U.S. Army Corps of Engineers
Walla Walla District

Numerical Model Analysis of System-wide Dissolved Gas Abatement Alternatives

Appendix F

Verification of MASS1 for Lower Columbia/Snake Temperature and Total Dissolved Gas Simulation

Draft Report

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1 Introduction

In order to make use of MASS1 for system-wide alternative comparison, it was calibrated and verified for the lower Columbia and Snake Rivers. This included hydrodynamics, water temperature, and total dissolved gas. This appendix describes the calibration process and presents the results.

The modeled region extended downstream from Dworshak dam on the North Fork of the Clearwater, Orofino on the Clearwater (RM 41), below the mouth of the Grand Rhonde on the Snake (RM 169), and Priest Rapids dam on the Columbia (RM 397) to about Astoria on the Columbia (RM 21). In all, over 600 river miles of lower Columbia and Snake basins were simulated, including the effects of ten hydroelectric projects.

The model was configured in two ways, which differed in the way boundary conditions were specified at dams. In the first configuration, observed forebay stage was specified at each project. In the second configuration, observed flows were specified at each project. The hydrodynamic calibration was performed using the former; water quality with the latter. A more complete description is presented in Section 2.1.

In order to make both of the MASS1 configurations work properly, it was necessary to "correct" observed flows. The correction took the form of a lateral inflow (or outflow) contributing to the pool above the project. This was done in order to make both the simulated project forebay stage and flows consistent with each other and with the observed. The reasons for this, and a description of the procedure are presented in Section 2.2.

In the hydrodynamic calibration, simulated stage was matched to recorded stage in the tailwaters of individual projects. The process is described in Section 2.3.

2 Methods

2.1 MASS1 Configuration

The lower Columbia and Snake rivers were simulated using two configurations of the MASS1 model. A schematic of the first is shown in Figure 2.1, in which observed stages are used as boundary conditions at the projects. The second configuration, shown in Figure 2.2, uses observed flows as boundary conditions at the projects.

The first configuration was used for model initialization, project flow correction and hydrodynamic calibration and verification simulations. The second configuration was used for temperature and TDG calibration and verification simulations.

MASS1 requires a boundary condition be specified at each dam to represent the dam operation. Usually, the model is forced to follow forebay stage and simulate project flow. The simulated flow will not necessarily match the observed flow, in this case. In this application, however, inputs of dissolved gas were directly dependent upon the project flow, so it was necessary to force MASS1 to follow dam flows and simulate forebay stage. This leads to an error in forebay stage, but with much less impact to the water quality simulation. An error in forebay stage would lead to an error in cross section area, which would cause an error in gas movement, timing of front arrival, e.g. An error in project flow would lead to an error in the *mass* of gas input to the simulation.

2.1.1 Bathymetry

The bathymetry used by MASS1 was derived from the same bathymetry used by the MASS2 2-D model. In the Snake River, this consisted primarily of NOAA navigation charts, where available, dense bathymetric surveys near the projects, and sedimentation survey range lines. In the Columbia, relatively dense surveys were available for the entire pools, which were supplemented with denser surveys near the projects, navigation charts, and a series of surveyed cross sections in the Hanford reach. The specific sources of Snake River bathymetric data are listed in Richmond and Perkins (1999b), Richmond and Perkins (1999c), Richmond and Perkins (1999d) and Richmond and Perkins (1999e). Those for the Columbia are listed in Richmond and Perkins (1999f), Richmond and Perkins (1999g), Richmond and Perkins (1999h), Richmond and Perkins (1999i), and Richmond and Perkins (1999a).

These individual sets of bathymetry data were combined into a three-dimensional surface, from which cross section elevations were sampled using the process described by Hanrahan et al. (1998). Cross section spacing was approximately $1/4$ mile in the first few miles below the dams, and in the Hanford reach, and $1/2$ mile elsewhere.

2.1.2 Hydrodynamic Boundary Conditions

Observed flows were used as boundary conditions at the uppermost limits of the modeled region. Flow data for Priest Rapids on the Columbia River and Dworshak dam on the North Fork of the Clearwater were obtained from the DGAS project operations database (Carroll et al., 1998). Observed flows for the upstream boundaries on Clearwater and Snake rivers were obtained from

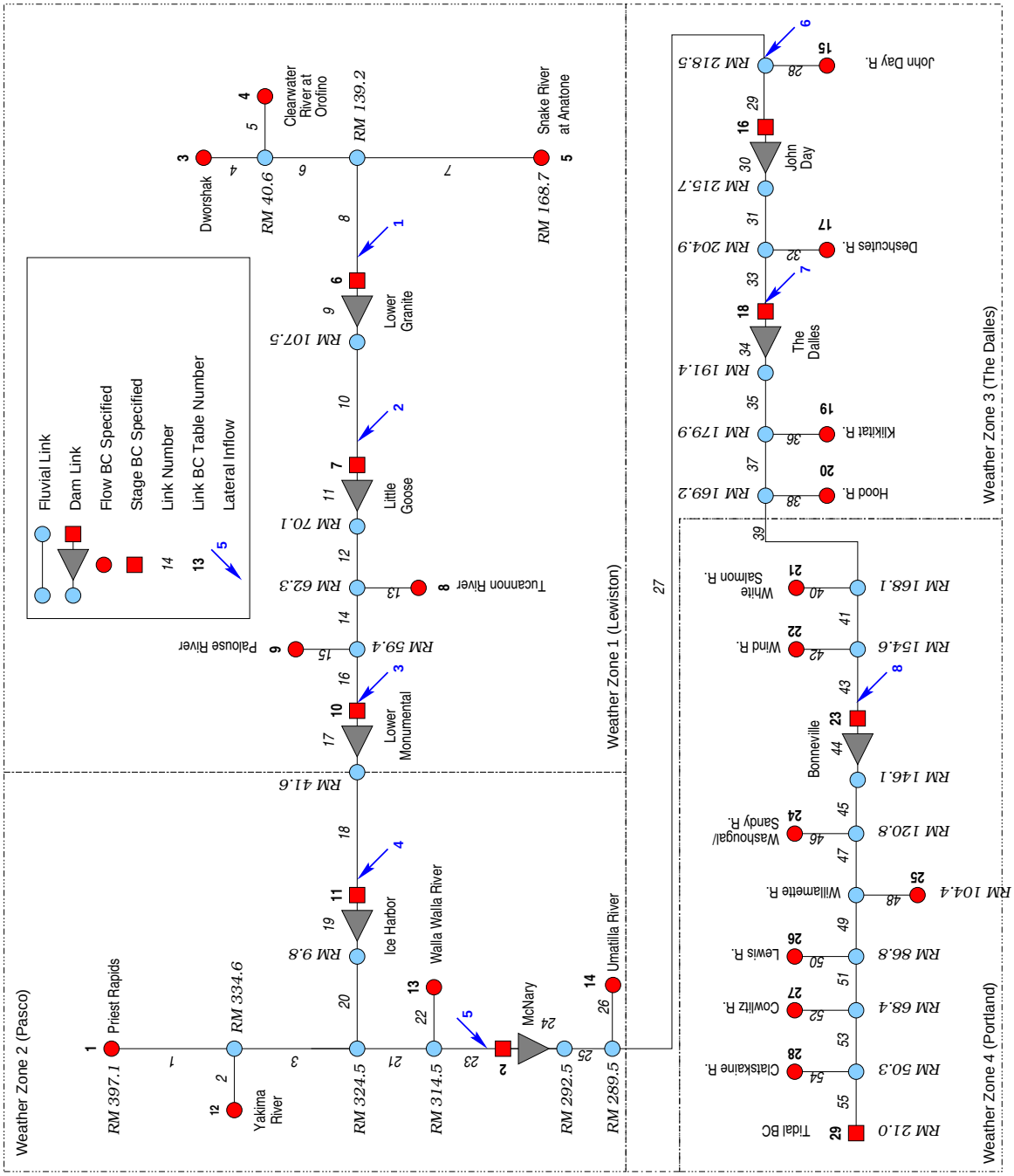

Figure 2.1: Schematic of the initial MASS1 configuration for the lower Columbia and Snake rivers, using stage boundary conditions at the dams.

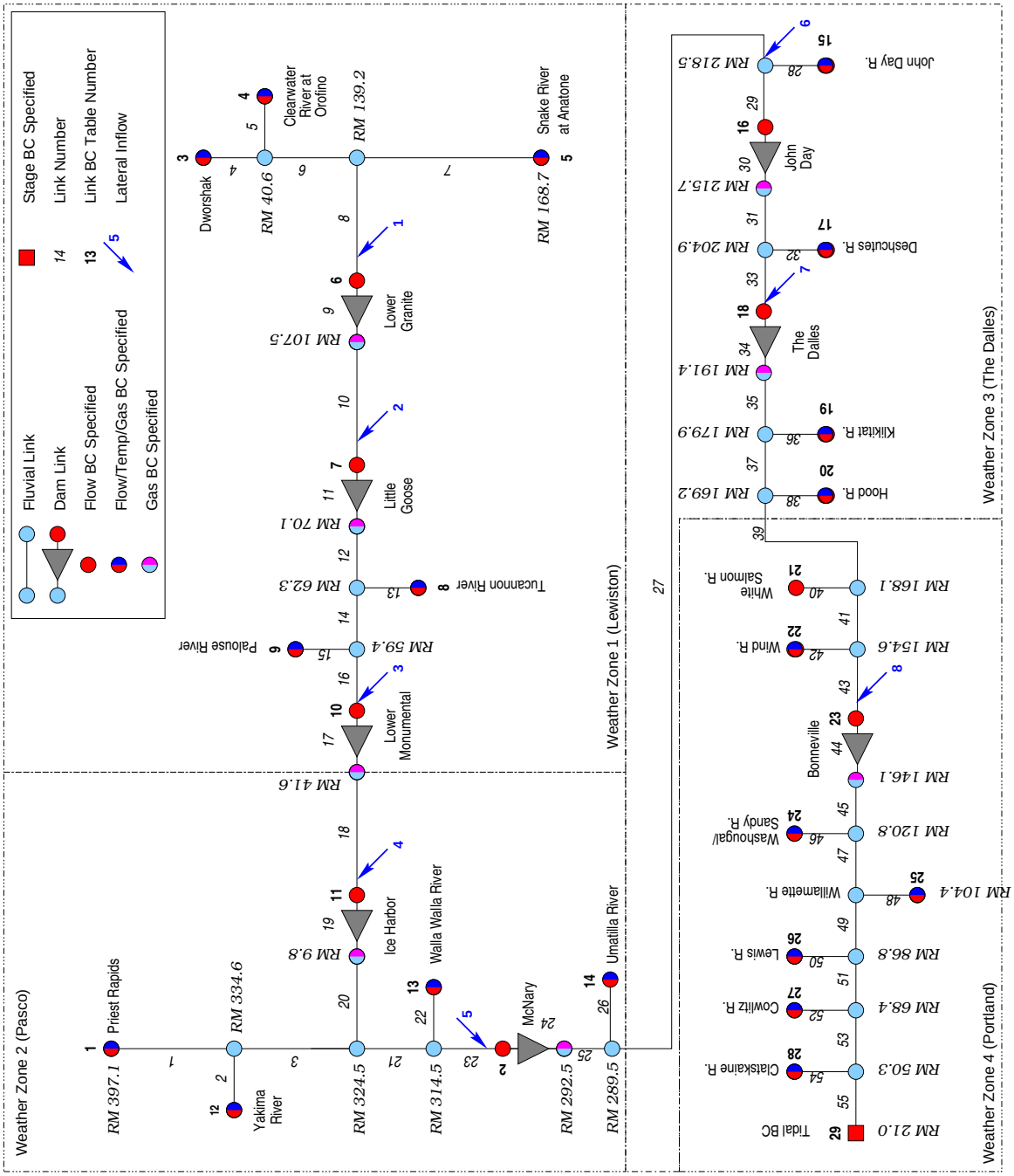

Figure 2.2: Schematic of the MASS1 configuration for the lower Columbia and Snake rivers, using flow boundary conditions at the dams and lateral inflow to "correct" forebay stages.

an appropriate USGS stream gage. Observed stage was used at the downstream boundary, near Astoria, Oregon. Stage data for that location was obtained from the NOAA tide gage near Astoria [1]

As stated above, MASS1 was configured in ways that required both observed flow and forebay stage at each of the Snake and Columbia river projects. These were also obtained from the DGAS project operations database (Carroll et al., 1998).

Tributaries were either assigned daily flows from an appropriate stream gage or assumed constant. In most cases, a USGS stream gage was located on the tributary and daily data from that gage was obtained using the USGS Water Data Retrieval service[2]. Table 2.1 lists the tributaries and the source of the discharge data.

Table 2.1: Sources of boundary condition and tributary flow for the lower Columbia and Snake River MASS1 application.

Boundary or Tributary	Gage Gage ID	Description
Clatskaine River		constant 500 cfs assumed
Cowlitz River	14243000	Cowlitz River At Castle Rock, Wa
Lewis River	Assumed to be the sum of	
	14220500	Lewis River At Ariel, Wa
	14222500	East Fork Lewis River Near Heisson, Wa
Willamette River	14211720	Willamette River At Portland, Or
Sandy/Washougal Rivers		constant 1000 cfs assumed
Wind River		constant 0 cfs assumed
White Salmon River	14123500	White Salmon R Nr Underwood, Wa
Hood River	14120000	Hood River At Tucker Bridge,Nr Hood River,Or
Klikitat River	14113000	Klickitat River Near Pitt, Wa
Deschutes River	14103000	Deschutes River At Moody, Near Biggs, Or
John Day River	14048000	John Day R At Mcdonald Ferry, Or
Umatilla River	14033500	Umatilla R Nr Umatilla, Or
Walla Walla River	14018500	Walla Walla River Near Touchet, Wa
Yakima River	12510500	Yakima River At Kiona, Wa
Palouse River	13351000	Palouse River At Hooper, Wa
Tucannon River	13344500	Tucannon River Near Starbuck, Wa
Clearwater River	13340000	Clearwater River At Orofino, Id
Snake River	13334300	Snake River Nr Anatone, Wa

2.1.3 Meteorology

The MASS1 model can accept meteorological data for multiple weather zones. Four meteorologic zones were configured into MASS1, as shown in Figures 2.1 and 2.2. MASS1 requires the

[1] NOAA gage 94339040, "Astoria, Tongue Point, Columbia River, OR"; see http://www.co-ops.nos.noaa.gov/tidesonline/ for more information.

[2] URL:http://waterdata.usgs.gov/nwis-w/US/

following meteorological variables:

- air temperature,
- dew point temperature,
- wind speed,
- barometric pressure, and
- incoming short wave solar radiation.

For each of the zones, data was obtained for a nearby NWS station from the DGAS meteorological database (Carroll et al., 1998). Air and dew point temperatures were obtained from the NWS station. Barometric pressure was taken from a nearby FMS. Cloud cover from the NWS stations was used to estimate incoming solar radiation by the procedure presented by Richmond et al. (1999). Table 2.2 shows the weather station and FMS used for each zone.

Table 2.2: Sources of meteorological data for each of the zones in the lower Columbia and Snake river MASS1 application.

	Station		**Fixed**
Zone	**Name**	**Identifier**	**Monitor**
1	Lewiston (AMOS)	LWS	LGNW
2	Pasco	PSC	MCQO
3	The Dalles	DLS	TDA
4	Portland	PDX	BON

2.2 Project Flow Corrections

Specifying flows at projects made MASS1 somewhat more difficult to apply because small errors in specified flows, even as low a few hundred cfs, can lead to large errors in simulated forebay stage over time. Discharge differences in this range are well within the range of errors associated with stream gages, spillway and turbine ratings. The basic problem is that the observed forebay stage does not “match” the observed project discharge, as far as the model is concerned. This may be for several reasons, some of which are:

- the model may not account for all inflows to the pool upstream of the project;
- posted project discharge may differ from the actual flow and may not account or other miscellaneous flows;
- stage data is instantaneous, but flow data is an average over the last hour;
- measured stages and flows may have biases;
- the available bathymetry may not accurately represent the available reservoir storage

When these errors or inconsistencies were noticed, a procedure was developed which added a flow "correction" to the MASS1 configuration and made the observed project flows and stages more consistent. The result of the procedure was an additional inflow (or outflow) to the pool above the project which caused the simulated project forebay stage to stay reasonably close the observed, while the observed project flow was used as a boundary condition at the project.

1. A simulation was run for the period using observed forebay stage as a boundary condition at at all of the projects.

2. The simulated flow at the uppermost dam (Lower Granite) was compared to the observed flow. The differences were averaged over a day. This was the flow correction.

3. The flow correction was divided by the length of the link, or links, above the dam where the correction was to be applied as lateral inflow (referring to Figure 2.2, this would be link 8 in the Lower Granite case).

4. The second simulation imposed observed flow only at the uppermost dam (Lower Granite) and lateral inflow, computed in 3, only to the appropriate links above the dam.

5. Steps 2, 3, and 4 were repeated for the next dam downstream (Little Goose), and then for the rest of the projects (Lower Monumental, and so on), working downstream.

The results of this process are shown in Appendix .

2.3 Hydrodynamics Calibration/Verification

For the hydrodynamic calibration, MASS1 was configured to use observed forebay stage to represent dam operations, as discussed in Section 2.1. The lateral inflow discussed in Section 2.2 was also applied. The calibration attempted to match the simulated tailwater stage at individual projects to observed. Observed tailwater stage data was obtained from the DGAS operations database (Carroll et al., 1998).

Calibration consisted typically of adjusting a single value of roughness (Manning's n) throughout the pool. Only occasionally, cross section thalweg elevations were adjusted near the dam, but only when there was some question about the bathymetry near that dam. The spill season of 1996 was used for calibration; 1994 and 1997 were used for verification.

2.4 Temperature Verification

For the temperature verification, MASS1 was configured to use observed project flows to represent dam operations, with lateral inflow (Section 2.2) applied. Hourly (or more frequent) observed temperature values were supplied at the upstream boundaries, as shown in Table 2.3. A constant inflow temperature of 14°C was the specified inflow temperature for all other tributaries.

Temperature was simulated for two seasons: 1996 and 1997. No parameters for air/water heat exchange were adjusted. Consequently, the simulations made were for verification; no calibration was performed.

Table 2.3: Sources of boundary condition water temperature for the lower Columbia and Snake River MASS1 application.

Boundary	**Frequency**	**Source**
Columbia River @ Priest Rapids	hourly	FMS PRXW
North Fork Clearwater @ Dworshak	hourly	FMS DWQI
Clearwater River	hourly	USGS Gage 13340000
Snake River	15-minute	USGS Gage 13334300
all others	Assumed constant 14°C	

2.5 Total Dissolved Gas Calibration/Verification

The calibration and verification of dissolved gas transport in the lower Columbia and Snake rivers was complicated by the lack of reliable information on the contribution of gas by dams and influx at upstream tributaries. The approach taken was to assume that gas measurements made by fixed monitors in project tailwaters represented the gas levels in the spill from that project, or, in a few cases, the entire river flow. Upstream boundary and tributary TDG concentrations were specified as shown in Table 2.4.

