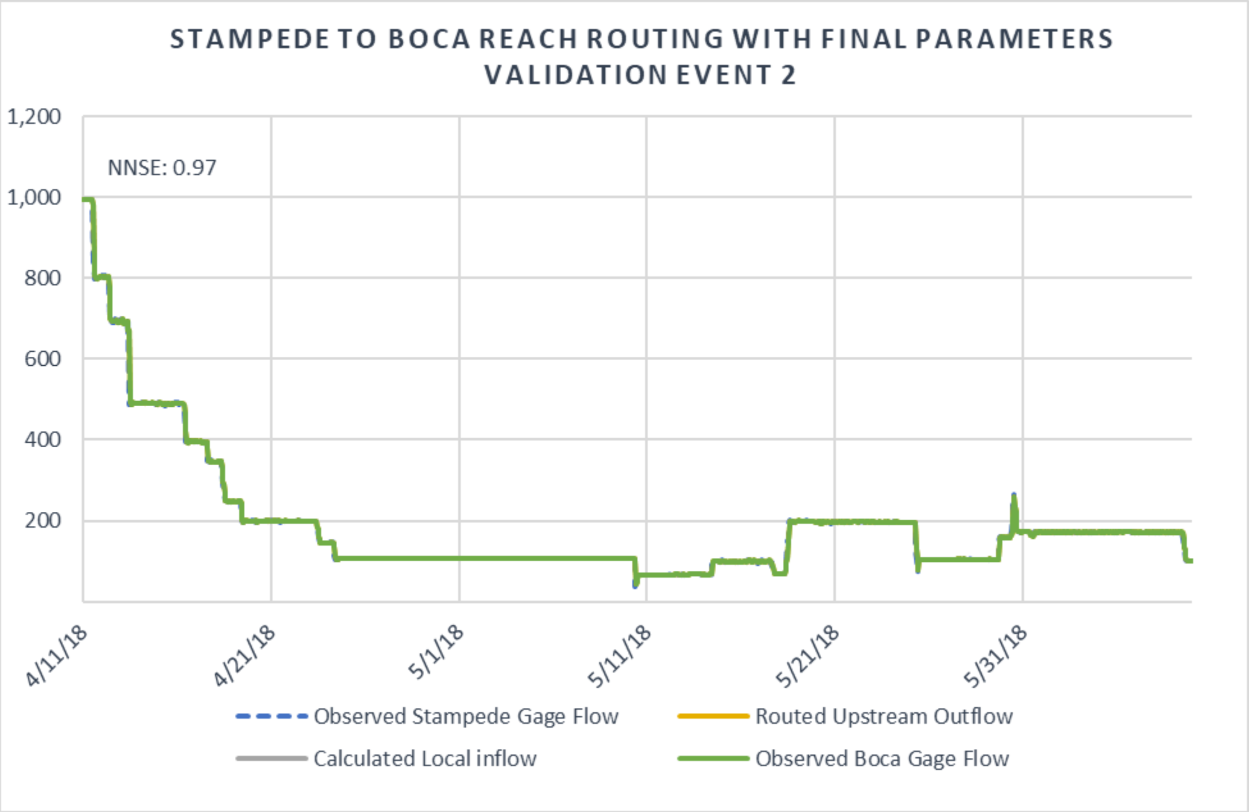
8.2 STAMPEDE TO BOCA REACH ROUTING

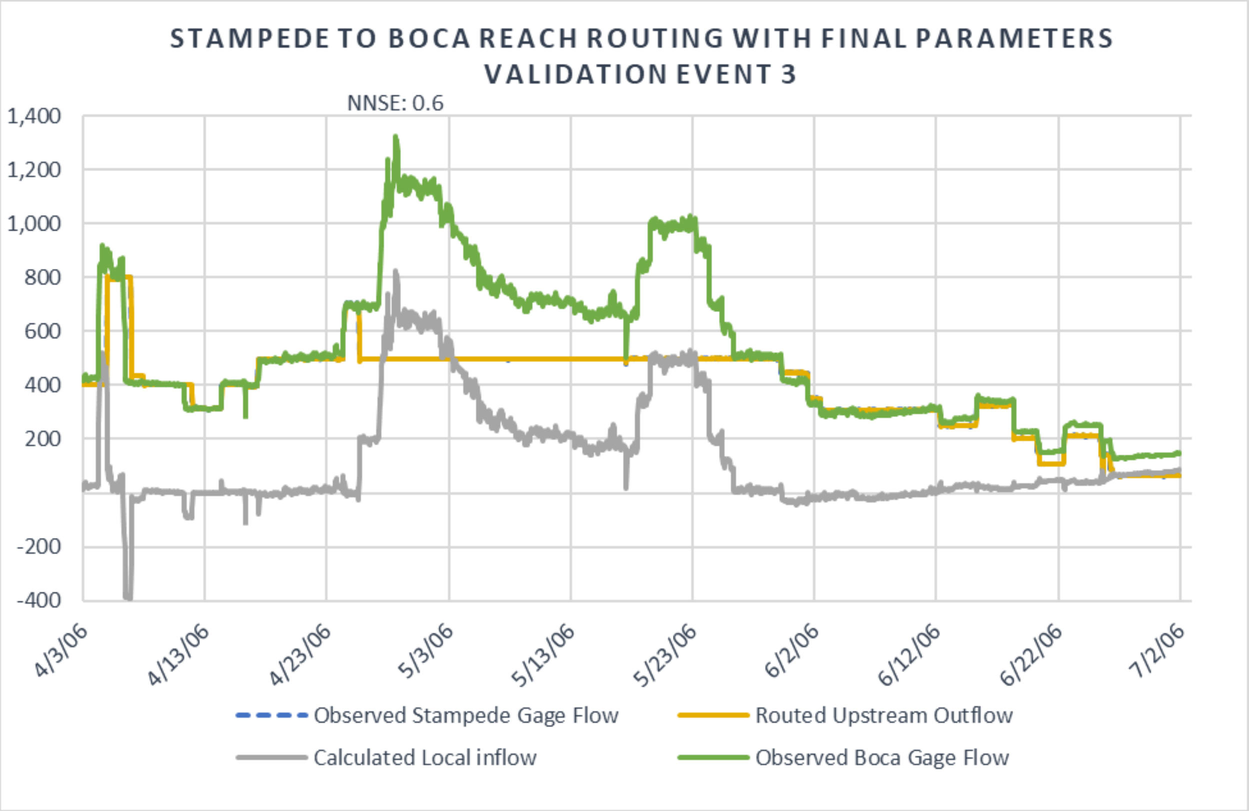




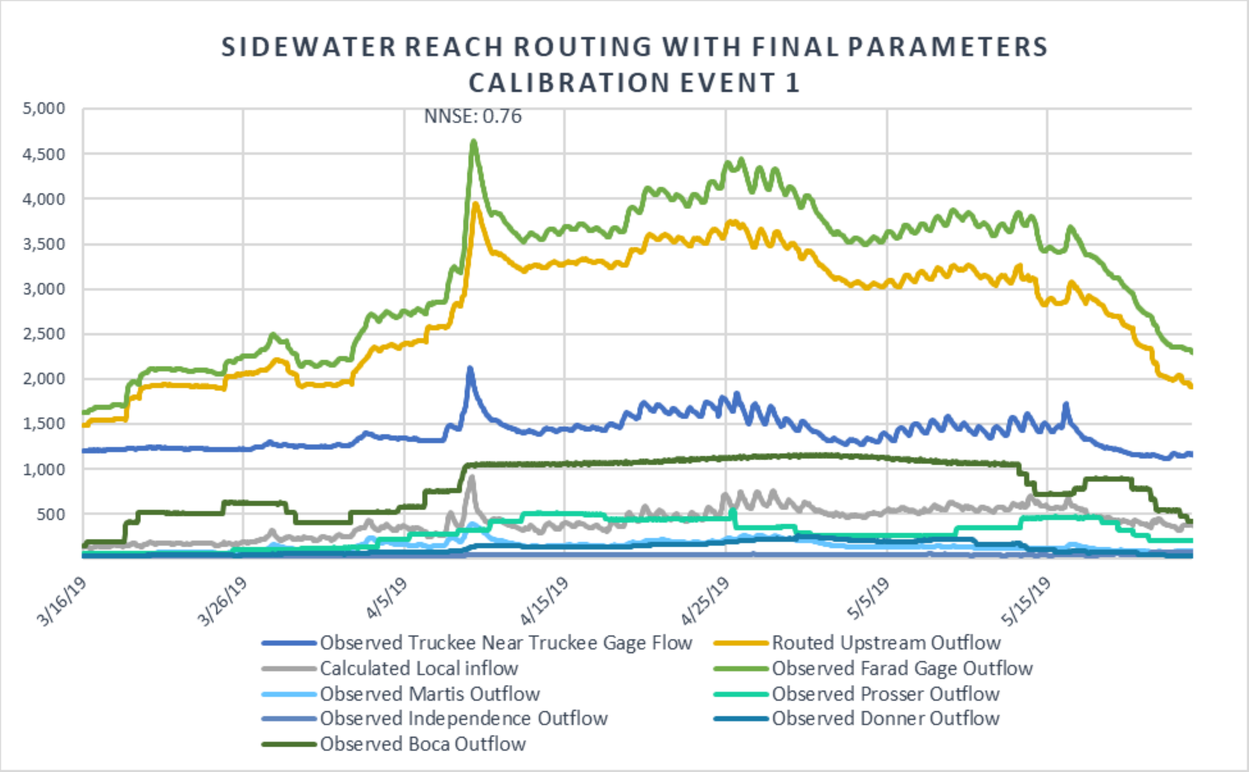

STAMPEDE TO BOCA REACH ROUTING WITH FINAL PARAMETERS
CALIBRATION EVENT 3
NNSE: 0.91
800
700
600
500
400
300
200
100
-100
-200
11/16/17
11/21/17
11/26/17
12/1/17
12/6/17
12/11/17
Observed Stampede Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Boca Gage Flow

