APPENDIX D

NOVEMBER 29, 2004 PI ENGINEERING DRAFT TECHNICAL MEMORANDUM – SKAGIT RIVER BASIN HISTORICAL FLOOD MODELING - HYDRAULICS

Draft Technical Memorandum

Skagit River Basin Historical Flood Modeling - Hydraulics

Introduction

This technical memorandum presents information on and analysis of the Skagit River Basin flood routing from Newhalem to Skagit Bay, using HEC-RAS modeling software (U.S. Army Corps of Engineers, 2004a). A HEC-5 model was also developed and used to facilitate flood control storage operation of existing dams located at the headwaters of the Skagit and Baker Rivers, which are owned and operated by Seattle City Light (SCL) and Puget Sound Energy (PSE), respectively. The HEC-5 model also performs stream flood routing from these dams to the Concrete gage on the Skagit River.

Model calibration and verification were carried out against available observed data for the four most recent major historical flood events: two occurring in November 1990, one in November 1995, and the other in October 2003. Required input hydrographs for the HEC-RAS and HEC-5 models, representing flow contribution during these floods from sequential subbasins along the Skagit River, were developed from the HEC-HMS watershed model. The HEC-HMS model development and analysis is described in a separate technical memorandum entitled *Skagit River Basin Historical Flood Modeling – Hydrology* (Pacific International Engineering, 2004b).

Development of HEC-RAS Model

The HEC-RAS model used for the Skagit River Basin flood routing is a one-dimensional unsteady-flow model. It routes and combines flood hydrographs representing flow contribution from sequential subbasins along the Skagit River from Newhalem [river mile (RM) 93.67] to Skagit Bay (RM 0.00). Development of the model involved modification and expansion of the UNET model for the lower Skagit River below Concrete (RM 55.40) and the HEC-RAS model for the upper Skagit River above Concrete (RM 55.40), both originally developed by the U.S. Army Corps of Engineers (Corps). Model inputs include observed flow hydrographs for gaged subbasins and hydrographs developed from the HEC-HMS model (Pacific International Engineering, 2004b) for ungaged subbasins.

The Corps-developed UNET and HEC-RAS models cover a flood routing reach of the Skagit River between Marblemount (RM 82.35) and Skagit Bay (RM 0.00). Information and data used in the Corps models were collected mainly from the 1984 Federal Emergency Management Agency (FEMA) Flood Insurance Study for Skagit County, the Corps' 1976 aerial photogrammetry survey, and the Skagit County 1999 field survey. Detailed descriptions of the Corps models are presented in the Skagit River Basin Hydraulics Technical Documentation (U.S. Army Corps of Engineers, 2004b). The primary expansions and modifications made to the Corps' UNET and HEC-RAS models for this Skagit River historical flood modeling study are summarized as follows:

- Added three routing reaches and storage in the Nookachamps Creek and floodplain area;

- Added an 11-mile routing reach above Marblemount (RM 82.35), effectively extending the upstream end of the model to the Newhalem streamgage (RM 93.67);

- Modified or added channel bathymetry at 16 cross sections near Concrete (RM 52.55 – RM 55.35) using new data surveyed in October 2004 by Pacific International Engineering (PI Engineering). Performed specific model calibration for seven October 2003 flood high water marks (HWMs) surveyed in summer 2004 by the U.S. Geological Survey (USGS) between RM 53.2 and RM 54.2 (Pacific International Engineering, 2004a);

- Modified cross sections at the confluence of the Sauk and Skagit Rivers to correct double-counted floodplain storage in the Corps' HEC-RAS model;

- Added/modified bridges, levee profiles, and ineffective flow areas based on the best available information; and

- Reviewed and adjusted Manning's 'n' coefficients based on available aerial photos, site visits, engineering judgment, and model runs for calibration and verification.

Other minor changes, such as adjustment of cross section orientations and distance between cross sections, were also made in order to enhance the consistency and accuracy of the model. Figure 1 shows the routing reaches of the modified and expanded Skagit River HEC-RAS model.

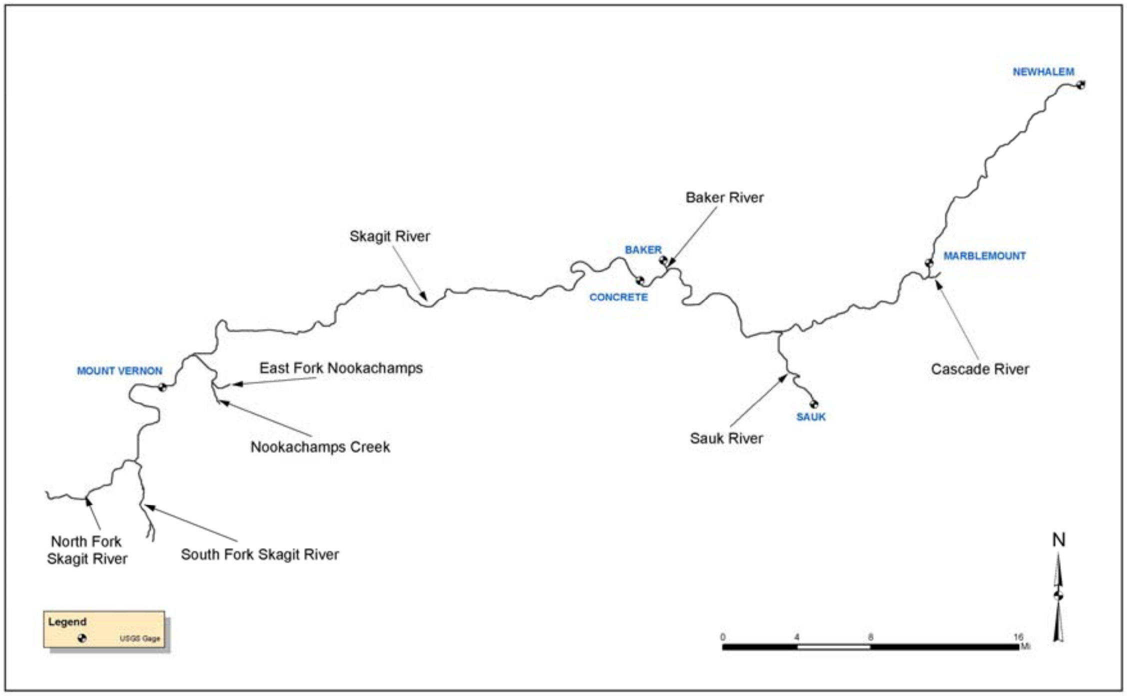


Figure 1 Skagit River HEC-RAS model routing reaches

For modeling efficiency and to meet the needs of the Skagit River Flood Damage Reduction and Ecosystem Restoration Feasibility Study Project (Project), the entire HEC-RAS model was divided into two segments. One segment contains the upper Skagit River from RM 93.67 to RM 22.40 (Newhalem to Sedro Woolley, and selected tributaries). The other segment contains the lower Skagit River from RM 55.40 to RM 0.00 (Concrete to Skagit Bay, and selected tributaries).

Upper Skagit River HEC-RAS Model

The upper Skagit River HEC-RAS model was developed to improve the accuracy and analysis of the hydrology of the upper Skagit River Basin above Concrete and to facilitate development of the HEC-5 model. Using both the observed hydrographs for gaged subbasins and the computed hydrographs from the HEC-HMS rainfall-runoff modeling for ungaged subbasins, the HEC-RAS model is theoretically the best one-dimensional hydrodynamic routing model to reproduce the historical flood hydrographs as observed along the Skagit River between Newhalem and Concrete. Once the historical flood events have been accurately reproduced, the HEC-HMS and HEC-RAS model results would then be used to help with calibration and verification of the HEC-5 model. Use of both calibrated and verified HEC-5 and HEC-RAS models for the routing of synthetic flood hydrographs from Newhalem to Concrete for large events, such as the 100-year flood, could also enhance confidence in both models if the results are comparable between the two models.

Section 4 – Feasibility Study Work Items of the Project Management Plan (PMP) (U.S. Army Corps of Engineers, 2004c) specifies use of the HEC-5 model for evaluation of flood control storage alternatives at SCL's Ross, Diablo, and Gorge Dams, and PSE's Upper and Lower Baker Dams. There are no flood damage assessments and no other alternatives or measures to be evaluated by use of the upper Skagit River HEC-RAS model.

The upper Skagit River model consists of seven reaches, starting at Newhalem (RM 93.67) and ending at Sedro Woolley (RM 22.40). The observed flow hydrographs at the Newhalem gage were used as the upstream boundary conditions, and the modeled stage hydrographs at Sedro Woolley from the lower Skagit River HEC-RAS model were used as the downstream boundary conditions. A summary of the river mile range, number of cross sections, and the ranges of Manning's 'n' coefficients for channel and overbanks determined for each reach is provided in Table 1.

Table 1 Characteristics of Upper Skagit River HEC-RAS Model Routing Reaches

HEC-RAS Reach		River Mile Range (RM)	No. of Cross-sections	Range of Manning's 'n'	
No.	Stream Name			Channel	Overbank
1	Baker River	0.70 to 0.00	7	0.04	0.08 to 0.12
2	Sauk River	5.40 to 0.00	13	0.027 to 0.028	0.06 to 0.07
3	Cascade River	0.95 to 0.00	5	0.035	0.075 to 0.10
4	Skagit River (Above Cascade River)	93.67 to 78.00	32	0.03 to 0.035	0.08 to 0.15
5	Skagit River (Cascade to Sauk)	78.00 to 67.10	32	0.03 to 0.04	0.08 to 0.18
6	Skagit River (Sauk to Baker)	67.10 to 55.75	25	0.03 to 0.045	0.06 to 0.15
7	Skagit River (Baker to Sedro Woolley)	55.75 to 22.40	62	0.03 to 0.038	0.08 to 0.15

Lower Skagit River HEC-RAS Model

The lower Skagit River HEC-RAS model was developed to improve the accuracy and analysis of the lower basin hydrology, to directly or indirectly provide flood depth estimates as input to the HEC-FDA model for baseline flood damage assessment, and to evaluate flood hydraulic and hydrologic consequences of various alternatives and measures of the Project, as specified in the PMP.

The lower Skagit River model consists of seven reaches, starting at Concrete (RM 55.40) and ending at Skagit Bay (RM 0.00). The observed flow hydrographs at the Concrete gage and predicted tidal elevation at Skagit Bay were used as upstream and downstream boundary conditions, respectively. A summary of the river mile range, number of cross sections, and the ranges of Manning's 'n' coefficients for channel and overbanks determined for each reach is provided in Table 2.

Table 2 Characteristics of Lower Skagit River HEC-RAS Model Routing Reaches

HEC-RAS Reach		River Mile Range (RM)	No. of Cross-sections	Range of Manning's 'n'	
No.	Stream Name			Channel	Overbank
1	Skagit River (Above Nookachamps)	55.35 to 20.00	76	0.03 to 0.038	0.08 to 0.15
2	Nookachamps Creek	4.06 to 3.02	4	0.07	0.08
3	East Fork Nookachamps	1.54 to 0.00	10	0.07	0.08
4	Nookachamps Creek	3.02 to 0.00	13	0.07	0.08
5	Skagit River (Nookachamps to N/S Forks)	20.00 to 9.25	29	0.03 to 0.035	0.08 to 0.15
6	North Fork, Skagit River	9.25 to 0.00	25	0.03 to 0.035	0.10
7	South Fork, Skagit River	9.25 to 0.00	15	0.035	0.10 to 0.12

Geometric Data

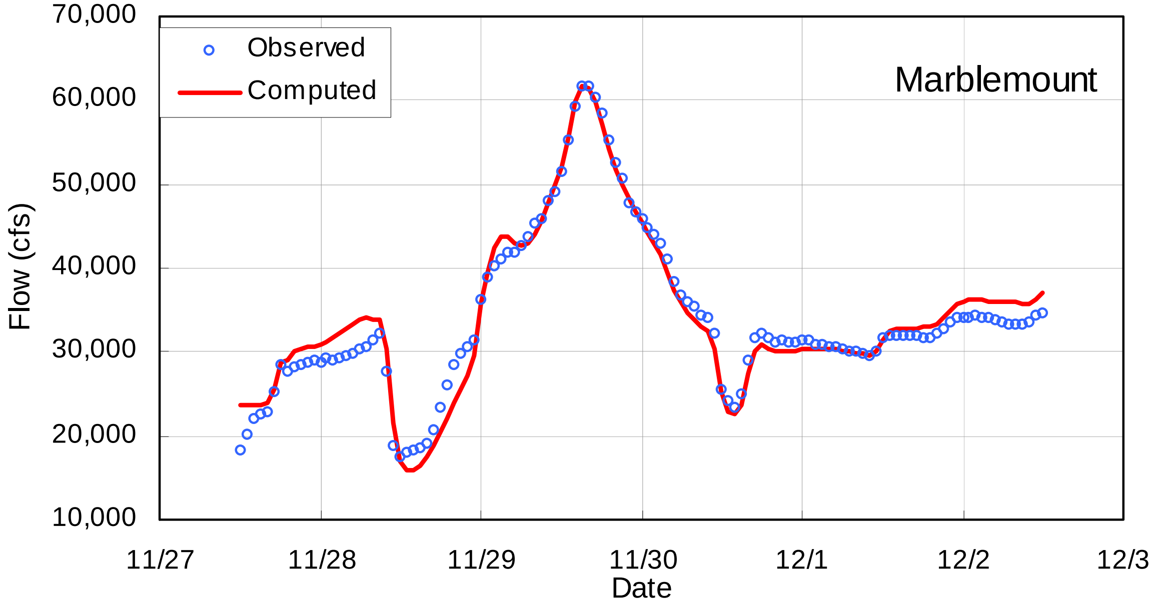
The topographic maps provided by the Corps were used for the model expansion and modifications of the Corps-developed UNET model from Sedro Woolley (RM 22.40) to Skagit Bay, including newly added Nookachamps Creek reaches and storage areas in the Nookachamps region. These maps are based on aerial photography taken in August 1998 at a scale of 1 inch to 400 feet. From Sedro Woolley (RM 22.40) to Marblemount (RM 82.35), geometric data used for the modifications were based on work maps from the 1976 Flood Insurance Study provided by the Corps and FEMA. Data used for the model expansion from Marblemount (RM 82.35) to Newhalem (RM 93.67) were based on USGS topographic maps. The levee profiles from Sedro Woolley to Skagit Bay were recently surveyed and provided by Skagit County. New channel bathymetry, surveyed by PI Engineering in October 2004 between RM 53.2 and RM 54.2 near Concrete, was also incorporated into the model.

Among the bridge data incorporated into the new model are a number of additional bridges not originally included in the Corps models. These bridges include Cascade River Road Bridge at Marblemount (over Skagit River), Skagit River Bridge at Rockport, Dalles Bridge, E. Fork Nookachamps Creek Bridge (State Route 9), Swan Road Bridge, Francis Road Bridge, South Fork of Skagit River Bridge on Fir Island Road, and North Fork of Skagit River Bridge on Chilberg Road. Bridge design drawings providing these data were obtained from either Skagit County or Washington State Department of Transportation (WSDOT).

Model Calibration

The upper and lower Skagit River HEC-RAS models were initially calibrated for the November 1995 flood using both observed stage and flow hydrographs at the Marblemount, Concrete, and Mount Vernon gages and the stage-only hydrographs at Newhalem, Rockport, and Sauk. The calibration procedures primarily involved adjustment of Manning's 'n' values for both channels and overbanks, as well as for the ineffective flow areas (locations and elevations). Upon satisfactory calibration of the stage and flow hydrographs, further calibration was performed using HWM data provided by the Corps and Skagit County. Bridge debris and logjams were observed during the November 1995 flood. Based on available photos taken during the flood, the effects of debris partially plugging the bridge opening were added to the lower Skagit River model at two locations: BNSF Bridge (RM 17.51) and the abandoned former Great Northern Railroad Bridge (RM 22.38). In order to match available HWMs upstream of these two bridges, debris-plugging conditions during the November 1995 flood were estimated to be approximately 20 feet high and 530 feet wide upstream of the BNSF Bridge (RM 17.51) and 9 feet high and 610 feet wide at the abandoned former Great Northern Railroad Bridge (RM 22.38).

Comparisons of stage and flow hydrographs at the Marblemount, Concrete, Mount Vernon, Newhalem, Rockport, and Sauk gages are shown in Figure 2. The figure indicates good matches overall between modeled and observed hydrographs, particularly during the flood peak hours. Figure 3 shows the comparison of stage-flow rating curves at the Marblemount, Concrete, and Mount Vernon gage locations. The flood stage calibration results at locations of available HWMs are presented in Table 3, which also shows good agreement, except at two locations (RM 46.97 and RM 40.03). The HWM data at these two locations, provided by the Corps, do not match the model results by several feet and are subject to further verification of data credibility.