TDG calibration and verification simulations were performed concurrently with the temperature verification simulations (Section 2.4). TDG concentrations were simulated. Simulated pressures, a function of both concentration and temperature, were used for comparison. The 1997 season was used for calibration; 1996 for verification. Calibration consisted of adjusting the function relating wind speed to the surface transfer coefficient (K_L) used in the representation air/water gas transfer process[3].

[3]MASS1 uses the same representation of air/water exchange as MASS2, which is documented by Richmond et al. (1999), Section 2.4.2.

Table 2.4: Sources of boundary condition dissolved gas saturation for the lower Columbia and Snake River MASS1 calibration and verification.

Boundary	**Frequency**	**Applied to**	**Source**
Columbia River @ Priest Rapids	hourly	entire river	FMS PRXW
North Fork Clearwater @ Dworshak	hourly	entire river	FMS DWQI
Clearwater River	constant	entire river	100% saturation
Snake River	constant	entire river	105% saturation
Lower Granite Tailwater	hourly	spill only	FMS LGNW
Little Goose Tailwater	hourly	spill only	FMS LGSW
Lower Monumental Tailwater	hourly	spill only	FMS LMNW
Ice Harbor Tailwater	hourly	spill only	FMS IDSW
McNary Tailwater	hourly	spill only	FMS MCPW
John Day Tailwater	hourly	spill only	FMS JHAW
The Dalles Tailwater	hourly	spill only	FMS TDDO
Bonneville Tailwater	hourly	spill only	FMS WRNO
all others	constant	entire river	100% saturation

3 Results and Discussion

3.1 Hydrodynamics Calibration/Verification

Comparison of simulated and observed stages are shown in Figures 3.1 (Bonneville tailwater) through 3.8 (Lower Granite tailwater). The Manning's *n* values determined provide the best results are shown in Table 3.1.

Stages in the Columbia river pools were simulated better than those in the Snake river. This is primarily because of the higher quality bathymetry data available for the Columbia. The Snake river bathymetry relied heavily on the NOAA navigation charts, which are a considerably sparser data set than the survey data used for the Columbia.

Through the calibration process, the main goal was to keep simulated stages within about a foot of the simulated stages. In some cases, MASS1 was unable stay within this range at lower flows. See, for example, Figure 3.3 showing John Day, and Figure 3.8 showing Lower Granite tailwater stage.

In general, MASS1 was able to simulate the tailwater stages well, even over the large variation in flows simulated. While some improvement could probably be made (perhaps with some additional bathymetry data), it was felt that this calibration was adequate for the task of gas abatement alternative comparison.

Table 3.1: Manning's coefficients resulting from hydrodynamic calibration of MASS1 for the lower Columbia and Snake Rivers.

Pool/Reach	**River**	**River Mile**		*n*
Tidal	Columbia	21.0	145.5	0.0285
Bonneville	Columbia	145.5	191.5	0.032
The Dalles	Columbia	191.5	215.8	0.032
John Day	Columbia	215.8	292.5	0.026
McNary	Columbia	334.5	292.5	0.027
	Snake	0.0	9.5	0.027
Hanford[a]	Columbia	334.5	344.65	0.025
		344.65	369.76	0.0286
		369.76	375.78	0.029
		375.78	382.81	0.025
		382.81	388.52	0.024
		388.52	396.8	0.030
Ice Harbor	Snake	9.5	41.6	0.024
Lower Monumental	Snake	41.6	70.1	0.025
Little Goose	Snake	70.1	107.5	0.028

[a]based on other studies

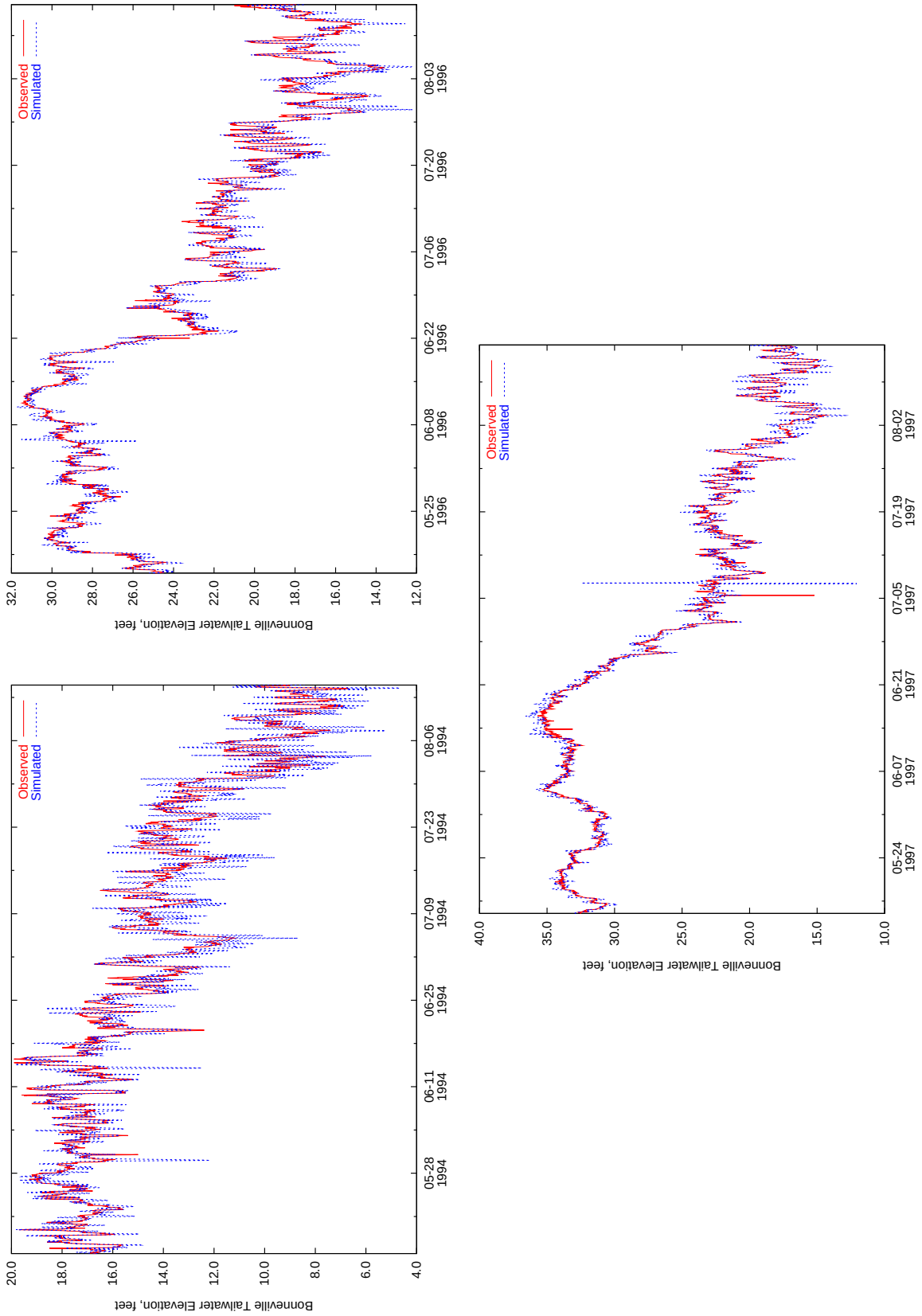

Figure 3.1: Comparison of simulated and observed stage below Bonneville dam for the spill seasons of 1994, 1996, and 1997.

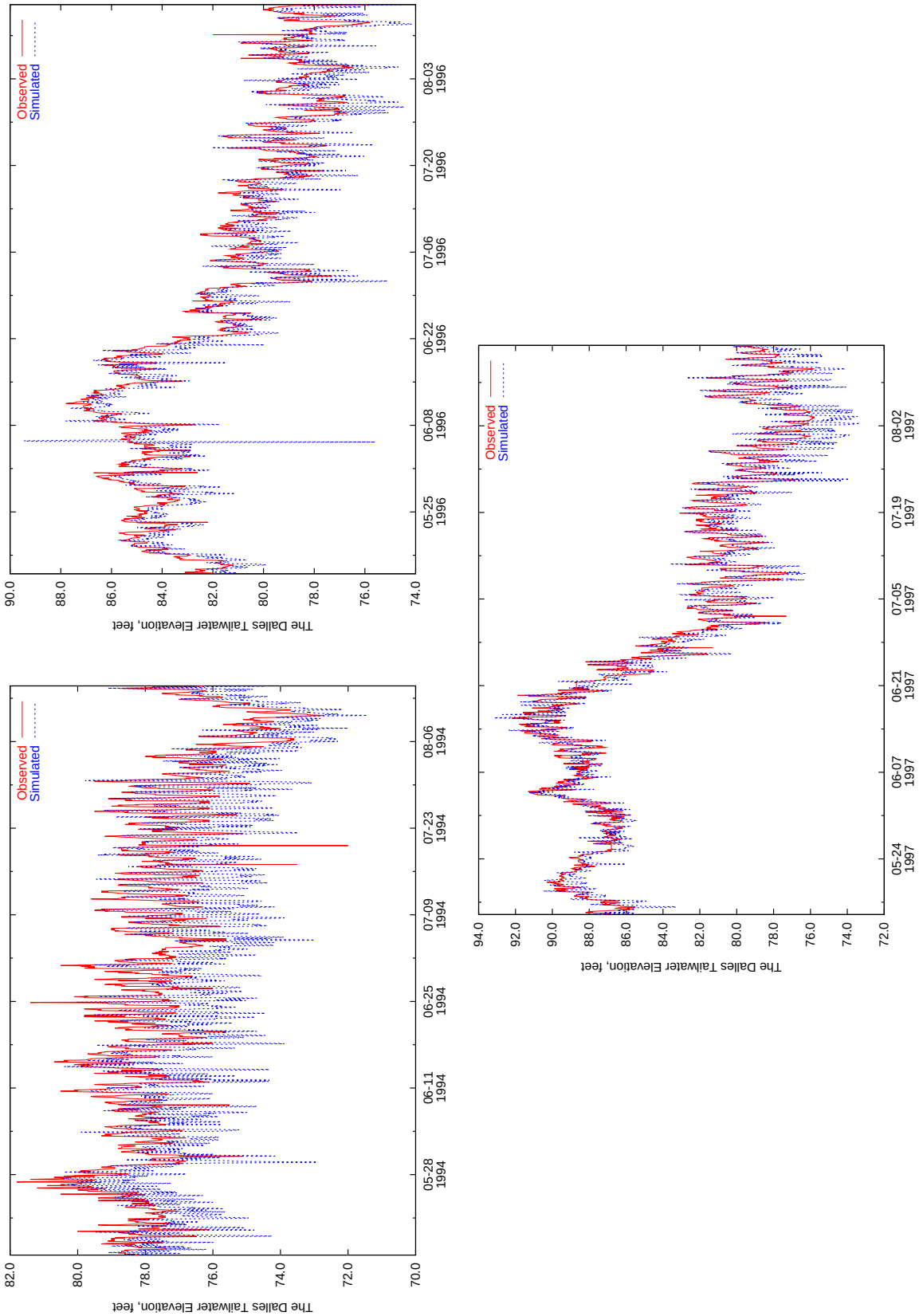

Figure 3.2: Comparison of simulated and observed stage below The Dalles dam for the spill seasons of 1994, 1996, and 1997.

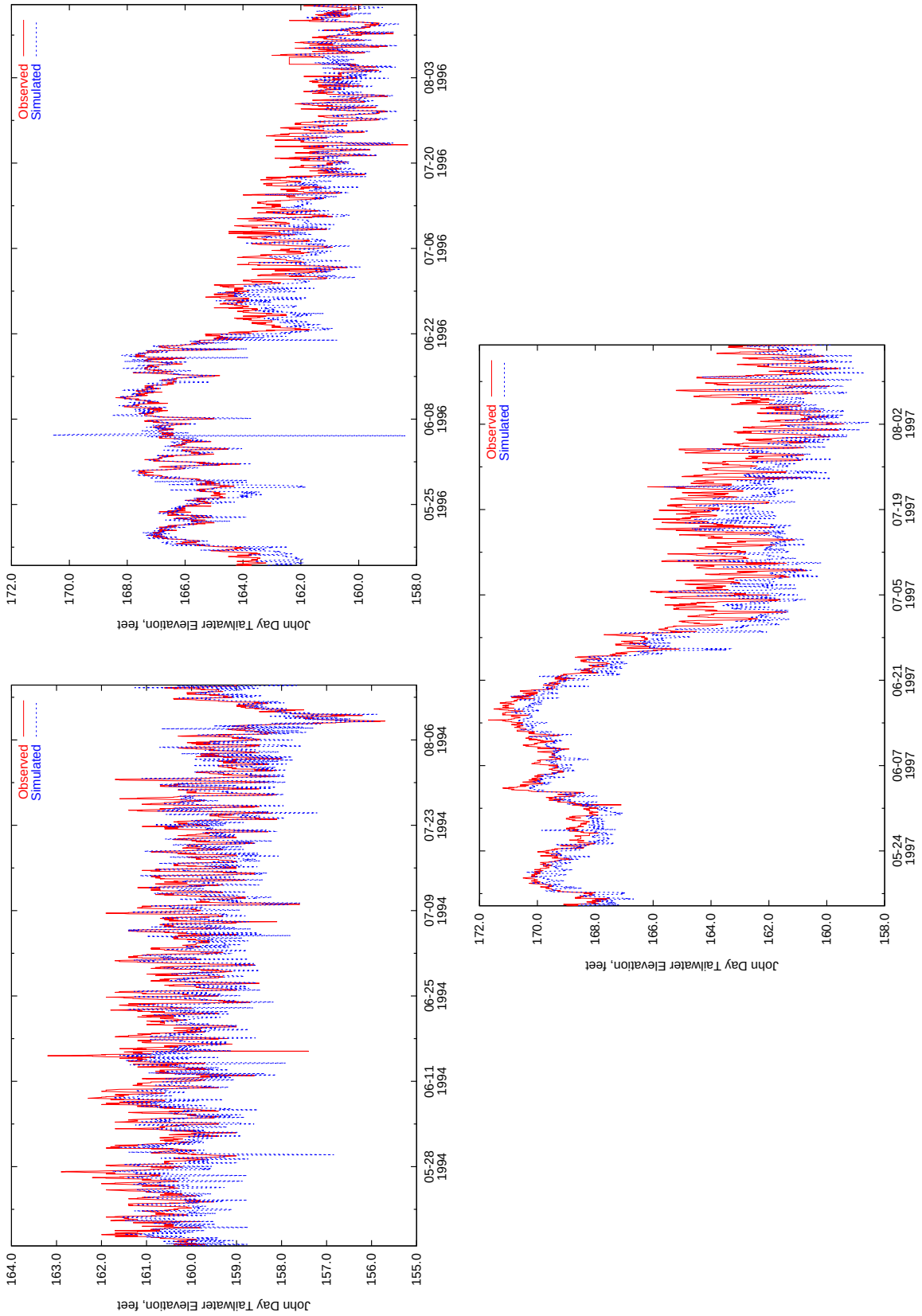

Figure 3.3: Comparison of simulated and observed stage below John Day dam for the spill seasons of 1994, 1996, and 1997.

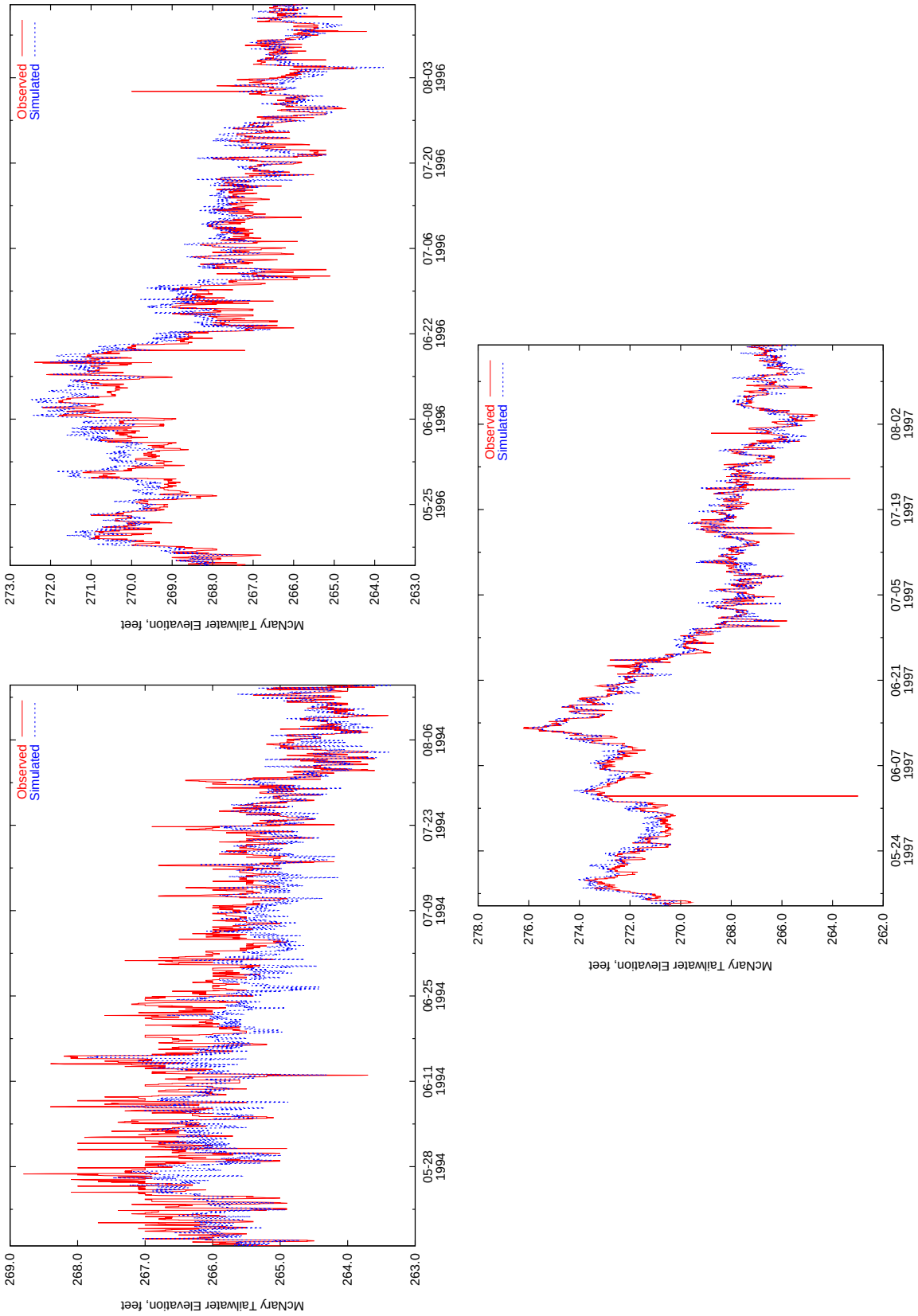

Figure 3.4: Comparison of simulated and observed stage below McNary dam for the spill seasons of 1994, 1996, and 1997.