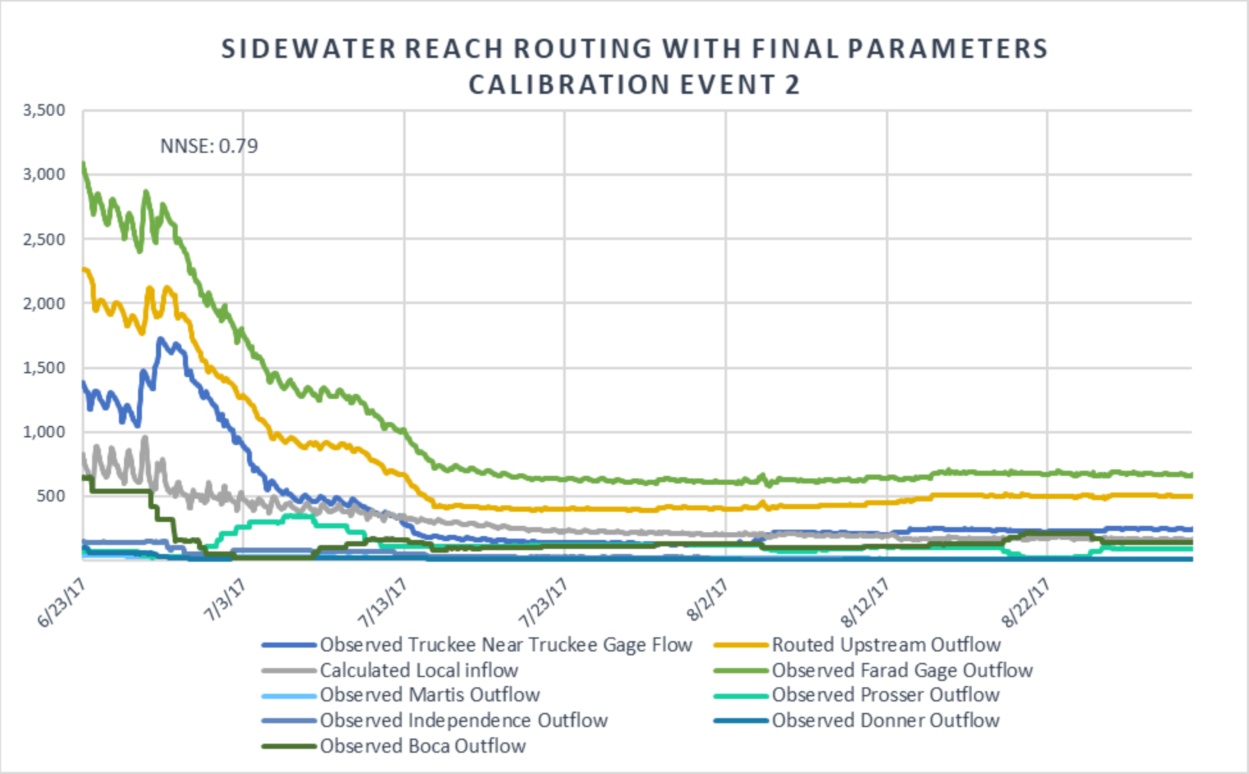

STAMPEDE TO BOCA REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 1
NNSE: 0.72
800
700
600
500
400
300
200
100
-100
2/1/17
2/6/17
2/11/17
2/16/17
2/21/17
2/26/17
Observed Stampede Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Boca Gage Flow

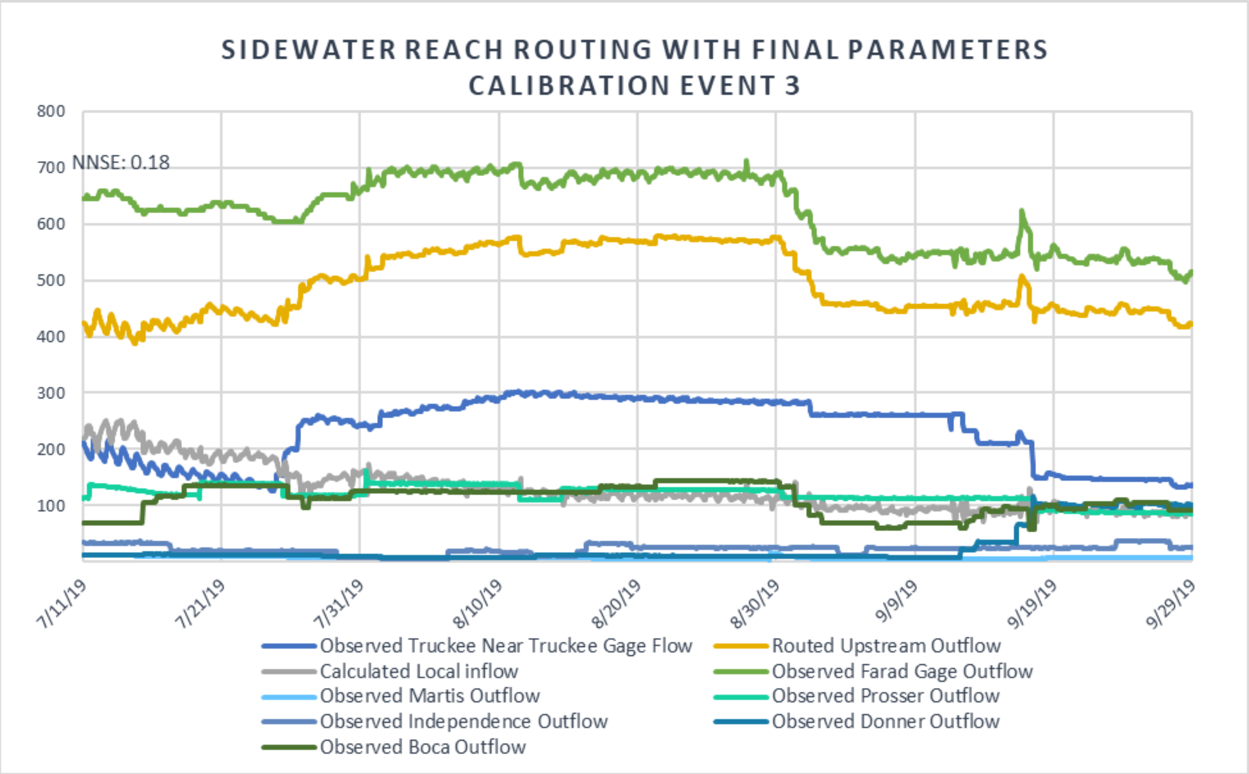

STAMPEDE TO BOCA REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 2
NNSE: 0.97
1,200
1,000
800
600
400
200
4/11/18
4/21/18
5/1/18
5/11/18
5/21/18
5/31/18
Observed Stampede Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Boca Gage Flow

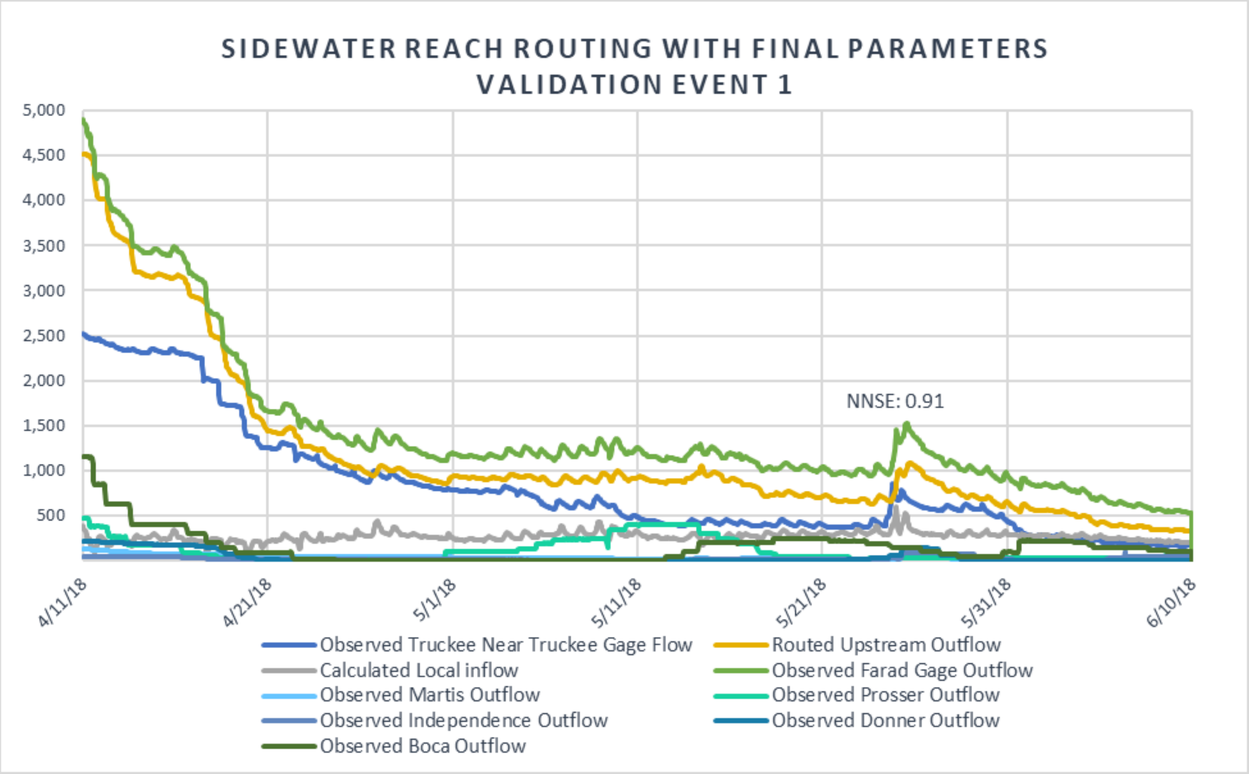

STAMPEDE TO BOCA REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 3
NNSE: 0.6
1,400
1,200
1,000
800
600
400
200
-200
-400
4/3/06
4/13/06
4/23/06
5/3/06
5/13/06
5/23/06
6/2/06
6/12/06
6/22/06
7/2/06
Observed Stampede Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Boca Gage Flow