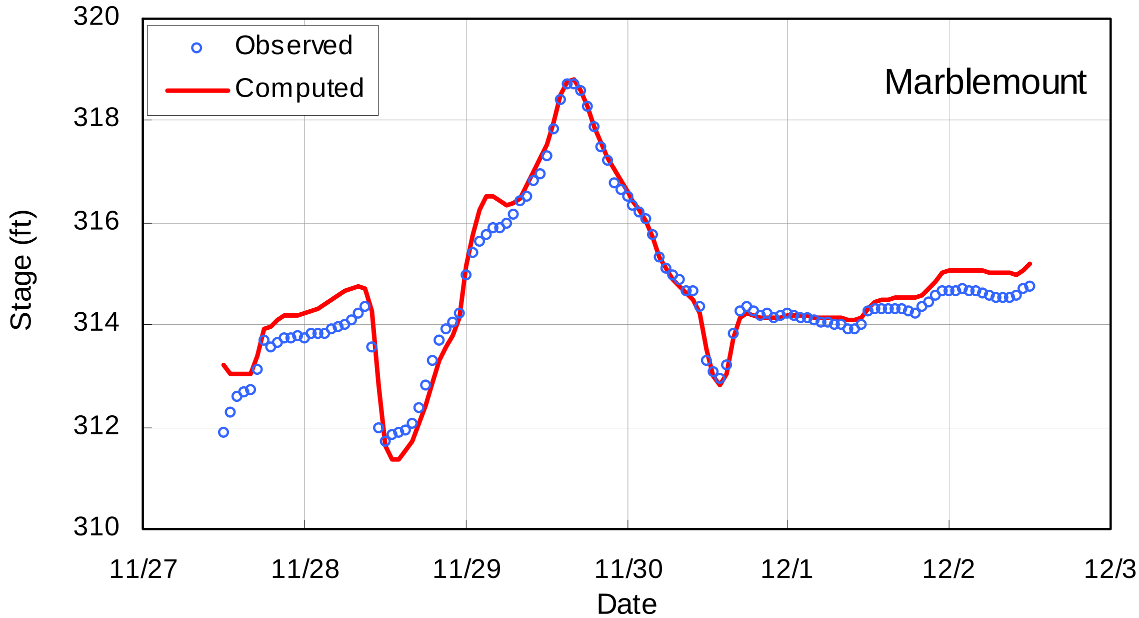
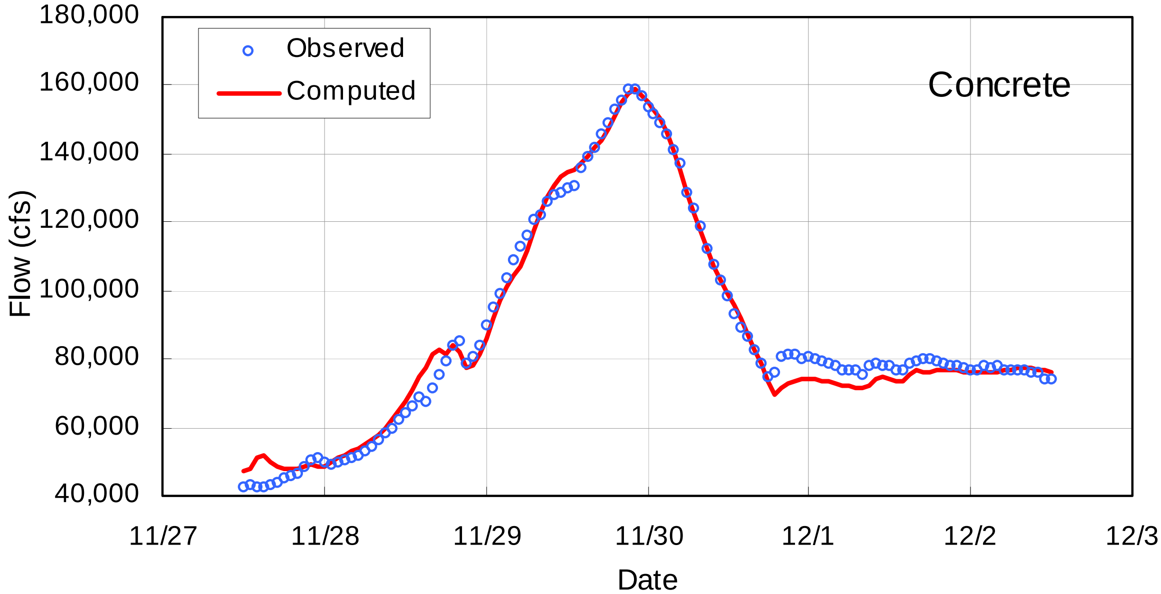


Figure 2a Model calibration: comparison of computed and observed flow and stage hydrographs at Marblemount, November 1995 flood



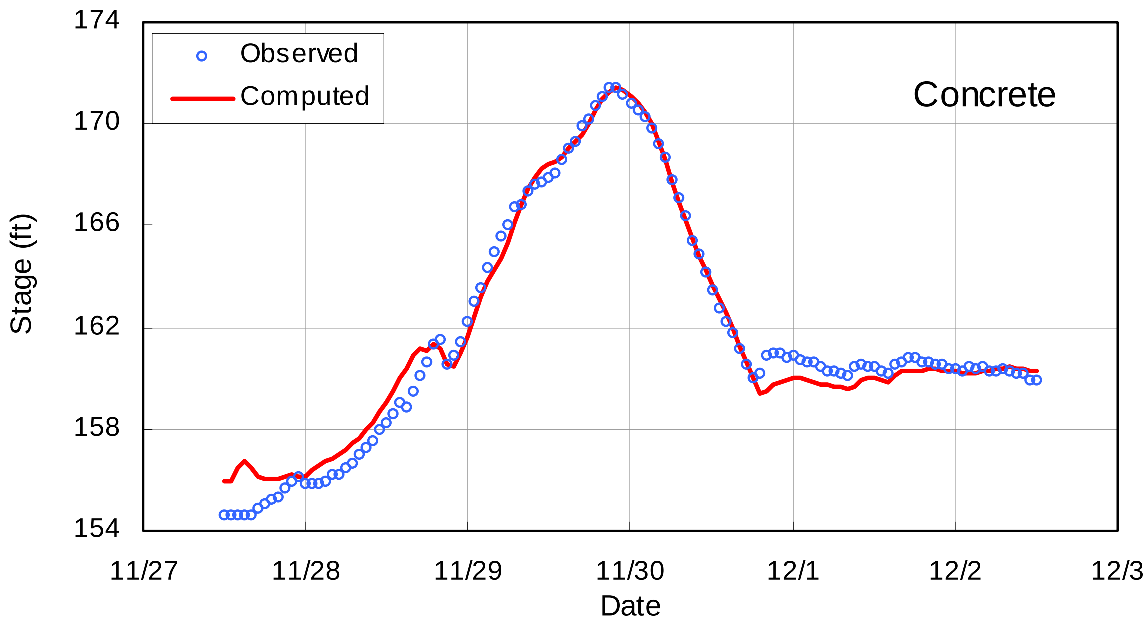


Figure 2b Model calibration: comparison of computed and observed flow and stage hydrographs at Concrete, November 1995 flood

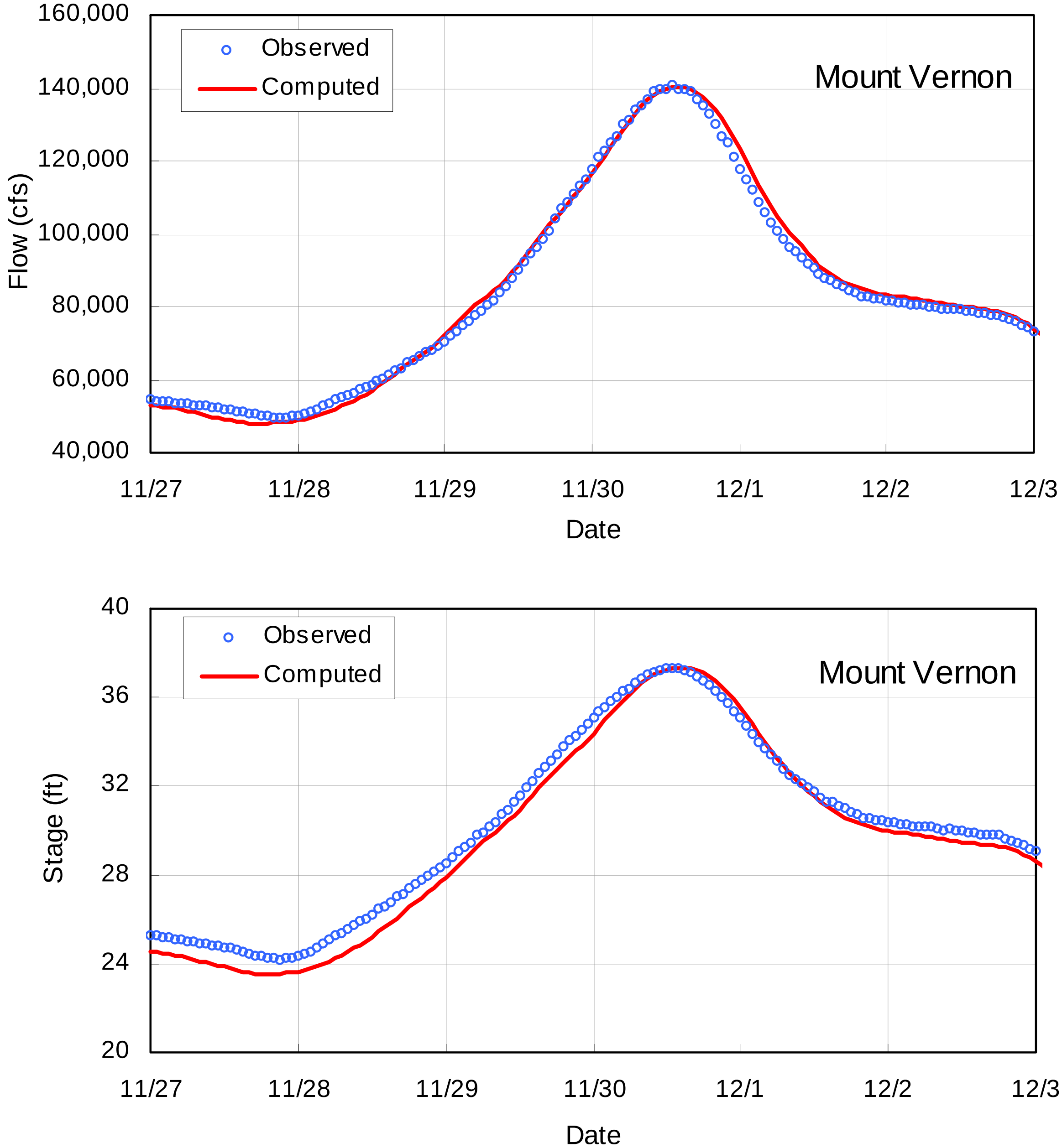


Figure 2c **Model calibration: comparison of computed and observed flow and stage hydrographs at Mount Vernon, November 1995 flood**

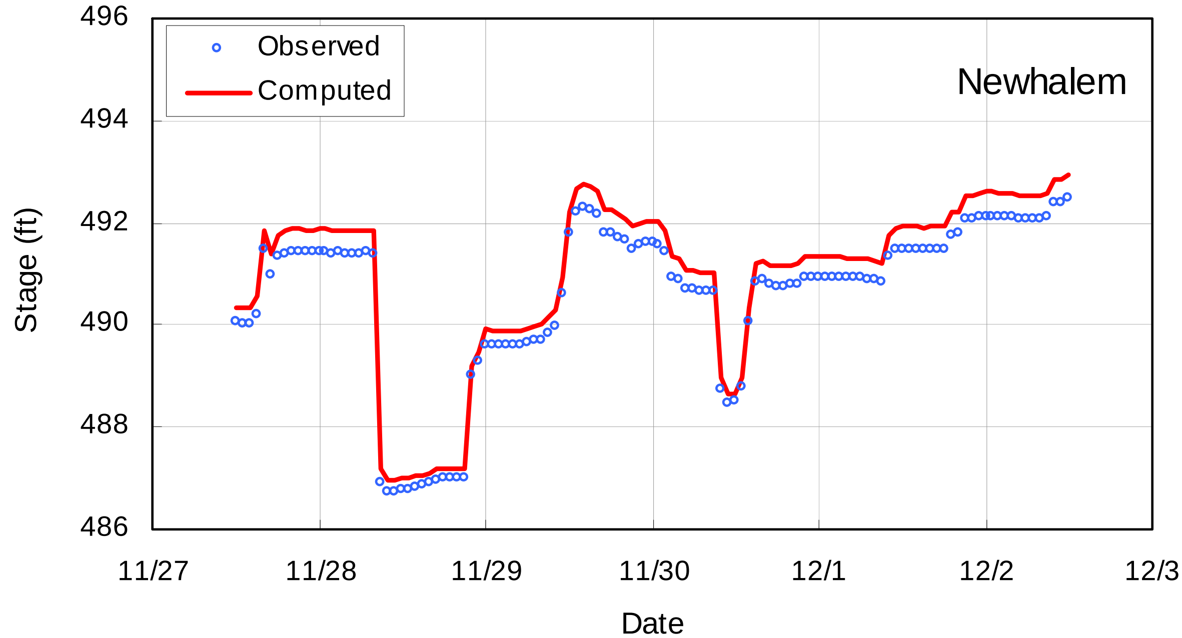


Figure 2d Model calibration: comparison of computed and observed stage hydrograph at Newhalem, November 1995 flood

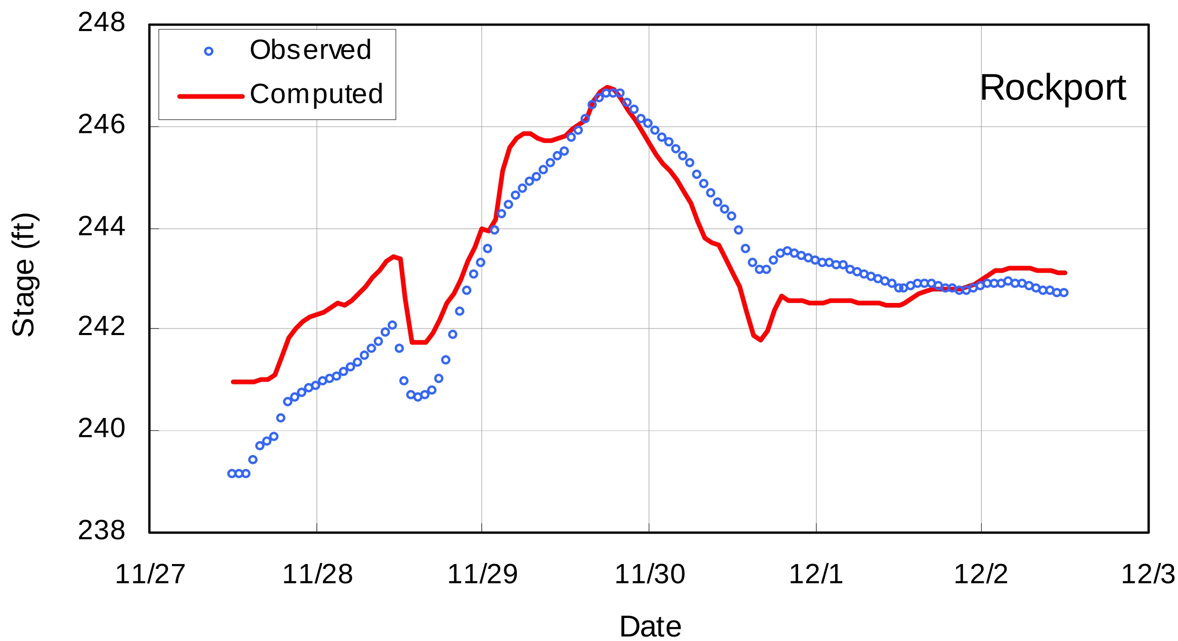


Figure 2e Model calibration: comparison of computed and observed stage hydrograph at Rockport, November 1995 flood

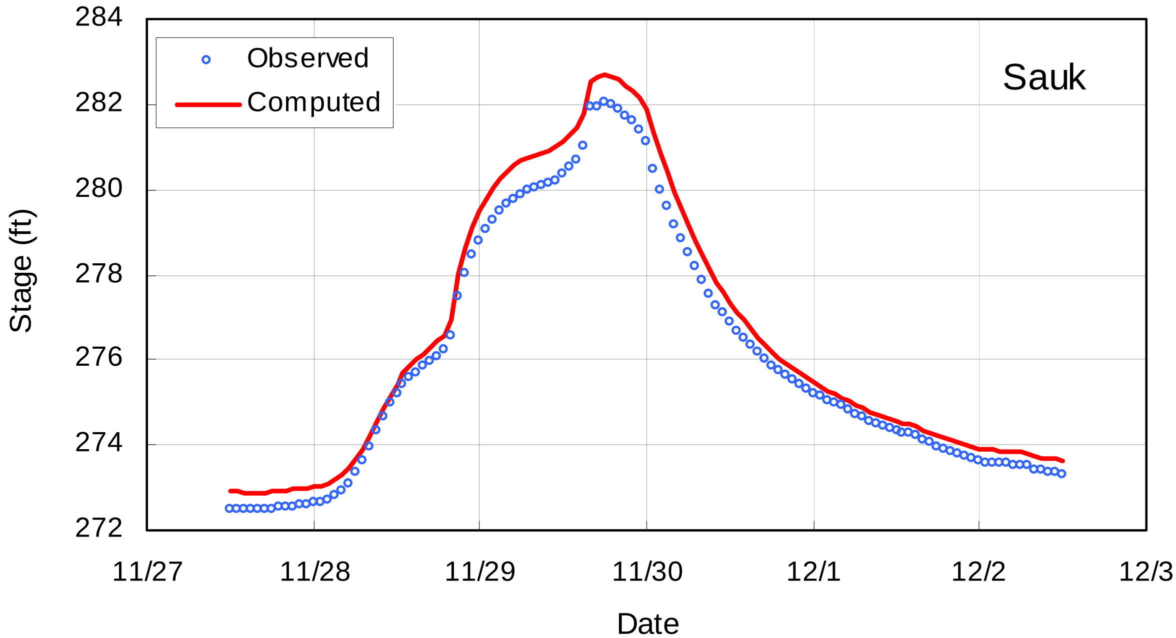


Figure 2f **Model calibration: comparison of computed and observed stage hydrograph at Sauk, November 1995 flood**

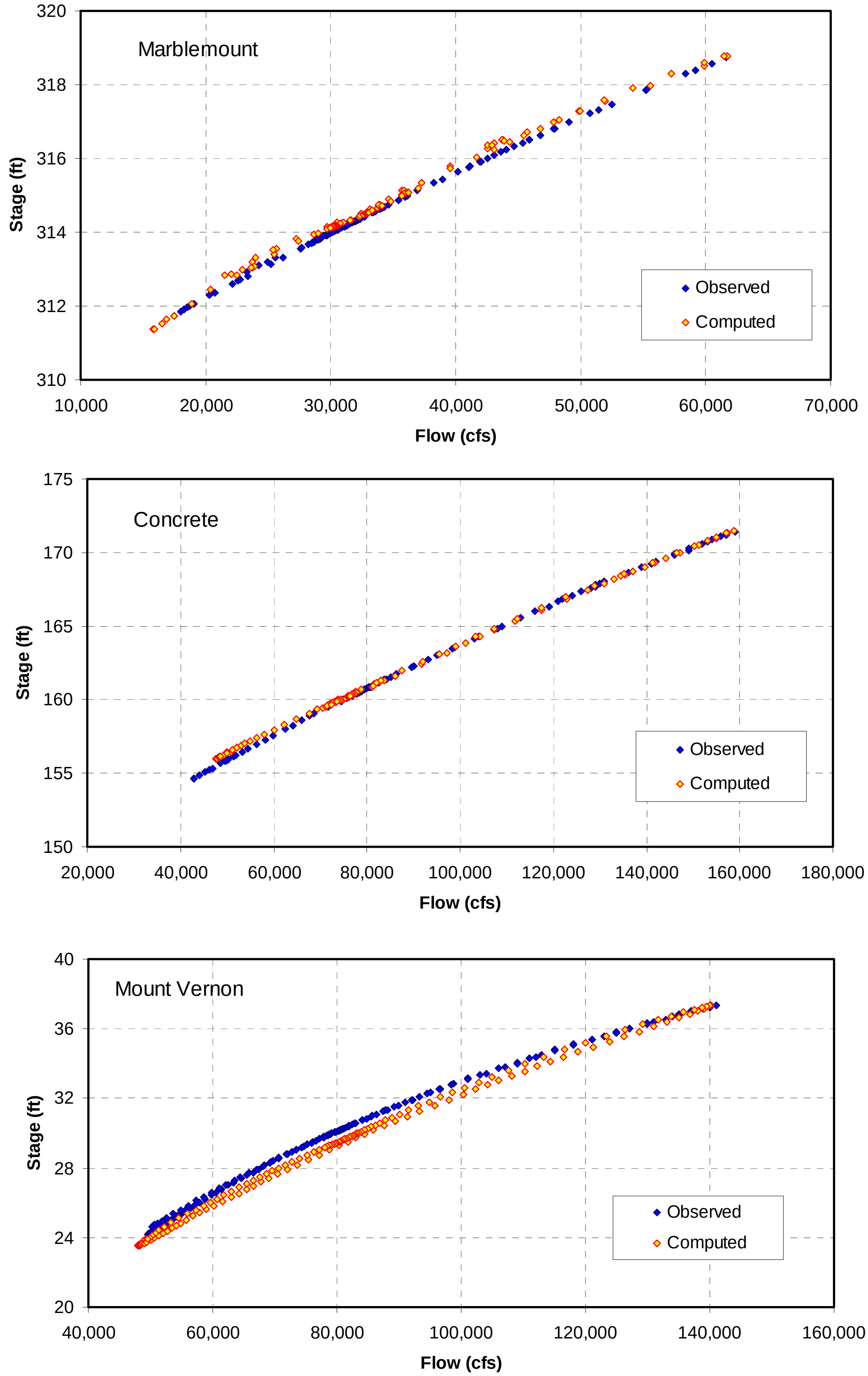


Figure 3 Comparison of computed and observed stage-flow rating curves at three gage stations, November 1995 flood