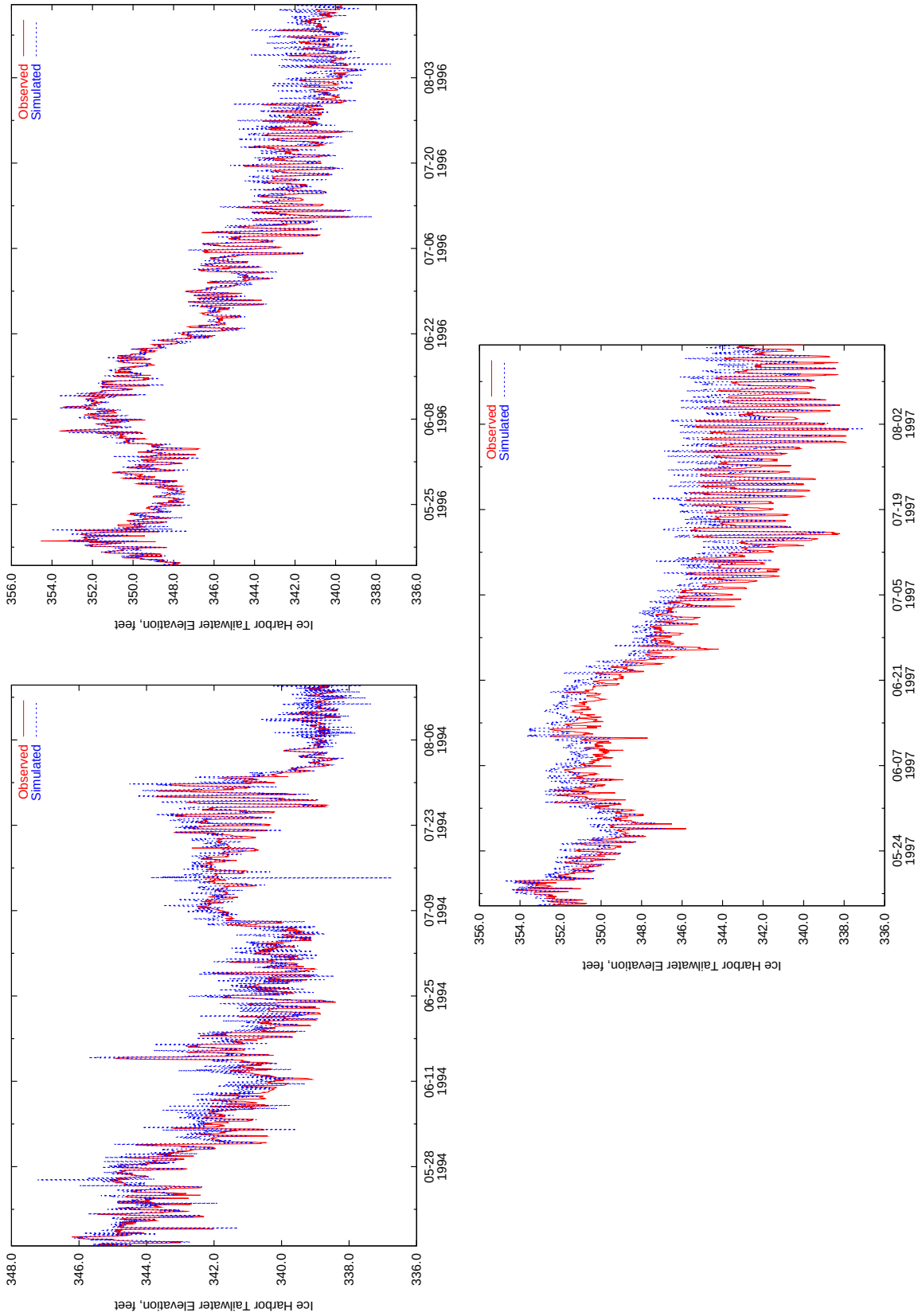

Figure 3.5: Comparison of simulated and observed stage below Ice Harbor dam for the spill seasons of 1994, 1996, and 1997.

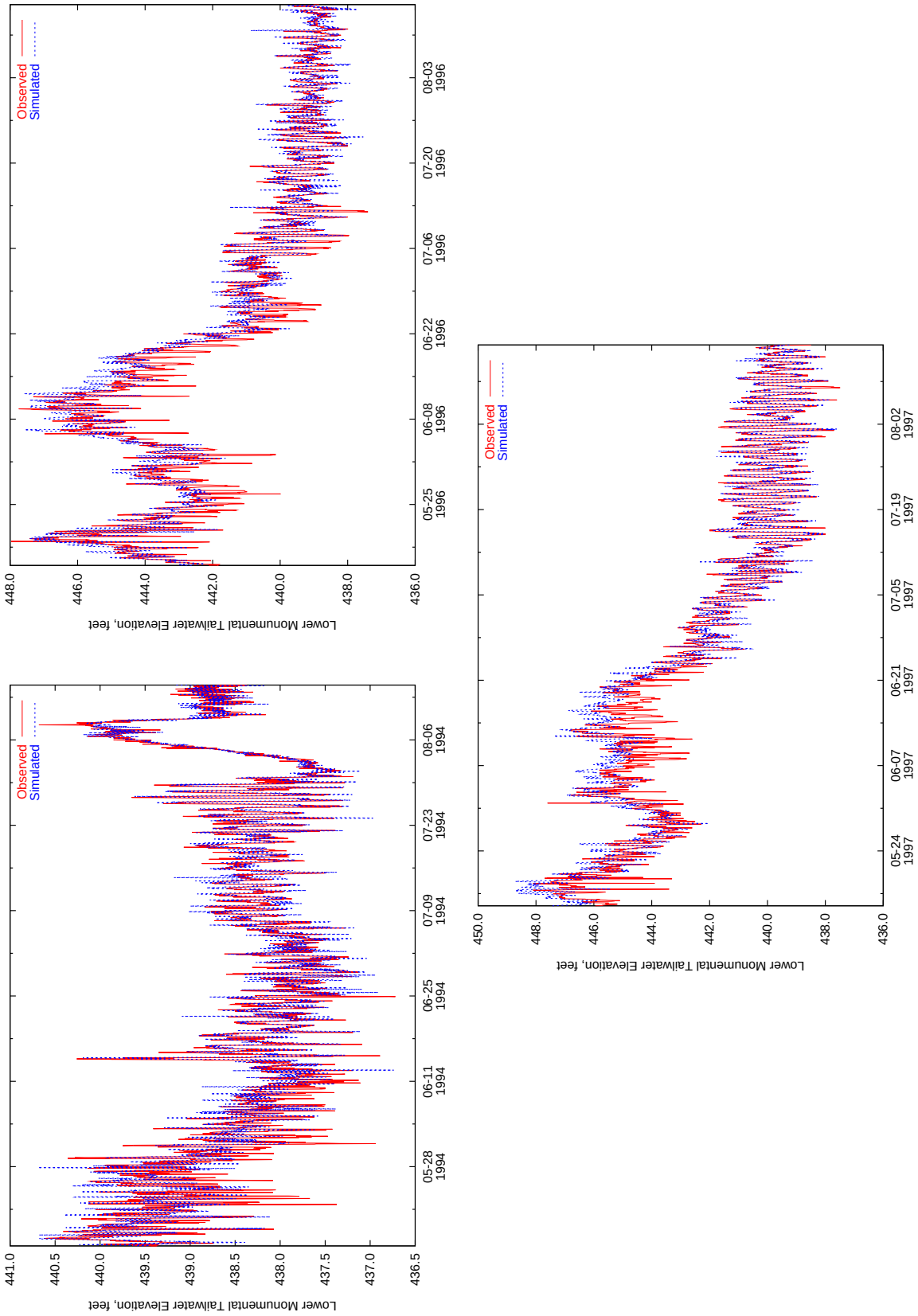

Figure 3.6: Comparison of simulated and observed stage below Lower Monumental dam for the spill seasons of 1994, 1996, and 1997.

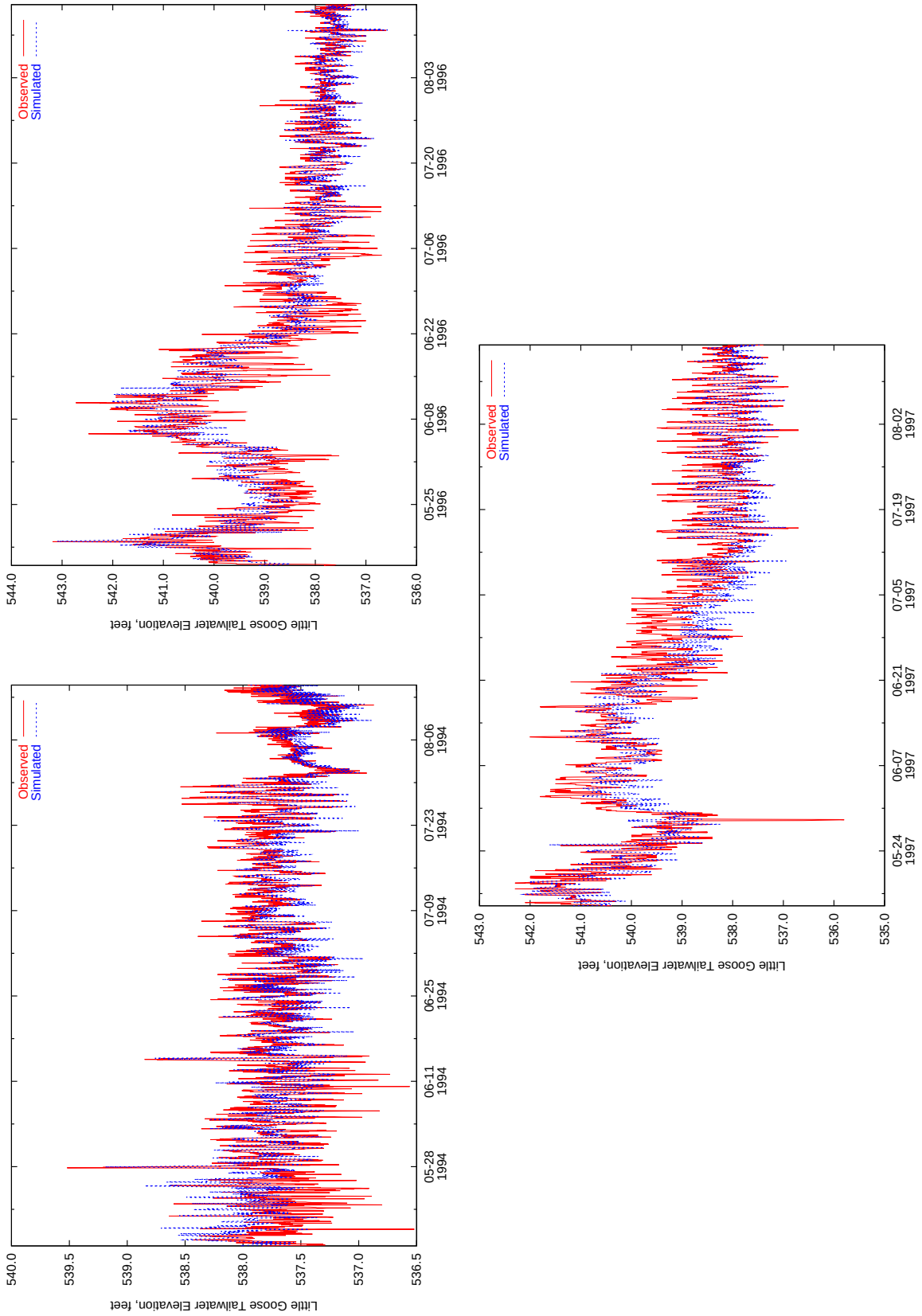

Figure 3.7: Comparison of simulated and observed stage below Little Goose dam for the spill seasons of 1994, 1996, and 1997.

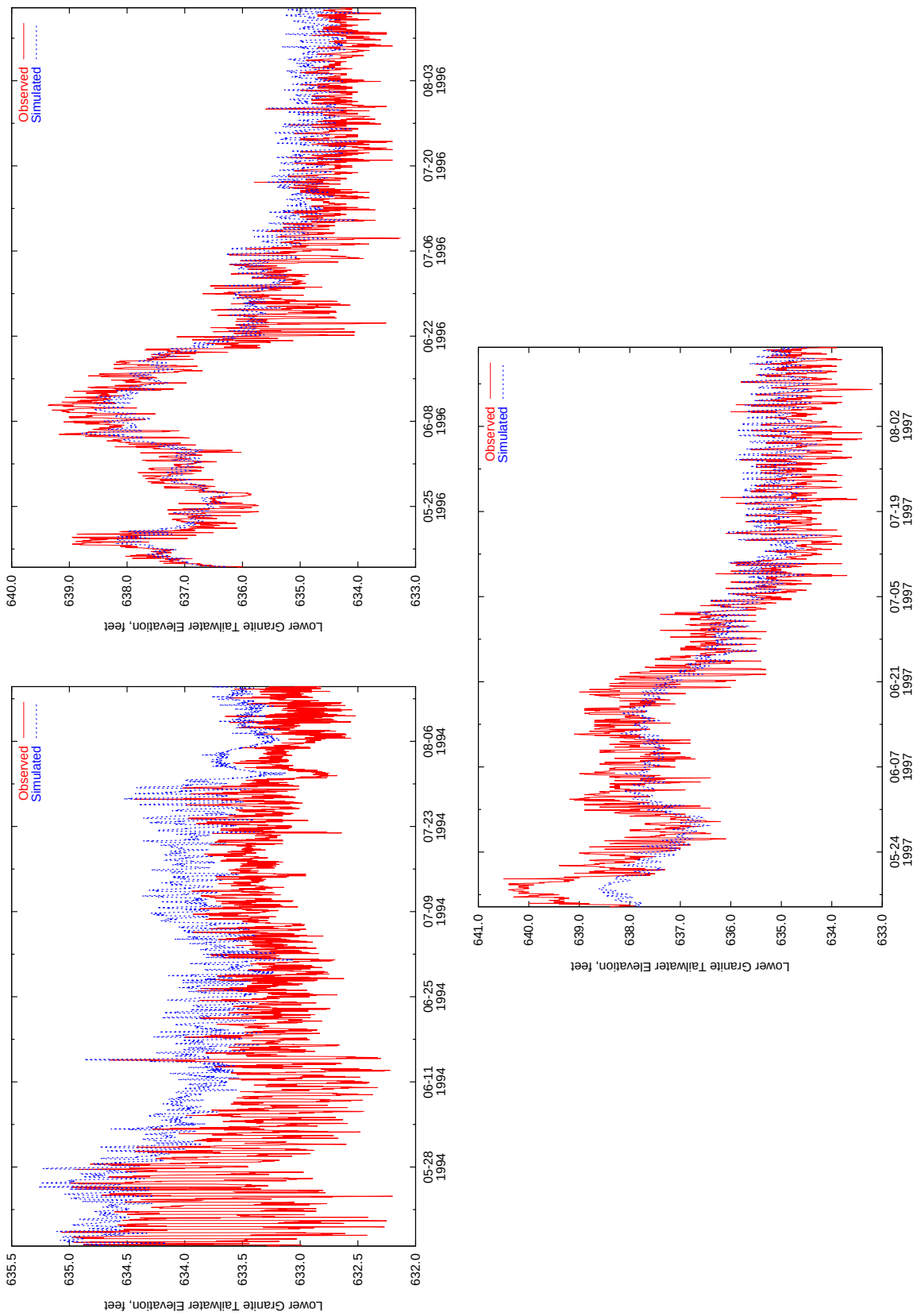

Figure 3.8: Comparison of simulated and observed stage below Lower Granite dam for the spill seasons of 1994, 1996, and 1997.

3.2 Temperature Verification

Comparisons of simulated and observed water temperatures in project forebays (or other appropriate FMS location) are shown in Figures 3.9 (Tidal Reach @ FMS CWMW) through 3.17 (Lower Granite). Table 3.2 very generally summarizes the overall predictive ability of MASS1 using various measures defined by Lettenmaier and Wood (1993): root-mean-square (RMS) error, bias, and R^2. For 1997, MASS1 predicts to within 1°C, the criteria to which MASS2 was held for its calibration and verification (Richmond et al., 1999). In 1996, MASS1 tends to underpredict the water temperature.

In some specific cases, differences in observed and simulated temperatures were clearly instrumentation errors. Clear examples include most of May 1996 in Lower Monumental pool (Figure 3.15), the early part of 1996 in the Ice Harbor pool (Figure 3.14), and July and August of 1996 in McNary pool (Figure 3.13). Further comparison with the DGAS field data set (Carroll et al., 1998) would help to identify these instrumentation errors.

Table 3.2: Summary of simulated temperature compared to observed for the Lower Columbia and Snake simulation. Definitions of the error measures used can be found in Lettenmaier and Wood (1993).