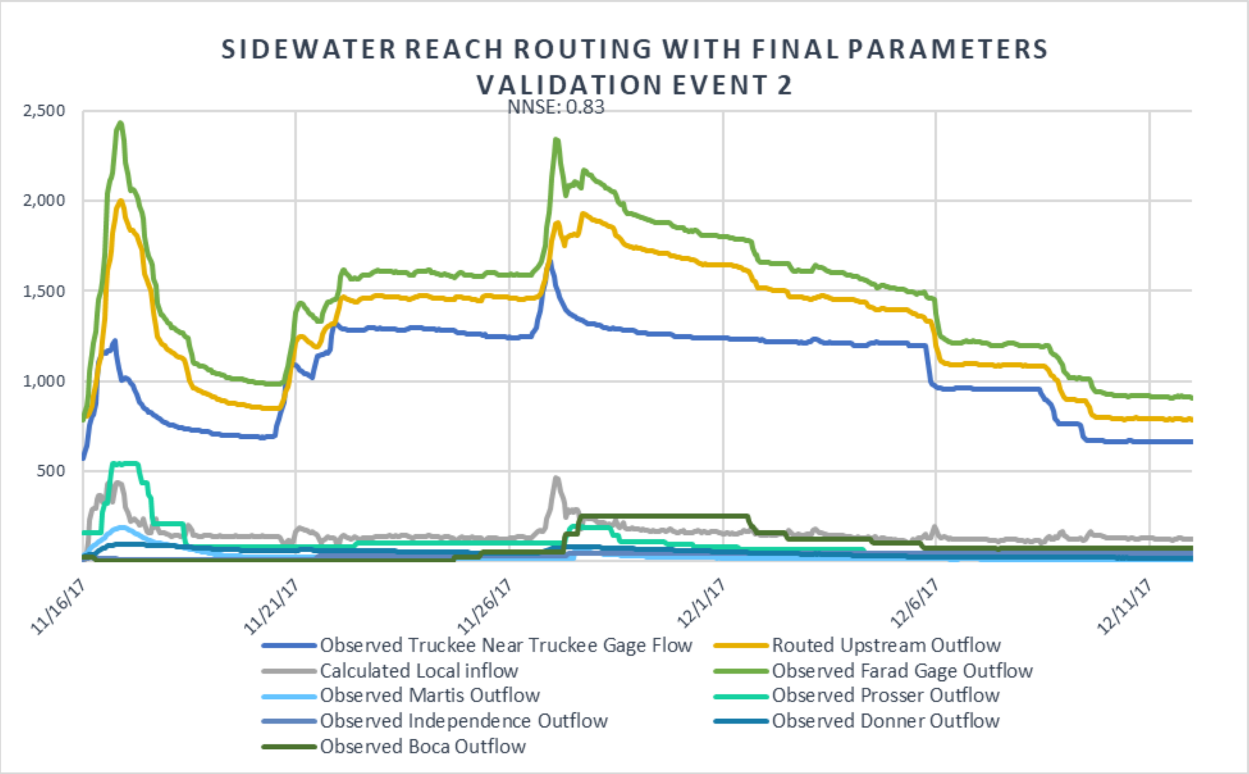
8.3 SIDEWATER REACH ROUTING

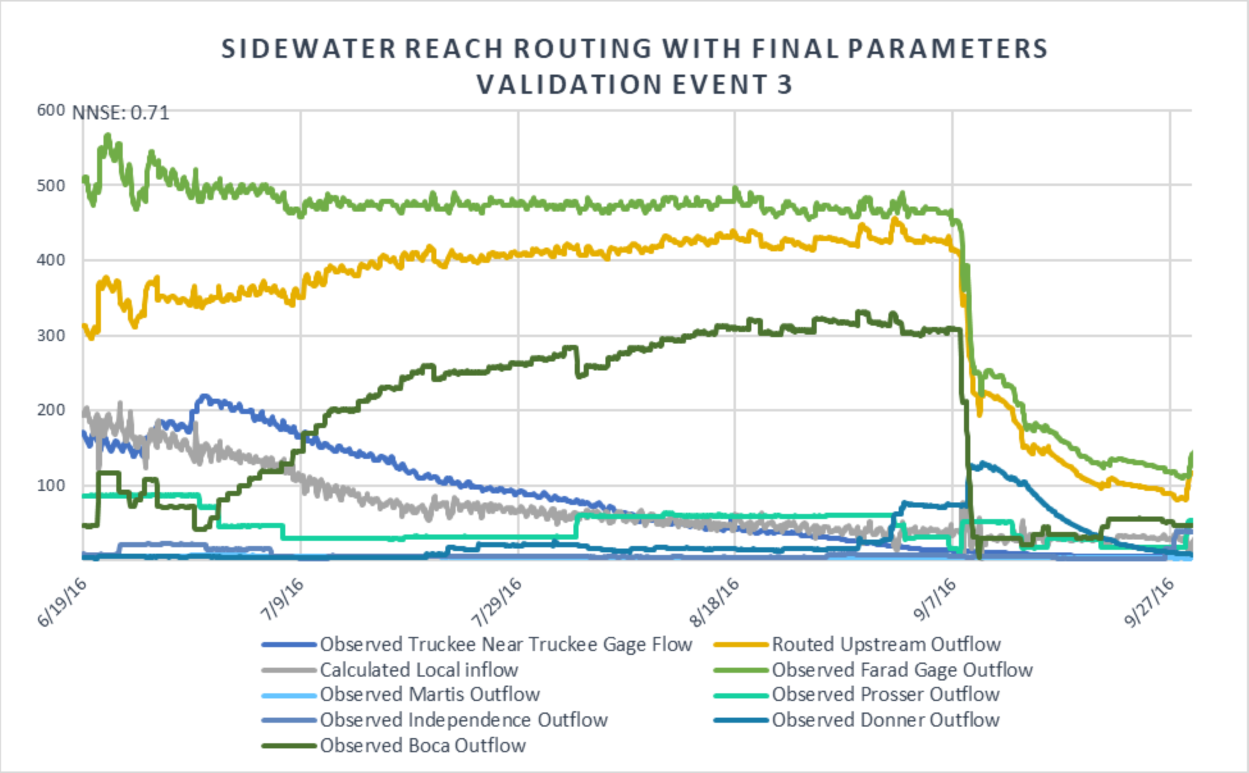




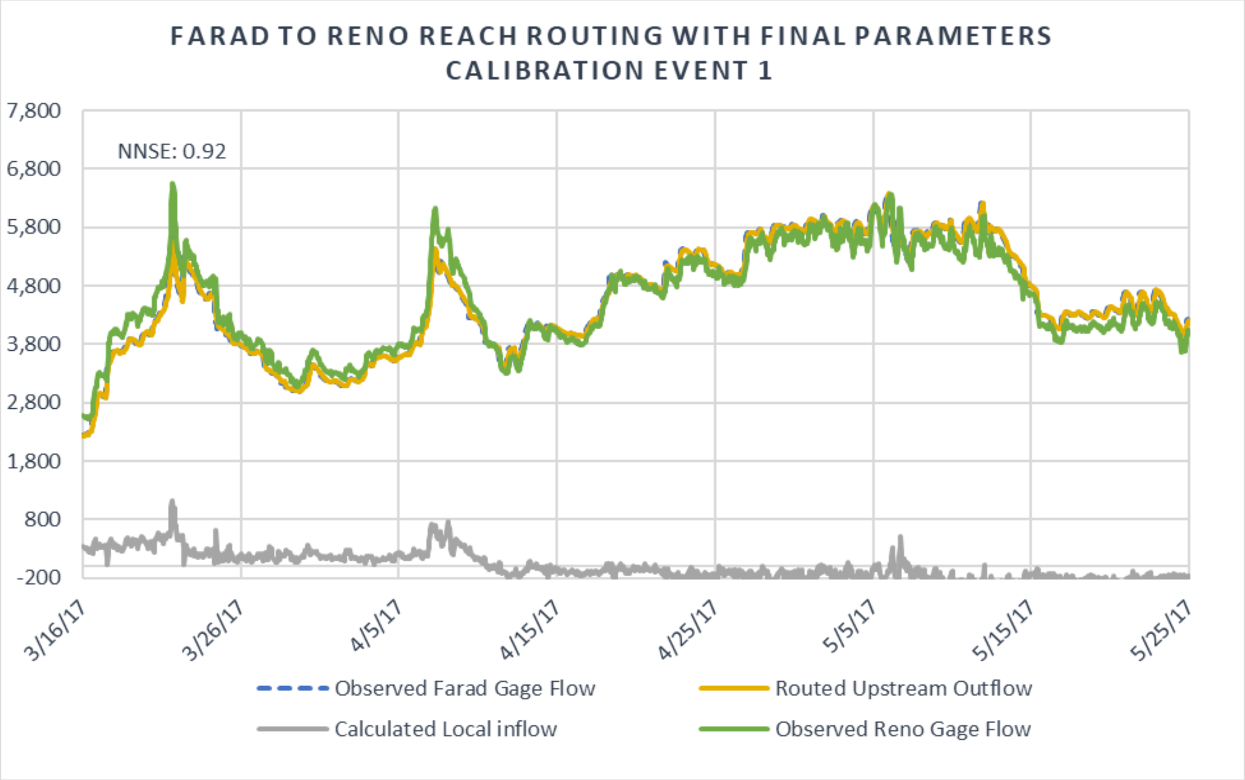

SIDEWATER REACH ROUTING WITH FINAL PARAMETERS
CALIBRATION EVENT 3
NNSE: 0.18
800
700
600
500
400
300
200
100
7/11/19
7/21/19
7/31/19
8/10/19
8/20/19
8/30/19
9/9/19
9/19/19
9/29/19
Observed Truckee Near Truckee Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Farad Gage Outflow
Observed Martis Outflow
Observed Prosser Outflow
Observed Independence Outflow
Observed Donner Outflow
Observed Boca Outflow

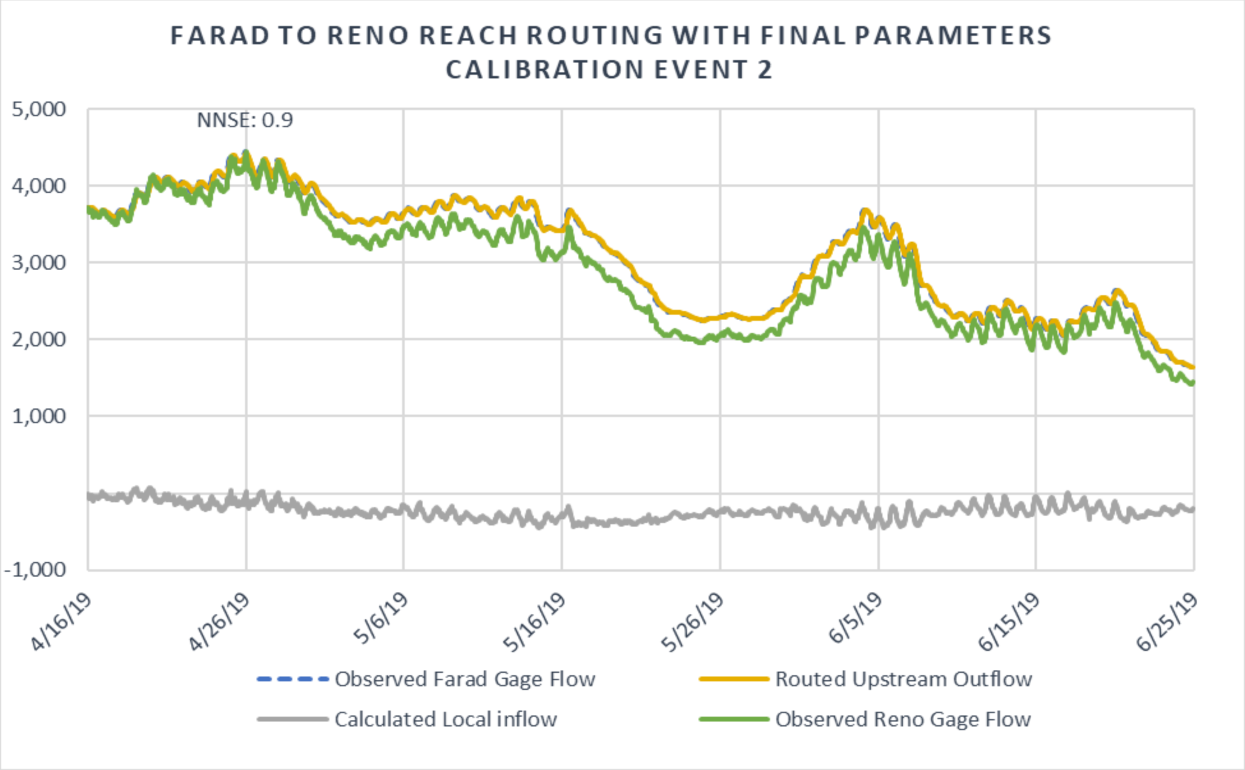

SIDEWATER REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 1
NNSE: 0.91
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
4/11/18
4/21/18
5/1/18
5/11/18
5/21/18
5/31/18
6/10/18
Observed Truckee Near Truckee Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Farad Gage Outflow
Observed Martis Outflow
Observed Prosser Outflow
Observed Independence Outflow
Observed Donner Outflow
Observed Boca Outflow