Table 3 Comparison of Computed and Observed Maximum Water Surface Elevations (November 1995 Flood)

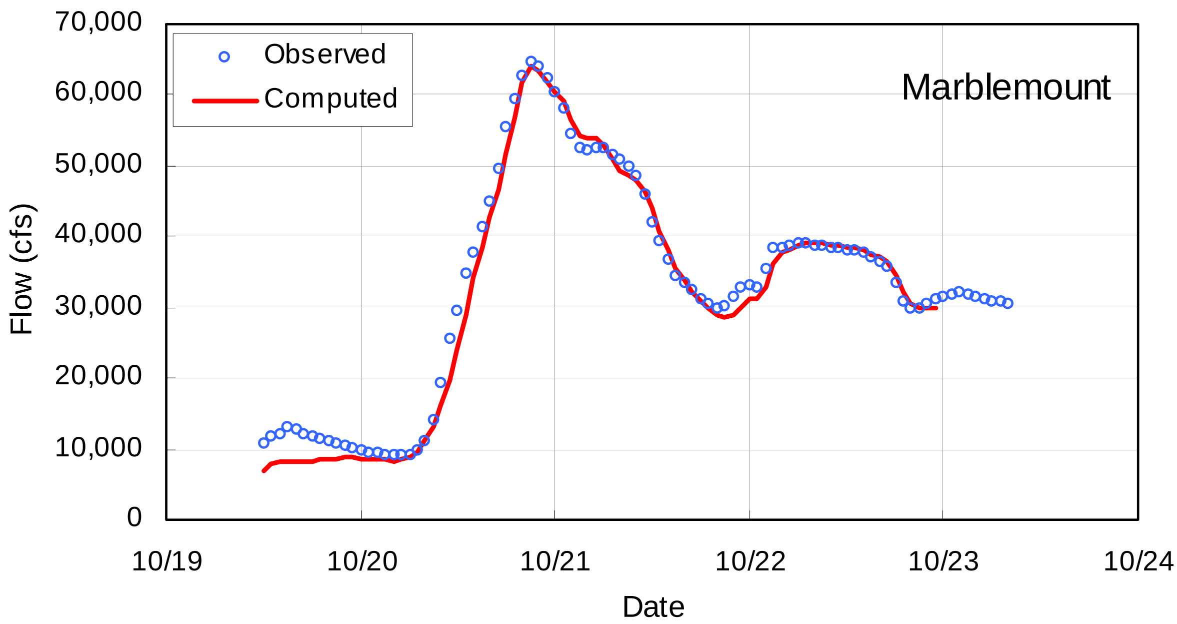
Event	Date	Time	Location (RM)	Data Source	Computed (ft)	Observed (ft)	Difference Between Computed and Observed (ft)
Nov-95			54.15	Corps	171.51	171.60	-0.09
Nov-95			52.90	Corps	163.33	162.80	0.53
Nov-95			46.97	Corps	132.78	138.70	-5.92
Nov-95			40.03	Corps	99.76	103.30	-3.54
Nov-95			32.93	Corps	71.51	71.90	-0.39
Nov-95			30.30	Corps	62.12	61.30	0.82
Nov-95			24.70	Corps	50.90	50.80	0.10
Nov-95			22.45	Corps	46.29	46.18	0.11
Nov-95	30-Nov	14:38	22.20	County	41.56	41.90	-0.34
Nov-95	30-Nov	11:07	21.93	County	41.24	41.30	-0.06
Nov-95	30-Nov	11:40	21.93	County	41.24	41.40	-0.16
Nov-95	30-Nov	13:17	20.80	County	41.19	41.10	0.09
Nov-95	30-Nov	13:30	20.80	County	41.19	40.90	0.29
Nov-95	30-Nov	12:50	18.40	County	40.18	39.80	0.38

Model Verification

The upper and lower Skagit River Basin HEC-RAS models calibrated for the November 1995 flood were verified against observed stage and flow hydrographs at the Marblemount, Concrete, Mount Vernon, Newhalem, Rockport, and Sauk gages for the October 2003 flood and the two November 1990 floods. For model verification, geometry and Manning's 'n' values remain unchanged, while debris conditions at four bridges [the BNSF Bridge (RM 17.51), the former Great Northern Railroad Bridge (RM 22.38), the Skagit River Bridge at Rockport (RM67.86), and the Cascade River Road Bridge at Marblemount (RM 78.30)] were adjusted to account for differences between flood events and to match available HWMs.

October 2003 Flood

For the October 2003 flood, no debris conditions were specified at the BNSF Bridge (RM 17.51) and the debris heights at the abandoned former Great Northern Railroad Bridge (RM 22.38) were adjusted to about 6 to 7 ft in order to match the HWMs upstream. Debris conditions were also applied to the Skagit River Bridge at Rockport in the upper Skagit River model. According to Skagit County's 2003 flood monitoring records, a logjam caused Skagit River water to break out and overflow Martin Road (elevation 225 feet, RM 68.25) at approximately 12:30PM on October 20, 2003. Figures 4 and 5 show a comparison of the computed and observed hydrographs and rating curves at the same gage stations as used in the calibration model for the 1995 flood. The computed hydrographs match the observation reasonably well at the Newhalem, Rockport, Sauk River, and Marblemount gages. At the Concrete and Mount Vernon gages, however, the computed hydrographs appear to have higher peaks than those observed. In a recent discussion, USGS stated that power outages at the Mount Vernon gage occurred twice during the hours before and around the flood peak, which had caused some data to be missed. This could be the reason for the lack of flood peak in the observed flow and stage hydrographs at the Mount Vernon gage. In fact, as shown in Table 4, the USGS peak stage reading at the Mount Vernon gage is 0.46 foot lower than Skagit County's HWM reading at the same location (RM 17.05), while the model-computed peak stage has a better match to Skagit County's HWM. Further comparison of the computed maximum water surface elevations and all observed HWMs for the October 2003 flood, shown in Table 5, indicates overall good agreement.



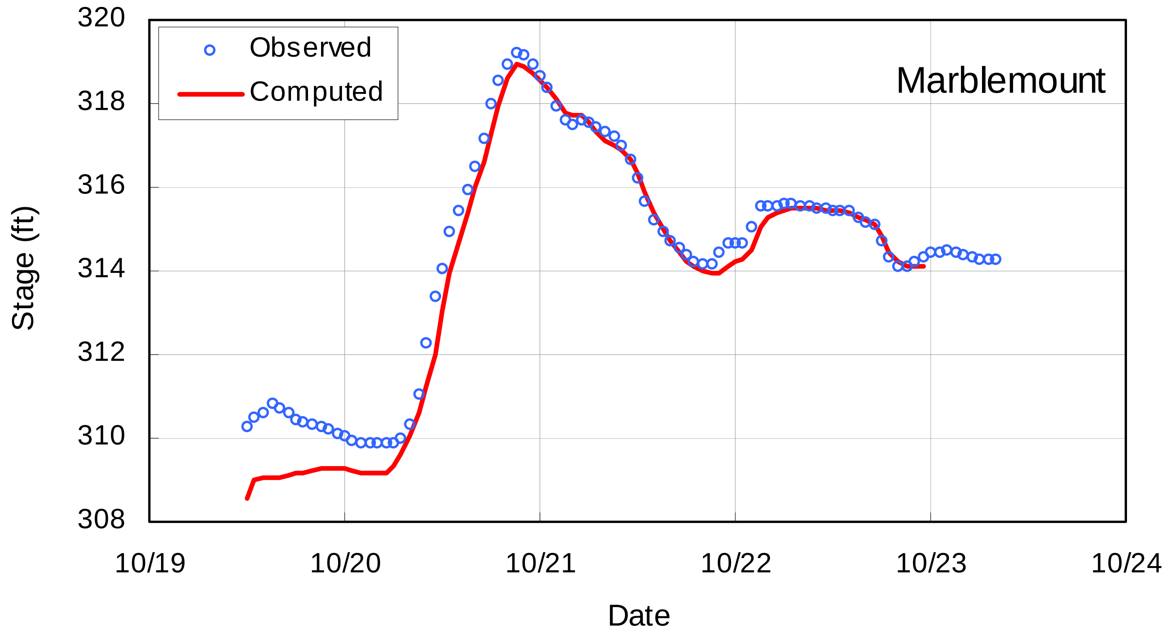


Figure 4a **Model verification: comparison of computed and observed flow and stage hydrographs at Marblemount, October 2003 flood**

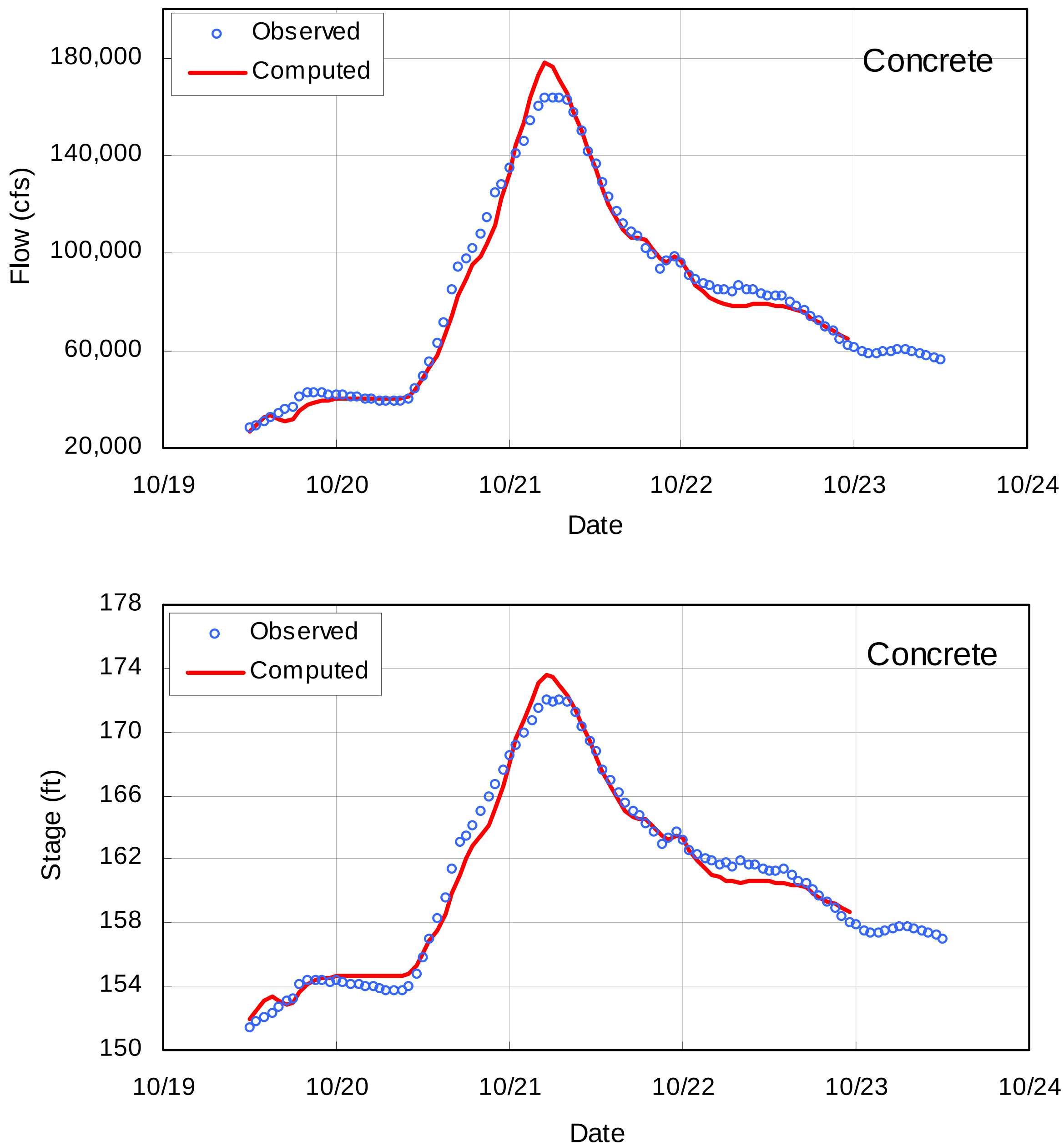
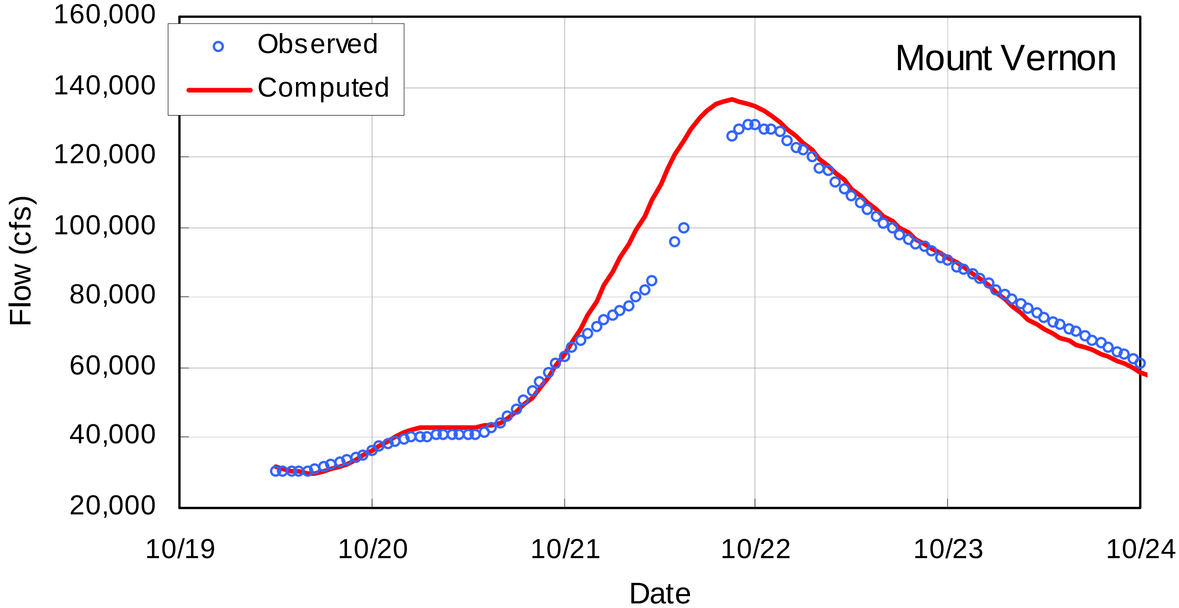


Figure 4b Model verification: comparison of computed and observed flow and stage hydrographs at Concrete, October 2003 flood



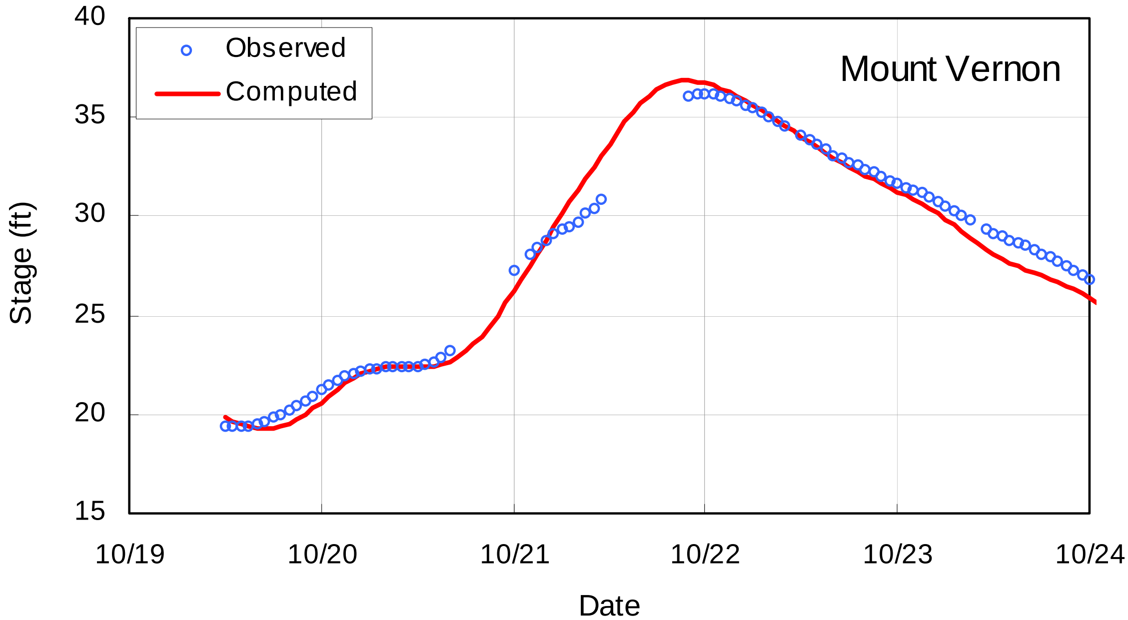


Figure 4c **Model verification: comparison of computed and observed flow and stage hydrographs at Mount Vernon, October 2003 flood**

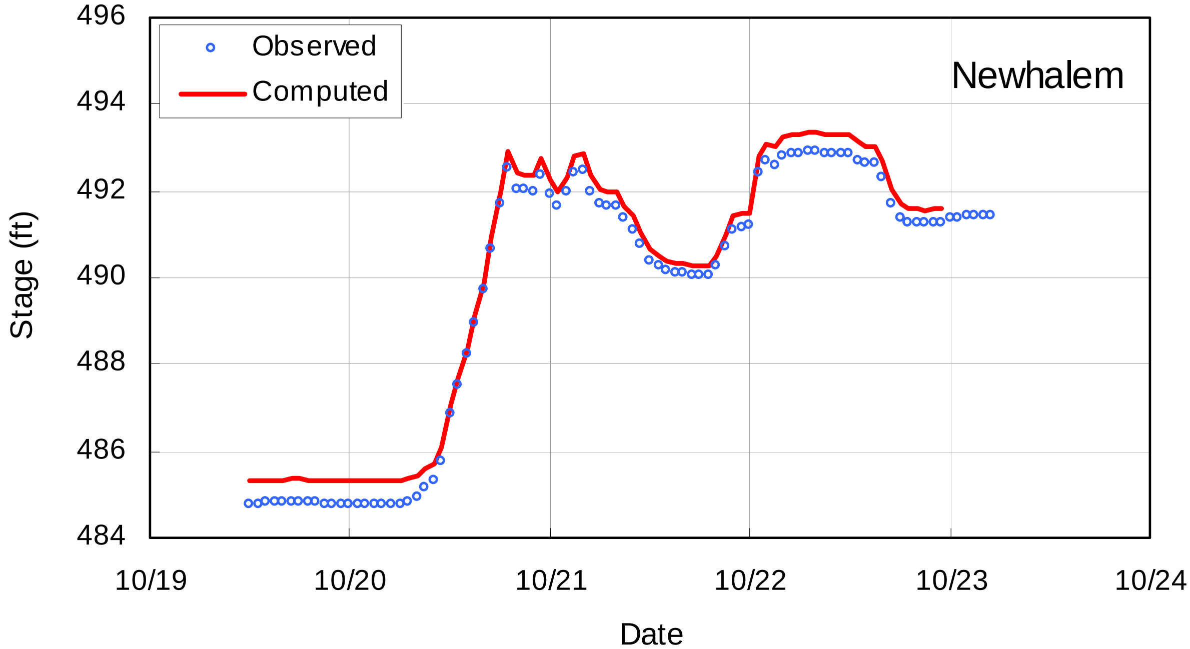


Figure 4d **Model verification: comparison of computed and observed stage hydrograph at Newhalem, October 2003 flood**