Pool/Reach	**Fixed Monitor**	**RMS Error °C**	**Bias °C**	R^2
	1997			
Tidal	CWMW	0.5	−0.2	0.99
Bonneville	BON	1.0	−0.6	0.97
The Dalles	TDA	0.5	0.1	0.99
John Day	JDA	0.6	−0.1	0.99
McNary	MCQO	0.7	0.4	0.99
	MCQW	0.5	0.2	0.99
Ice Harbor	IHR	0.7	−0.5	0.99
Lower Monumental	LMN	0.8	−0.5	0.97
Little Goose	LGS	0.7	−0.4	0.98
Lower Granite	LWG	0.9	−0.6	0.99
	1996			
Tidal	CWMW	1.1	−0.9	0.97
Bonneville	BON	0.8	−0.7	0.99
The Dalles	TDA	0.9	−0.7	0.98
John Day	JDA	1.0	−0.8	0.97
McNary	MCQO	2.4	−1.8	0.94
	MCQW	1.8	−1.6	0.97
Ice Harbor	IHR	1.6	−0.3	0.85
Lower Monumental	LMN	1.2	−0.2	0.95
Little Goose	LGS	1.3	−0.6	0.93
Lower Granite	LWG	1.3	−0.1	0.92

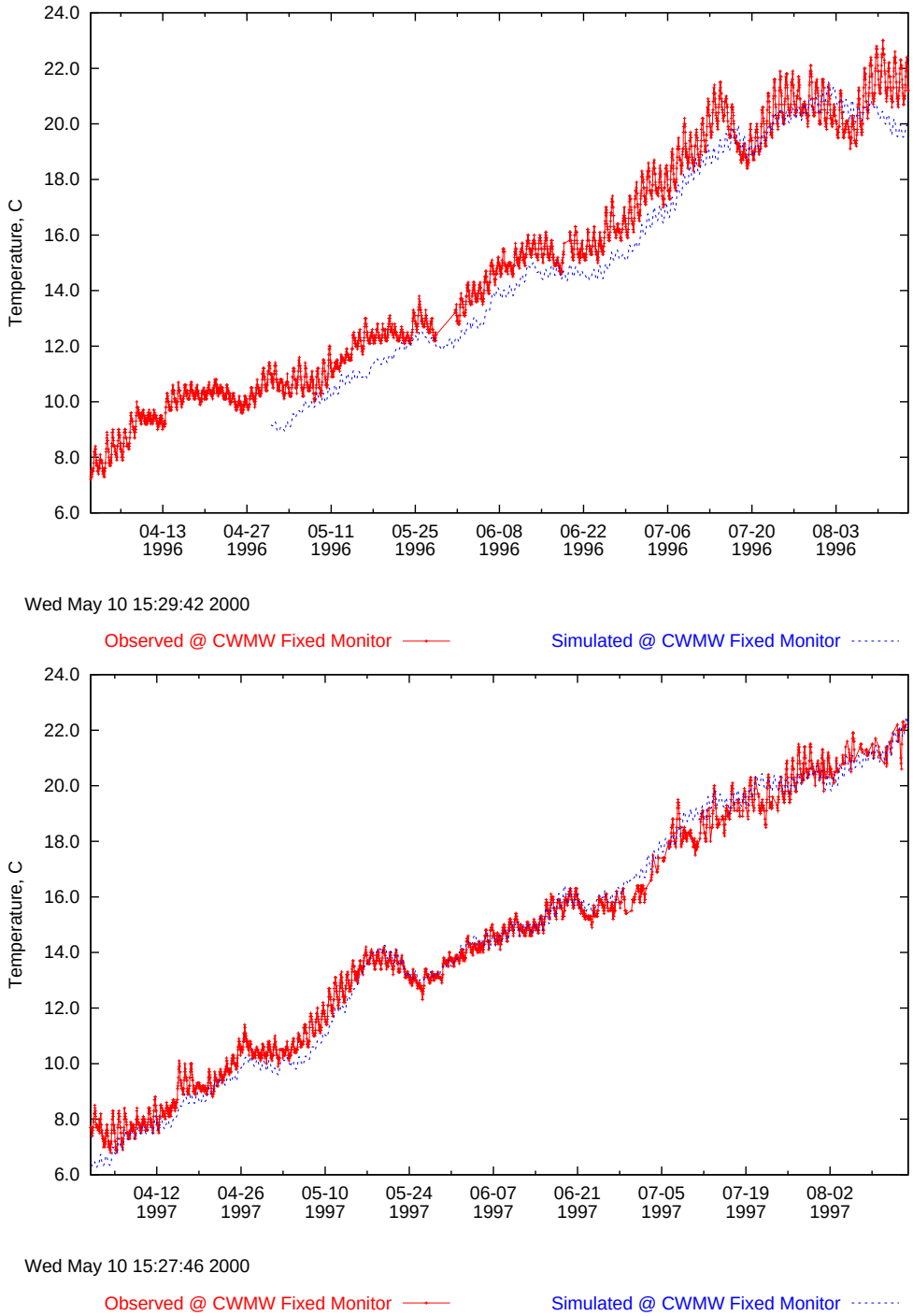

Figure 3.9: Comparison of simulated and observed water temperatures in the Columbia River tidal reach at the CWMW fixed monitorfor 1996 and 1997.

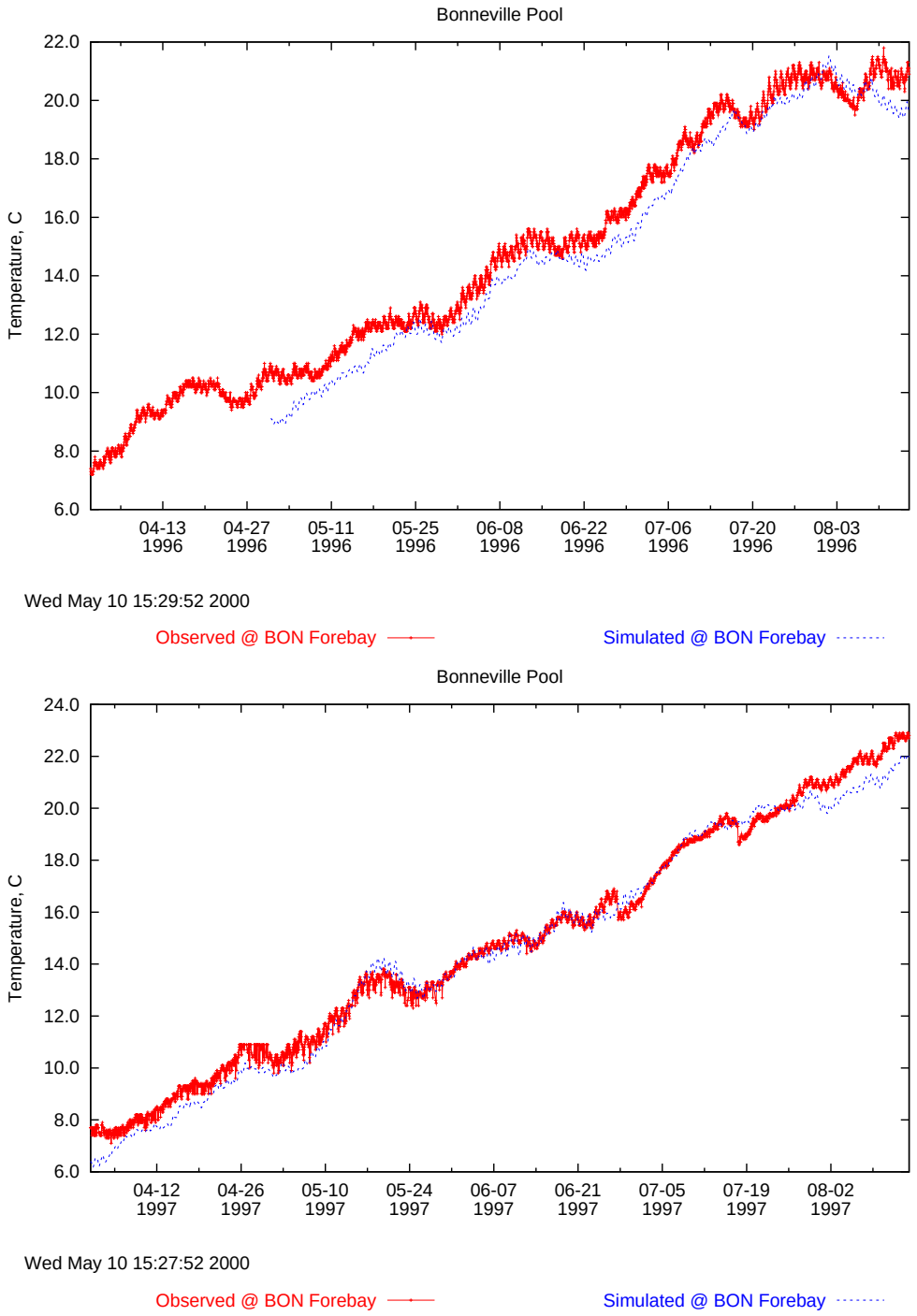

Figure 3.10: Comparison of simulated and observed water temperatures in the forebay of Bonneville dam for 1996 and 1997.

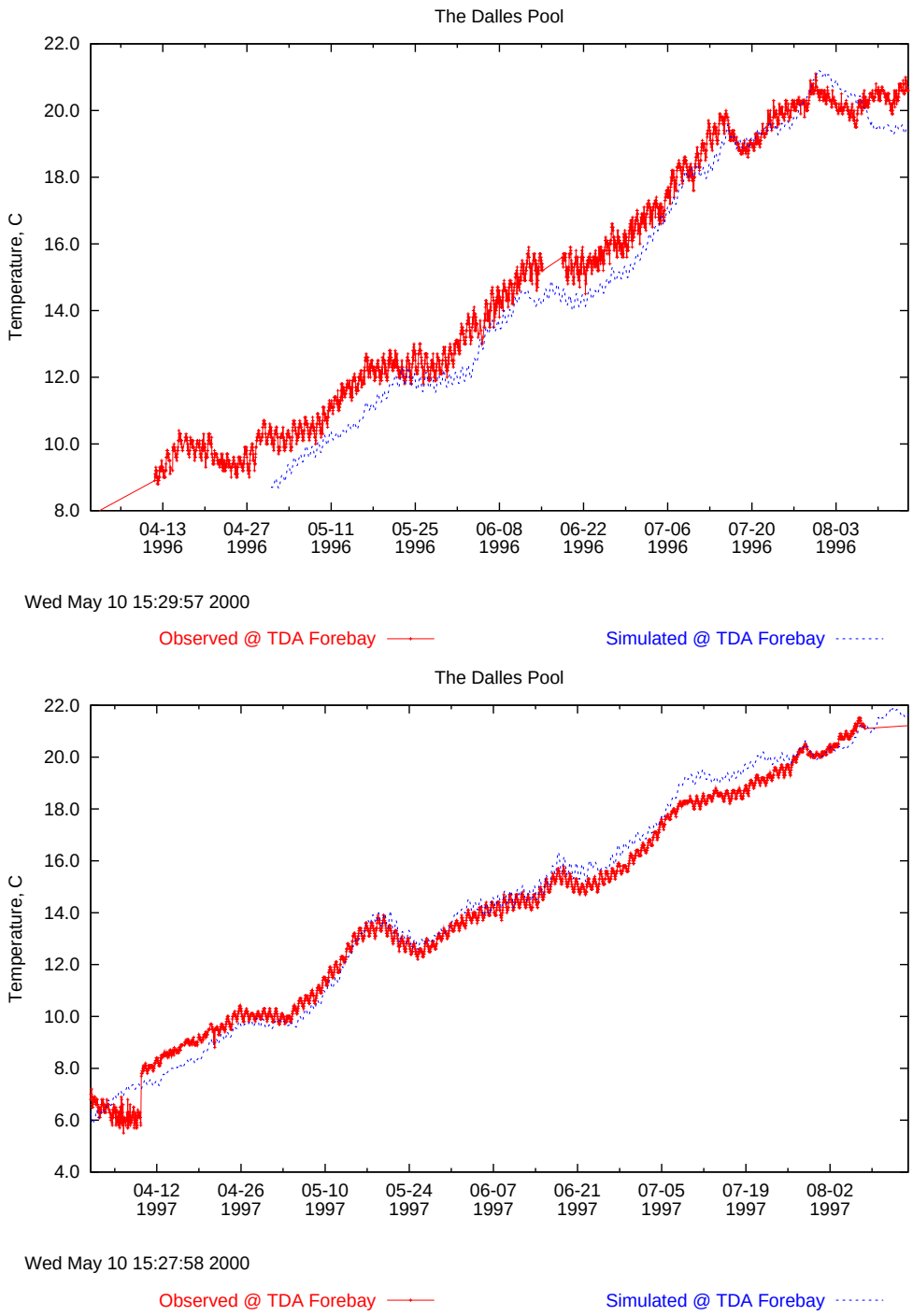

Figure 3.11: Comparison of simulated and observed water temperatures in the forebay of The Dalles dam for 1996 and 1997.

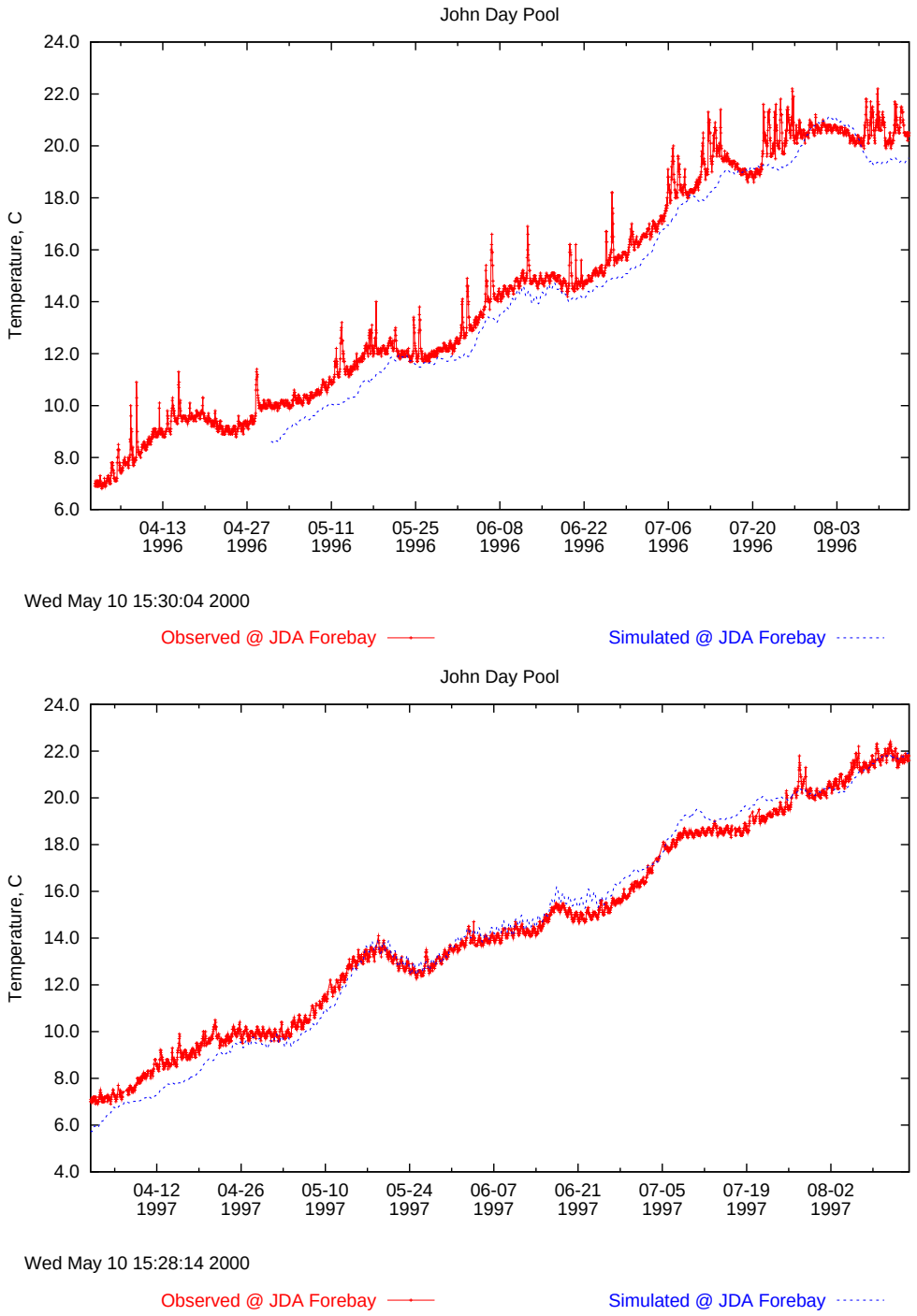

Figure 3.12: Comparison of simulated and observed water temperatures in the forebay of John Day dam for 1996 and 1997.

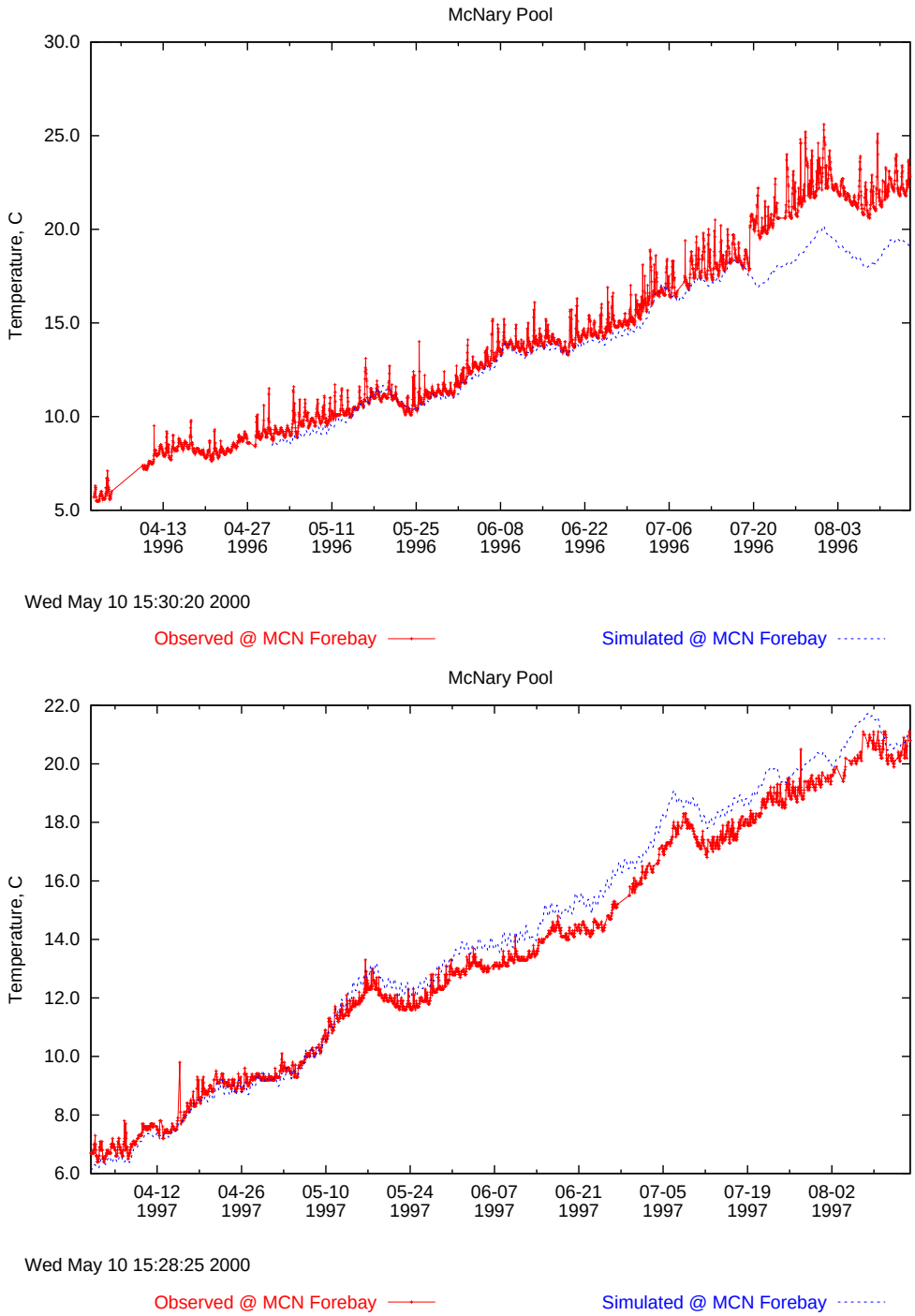

Figure 3.13: Comparison of simulated and observed water temperatures in the forebay of McNary dam for 1996 and 1997.