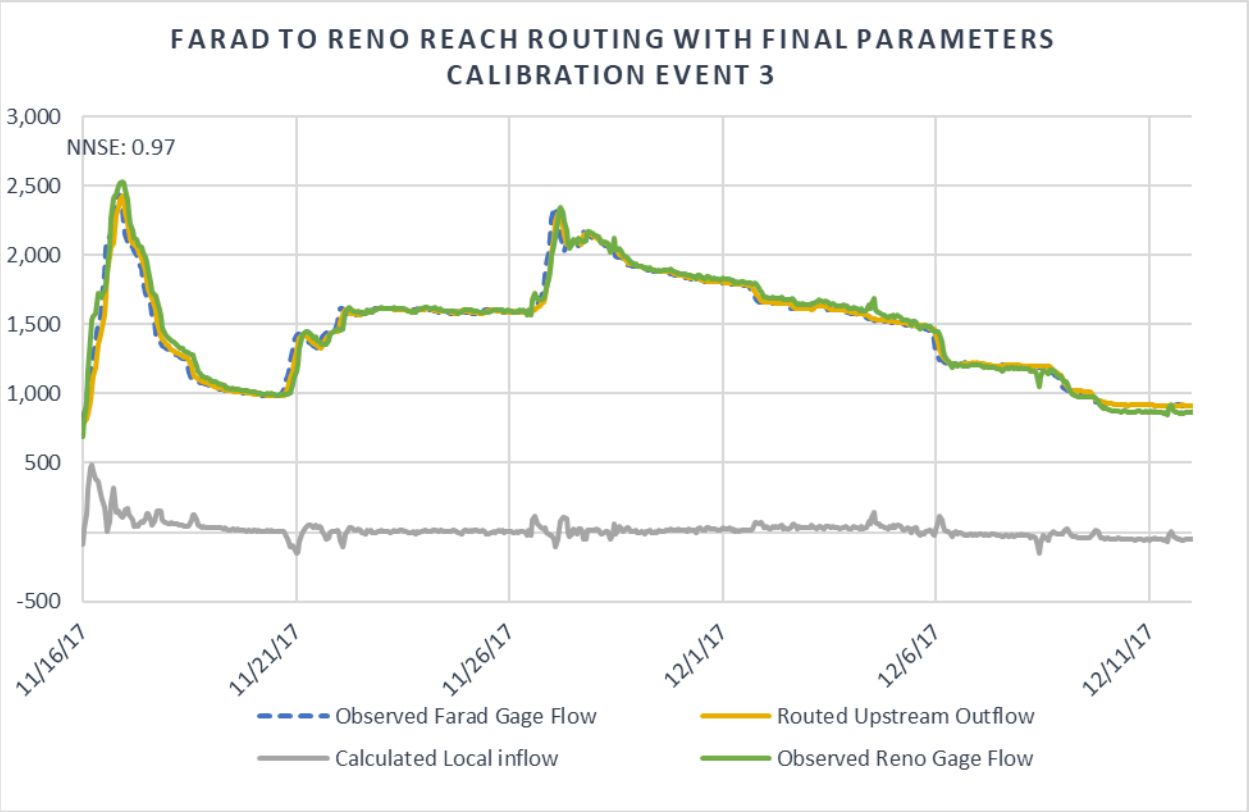

SIDEWATER REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 2
NNSE: 0.83
2,500
2,000
1,500
1,000
500
11/16/17
11/21/17
11/26/17
12/1/17
12/6/17
12/11/17
Observed Truckee Near Truckee Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Farad Gage Outflow
Observed Martis Outflow
Observed Prosser Outflow
Observed Independence Outflow
Observed Donner Outflow
Observed Boca Outflow

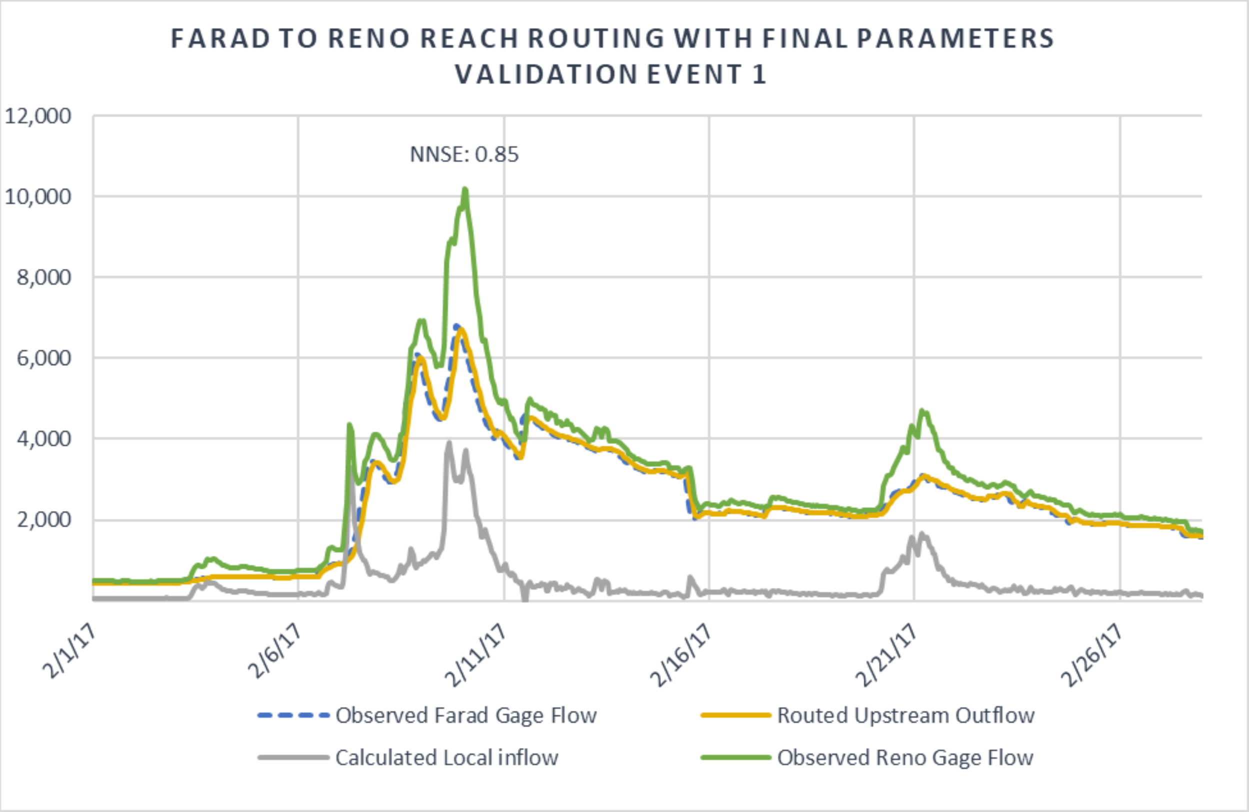

SIDEWATER REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 3
NNSE: 0.71
600
500
400
300
200
100
6/19/16
7/9/16
7/29/16
8/18/16
9/7/16
9/27/16
Observed Truckee Near Truckee Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Farad Gage Outflow
Observed Martis Outflow
Observed Prosser Outflow
Observed Independence Outflow
Observed Donner Outflow
Observed Boca Outflow