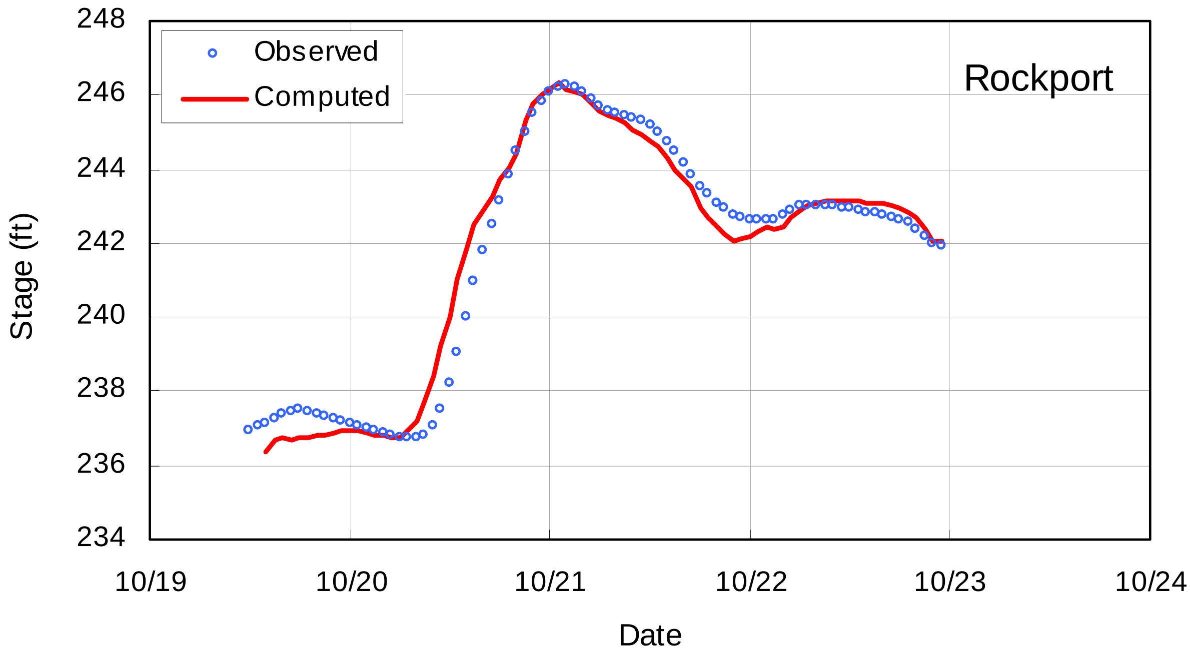


Figure 4e **Model verification: comparison of computed and observed stage hydrograph at Rockport, October 2003 flood**

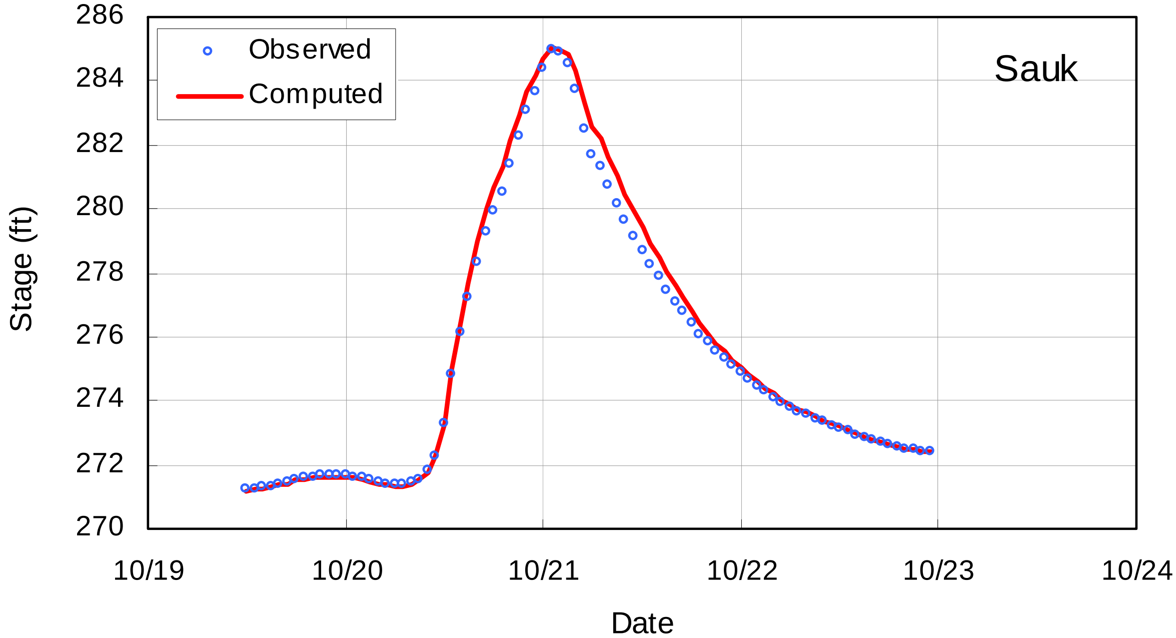


Figure 4f **Model verification: comparison of computed and observed stage hydrograph at Sauk, October 2003 flood**

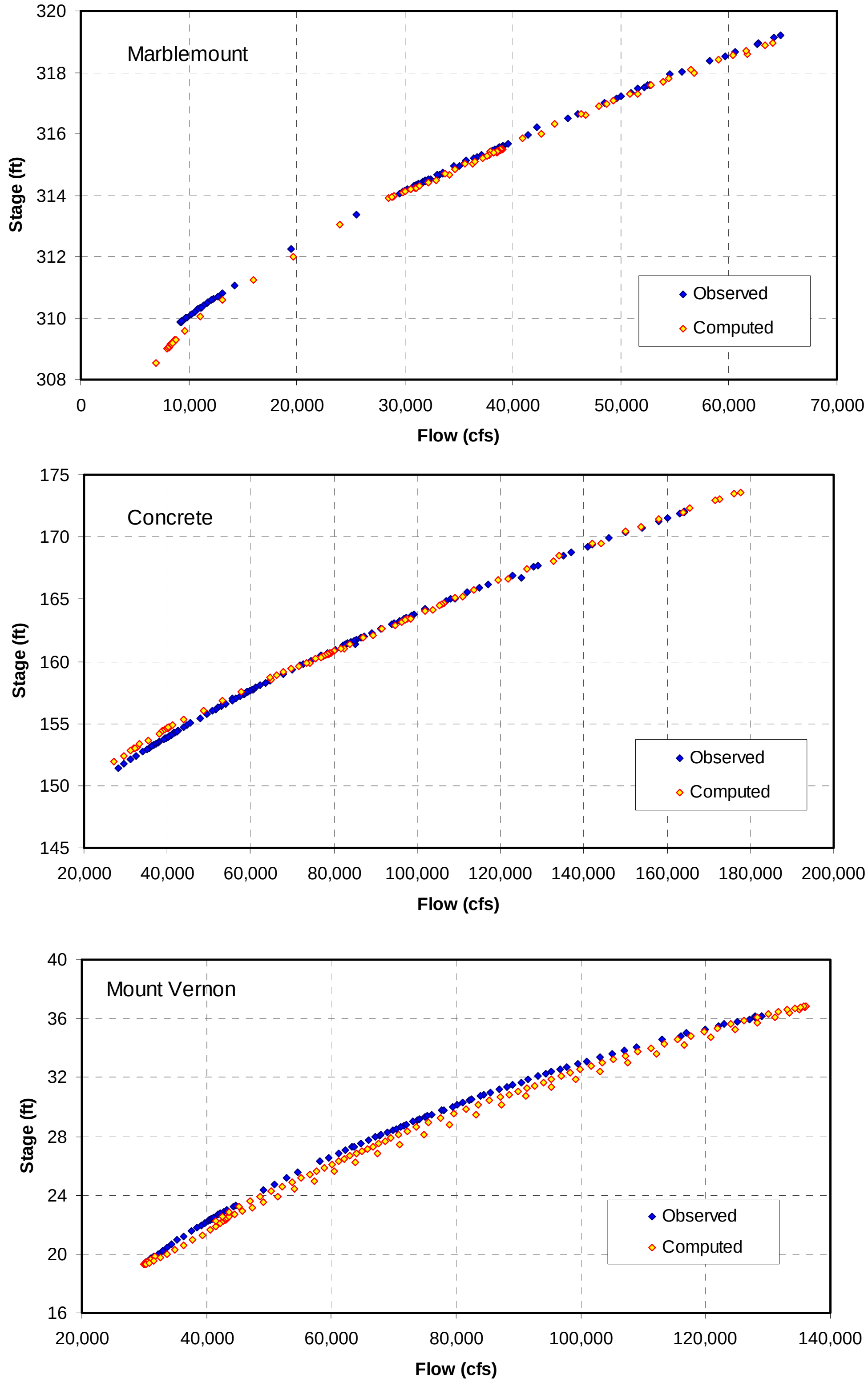


Figure 5 Comparison of computed and observed stage-flow rating curves at three gage stations, October 2003 flood

Table 4 Comparison of 2003 Peak Flood Stage at the Mount Vernon Gage

	Peak Stage (ft)	Difference from Skagit County Reading* (ft)
USGS gage station reading	36.18	-0.46
Model computed	36.86	0.22

*Skagit County HWM reading is 36.64 feet.

Table 5 Comparison of Computed and Observed Maximum Water Surface Elevations (October 2003 and November 1990 Floods)

Event	Date	Time	Location (RM)	Data Source	Computed (ft)	Observed (ft)	Difference Between Computed and Observed (ft)
Oct-03	20-Oct	Peak	59.62	County	195.40	195.48	-0.08
Oct-03	20-Oct	Peak	50.3	County	150.08	150.01	0.07
Oct-03	20-Oct	Peak	40.10	County	100.58	100.66	-0.08
Oct-03	20-Oct	Peak	30.65	County	63.52	63.51	0.01
Oct-03	20-Oct	Peak	22.80	County	45.12	45.17	-0.05
Oct-03	20-Oct	Peak	21.30	County	40.06	40.71	-0.65
Oct-03	20-Oct	Peak	19.48	County	40.03	39.72	0.31
Oct-03	20-Oct	Peak	17.05	County	36.86	36.64	0.22
Oct-03	20-Oct	Peak	15.95	County	35.12	35.21	-0.09
Oct-03	20-Oct	Peak	13.15	County	29.90	30.22	-0.32
Oct-03	20-Oct	Peak	12.20	County	28.28	28.19	0.11
Oct-03	20-Oct	Peak	8.10 (NF Skagit)	County	21.37	21.23	0.14
Oct-03	20-Oct	Peak	5.9 (SF Skagit)	County	15.76	15.89	-0.13
Oct-03	20-Oct	Peak	4.50 (NF Skagit)	County	11.75	11.74	0.01
Oct-03	20-Oct	Peak	2.50 (SF Skagit)	County	10.01	10.32	-0.31
Nov-90	11-Nov	Peak	17.53	County	40.88	41.32	-0.44
Nov-90	25-Nov	Peak	17.53	County	41.98	41.93	0.05

November 1990 Floods

Two November 1990 floods (November 8-14 and November 22-27) were simulated and plotted separately against the observed flow and stage hydrographs and stage-flow rating curves in Figures 6 through 9. Debris conditions were applied to the BNSF Bridge and the Cascade River Road Bridge at Marblemount (RM 78.30). The same debris-plugging conditions were applied to both floods. At BNSF Bridge, debris heights were adjusted to match two HWMs at RM 17.53 (Table 5). At the Cascade River Road Bridge on the upper Skagit River, logjam conditions during the 1990 floods were confirmed by the Skagit County bridge inspector. By specifying debris upstream of the bridge, the observed stage hydrographs of the two floods at the Marblemount gage were reasonably reproduced by the calibrated HEC-RAS model. As shown in Figures 6 through 9, reasonable agreement between computed and observed flow hydrographs was achieved at all gages for both peak floods. The two peak stages at the Mount Vernon gage were overestimated by about 1 foot, probably due to the assumption of no levee failure in the current HEC-RAS model. Levee failures downstream on Fir Island occurred during both November 1990 floods, reportedly causing the Skagit River stage to decrease by up to two feet upstream during the first peak period.

The calibrated and verified unsteady-flow HEC-RAS model was also used to simulate the 1990 floods as a double-peak event. Figure 10 shows the overall comparison of the 20-day model simulation against the observed flow hydrograph at the Mount Vernon gage. Figure 11 indicates the process of double-peak flood routing from the Concrete gage to Sedro Woolley and to Mount Vernon.

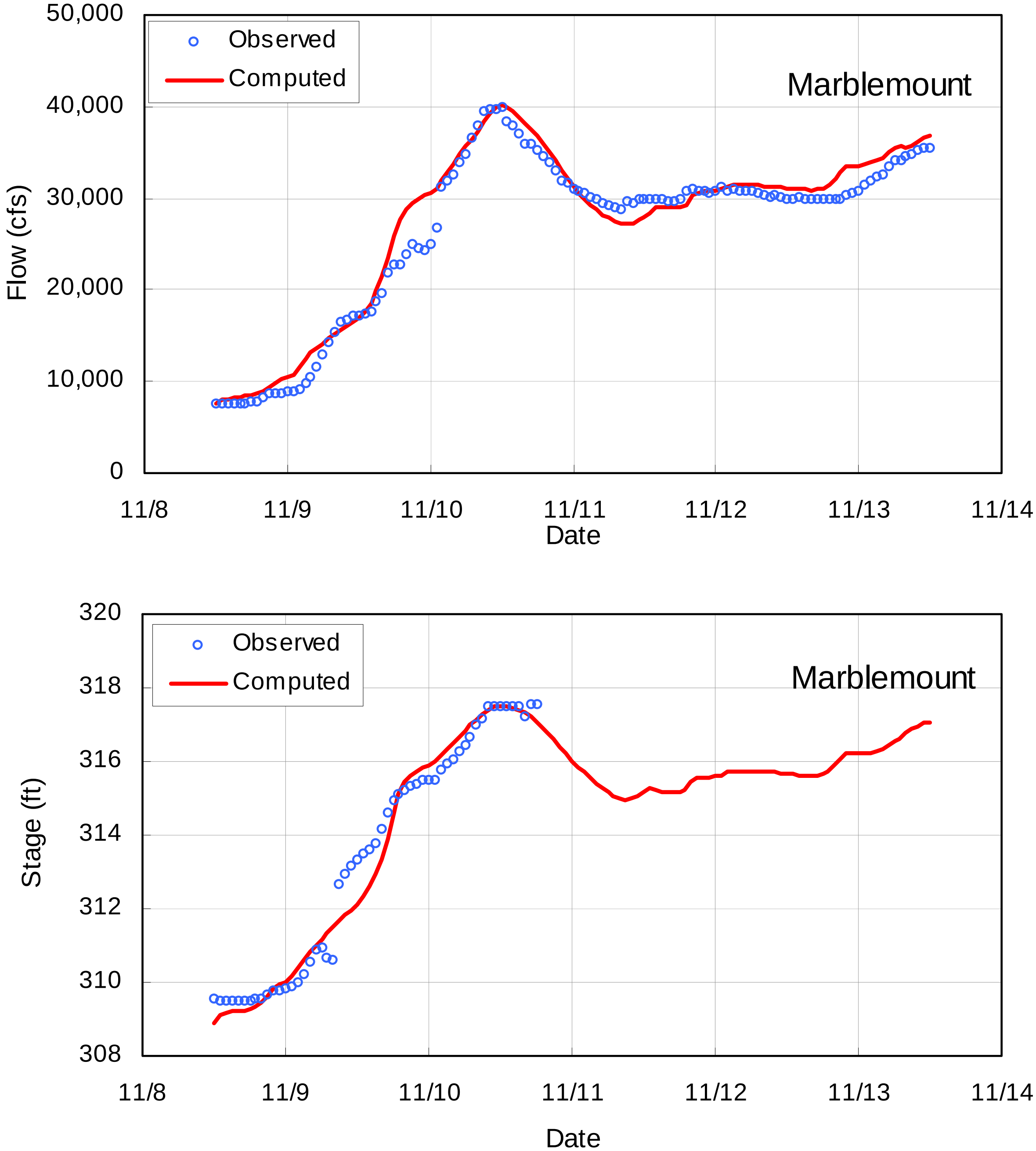
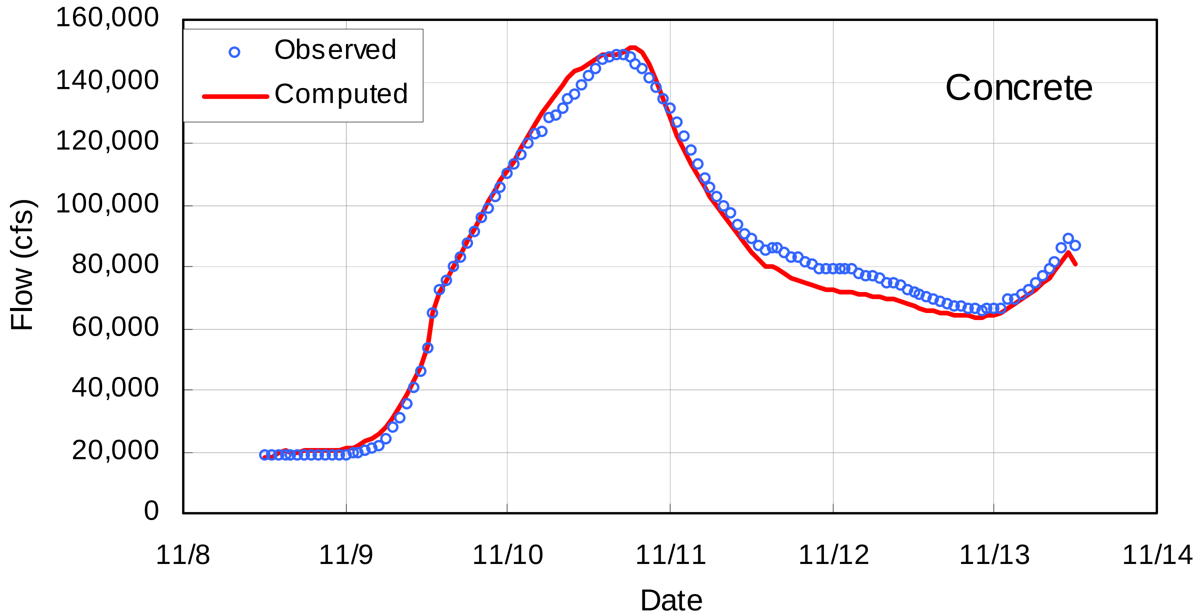