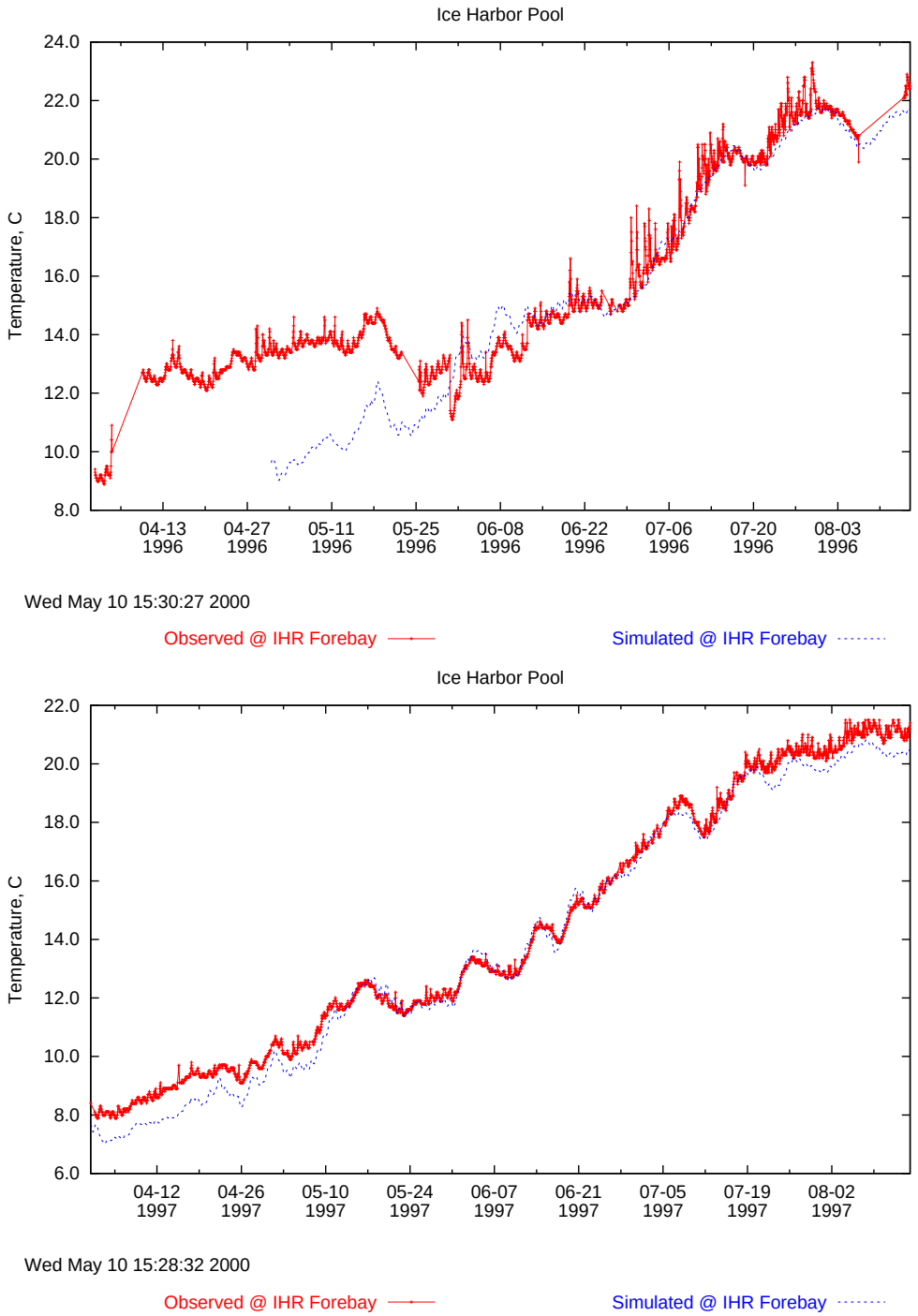

Figure 3.14: Comparison of simulated and observed water temperatures in the forebay of Ice Harbor dam for 1996 and 1997.

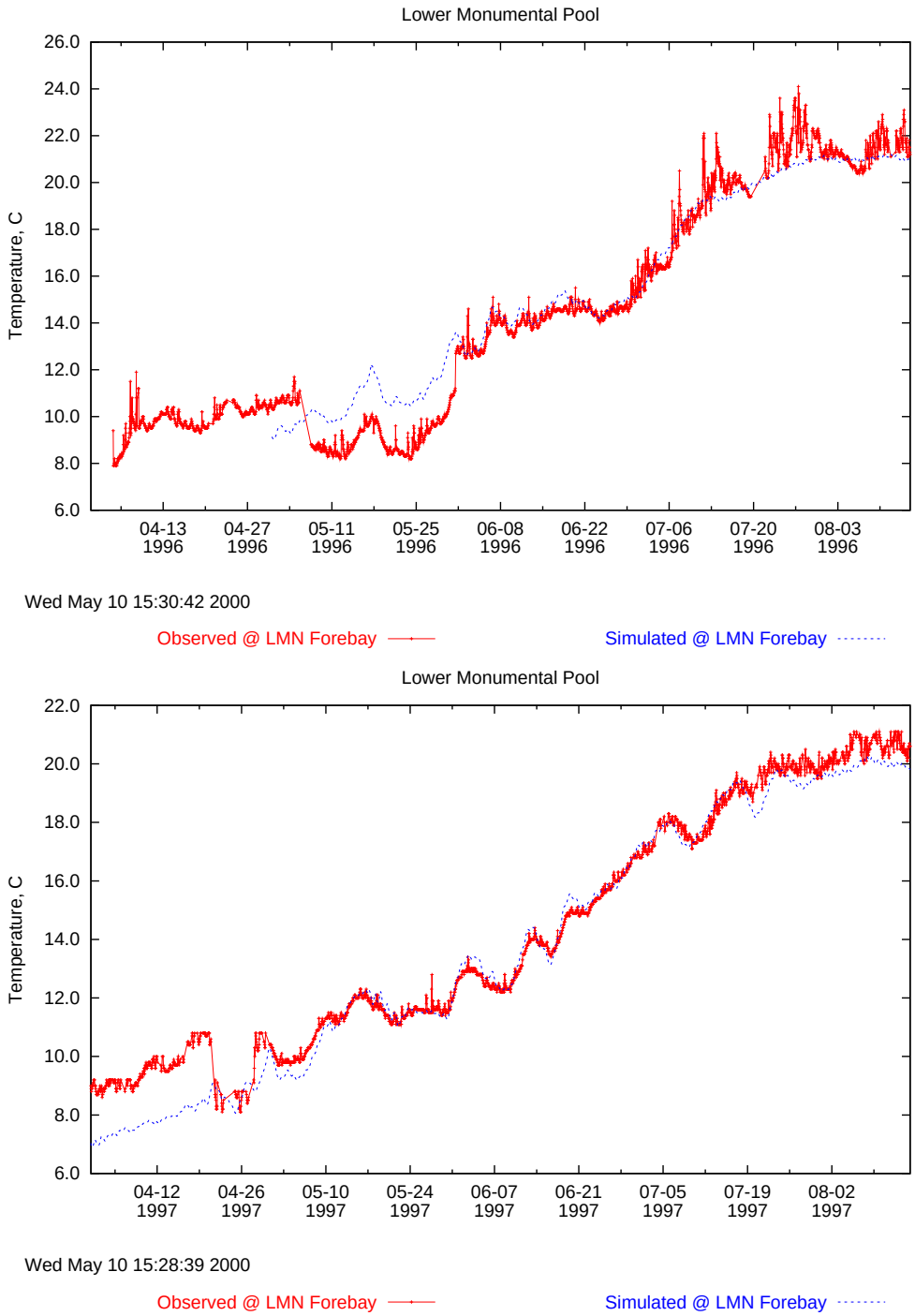

Figure 3.15: Comparison of simulated and observed water temperatures in the forebay of Lower Monumental dam for 1996 and 1997.

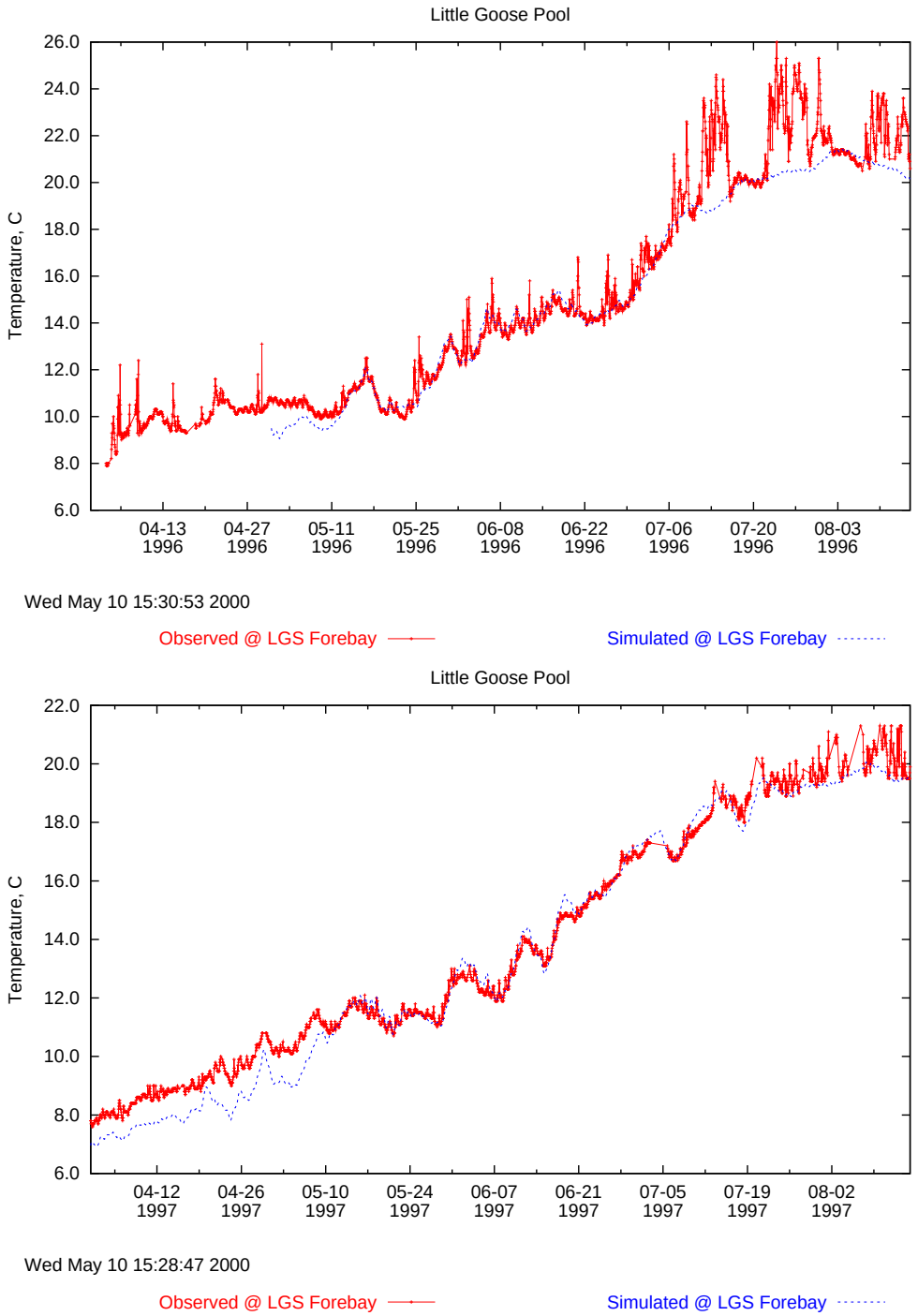

Figure 3.16: Compariswon of simulated and observed water temperatures in the forebay of Little Goose dam for 1996 and 1997.

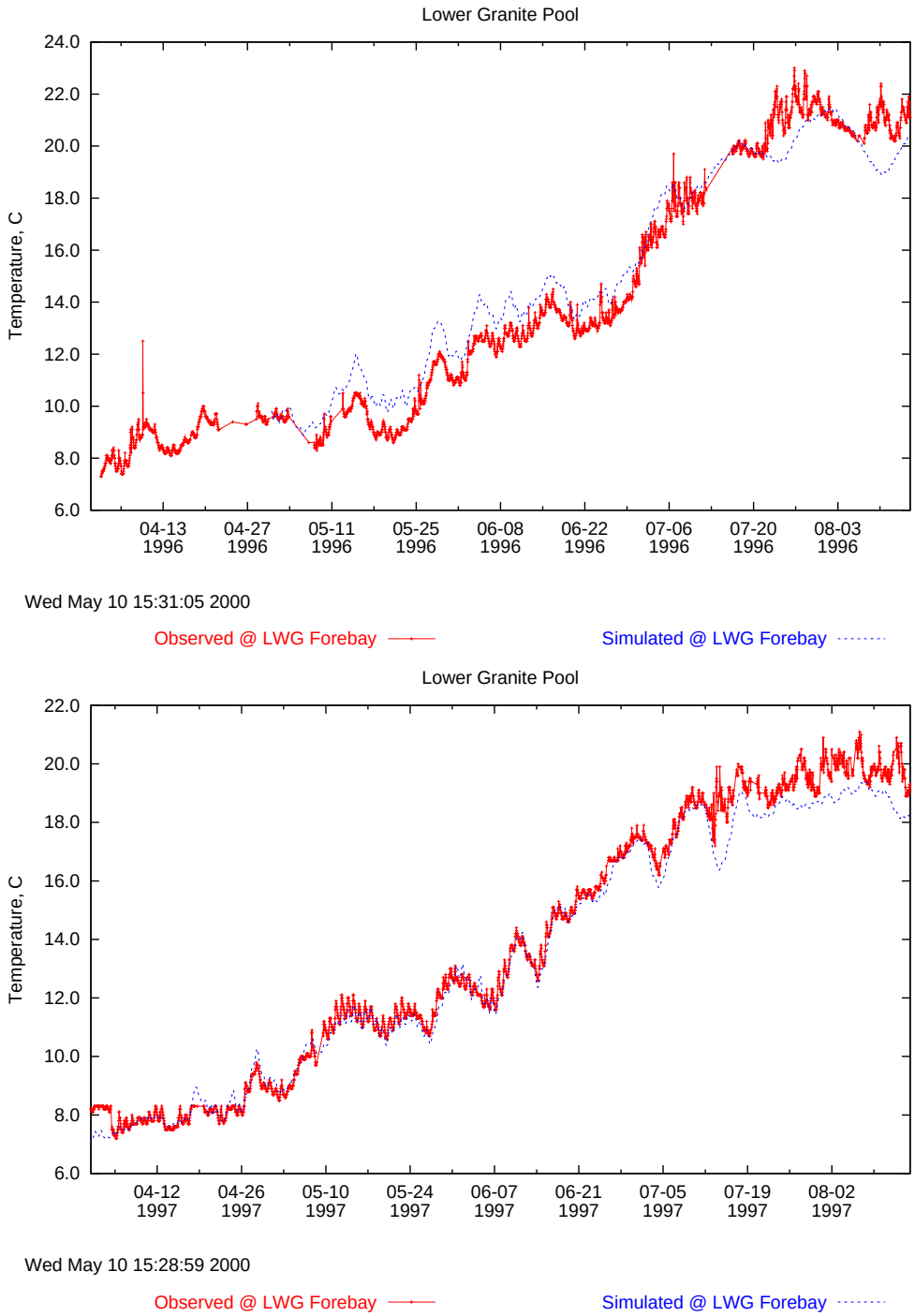

Figure 3.17: Comparison of simulated and observed water temperatures in the forebay of Lower Granite dam for 1996 and 1997.

3.3 Dissolved Gas Calibration/Verification

The dissolved gas simulations were run concurrently with the temperature verification simulations. A shorter time period was simulated in 1996 because of large gaps, and erroneous values, in April and earlier TDG measurements at the PRXW monitor. After trying several other forms, the original surface transfer coefficient function (which varies with wind speed) used by MASS2 (Richmond et al., 1999) was deemed best. Thus, the simulations are effectively verification results.

Comparisons of observed and simulated gas pressures are shown in Figures 3.18 (Tidal Reach @ FMS CWMW) through 3.26 (Lower Granite). In each graph, the observed TDG pressures at the downstream end of the pool or reach, or forebay, is compared to simulated. Additionally, the upstream TDG pressure, resulting from fully mixing the spill and powerhouse flow pressures. The simulations are more generally summarized in Table 3.3 using various measures of error defined by Lettenmaier and Wood (1993).

In the 1997 simulations, simulated pressures in the Columbia River match the observed pressures well. In the Snake River, however, simulated pressures were consistently lower than those observed. This is probably due to the Snake and Clearwater River TDG boundary conditions. Gas saturations at Anatone are, in reality, probably greater than 100 percent. The 1996 results are less consistent in the Columbia River, but similar in the Snake. The criteria used for the MASS2 calibration/verification (Richmond et al., 1999) was ± 38 mm Hg (nominally corresponds to $\pm 5\%$ saturation. Gas pressures predicted by MASS1 stay within this criteria most of the time. In addition to comparison with the FMS data, MASS1 needs to undergo a rigorous comparison with the DGAS field data, as was done with MASS2 (Richmond et al., 1999).

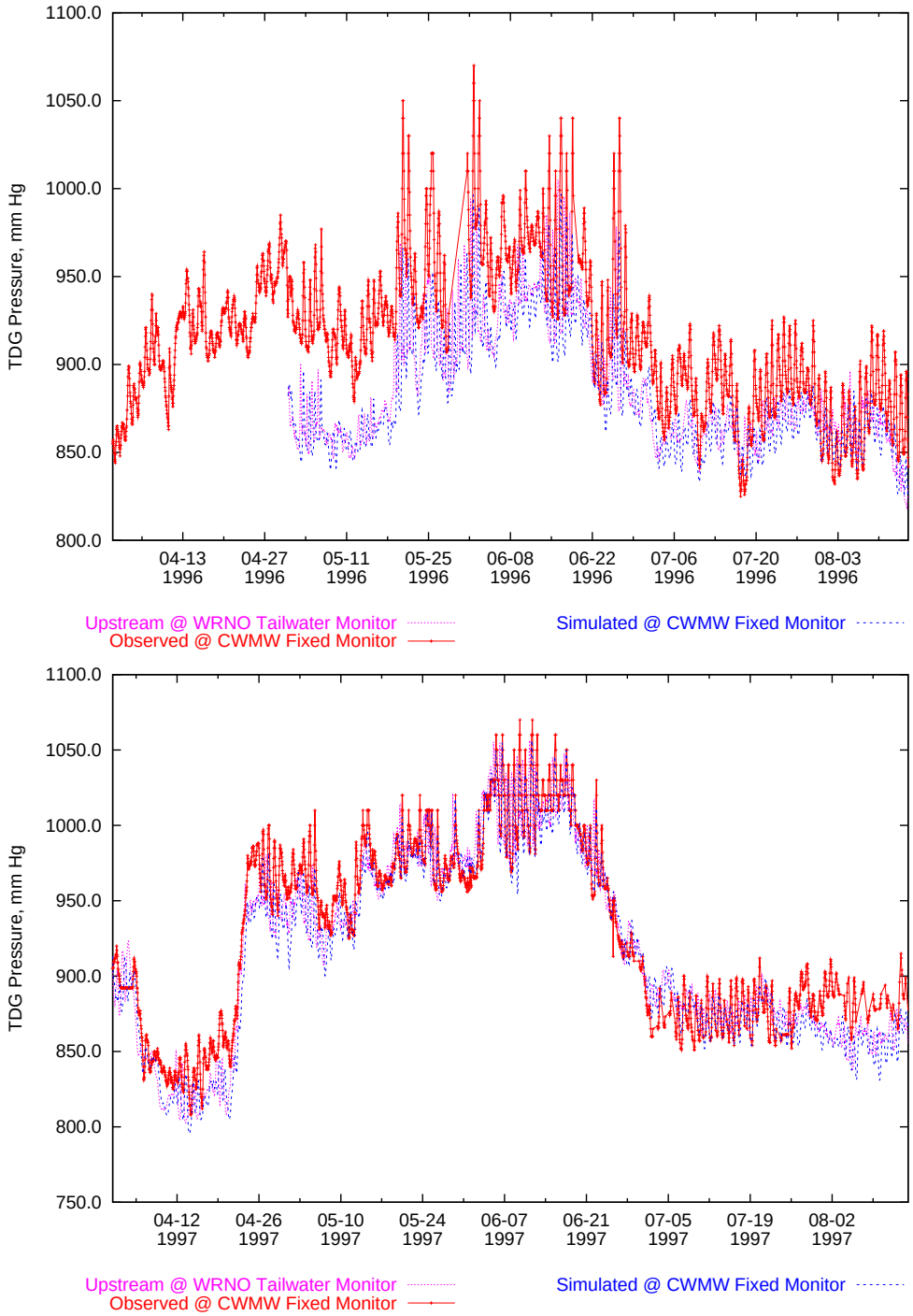

Figure 3.18: Comparison of simulated and observed TDG pressures at the CWMW fixed monitor in the Tidal Reach for 1996 and 1997.