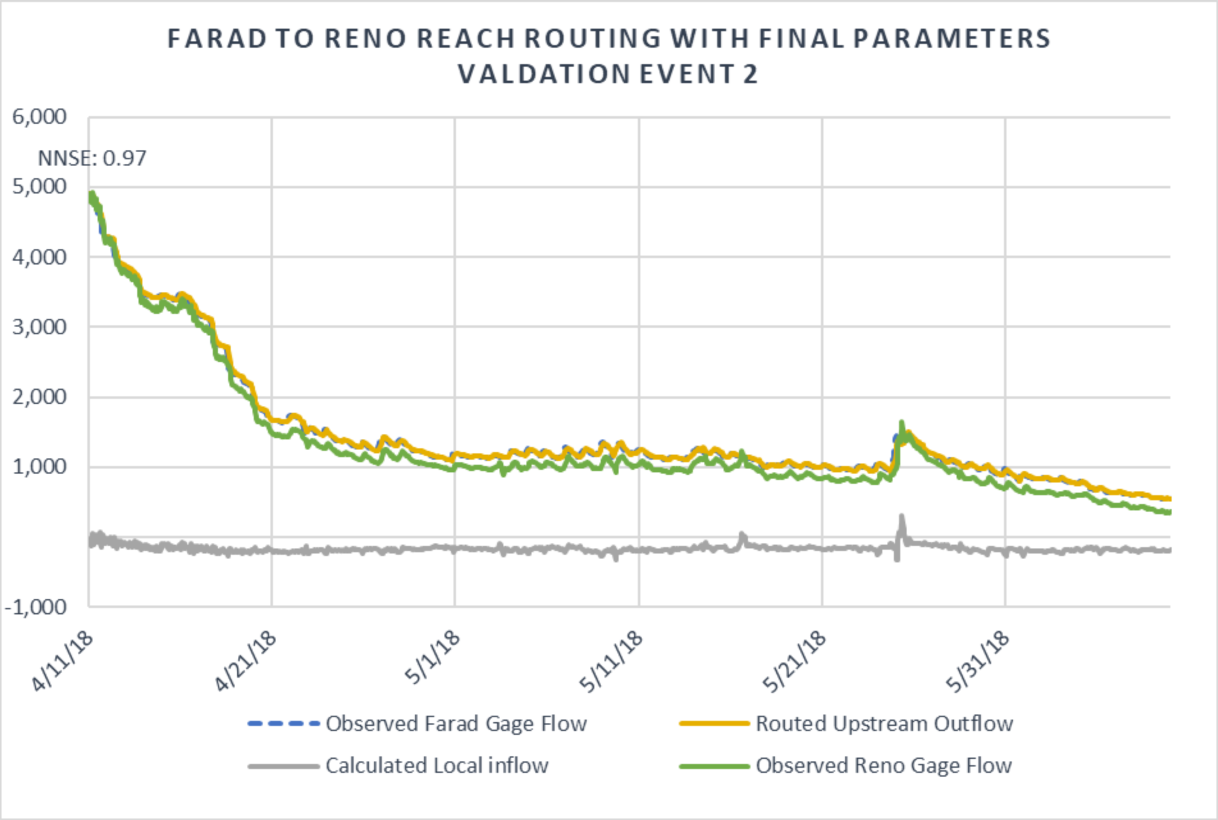
8.4 FARAD TO RENO REACH ROUTING



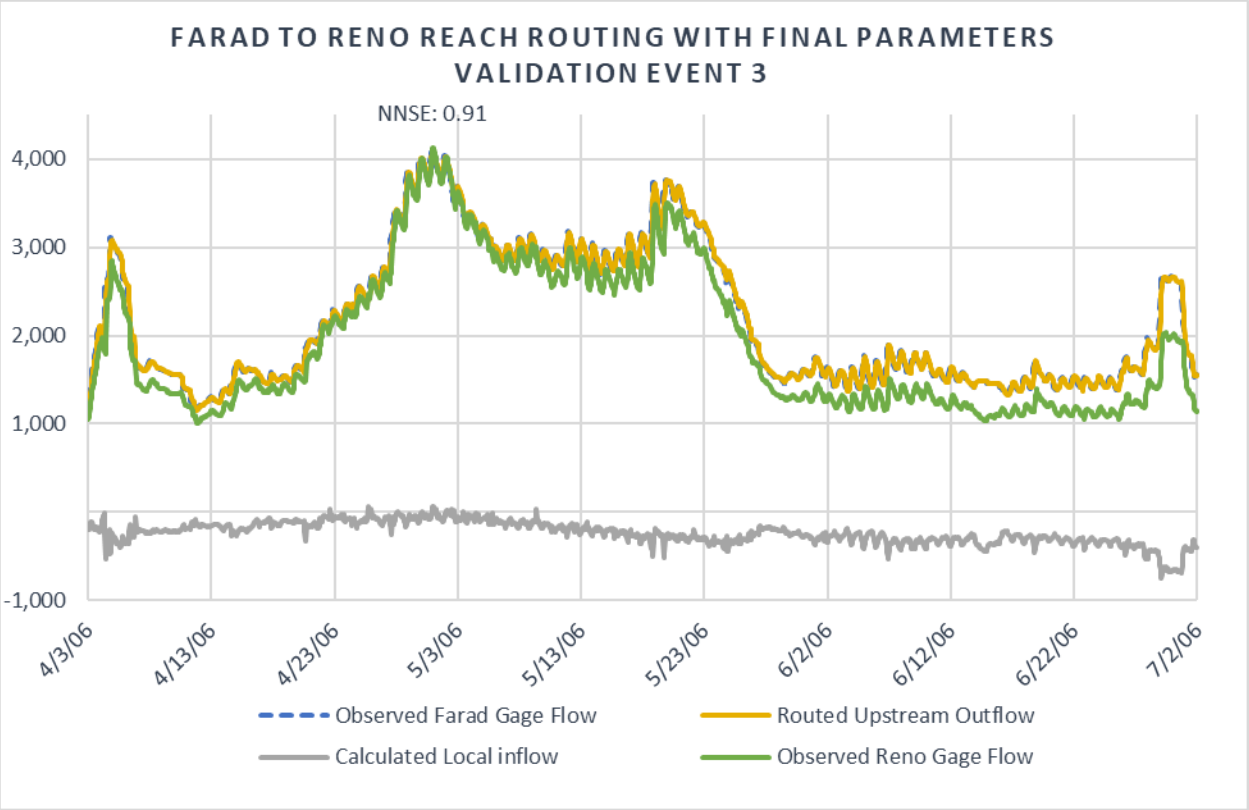



FARAD TO RENO REACH ROUTING WITH FINAL PARAMETERS
CALIBRATION EVENT 3
NNSE: 0.97
3,000
2,500
2,000
1,500
1,000
500
-500
11/16/17
11/21/17
11/26/17
12/1/17
12/6/17
12/11/17
Observed Farad Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Reno Gage Flow


FARAD TO RENO REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 1
NNSE: 0.85
12,000
10,000
8,000
6,000
4,000
2,000
2/1/17
2/6/17
2/11/17
2/16/17
2/21/17
2/26/17
Observed Farad Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Reno Gage Flow