Figure 6a **Model verification: comparison of computed and observed flow and stage hydrographs at Marblemount, November 8-14, 1990 flood**



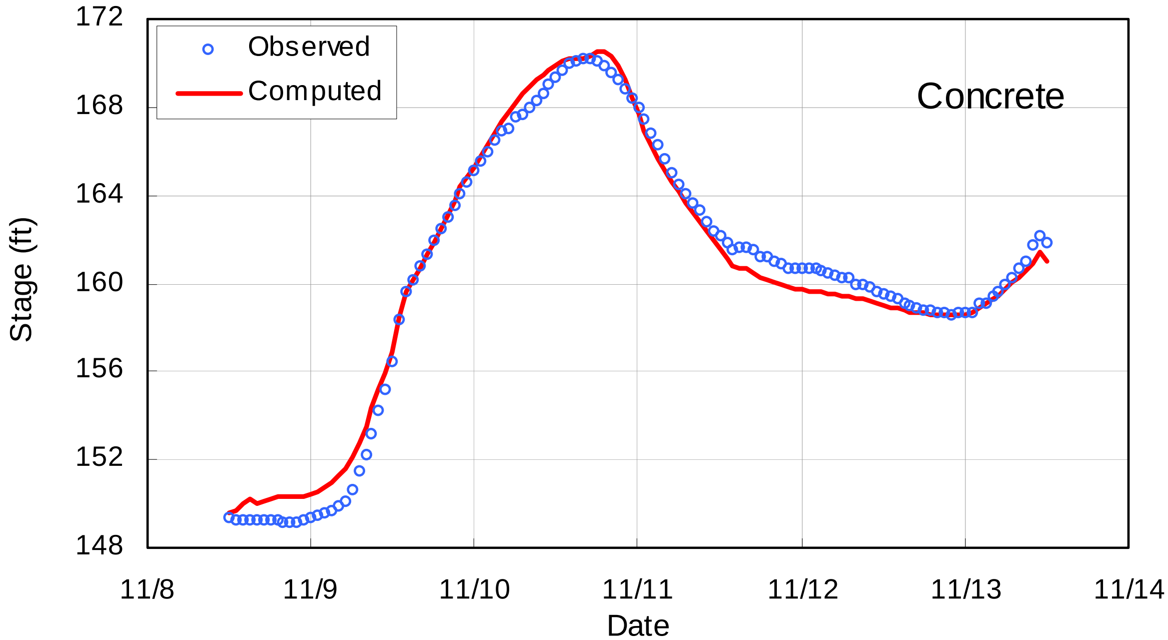


Figure 6b **Model verification: comparison of computed and observed flow and stage hydrographs at Concrete, November 8-14, 1990 flood**

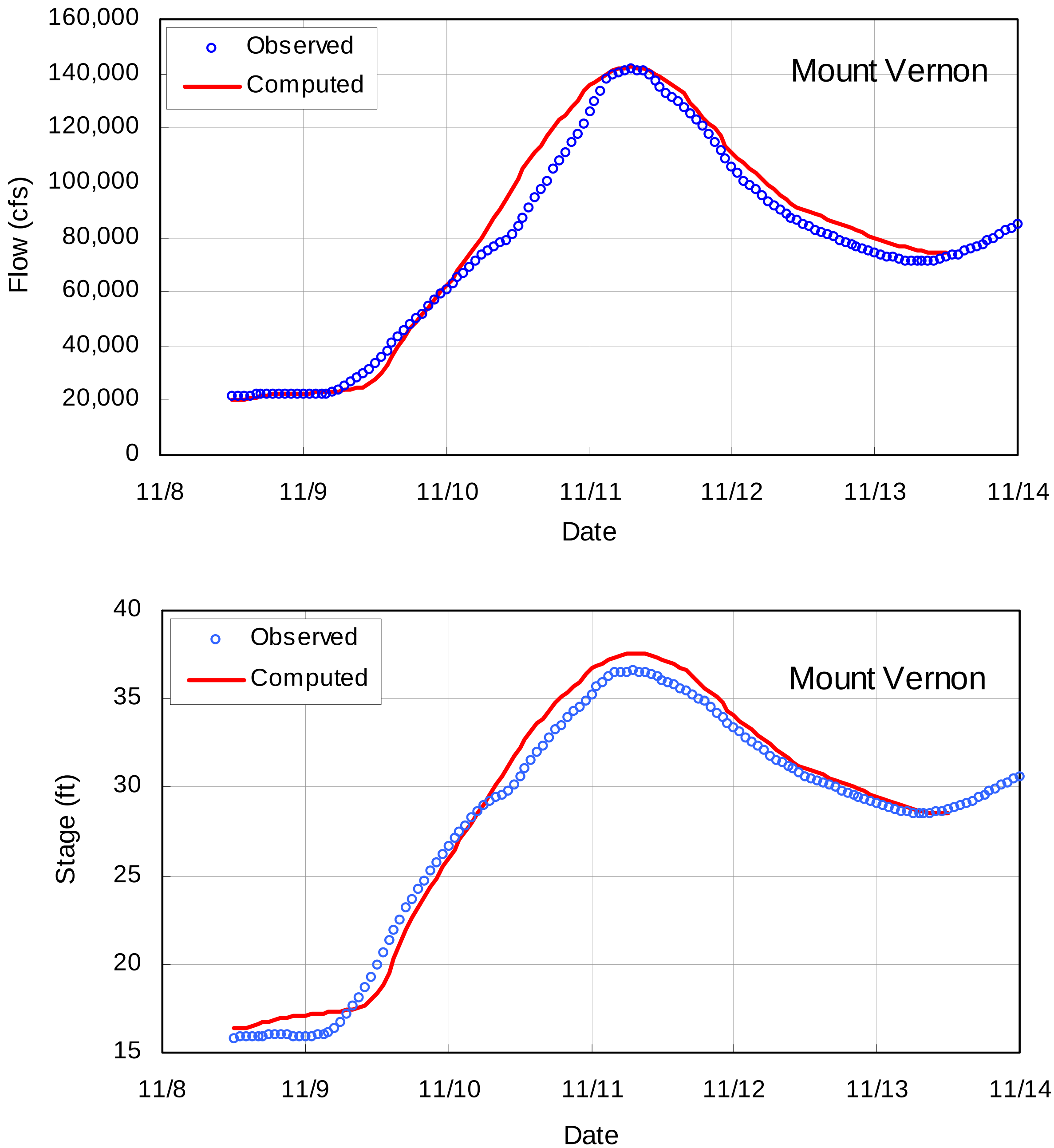


Figure 6c Model verification: comparison of computed and observed flow and stage hydrographs at Mount Vernon, November 8-14, 1990 flood

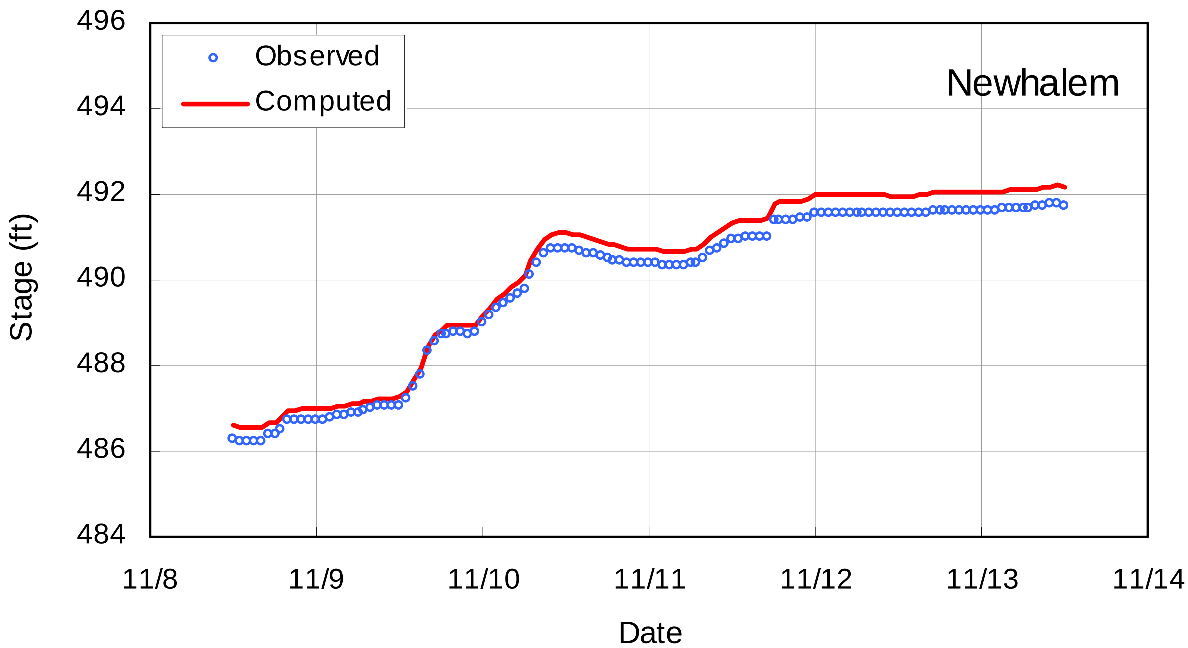


Figure 6d **Model verification: comparison of computed and observed stage hydrograph at Newhalem, November 8-14, 1990 flood**

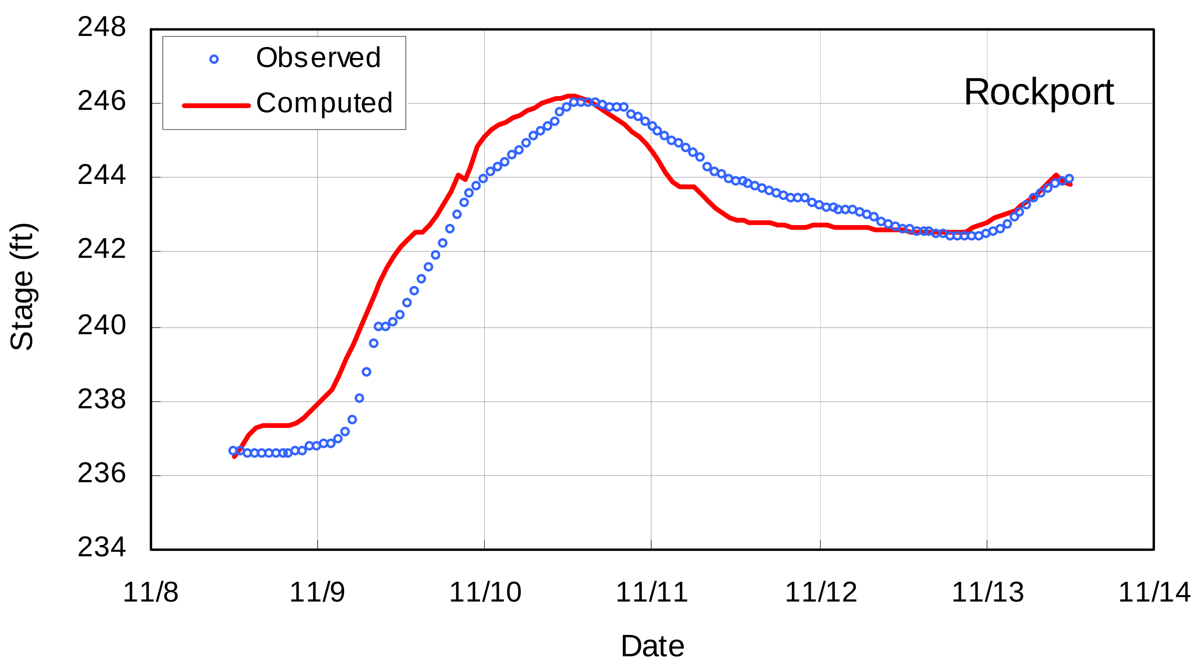


Figure 6e **Model verification: comparison of computed and observed stage hydrograph at Rockport, November 8-14, 1990 flood**

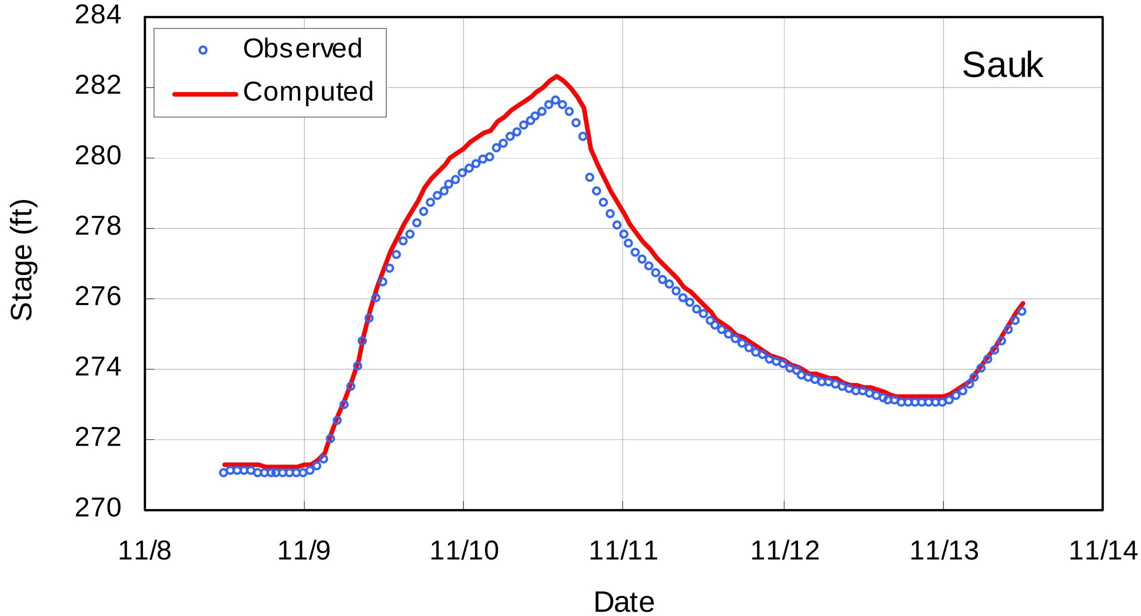


**Figure 6f	Model verification: comparison of computed and observed stage hydrograph at Sauk, November 8-14, 1990 flood**

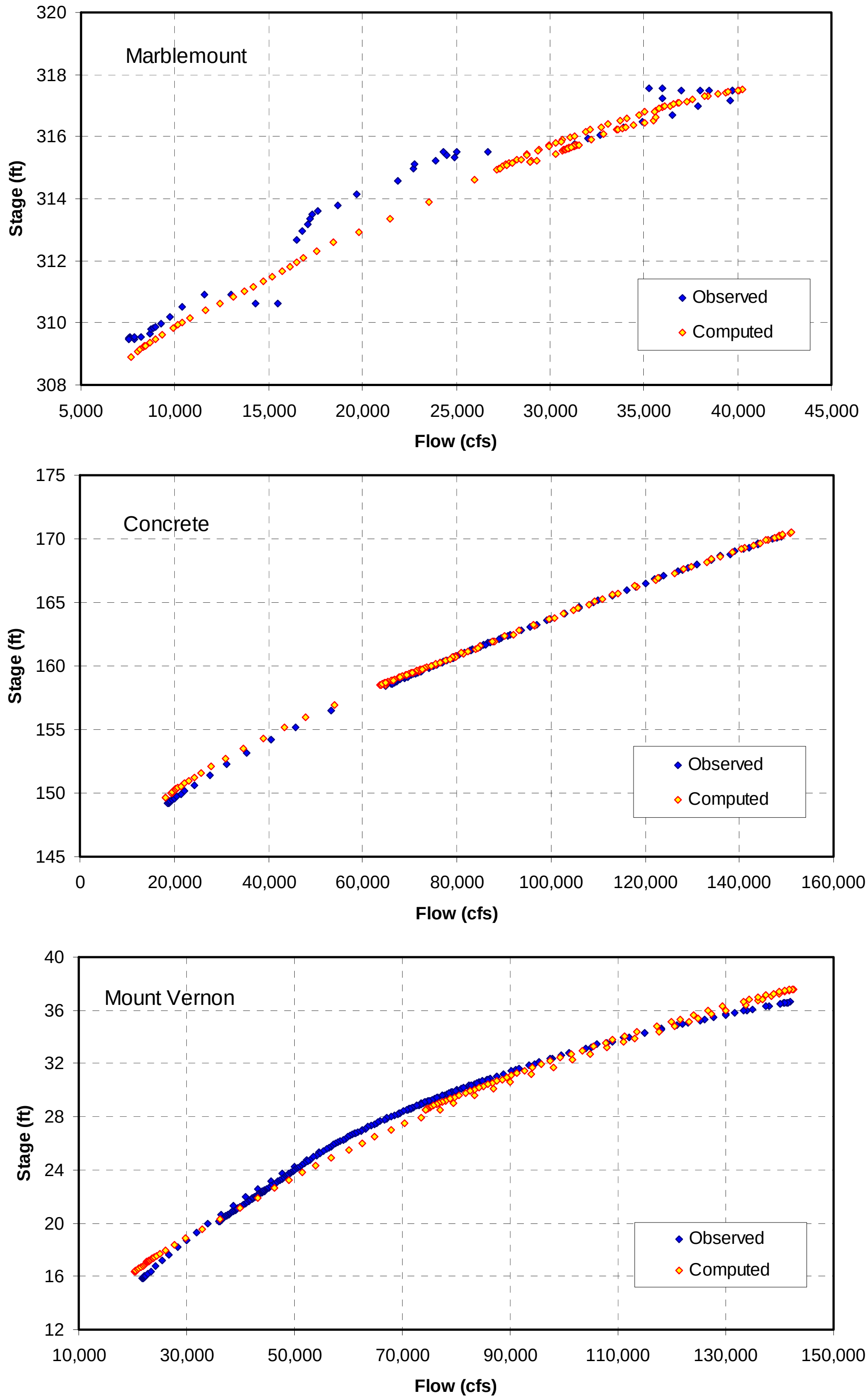


Figure 7 Comparison of computed and observed stage-flow rating curves at three gage stations, November 8-14, 1990 flood