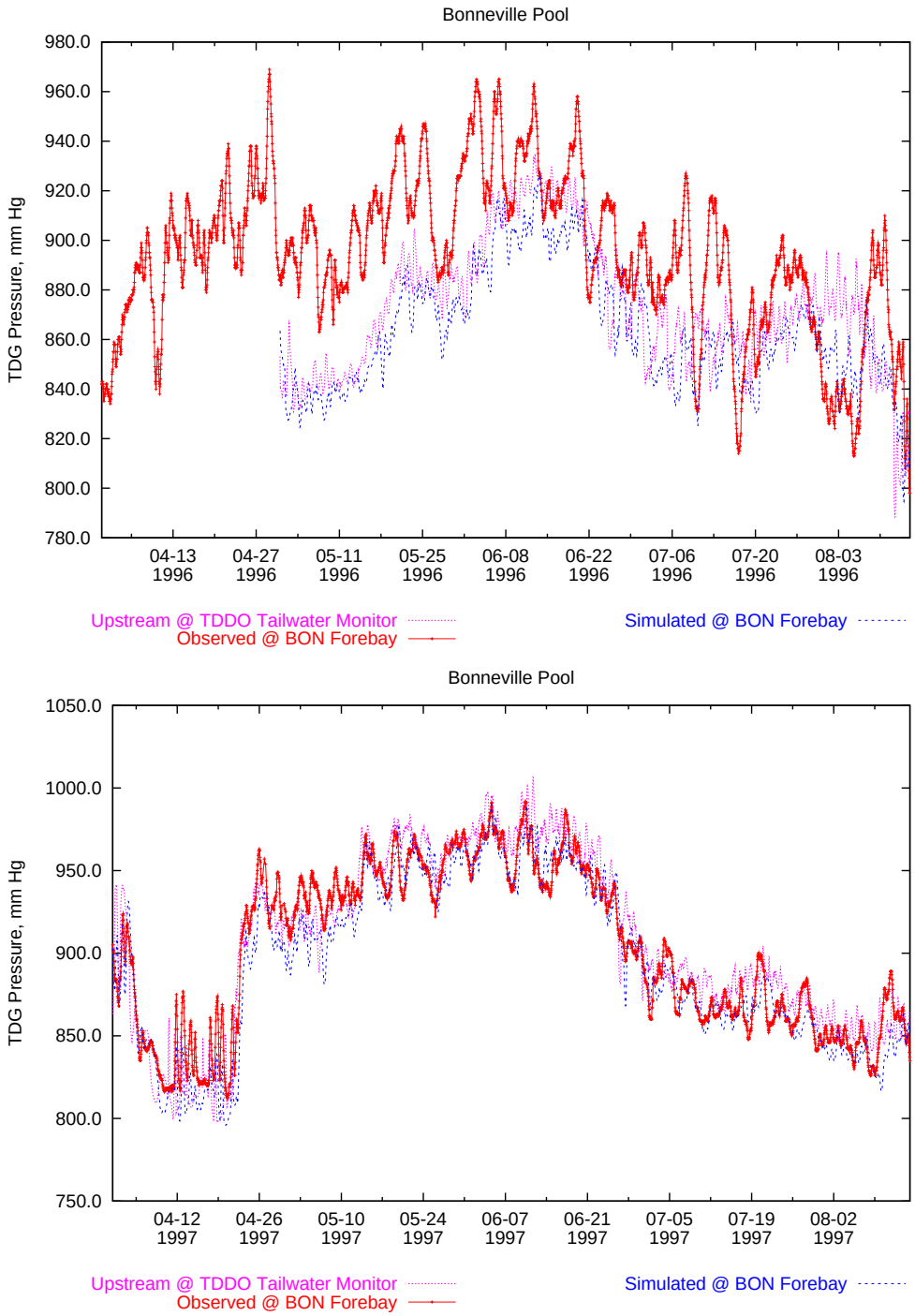

Figure 3.19: Comparison of simulated and observed TDG pressures in the forebay of Bonneville dam for 1996 and 1997.

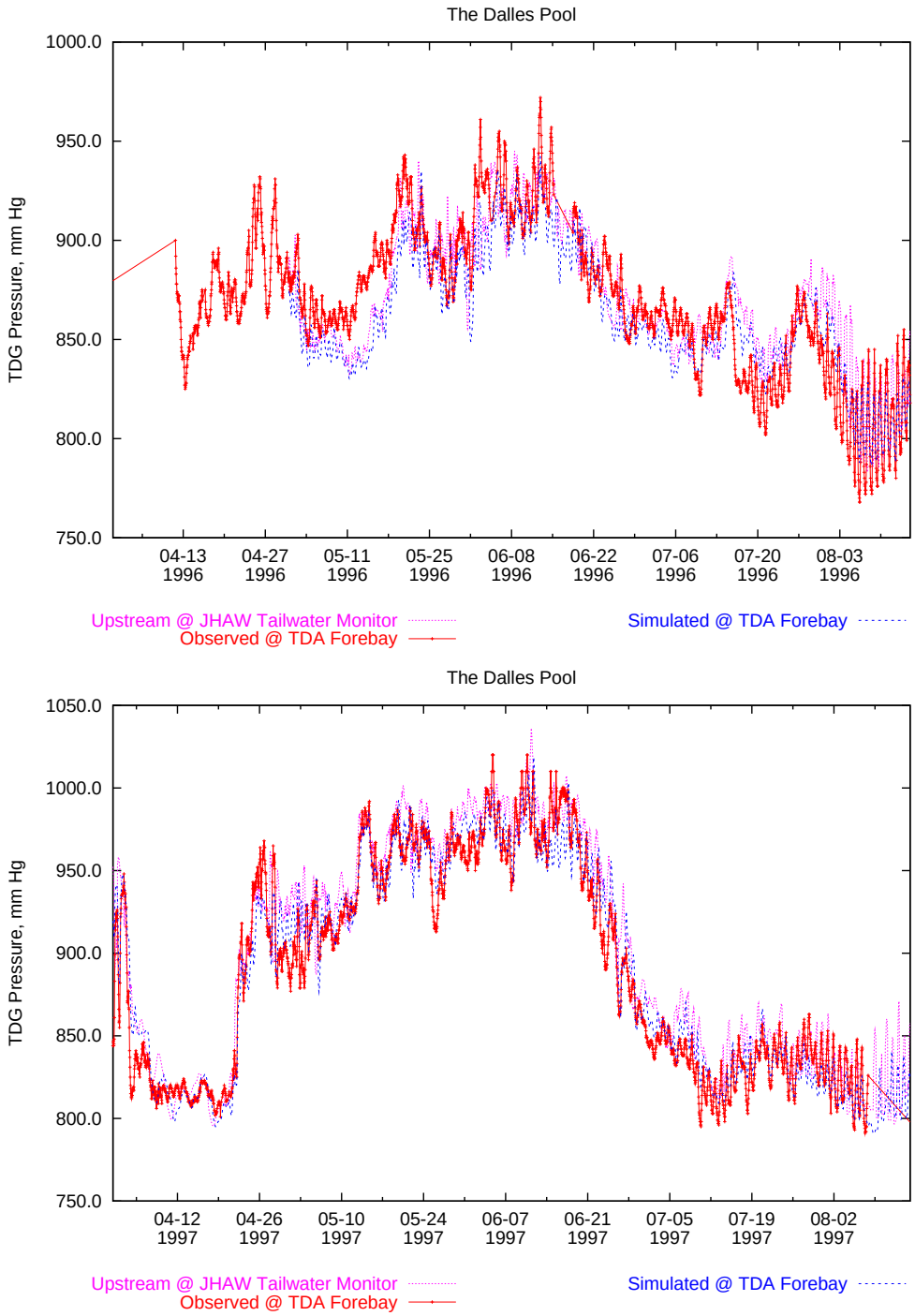

Figure 3.20: Comparison of simulated and observed TDG pressures in the forebay of The Dalles dam for 1996 and 1997.

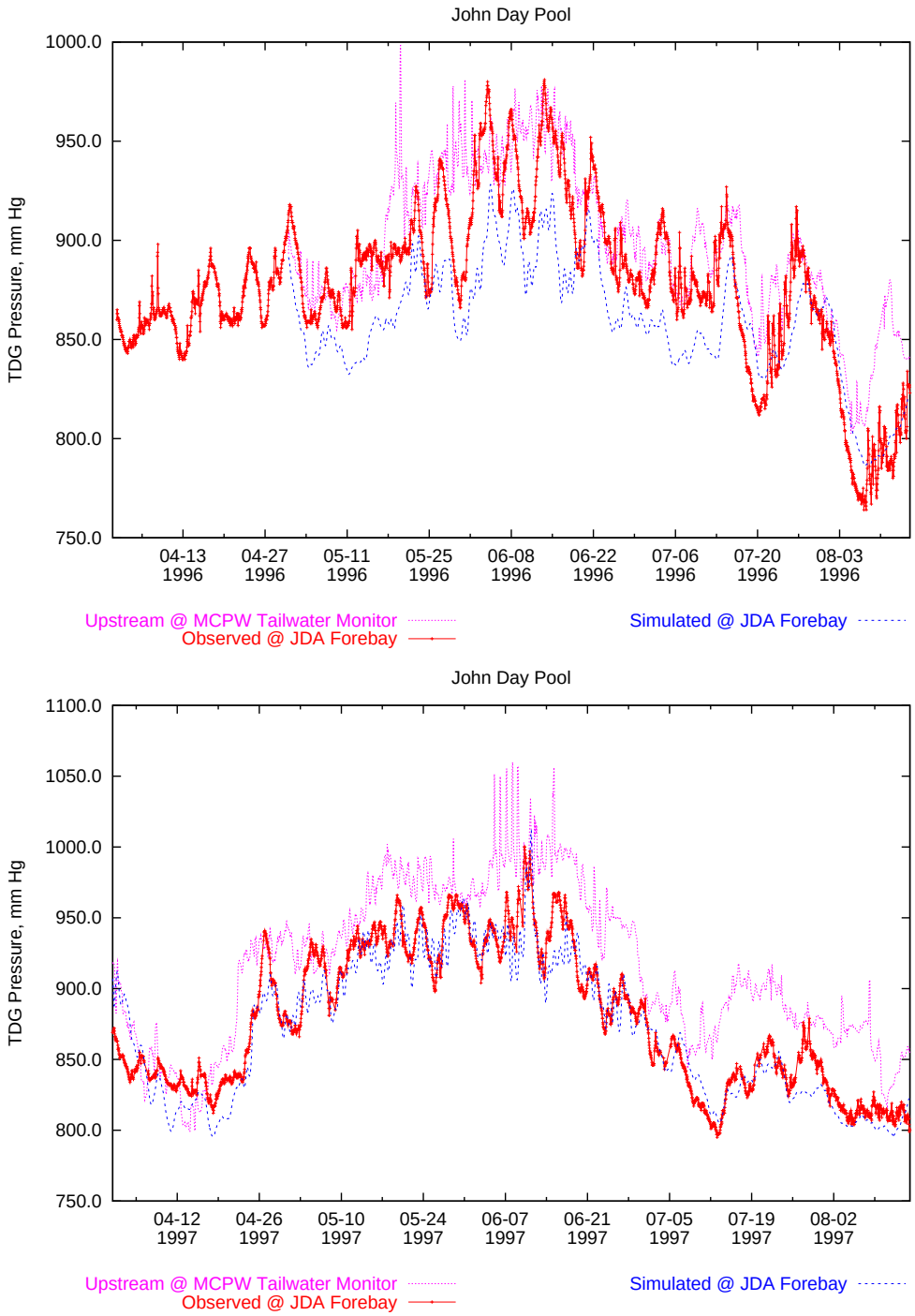

Figure 3.21: Comparison of simulated and observed TDG pressures in the forebay of John Day dam for 1996 and 1997.

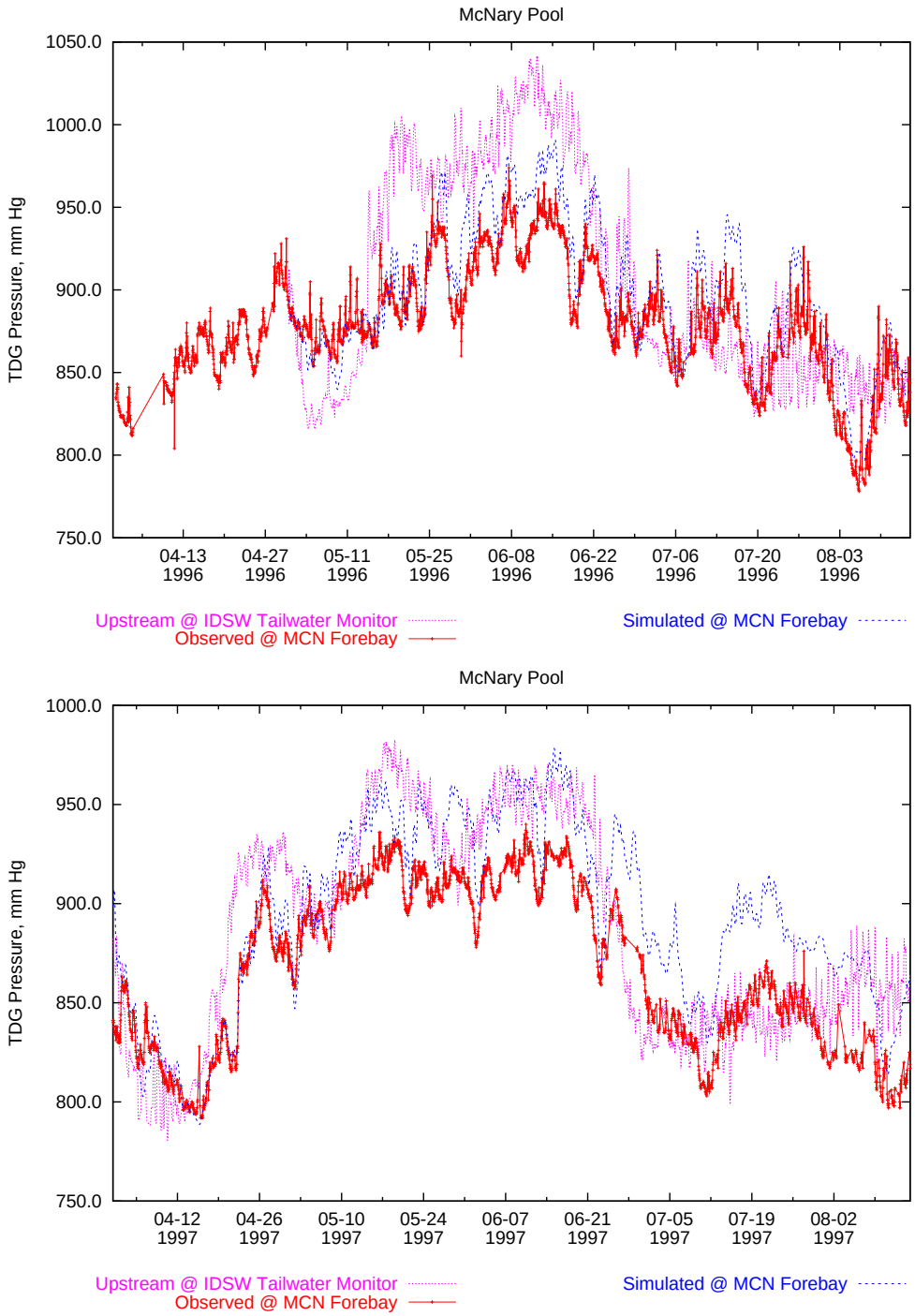

Figure 3.22: Comparison of simulated and observed TDG pressures in the forebay of McNary dam for 1996 and 1997.

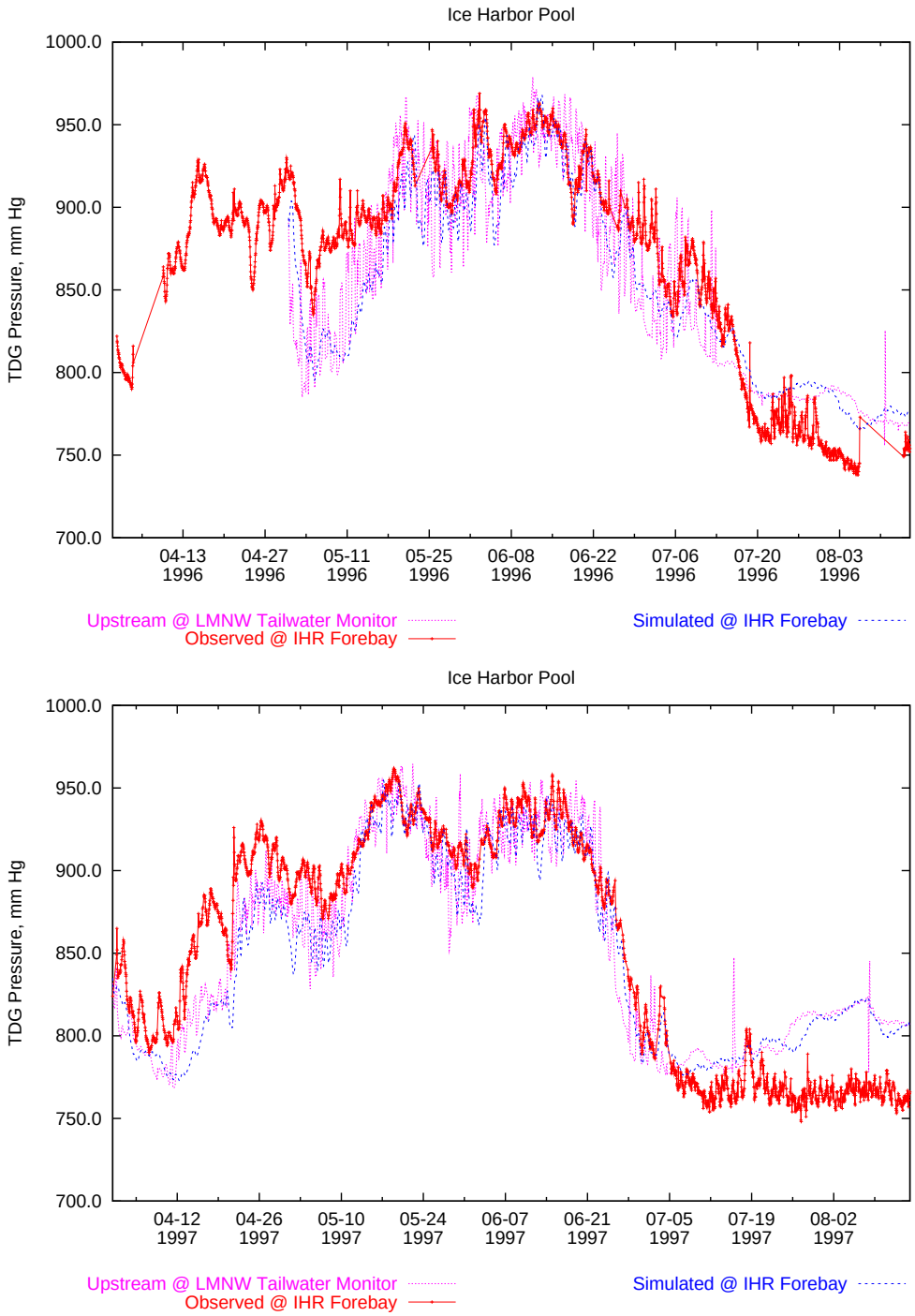

Figure 3.23: Comparison of simulated and observed TDG pressures in the forebay of Ice Harbor dam for 1996 and 1997.