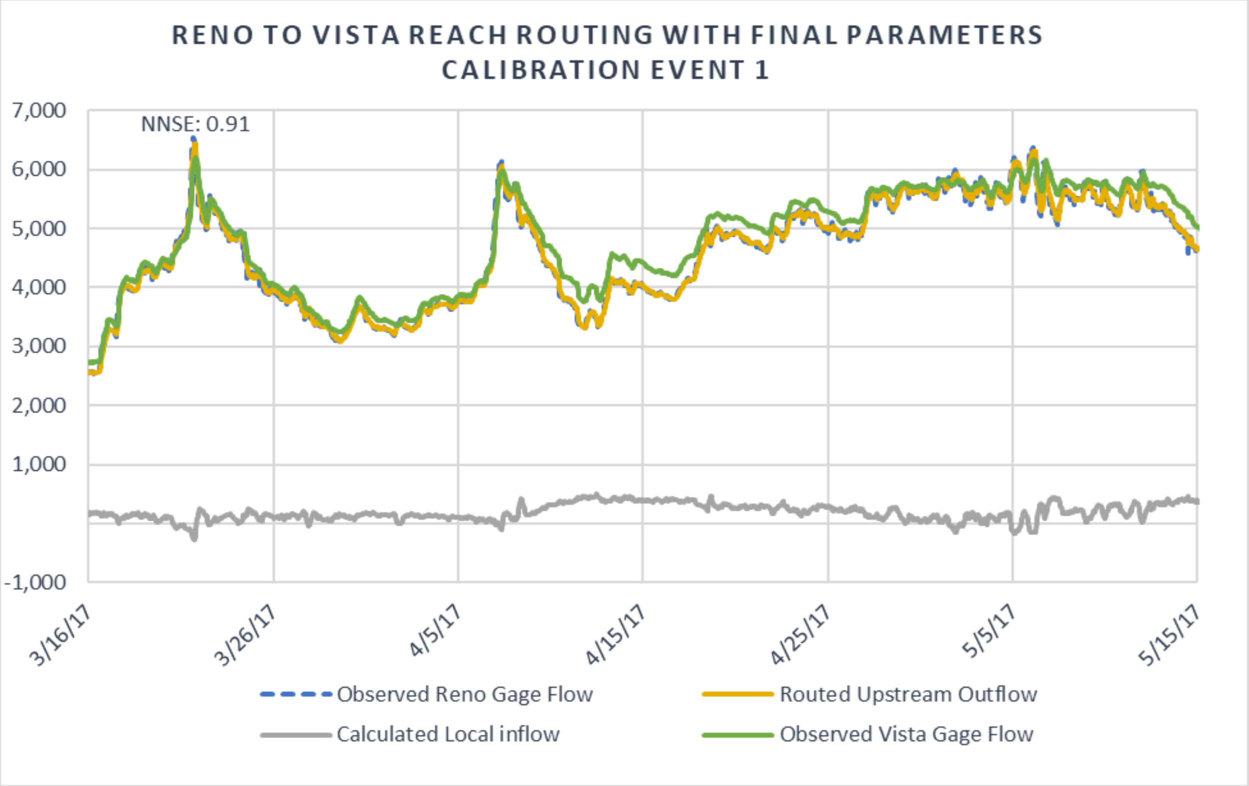


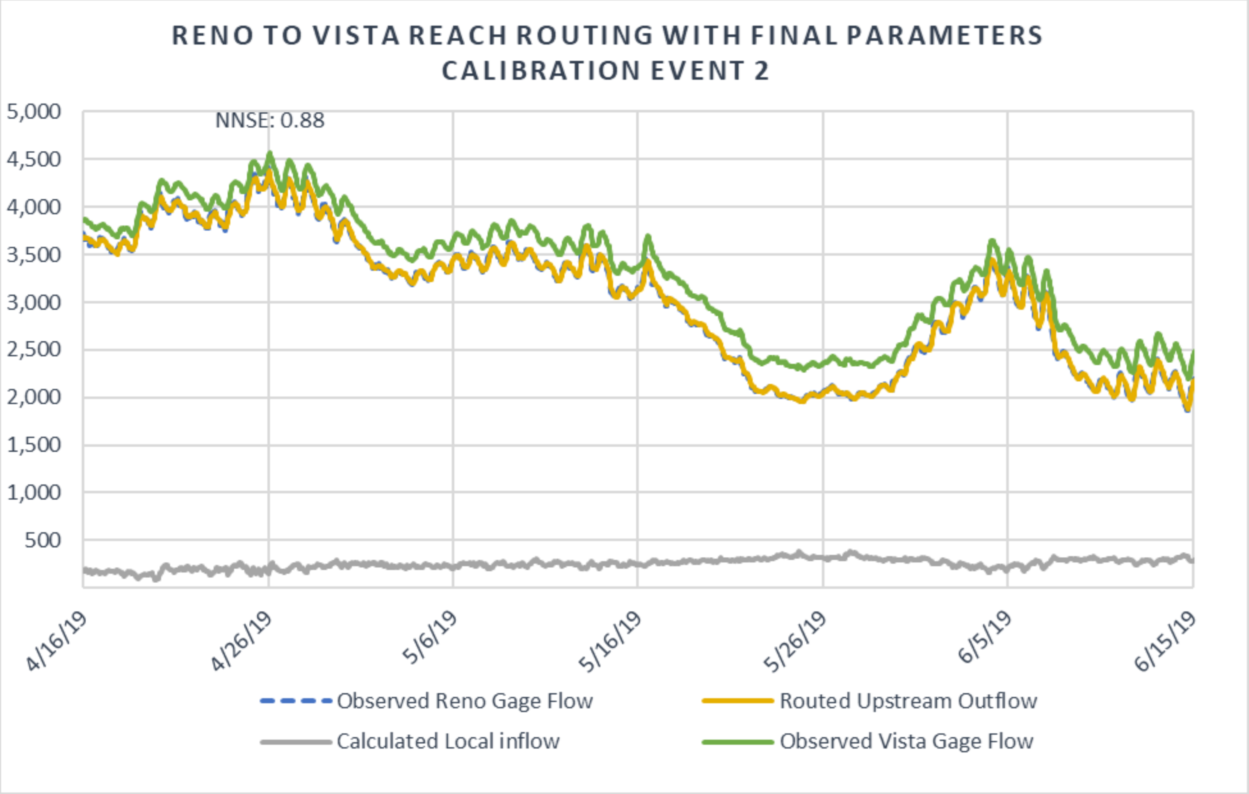
FARAD TO RENO REACH ROUTING WITH FINAL PARAMETERS
VALDATION EVENT 2

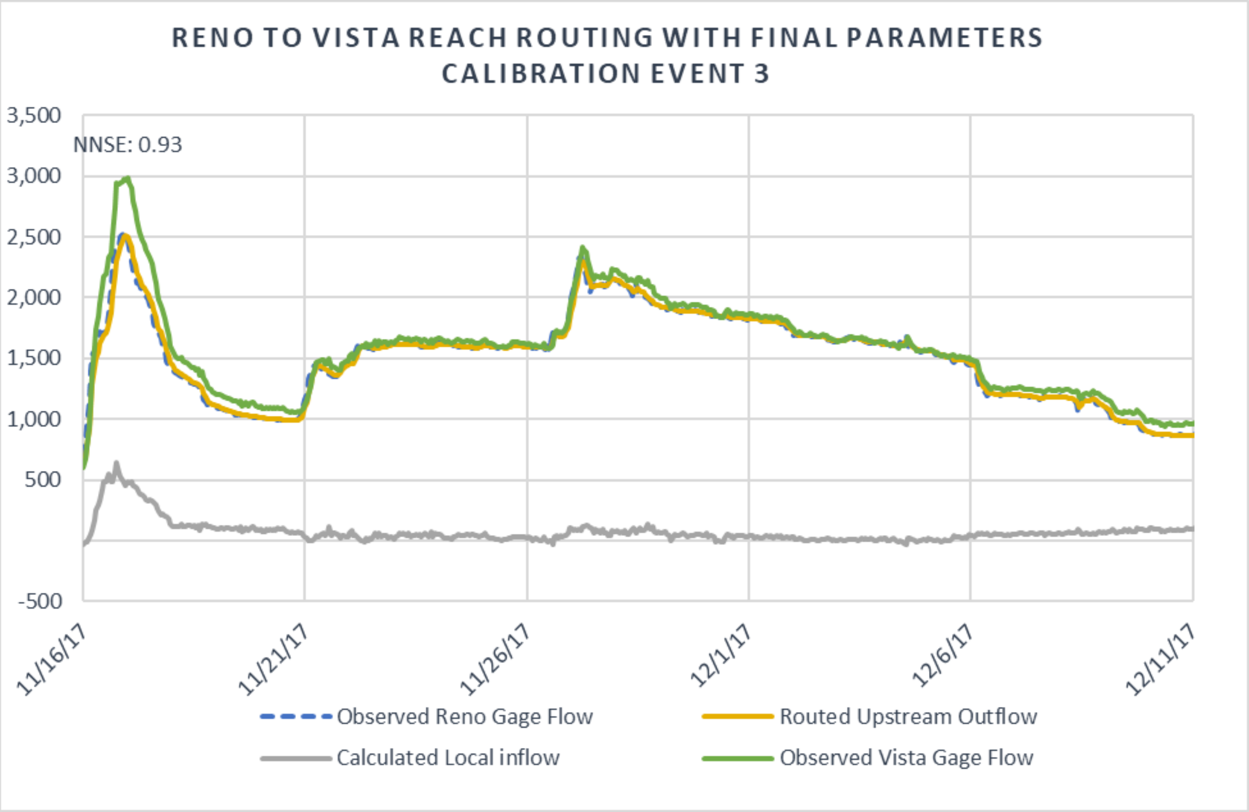


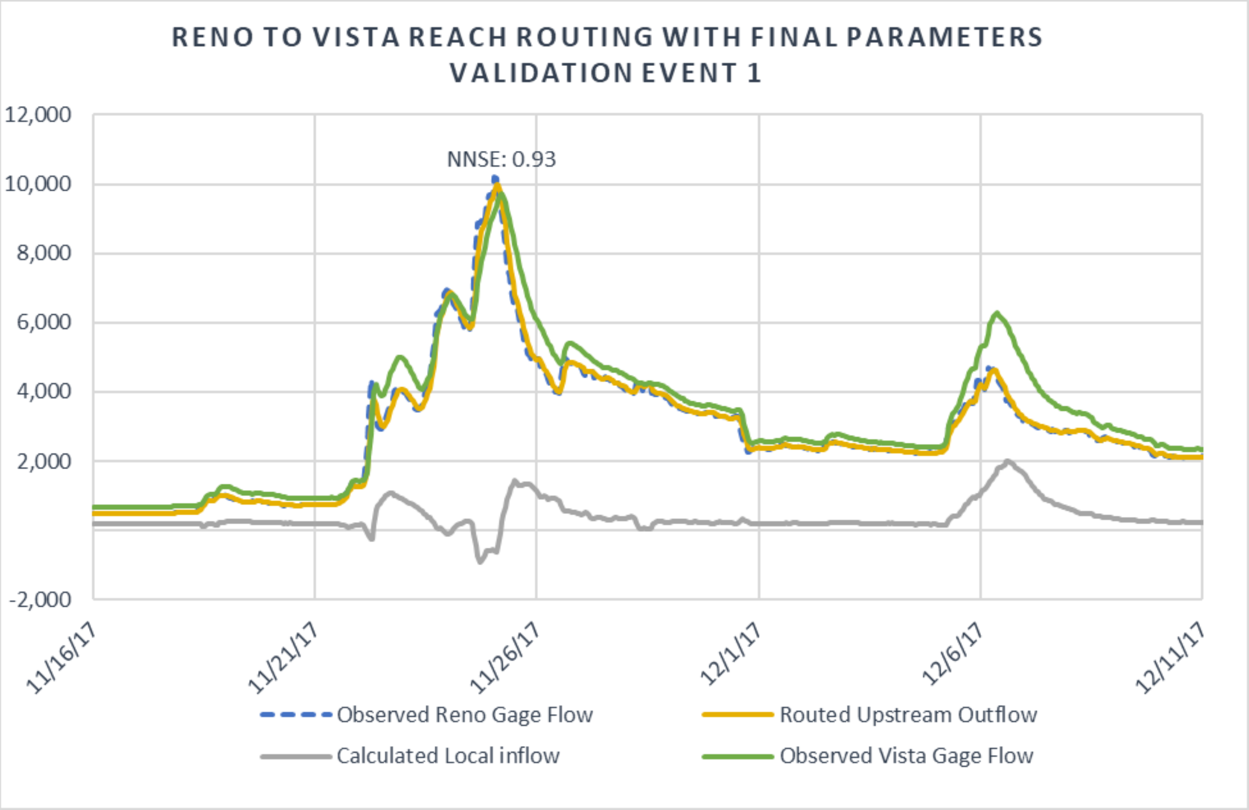
FARAD TO RENO REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 3

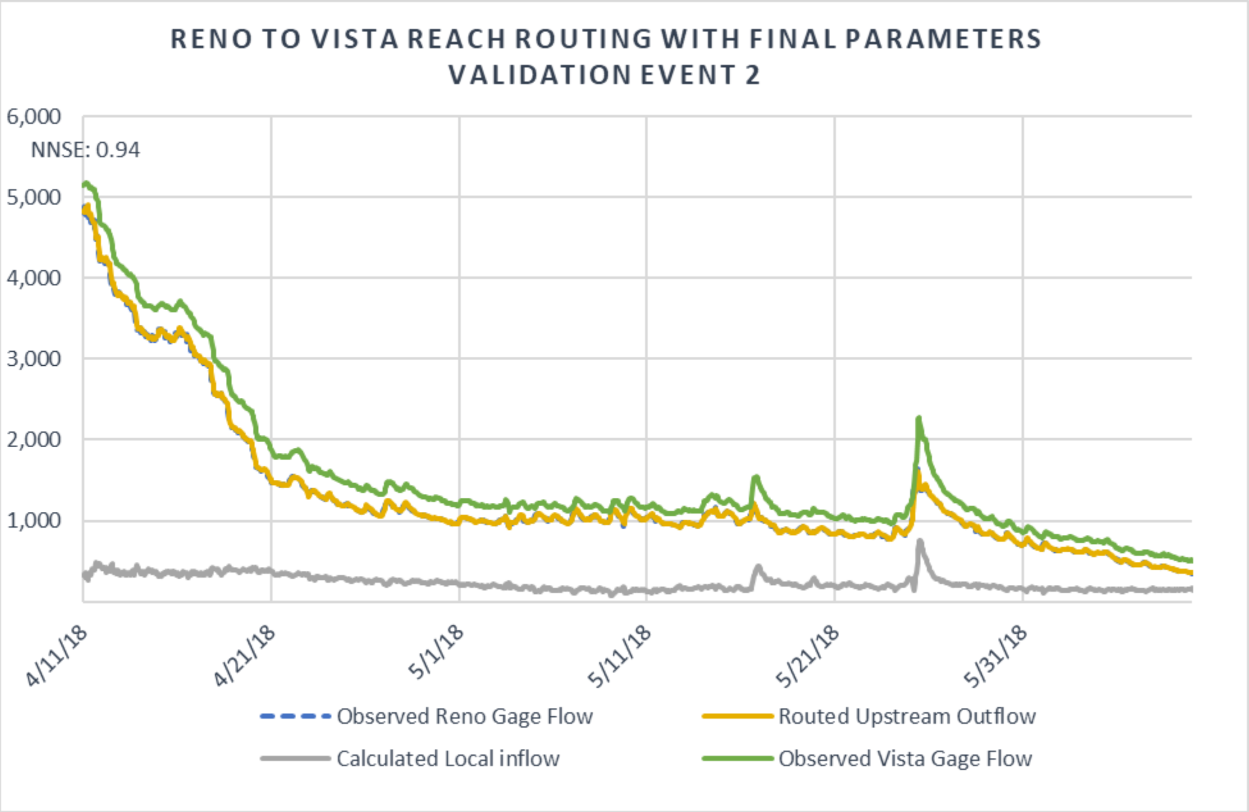
8.5 RENO TO VISTA REACH ROUTING



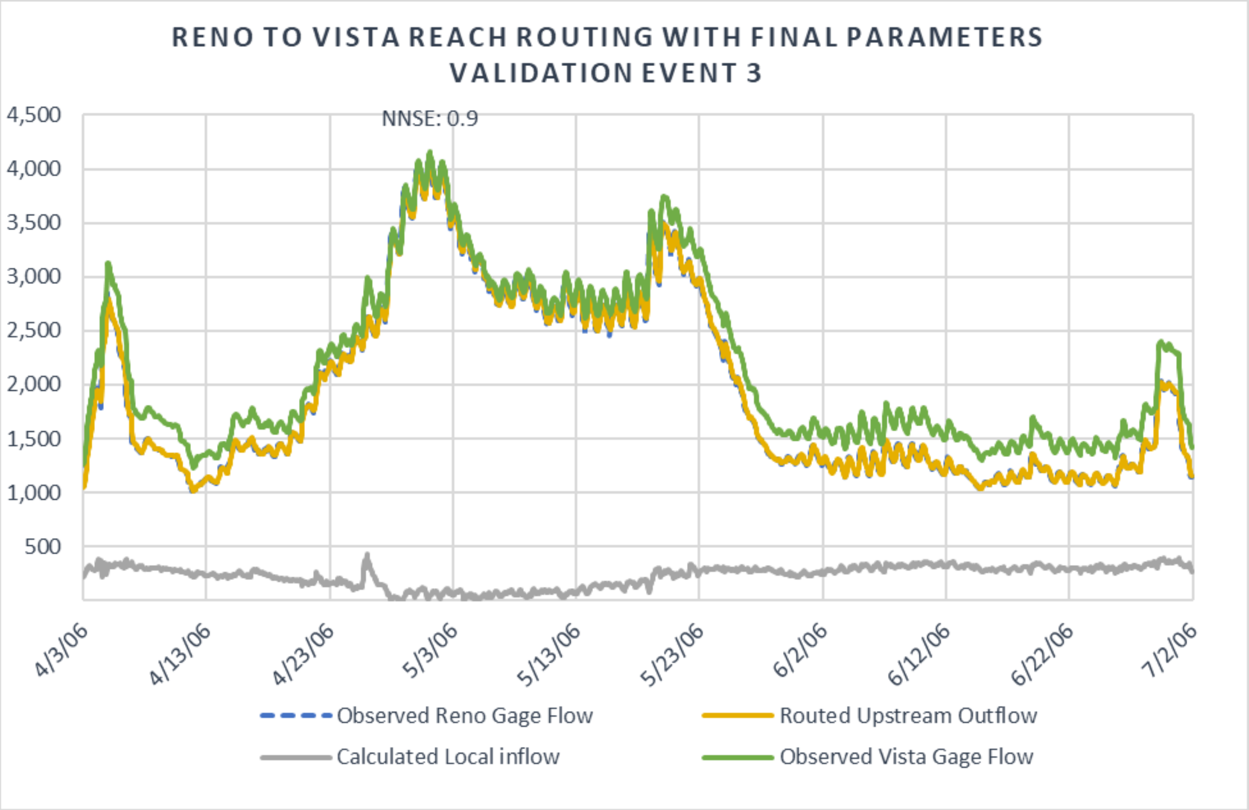



RENO TO VISTA REACH ROUTING WITH FINAL PARAMETERS
CALIBRATION EVENT 3
NNSE: 0.93
3,500
3,000
2,500
2,000
1,500
1,000
500
-500
11/16/17
11/21/17
11/26/17
12/1/17
12/6/17
12/11/17
Observed Reno Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Vista Gage Flow


RENO TO VISTA REACH ROUTING WITH FINAL PARAMETERS
VALIDATION EVENT 1
NNSE: 0.93
12,000
10,000
8,000
6,000
4,000
2,000
-2,000
11/16/17
11/21/17
11/26/17
12/1/17
12/6/17
12/11/17
Observed Reno Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Vista Gage Flow