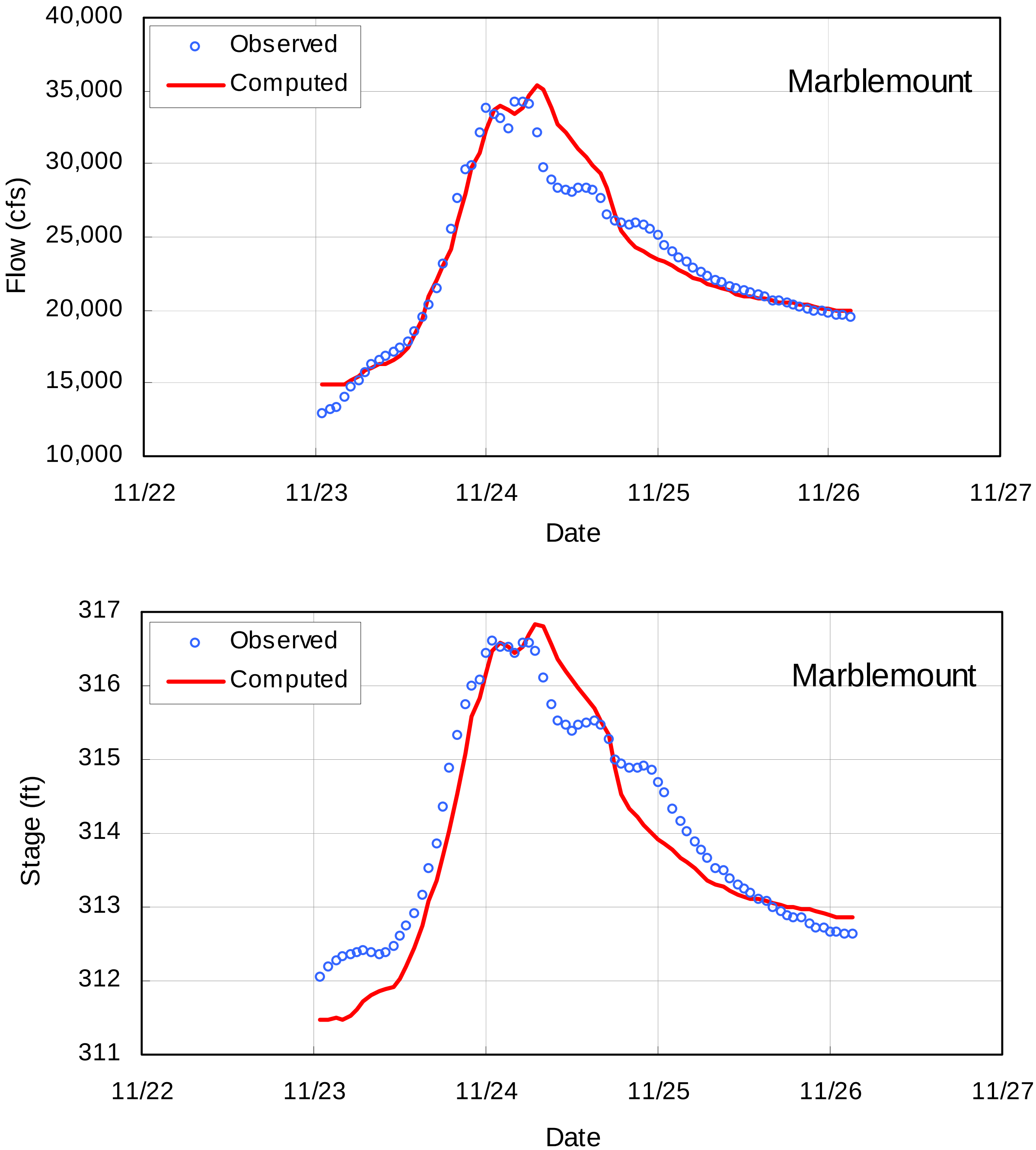
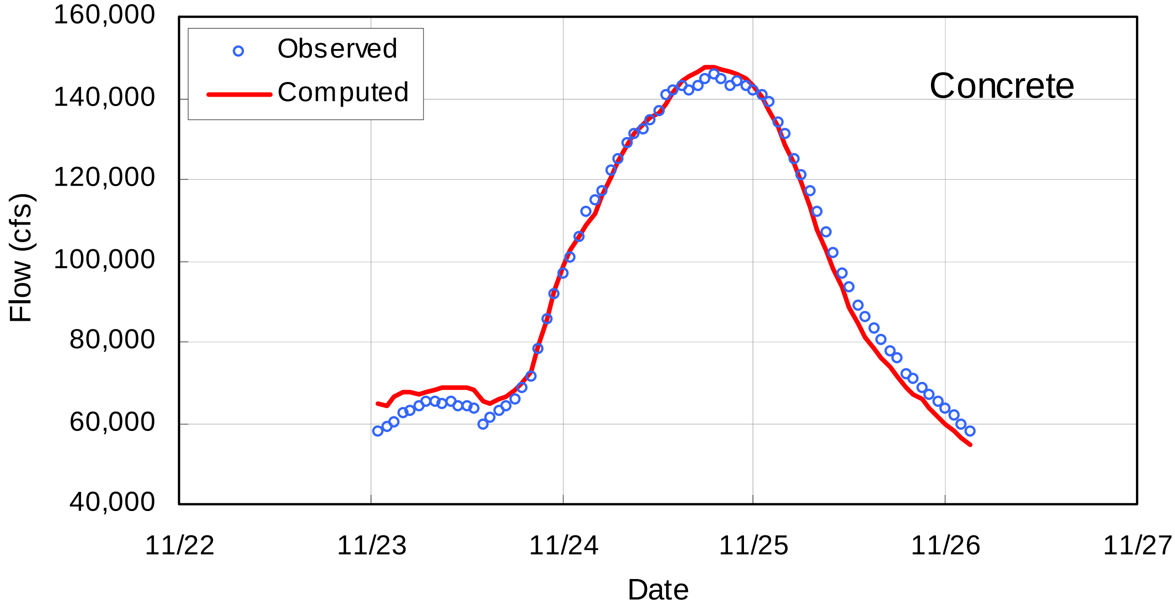


Figure 8a Model verification: comparison of computed and observed flow and stage hydrographs at Marblemount, November 22-27, 1990 flood



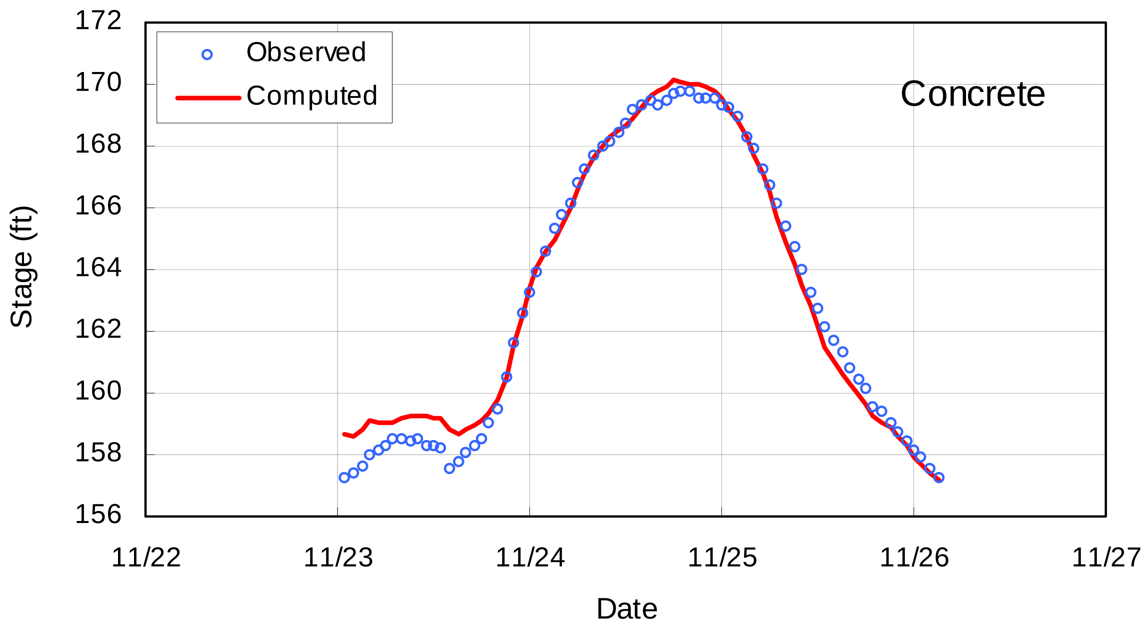
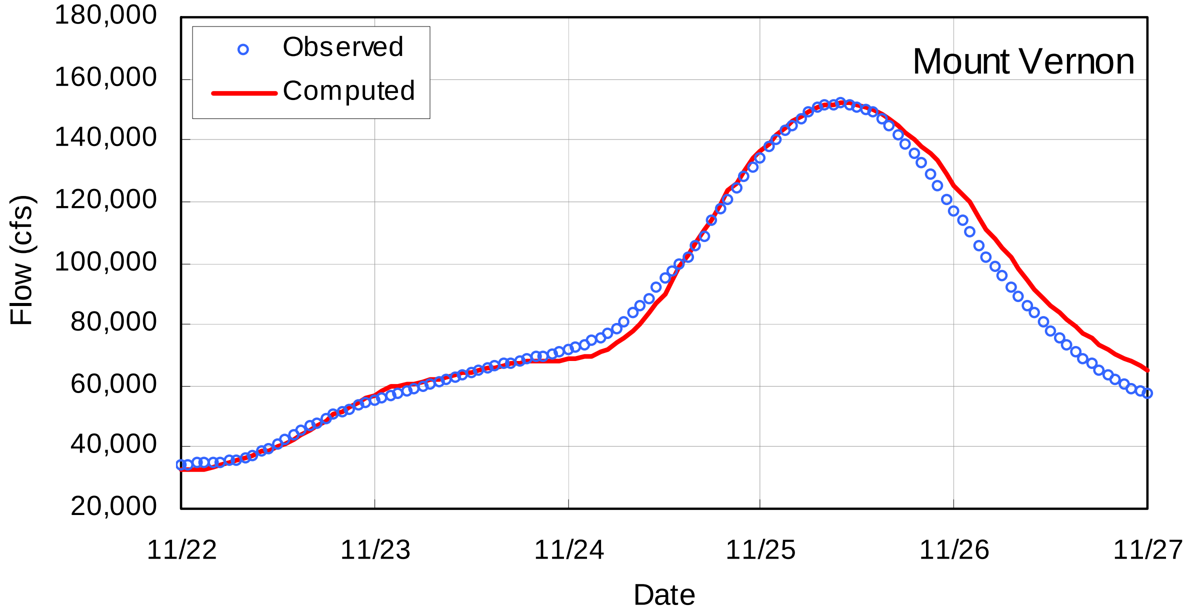


Figure 8b Model verification: comparison of computed and observed flow and stage hydrographs at Concrete, November 22-27, 1990 flood



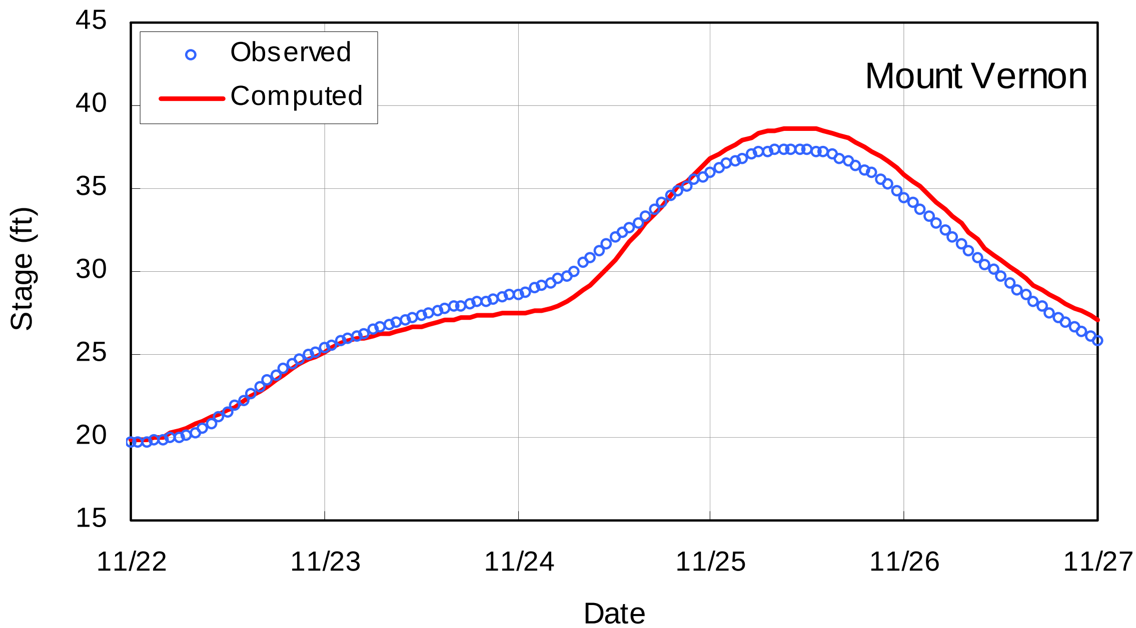


Figure 8c Model verification: comparison of computed and observed flow and stage hydrographs at Mount Vernon, November 22-27, 1990 flood

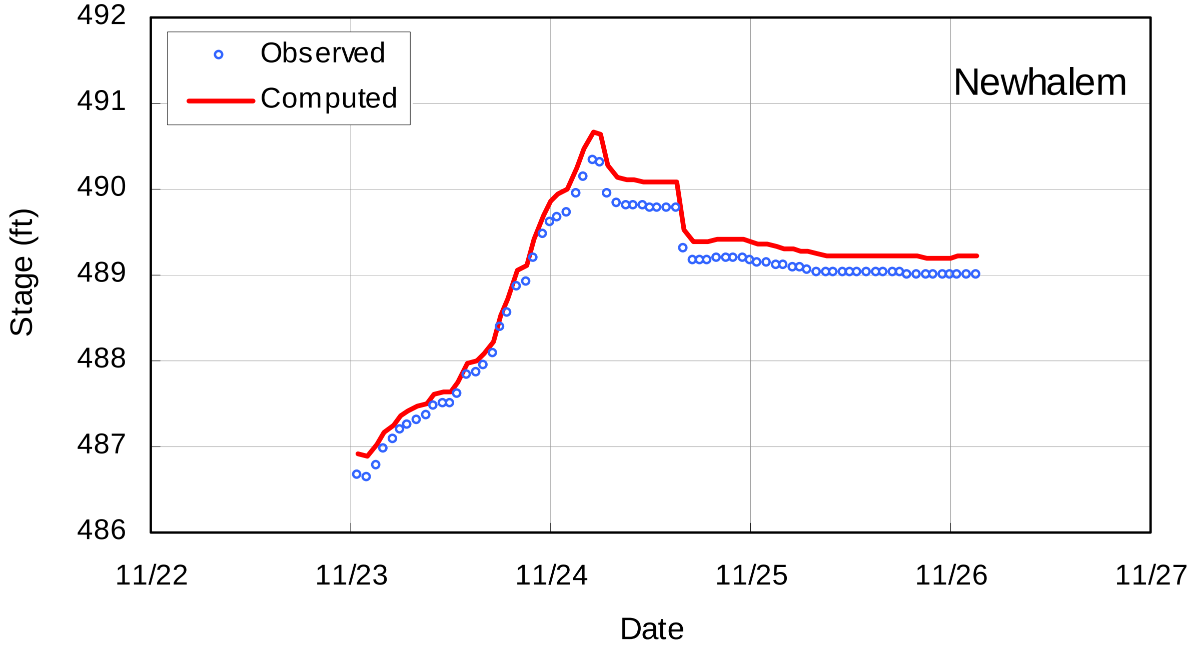


Figure 8d **Model verification: comparison of computed and observed stage hydrograph at Newhalem, November 22-27, 1990 flood**

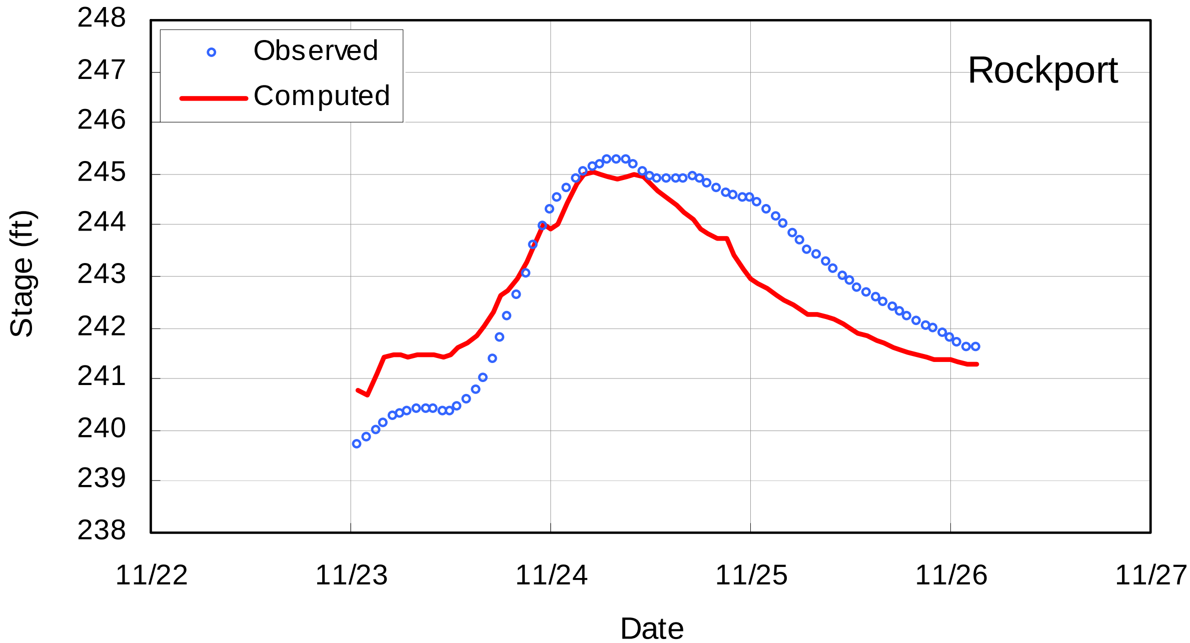


Figure 8e **Model verification: comparison of computed and observed stage hydrograph at Rockport, November 22-27, 1990 flood**

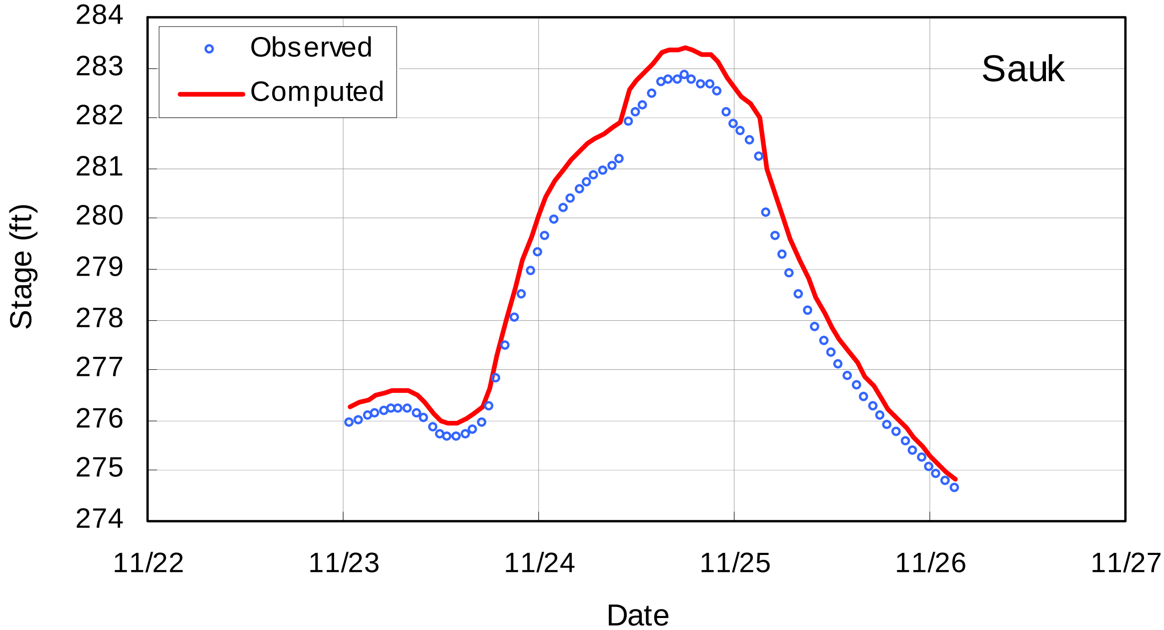


Figure 8f **Model verification: comparison of computed and observed stage hydrograph at Sauk, November 22-27, 1990 flood**