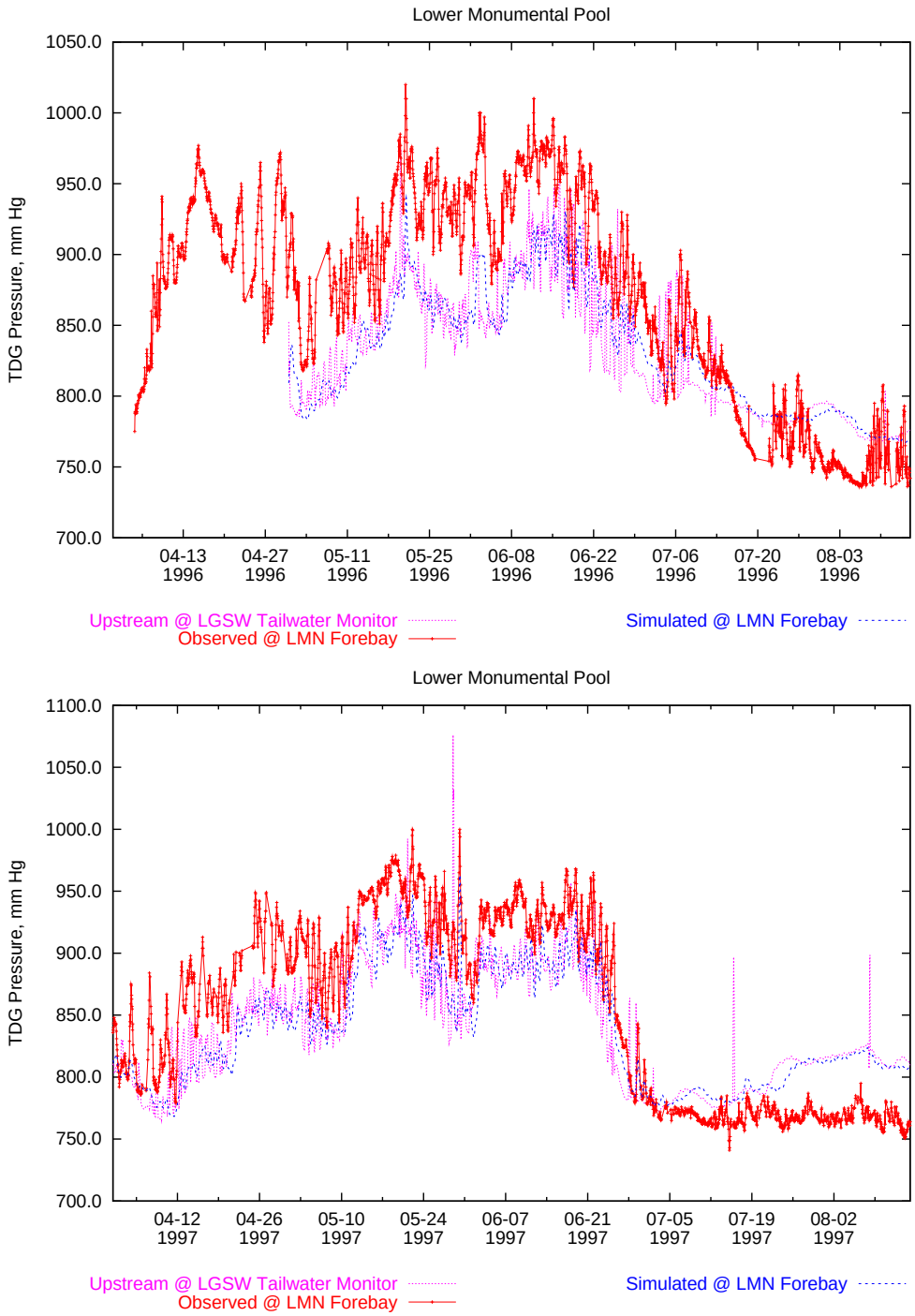

Figure 3.24: Comparison of simulated and observed TDG pressures in the forebay of Lower Monumental dam for 1996 and 1997.

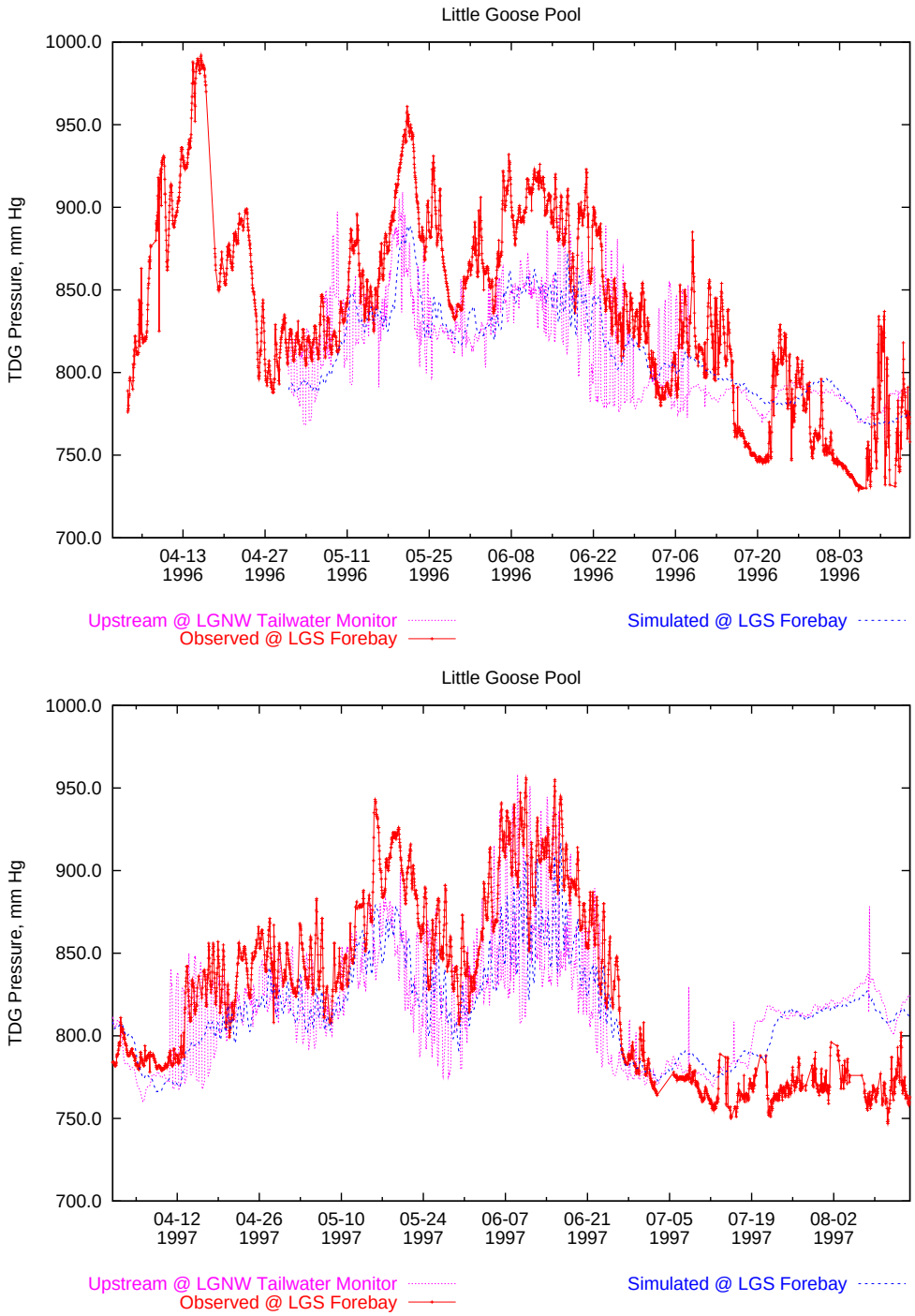

Figure 3.25: Compariswon of simulated and observed TDG pressures in the forebay of Little Goose dam for 1996 and 1997.

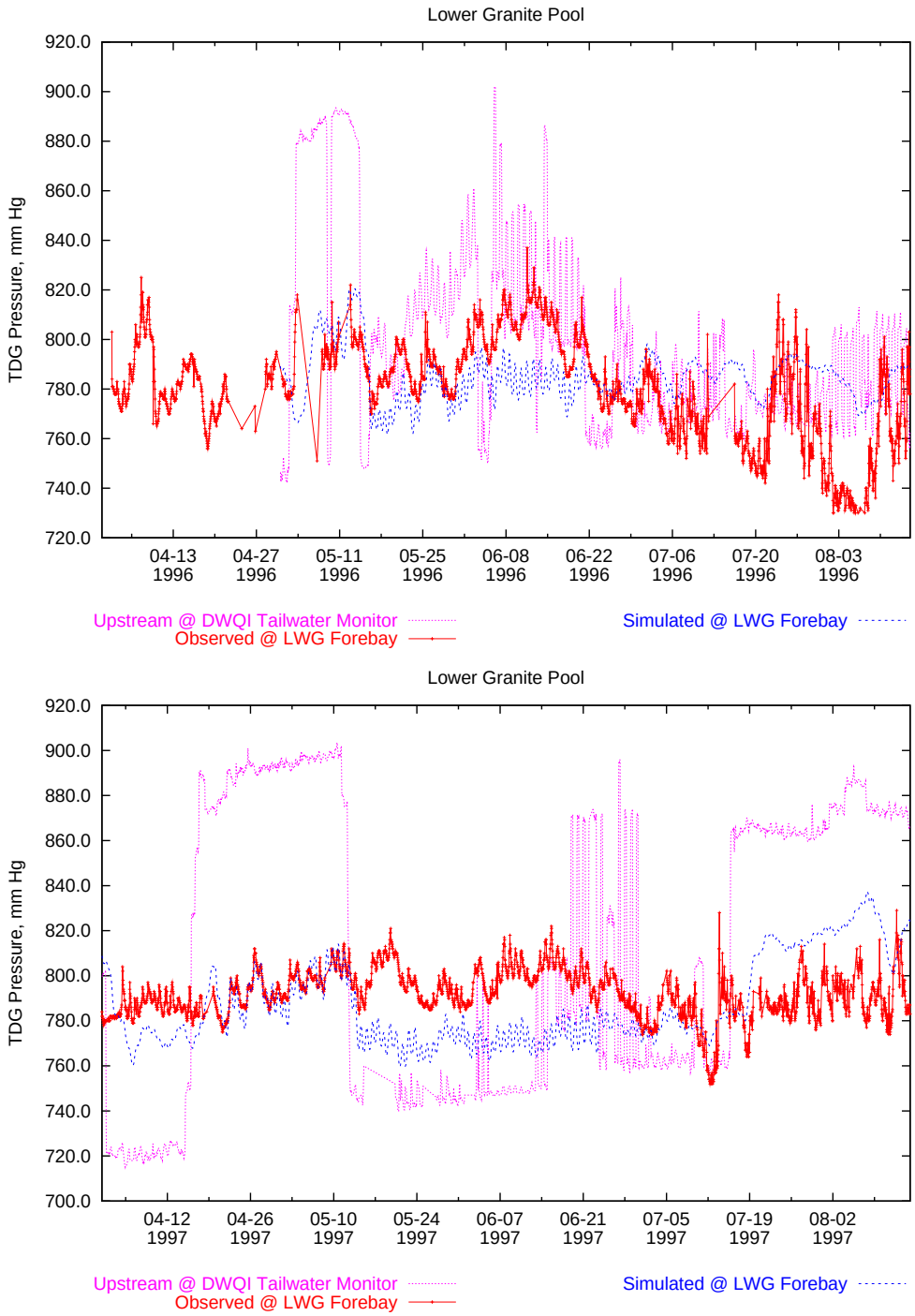

Figure 3.26: Comparison of simulated and observed TDG pressures in the forebay of Lower Granite dam for 1996 and 1997.

Table 3.3: Summary of error in simulated pressure for the Lower Columbia and Snake simulations. Definitions of the error measures used can be found in Lettenmaier and Wood (1993).

Pool/Reach	**Fixed Monitor**	**RMS Error mm Hg**	**Bias mm Hg**	R^2
	1997			
Tidal	CWMW	18.8	−11.9	0.96
Bonneville	BON	16.9	−9.2	0.95
The Dalles	TDA	14.0	1.9	0.96
John Day	JDA	17.0	−4.0	0.92
McNary	MCQO	31.1	26.0	0.91
	MCQW	33.1	27.5	0.90
Ice Harbor	IHR	30.2	2.2	0.87
Lower Monumental	LMN	40.1	−5.4	0.87
Little Goose	LGS	34.8	−7.3	0.71
Lower Granite	LWG	23.0	1.7	0.21
	1996			
Tidal	CWMW	36.1	−28.3	0.89
Bonneville	BON	35.0	−24.1	0.75
The Dalles	TDA	17.8	−4.7	0.90
John Day	JDA	27.6	−17.3	0.88
McNary	MCQO	23.2	10.4	0.91
	MCQW	26.1	13.3	0.91
Ice Harbor	IHR	29.9	−0.6	0.88
Lower Monumental	LMN	47.7	−12.7	0.84
Little Goose	LGS	37.6	−5.4	0.65
Lower Granite	LWG	29.3	11.7	0.04

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A Flow Correction Results

The “flow corrections” resulting from the procedure in Section 2.2, and used for further simulations, are shown in Figures A.1 (Bonneville pool) through A.8 (Lower Granite pool). The sign of the “correction” shown in the Figures was the sign used when correction was used as lateral inflow. This means that if there is a negative correction, either the inflow to the pools is too high, or the outflow from the pool is too low. For instance, in Bonneville pool, Figure A.1, the correction is generally positive in 1994 and 1996, and that makes sense because there was probably a considerable amount of ungaged inflow to that pool which was not otherwise considered. On the other hand, in The Dalles pool, Figure A.2, the corrections are almost always negative. This may indicate that there is a bias in flow estimates at either The Dalles (too low) or John Day (too high). In general, though, the magnitudes of these corrections are low, less than 5% of the total project flow.

Figures A.16 (Lower Granite) through A.9 (Bonneville) compare observed forebay stages with those simulated when using the flow corrections. In general, the simulated stages stay near the observed. In some cases, like at John Day (Figure A.11), simulated stages track the observed stages even through some rather large changes. In other cases, though, the simulated stage drifts from the observed markedly during the course of the season. The most striking example is McNary (Figure A.12).

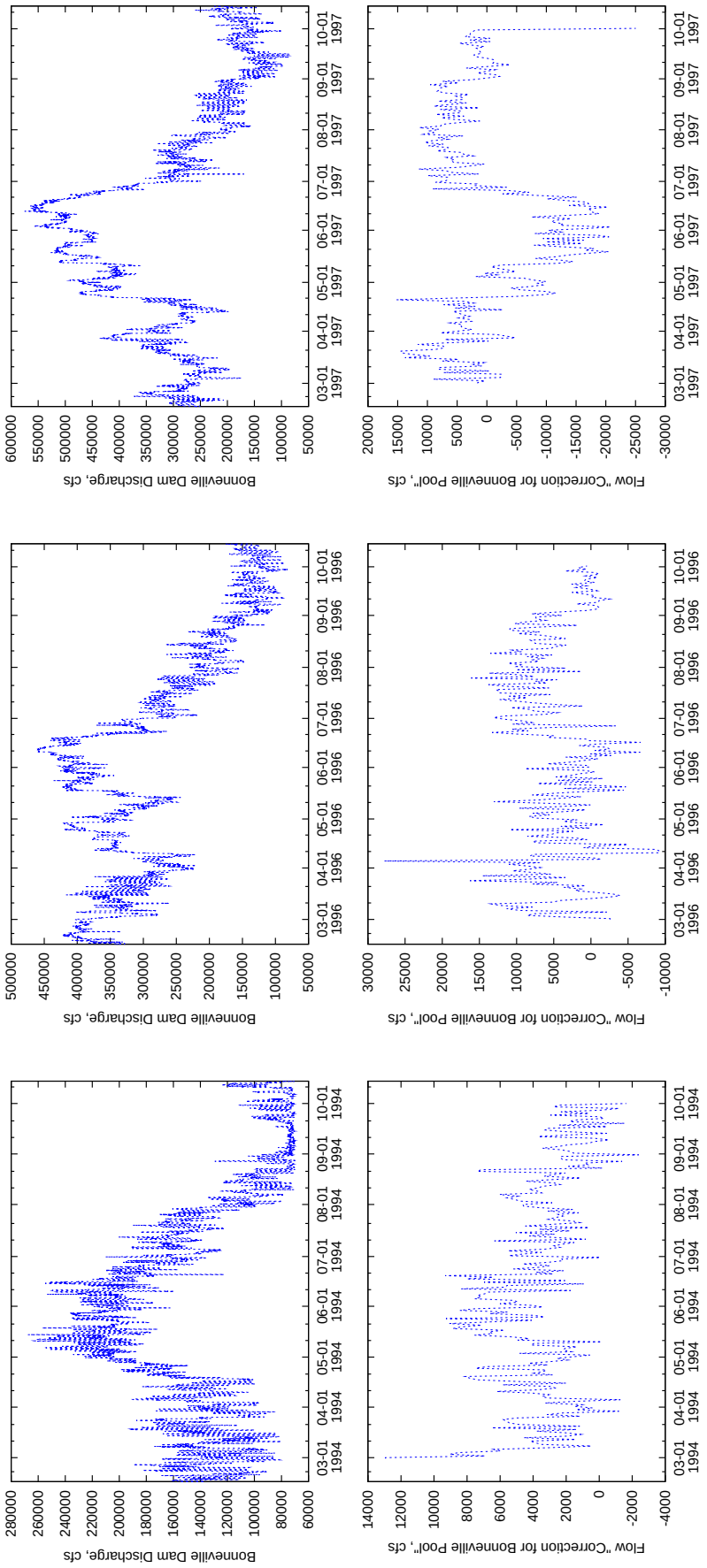

Figure A.1: Computed "flow corrections" applied as lateral inflow compared to total project flow for the Bonneville pool.