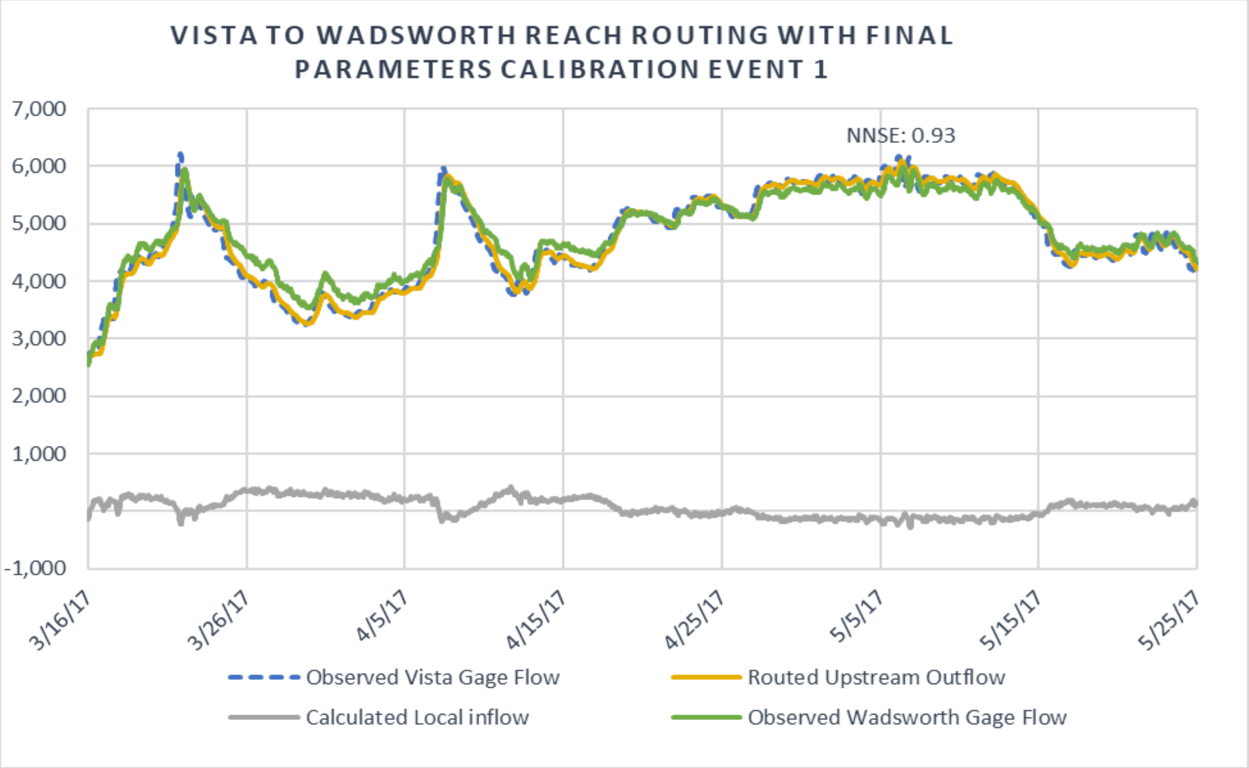


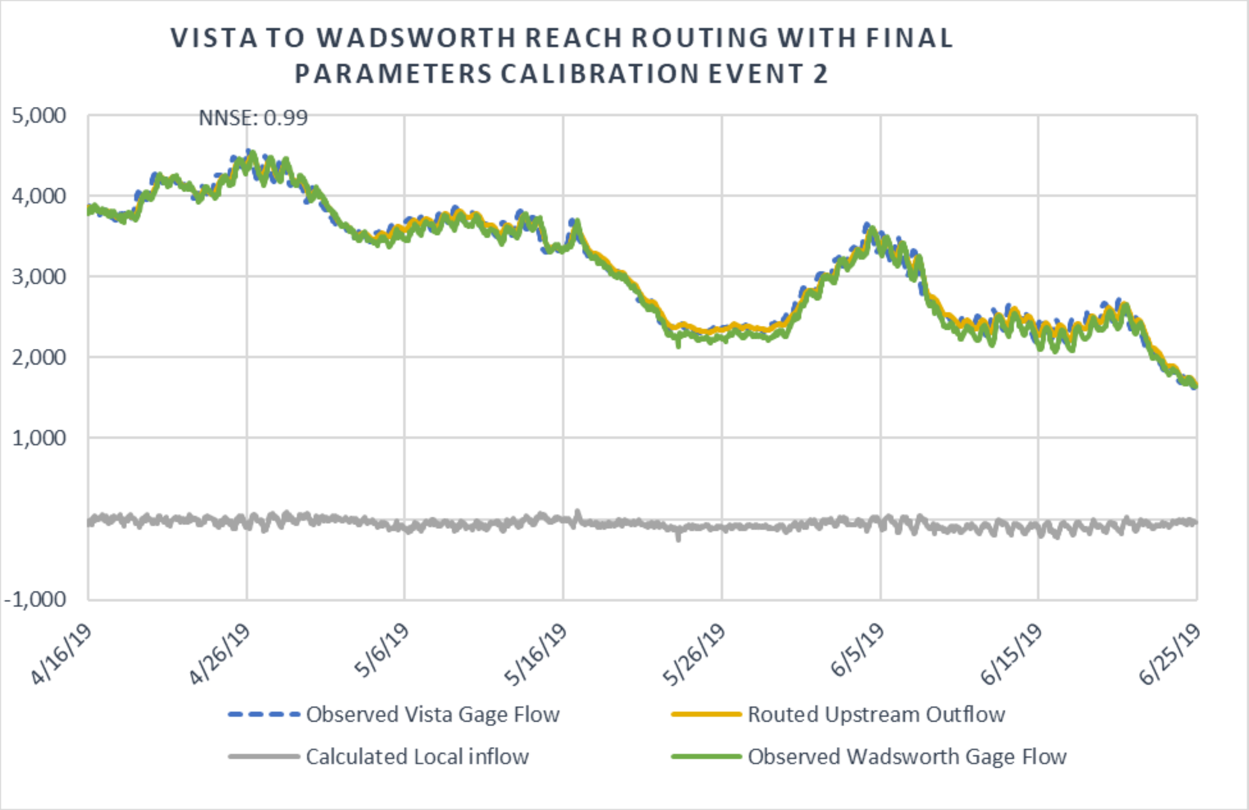
RENO TO VISTA REACH ROUTING WITH FINAL PARAMETERS VALIDATION EVENT 2

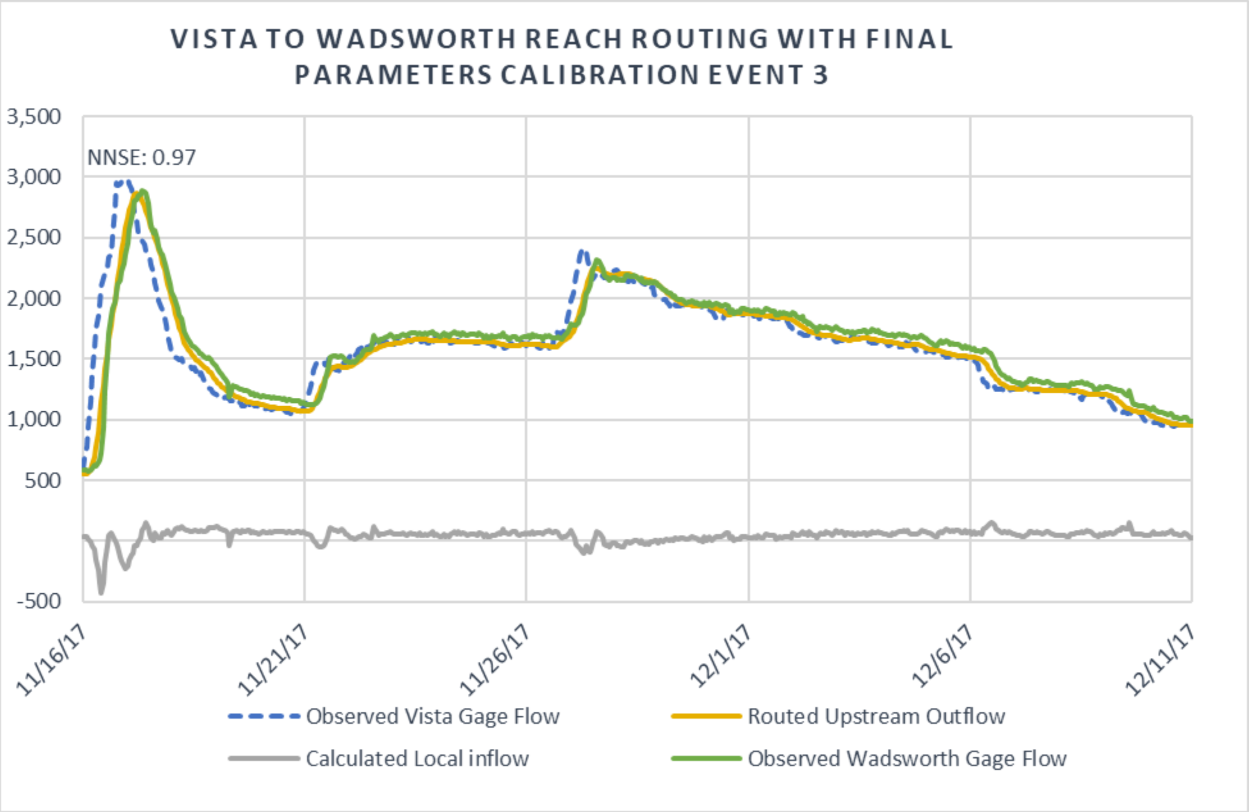


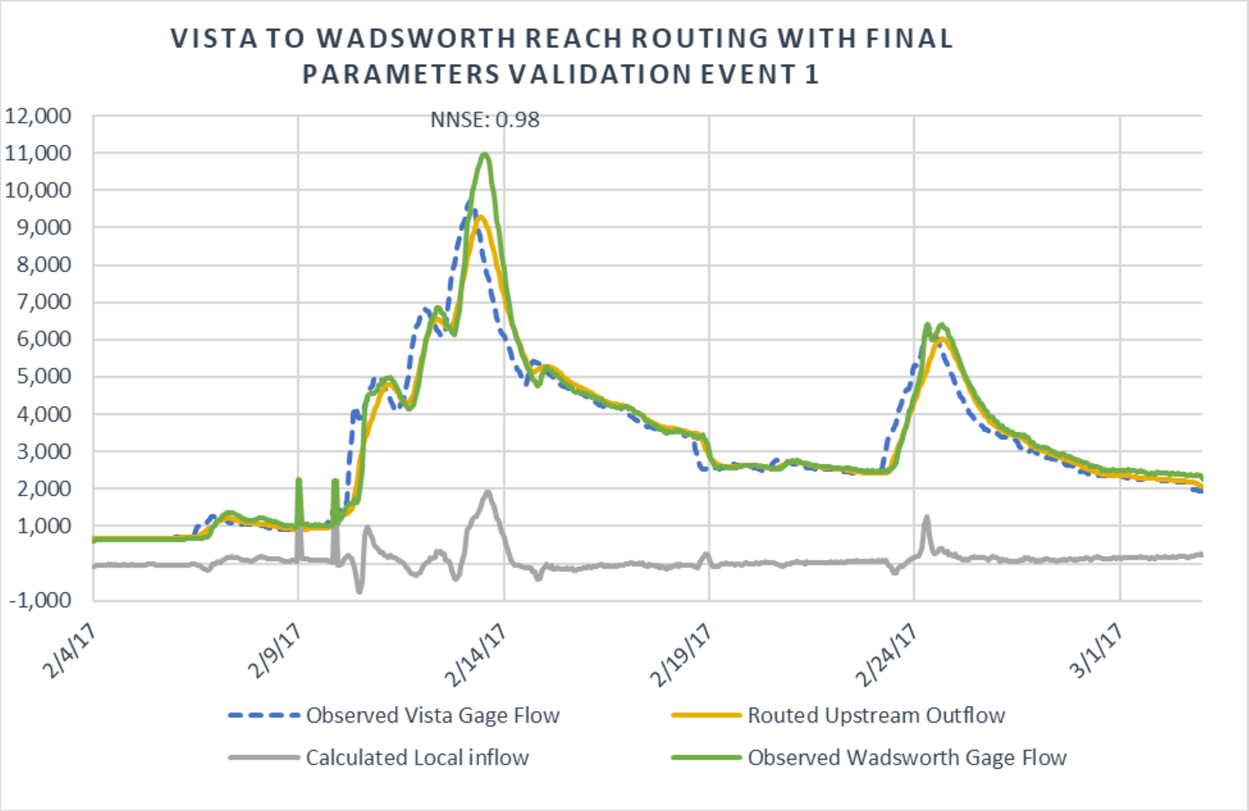
RENO TO VISTA REACH ROUTING WITH FINAL PARAMETERS VALIDATION EVENT 3

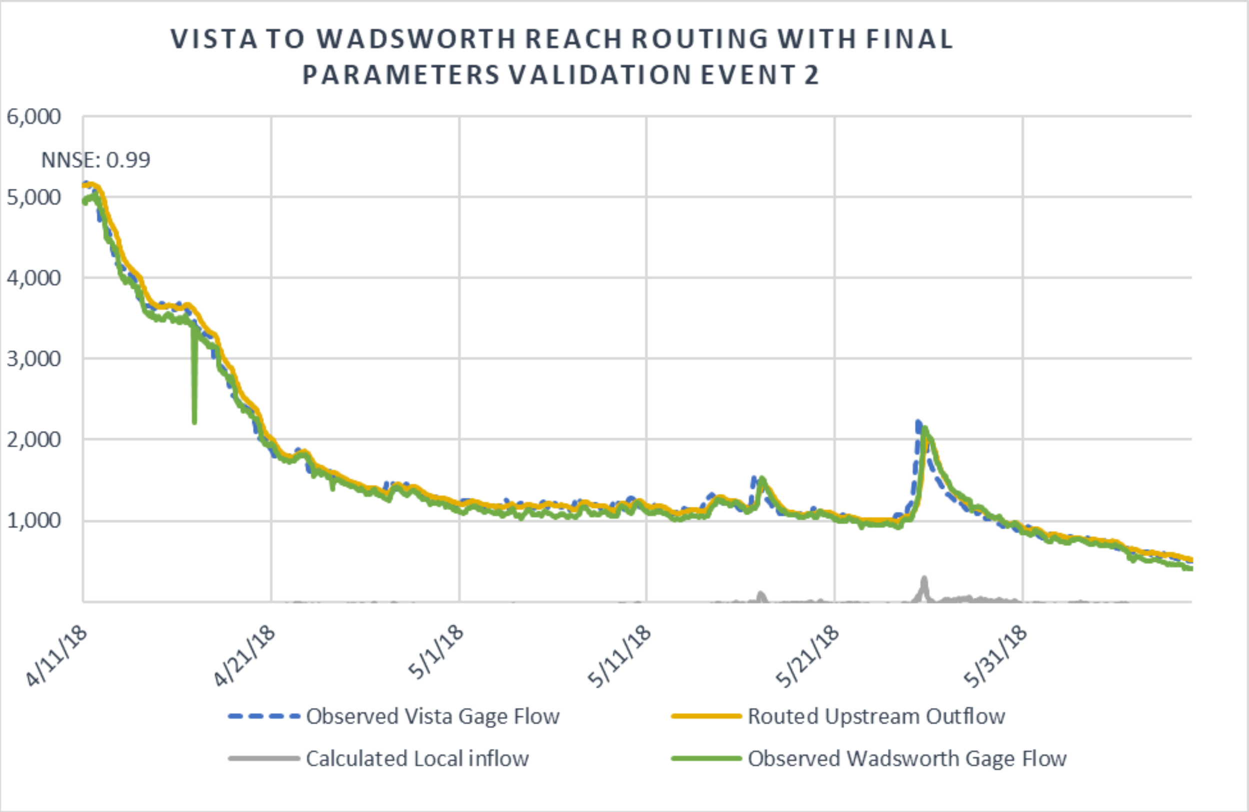
8.6 VISTA TO WADSWORTH REACH ROUTING

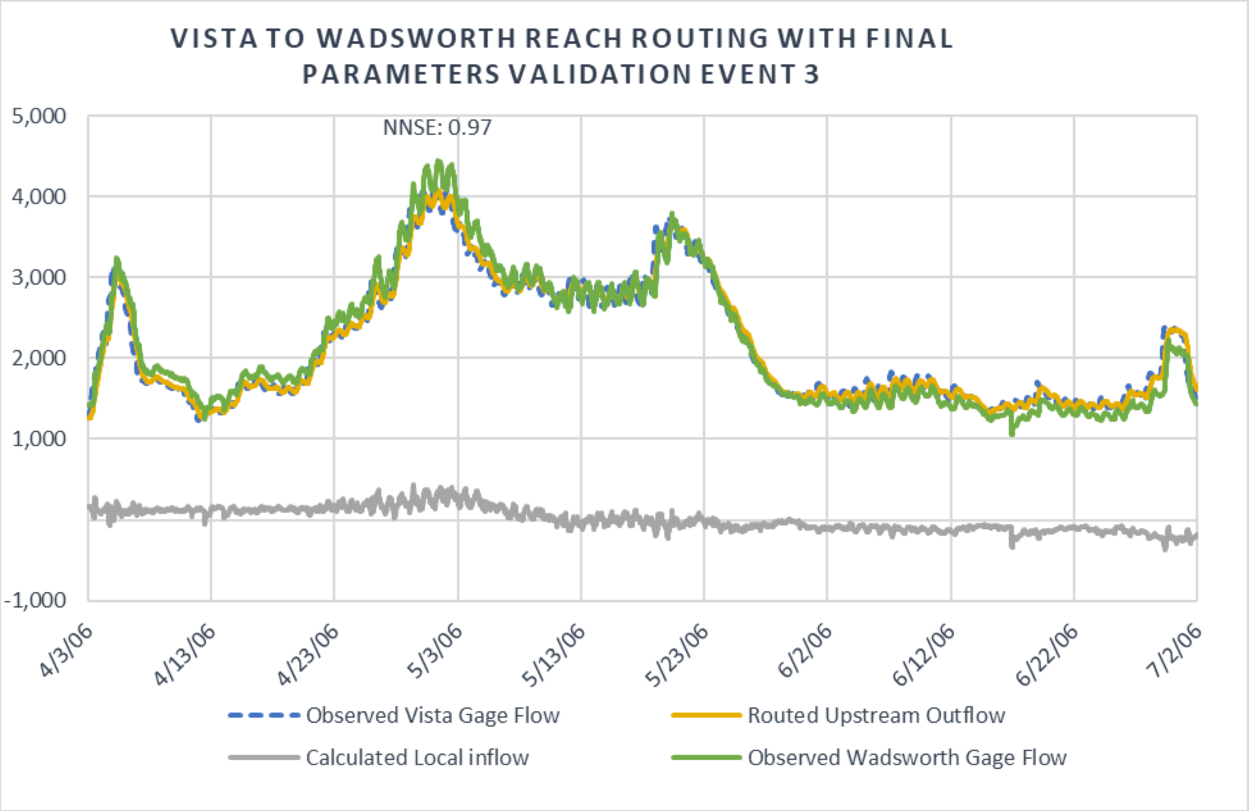





VISTA TO WADSWORTH REACH ROUTING WITH FINAL PARAMETERS CALIBRATION EVENT 3
NNSE: 0.97
3,500
3,000
2,500
2,000
1,500
1,000
500
-500
11/16/17
11/21/17
11/26/17
12/1/17
12/6/17
12/11/17
Observed Vista Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Wadsworth Gage Flow


VISTA TO WADSWORTH REACH ROUTING WITH FINAL PARAMETERS VALIDATION EVENT 1
NNSE: 0.98
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
-1,000
2/4/17
2/9/17
2/14/17
2/19/17
2/24/17
3/1/17
Observed Vista Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Wadsworth Gage Flow


VISTA TO WADSWORTH REACH ROUTING WITH FINAL PARAMETERS VALIDATION EVENT 2
NNSE: 0.99
6,000
5,000
4,000
3,000
2,000
1,000
4/11/18
4/21/18
5/1/18
5/11/18
5/21/18
5/31/18
Observed Vista Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Wadsworth Gage Flow


VISTA TO WADSWORTH REACH ROUTING WITH FINAL PARAMETERS VALIDATION EVENT 3
NNSE: 0.97
5,000
4,000
3,000
2,000
1,000
-1,000
4/3/06
4/13/06
4/23/06
5/3/06
5/13/06
5/23/06
6/2/06
6/12/06
6/22/06
7/2/06