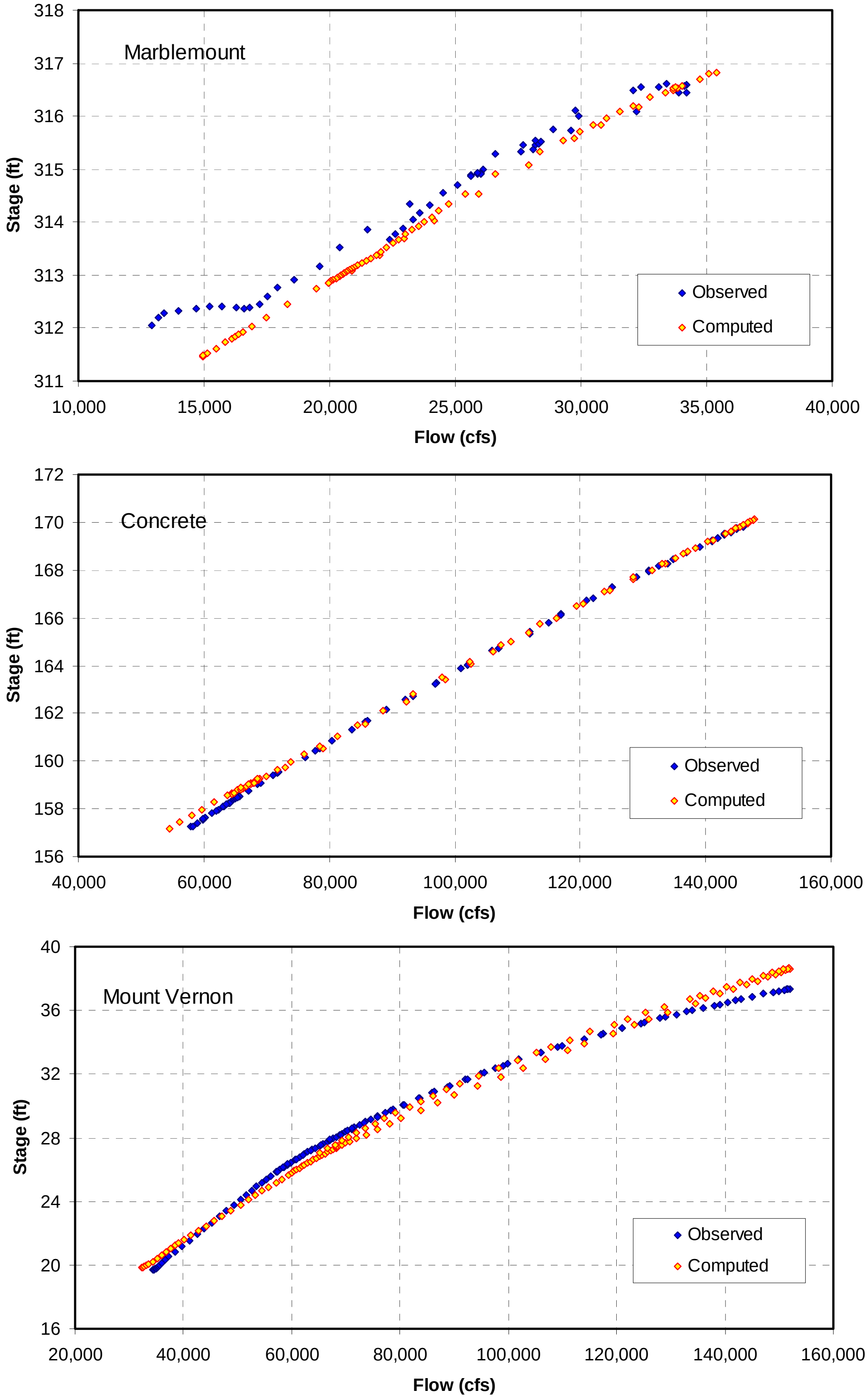


Figure 9 Comparison of computed and observed stage-flow rating curves at three gage stations, November 22-27, 1990 flood

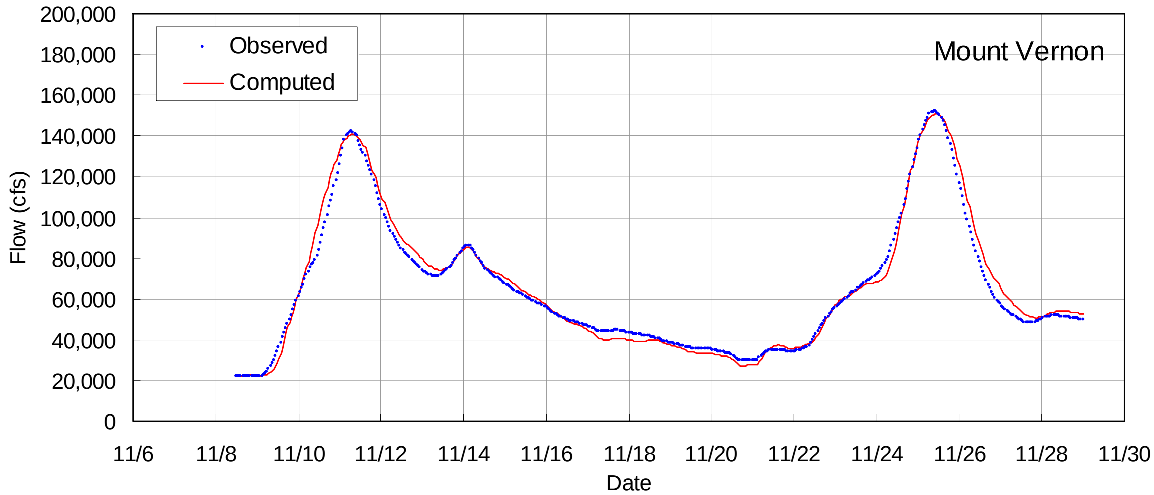


Figure 10 Comparison of 20-day model simulation against observed flow hydrograph at Mount Vernon gage during both November 1990 floods

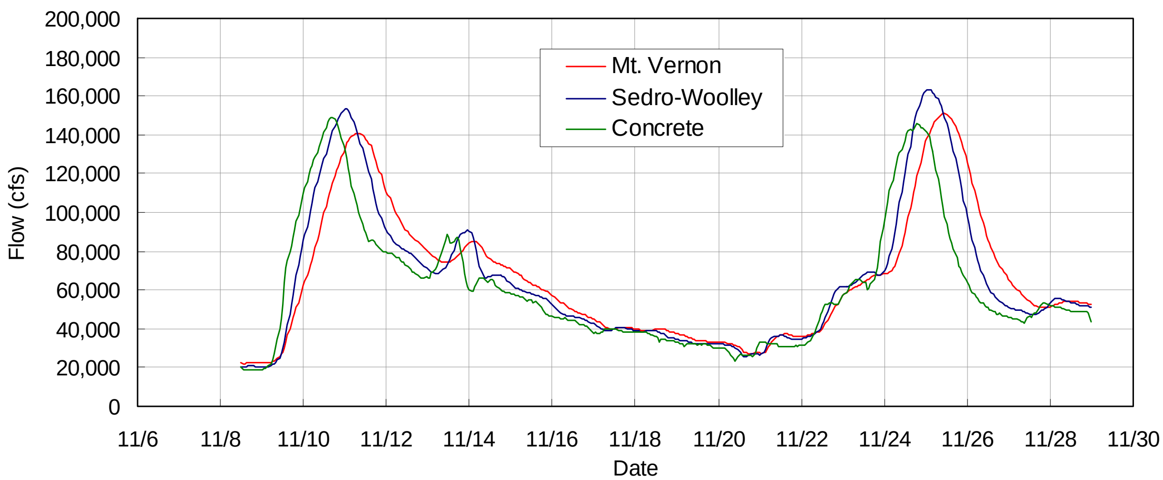


Figure 11 Comparison of process of double-peak flood routing from the Concrete gage to Sedro Woolley and to Mount Vernon during both November 1990 floods

Development of HEC-5 Model

The HEC-5 model was developed to route flood hydrographs through SCL and PSE dams and reservoirs for existing and alternative flood control storage operation conditions, and to quantify changes in flood hydrographs at the Skagit River gage near Concrete due to a change in flood control storage operation.

PI Engineering modified and calibrated the HEC-5 reservoir operation model, originally developed by the Corps and provided to PI Engineering in July 2003. The Corps' original HEC-5 model was developed from Ross Reservoir to the Skagit River gage near Concrete including the use of: existing Ross Lake flood control storage (120,000 acre-feet with 5,000 cfs outflow discharge); existing Baker Lake flood control storage (74,000 acre-feet with 5,000 cfs outflow discharge); and six routing reaches (Ross Dam to Newhalem, Newhalem to Cascade confluences, Cascade confluence to Sauk confluence, Sauk confluence to the Concrete gage, Upper Baker Dam to the Baker River gage at Concrete, and the Baker River gage at Concrete to the Skagit River gage near Concrete). The modifications to the Corps' HEC-5 model include using the latest Baker Lake reservoir storage-elevation curve provided by PSE (dated August 5, 2003); adding overtopping flow above the dam crest to the Baker Lake reservoir total outflow capacities; combining two Baker River routing reaches; and adding the routing reach at Sauk River from the Sauk River gage to Sauk confluence with Skagit River.

The Corps' original HEC-5 model was not calibrated for any observed flood events. The modified HEC-5 model was calibrated using the observed 1995 flood hydrograph of the Skagit River near Concrete. The observed flood hydrographs at the Skagit River gage at Newhalem, the Baker River gage at Concrete, and the Sauk River gage at Sauk were used as input hydrographs into the HEC-5 model. Calibrations to the HEC-5 model include adjusting Muskingum flood routing coefficients. Figures 12(a) and (b) present a comparison of the 1995 observed flood hydrographs as published by USGS, the hydrographs modeled by the calibrated HEC-5 model, and the hydrographs modeled by the upper Skagit River HEC-RAS model.

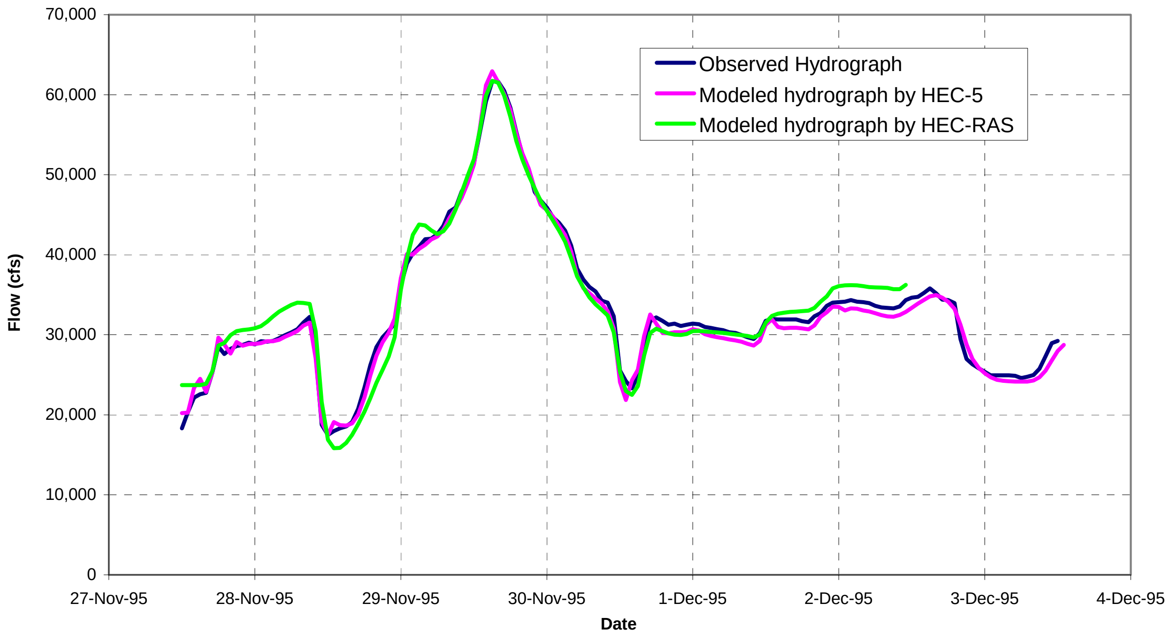


Figure 12a HEC-5 model calibration of 1995 flood hydrograph at Skagit River near Marblemount

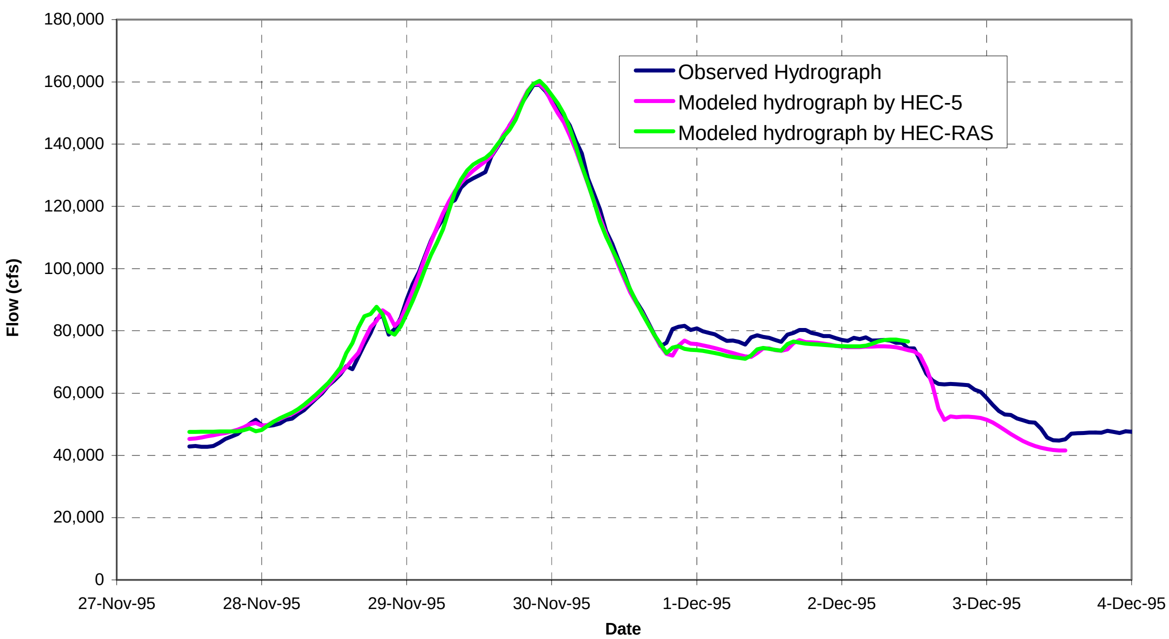


Figure 12b HEC-5 model calibration of 1995 flood hydrograph at Skagit River near Concrete

The modified and calibrated HEC-5 model was verified by routing flood hydrographs of the October 2003 flood and the two November 1990 floods. The routed flood hydrographs from the modified and calibrated HEC-5 model match well with the observed flood hydrographs of the Skagit River gages at Marblemount and near Concrete, as shown in Figures 13, 14, and 15. Also shown in these figures are the hydrographs modeled by the calibrated HEC-RAS model for these three flood events.

Table 6 shows the Muskingum routing parameters, *x* and *k*, for the calibrated and verified HEC-5 model. As shown in this table, the calibrated HEC-5 model indicates the travel time (*k*) of approximately 10 hours between Ross and Concrete. Based on many recent flood experiences, 10 hours is a reasonable value. The calibrated HEC-5 attenuation coefficient (x), varying from 0.0 to 0.5 depending on routing reach floodplain storage, also appears reasonable.

Table 6 Muskingum Routing Parameters Used in HEC-5 Model

Routing Reach	Travel Time (*k*) (hours)	Attenuation Coefficient (*x*)
Ross Dam to Newhalem	0.9*	0.5*
Newhalem gage to Marblemount gage	2.2	0.2
Marblemount gage to Cascade confluence	0.0	0.5
Cascade confluence to Sauk confluence	4.0	0.0
Sauk confluence to Concrete gage	3.0	0.0
Total - Skagit River from Ross Dam to Concrete gage	**10.1**	**0.0-0.5**
Baker River gage at Concrete to Skagit River gage near Concrete	0.5	0.45
Sauk River gage at Sauk to Sauk confluence	1.6	0.1

*Assumed value, not from modeling

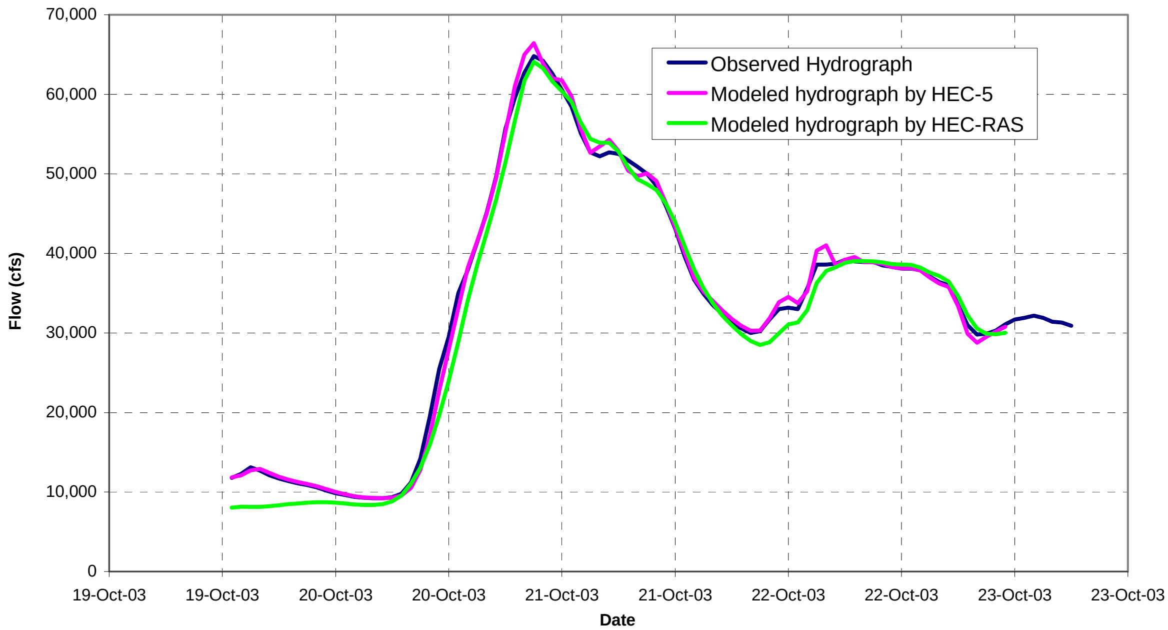


Figure 13a HEC-5 model verification of 2003 flood hydrograph at Skagit River near Marblemount

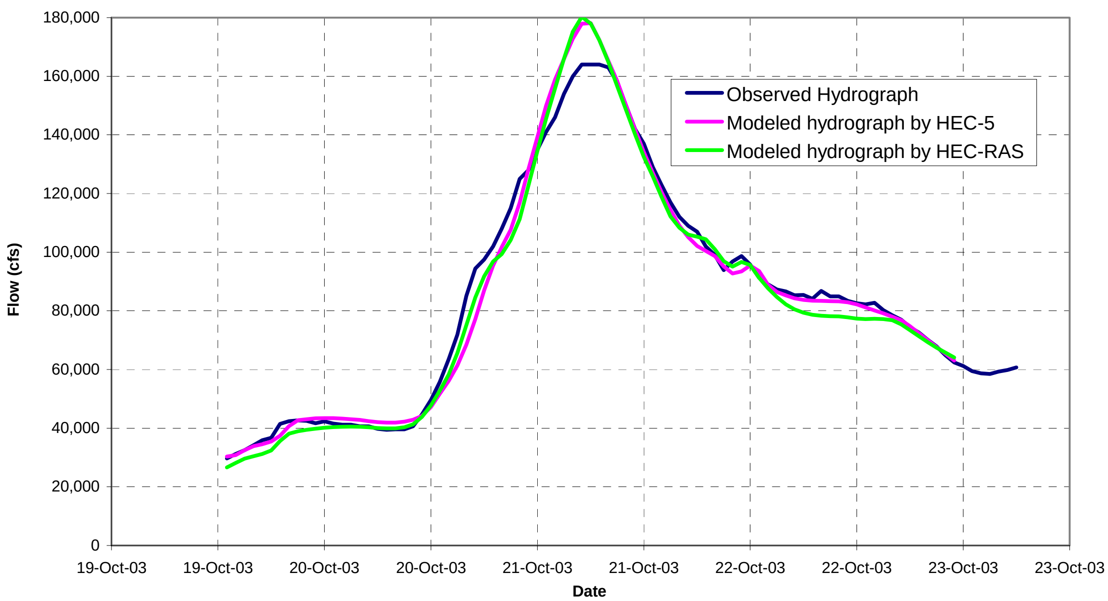


Figure 13b HEC-5 model verification of 2003 flood hydrograph at Skagit River near Concrete

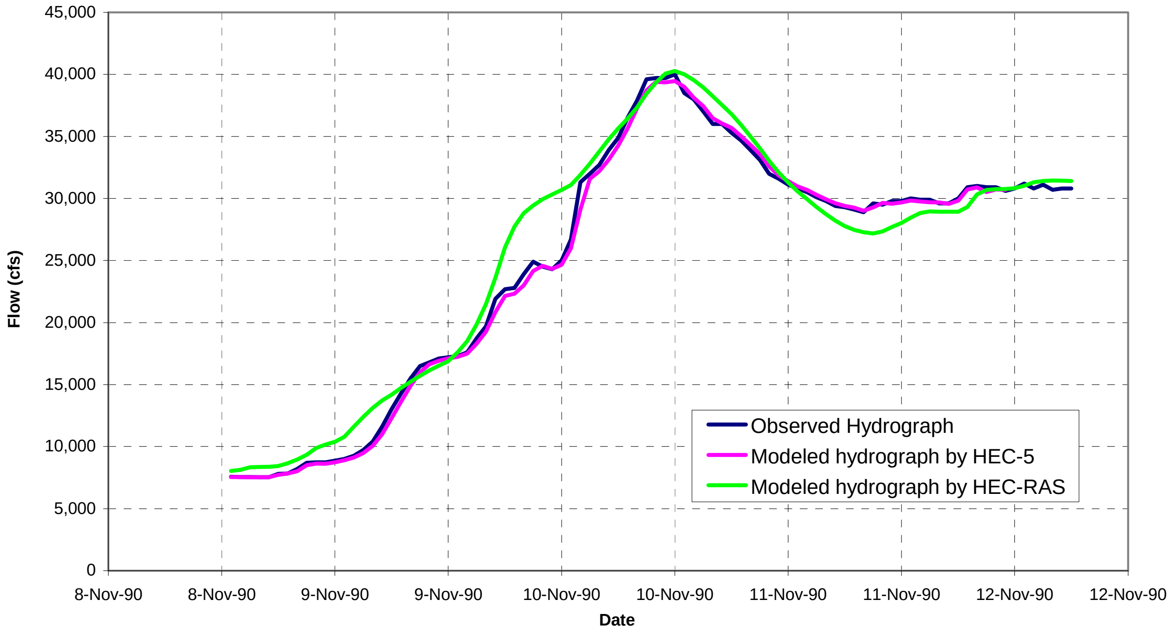


Figure 14a HEC-5 model verification of 1990(1) flood hydrograph at Skagit River near Marblemount

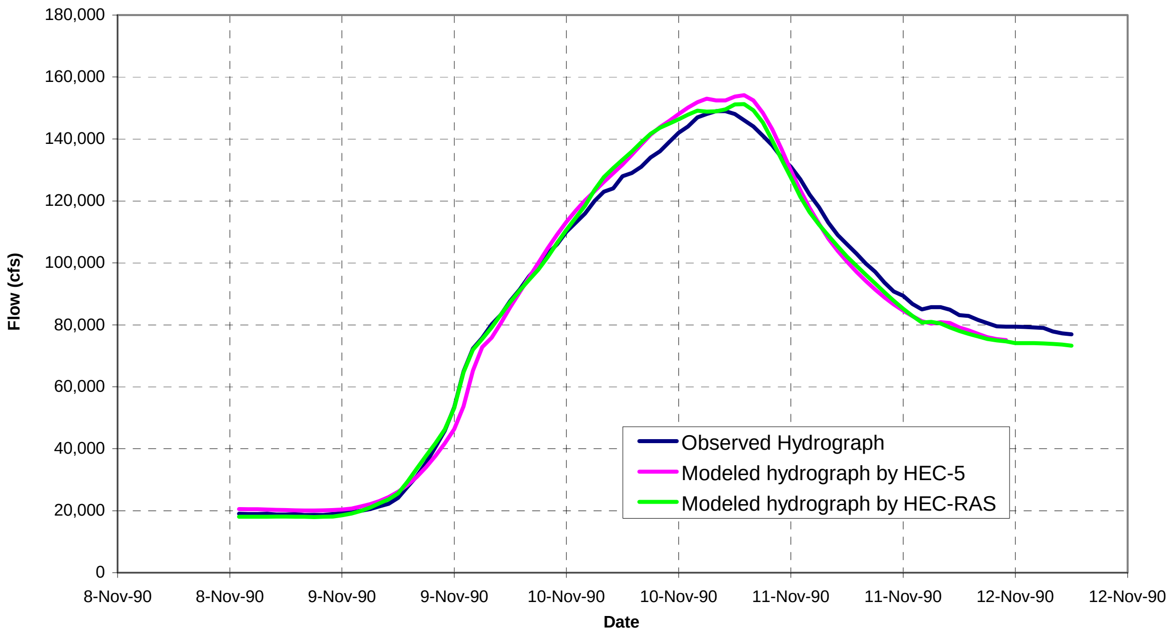


Figure 14b HEC-5 model verification of 1990(1) flood hydrograph at Skagit River near Concrete

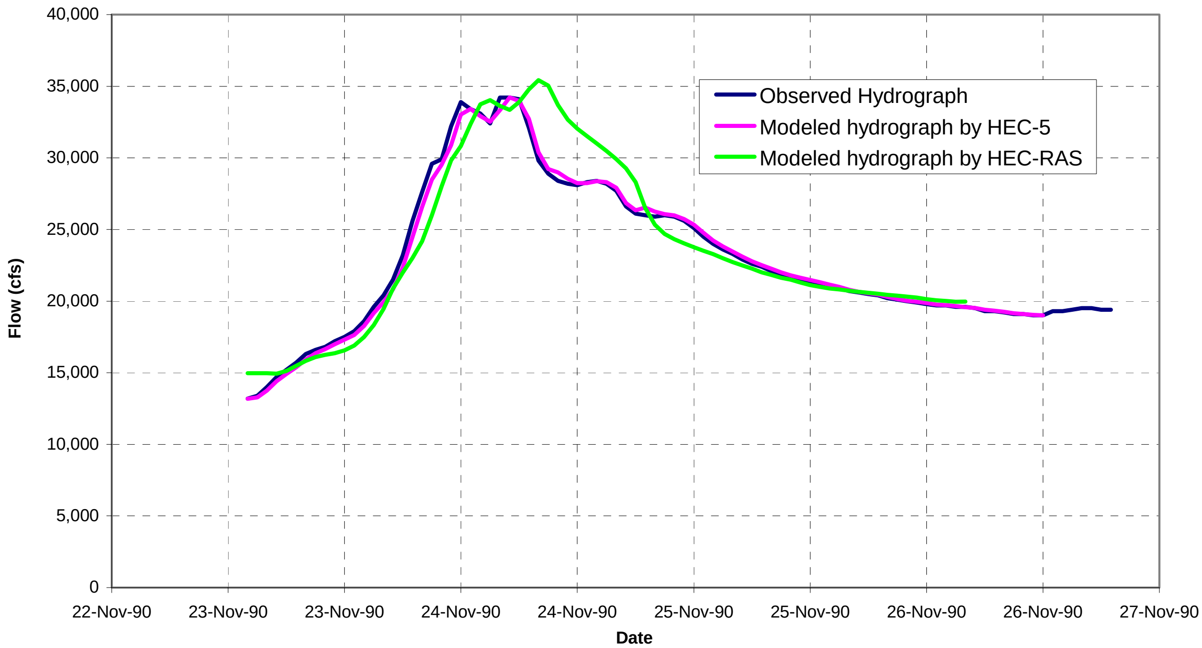


Figure 15a **HEC-5 model verification of 1990(2) flood hydrograph at Skagit River near Marblemount**

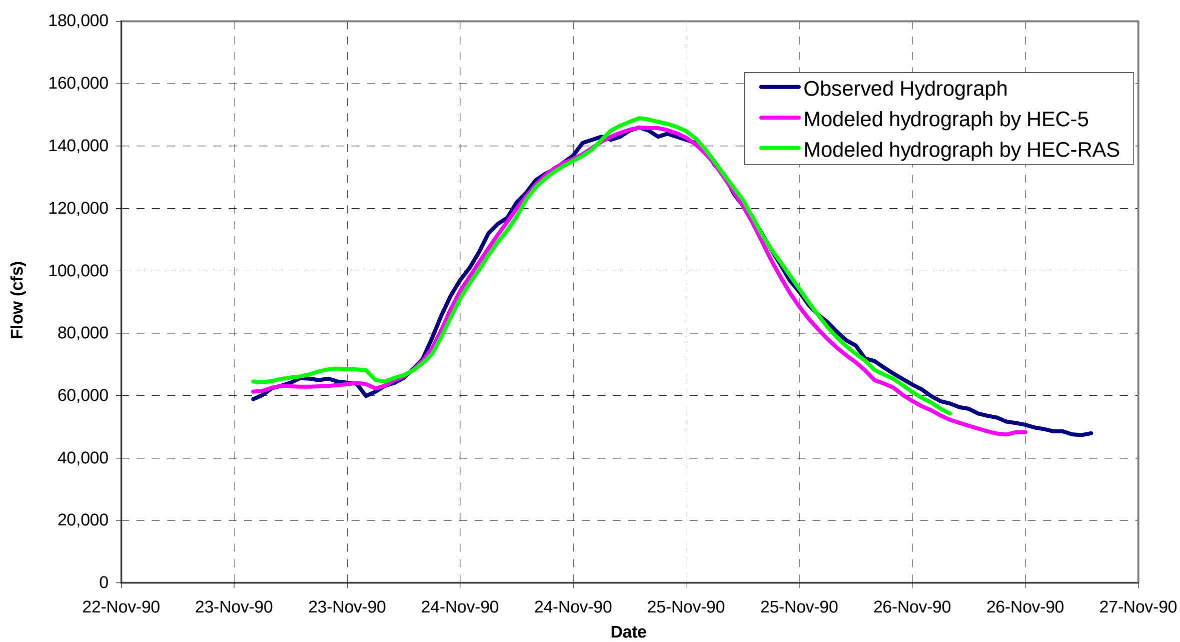
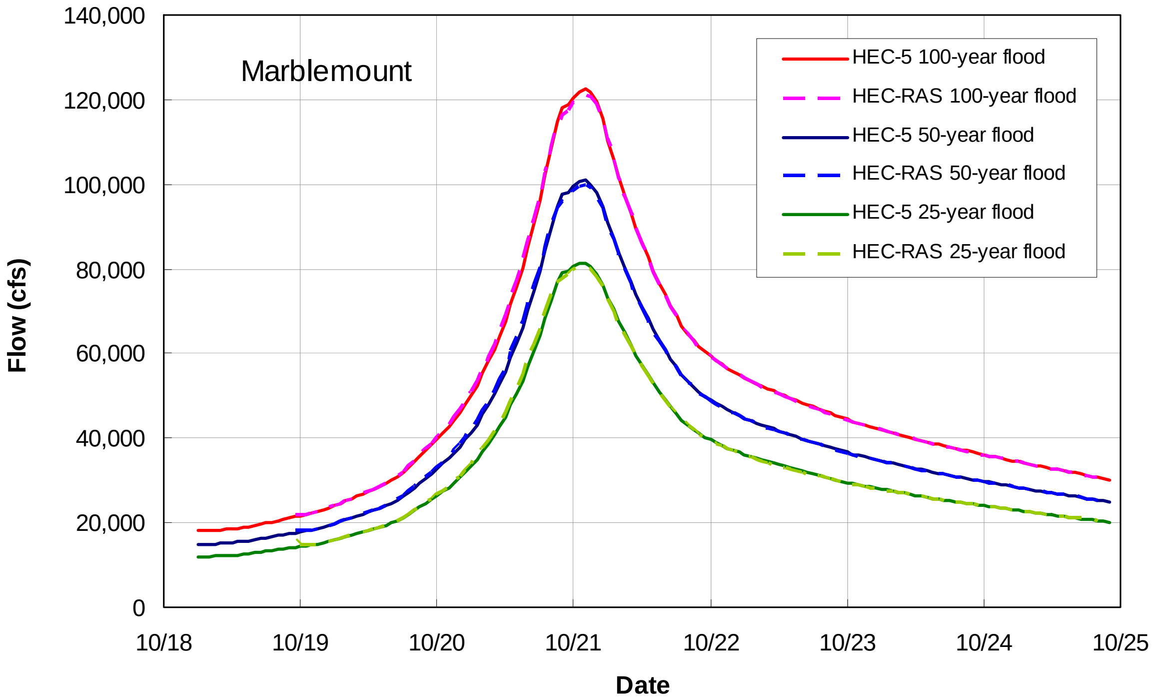


Figure 15b **HEC-5 model verification of 1990(2) flood hydrograph at Skagit River near Concrete**

Figure 16 shows a comparison of synthetic flood unregulated hydrographs at Marblemount and Concrete, resulting from the HEC-5 and HEC-RAS model runs for the 100-, 50-, and 25-year events. These synthetic flood hydrographs are based on the Corps' new hydrology for all subbasins above Concrete, with PI Engineering's suggested times of peak for various tributary hydrographs. Table 7 compares the suggested times of peak with those used in the Corps' HEC-RAS model. These suggested times of peak are the approximate averages for the HEC-HMS modeled hydrographs of the recent flood events. The comparison of the synthetic flood hydrographs at Marblemount and Concrete indicate that both calibrated and verified HEC-5 and HEC-RAS models can produce reasonable and comparable hydrographs for large synthetic floods.

Table 7 Tributary Time of Peak Prior to Peak of the Skagit River near Concrete

Tributary	Peak Timing Used for Corps HEC-RAS Model (hours)	Peak Timing Suggested for HEC-5 Model (hours)
Ross Inflow	5.0	5.0
Thunder Creek	8.0	8.0
Ross to Newhalem Local	6.0	6.0
Newhalem to Marblemount Local	13.0	10.0
Marblemount to Concrete Local	17.0	13.0
Sauk River at Sauk	5.0	5.0
Upper Baker Inflow	12.0	9.0
Lower Baker Inflow	14.0	10.0



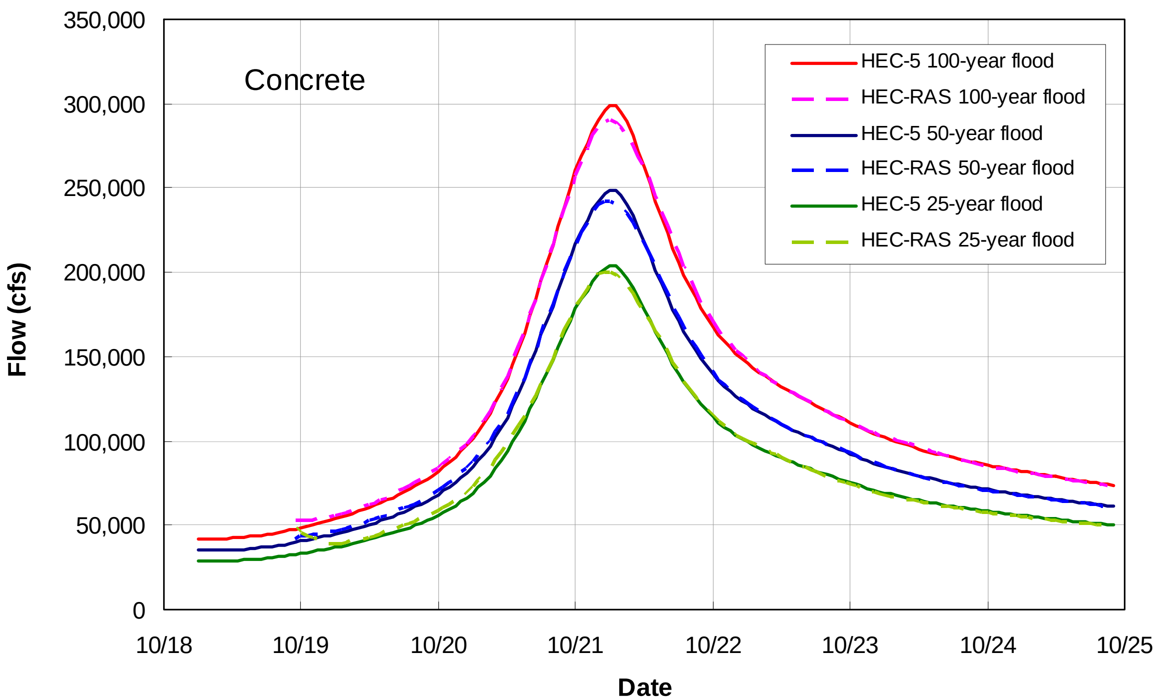


Figure 16 Comparison of synthetic flood unregulated flow hydrographs at Marblemount and Concrete

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