Observed Vista Gage Flow
Routed Upstream Outflow
Calculated Local inflow
Observed Wadsworth Gage Flow

9 APPENDIX C: NNSE CALCULATIONS

Table 12 and Table 13 summarize NNSE calculated in RiverWare by event and reach. The average NNSE for all events and the flow range of the downstream gage is also shown for reference. The averages for each reach were used in Table 11 to illustrate overall the accuracy of the routing parameters.

Table 12: Calibration NNSE Performance

Calibration Performance (NNSE)						
RiverWare Reach Routing Name	**Event 1**	**Event 2**	**Event 3**	**Average**	**NNSE Range**	**Flow Range (cfs)**
BlwTahoeRouting	0.92	0.99	0.96	0.96	0.07	100-1,200
LtBlwStampedeRouting	0.63	0.67	0.91	0.74	0.28	100-1,500
SidewaterRouting	0.76	0.79	0.18	0.58	0.61	500-4,600
FaradtoRenoRouting	0.92	0.90	0.97	0.93	0.07	600-6,600
RenoToVistaRouting	0.91	0.88	0.93	0.91	0.05	400-5,100
VistaToWadsworthRouting	0.93	0.99	0.97	0.96	0.06	400-5,100

Table 13: Validation NNSE Performance

Validation Performance (NNSE)						
RiverWare Reach Routing Name	**Event 1**	**Event 2**	**Event 3**	**Average**	**NNSE Range**	**Flow Range (cfs)**
BlwTahoeRouting	0.77	0.88	0.98	0.88	0.21	100-2,600
LtBlwStampedeRouting	0.72	0.97	0.60	0.76	0.37	0-1,300
SidewaterRouting	0.91	0.83	0.71	0.82	0.20	100-4,900
FaradtoRenoRouting	0.85	0.97	0.91	0.91	0.12	300-10,200
RenoToVistaRouting	0.93	0.94	0.90	0.92	0.04	100-9,700
VistaToWadsworthRouting	0.98	0.99	0.97	0.98	0.02	100-11,000