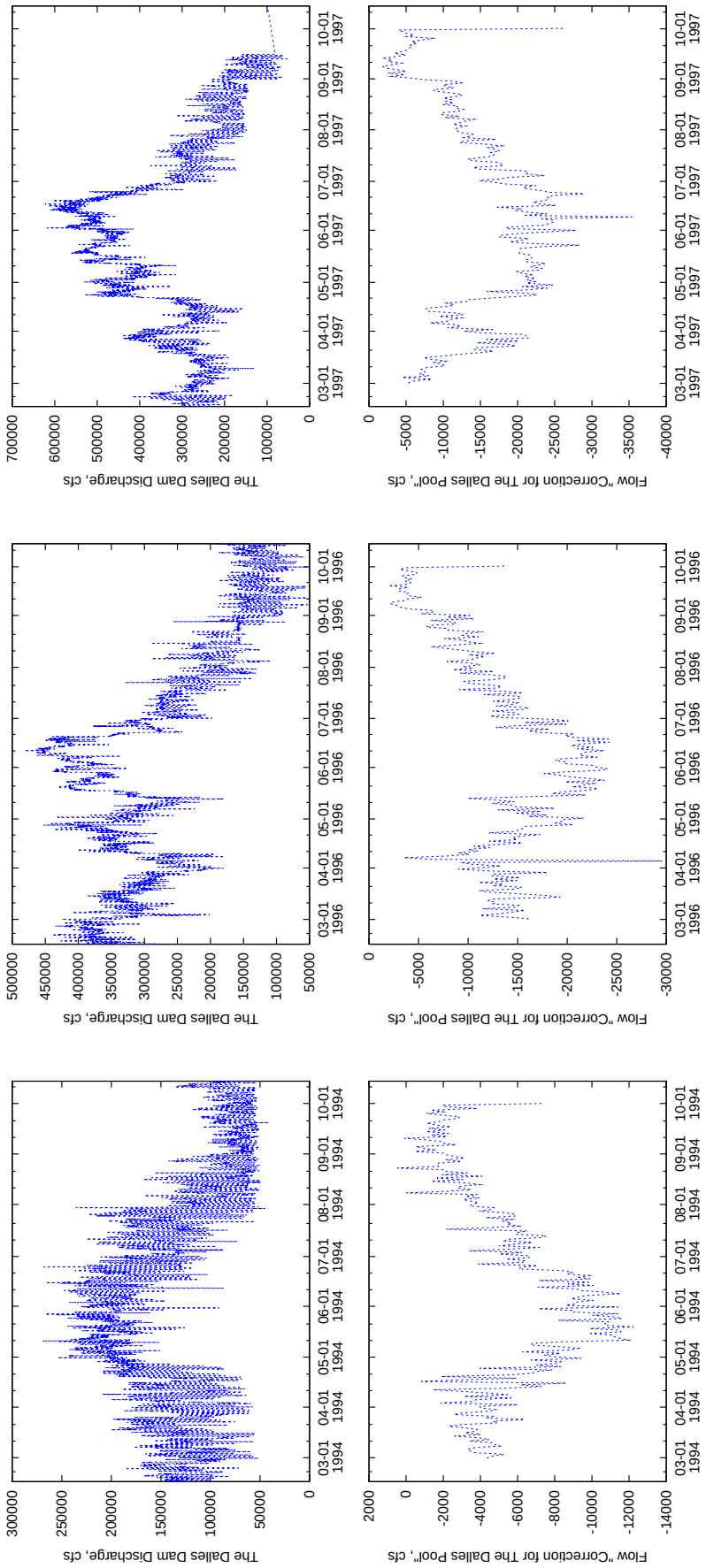

Figure A.2: Computed "flow corrections" applied as lateral inflow compared to total project flow for the The Dalles pool.

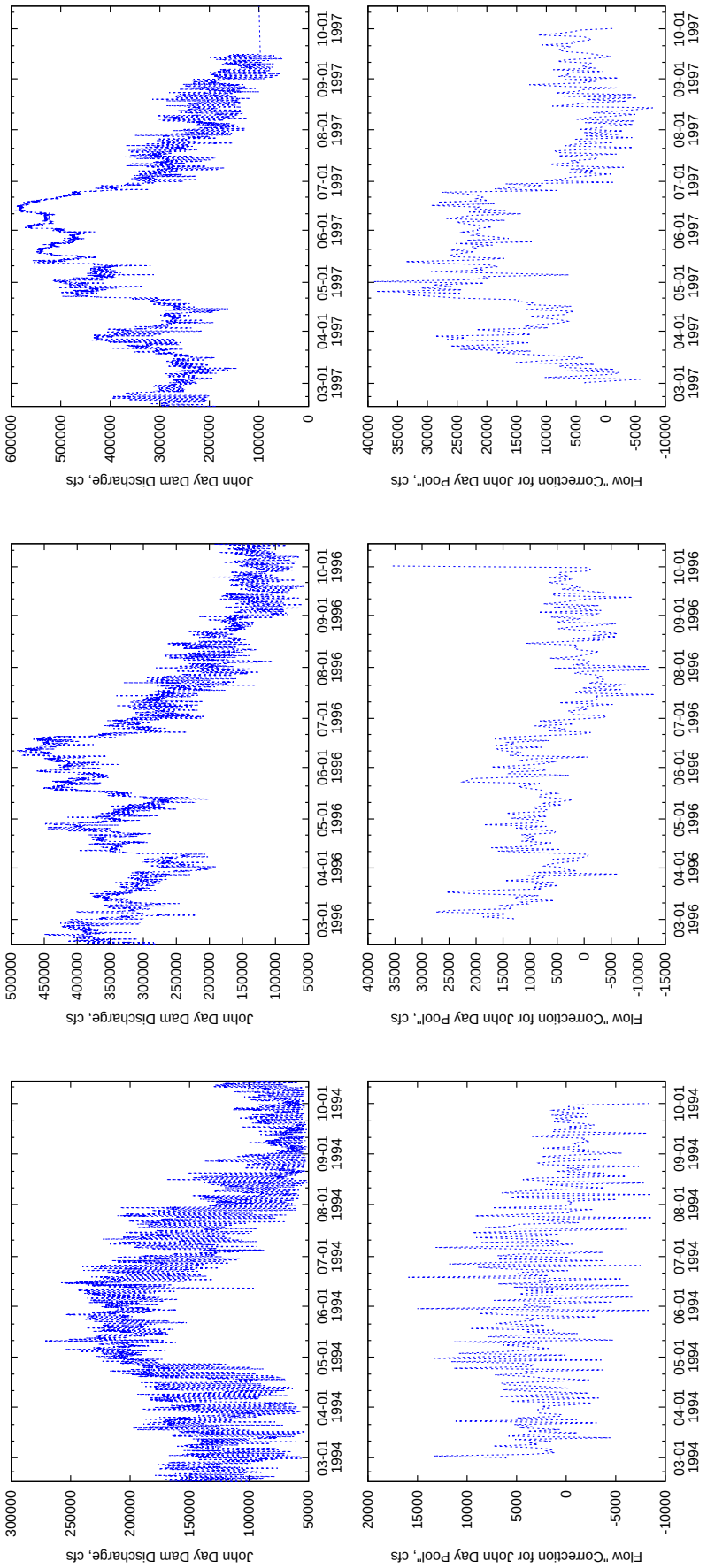

Figure A.3: Computed "flow corrections" applied as lateral inflow compared to total project flow for the John Day pool.

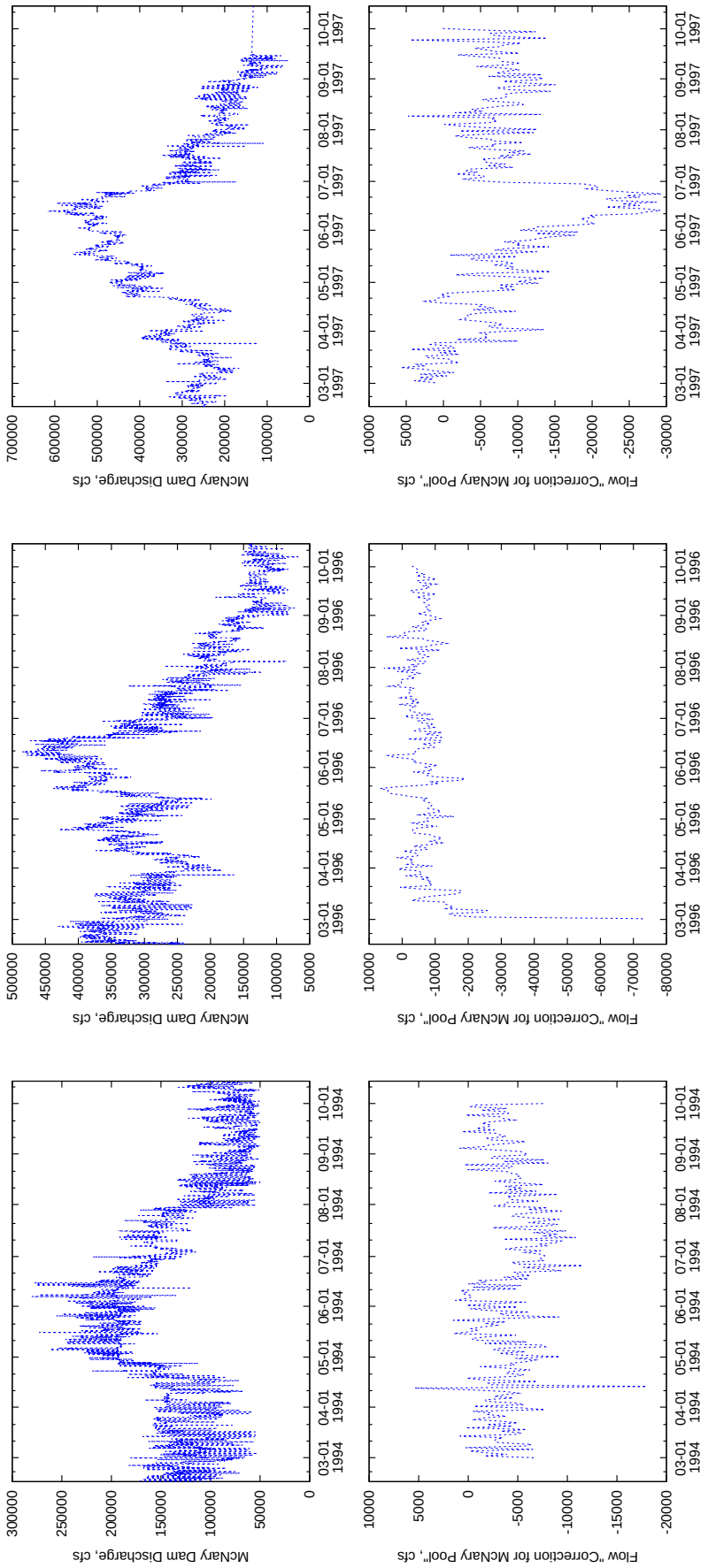

Figure A.4: Computed "flow corrections" applied as lateral inflow compared to total project flow for the McNary pool.

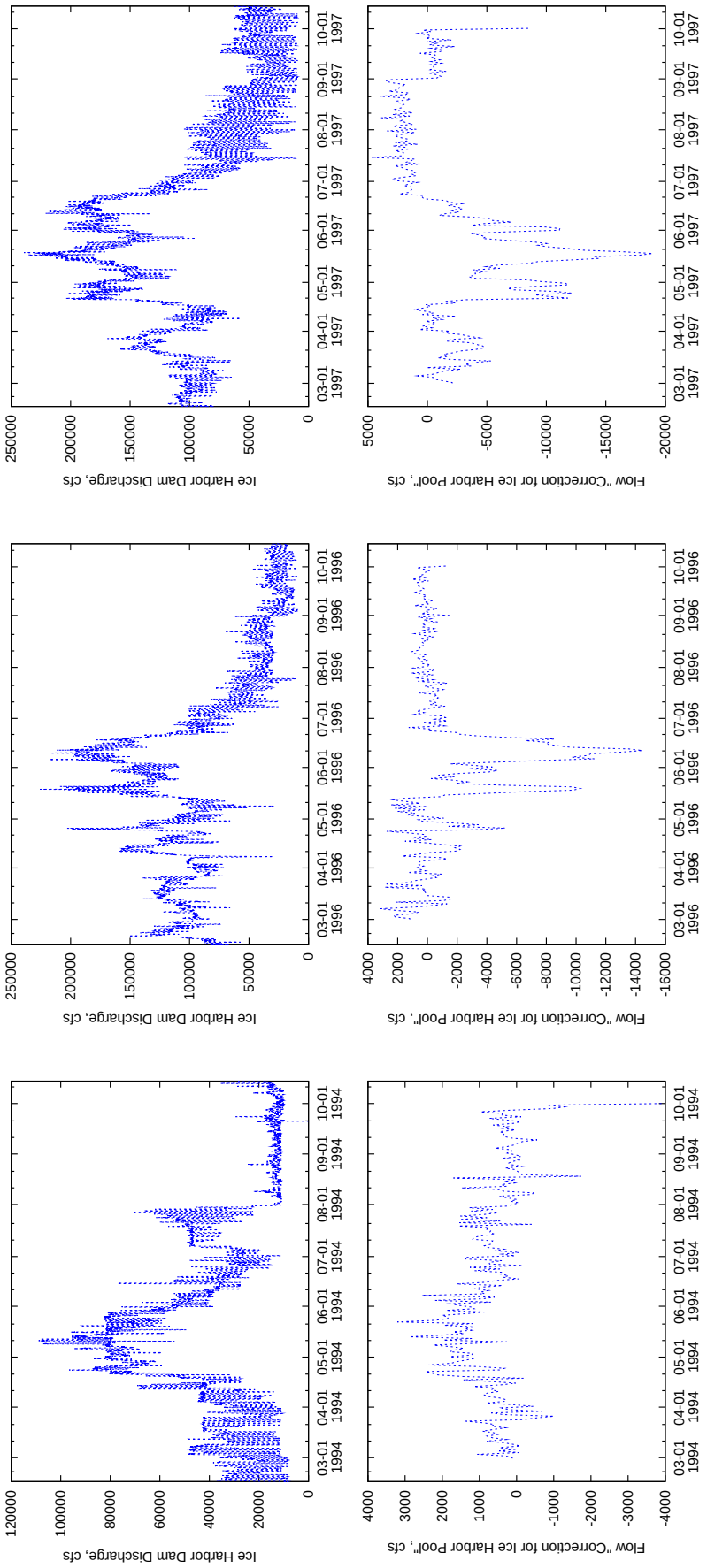

Figure A.5: Computed "flow corrections" applied as lateral inflow compared to total project flow for the Ice Harbor pool.

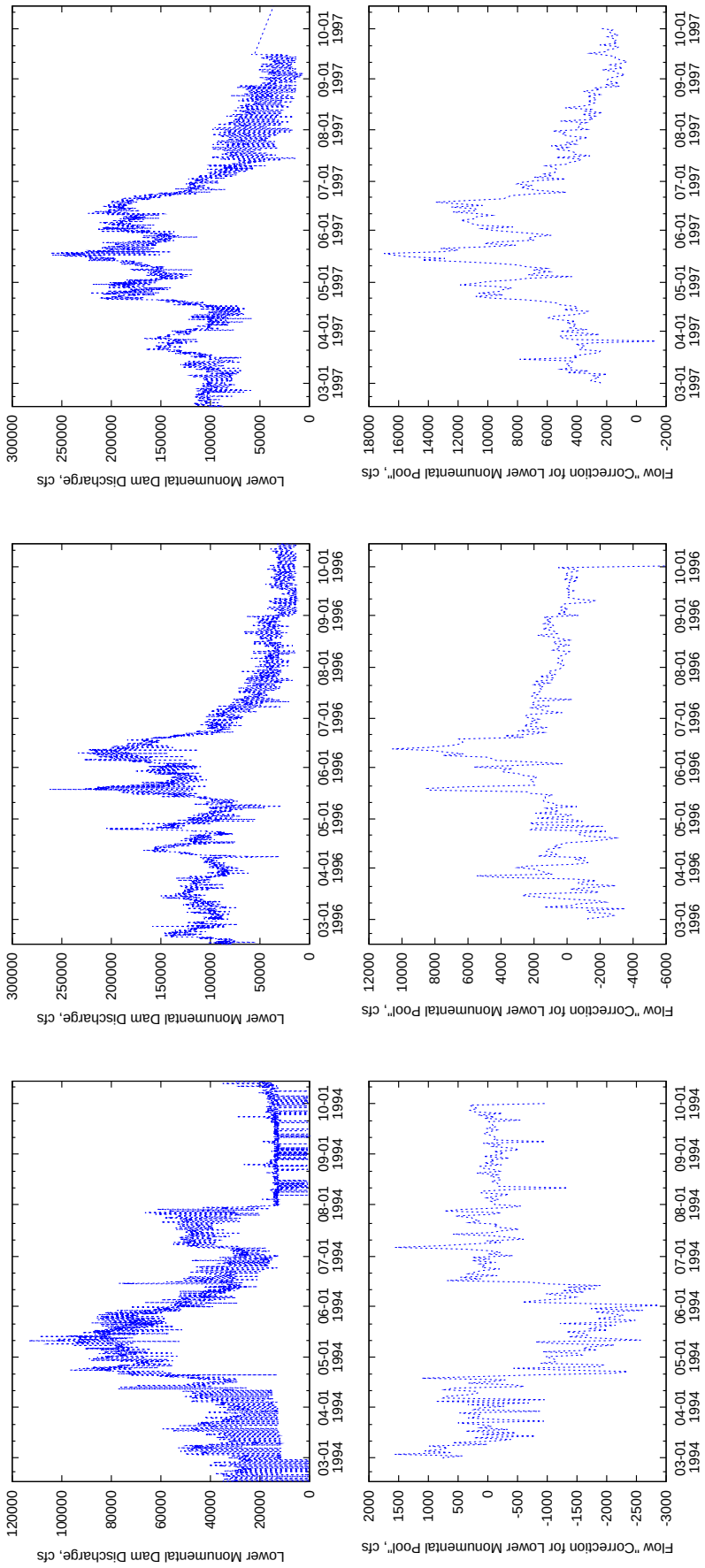

Figure A.6: Computed "flow corrections" applied as lateral inflow compared to total project flow for the Lower Monumental pool.

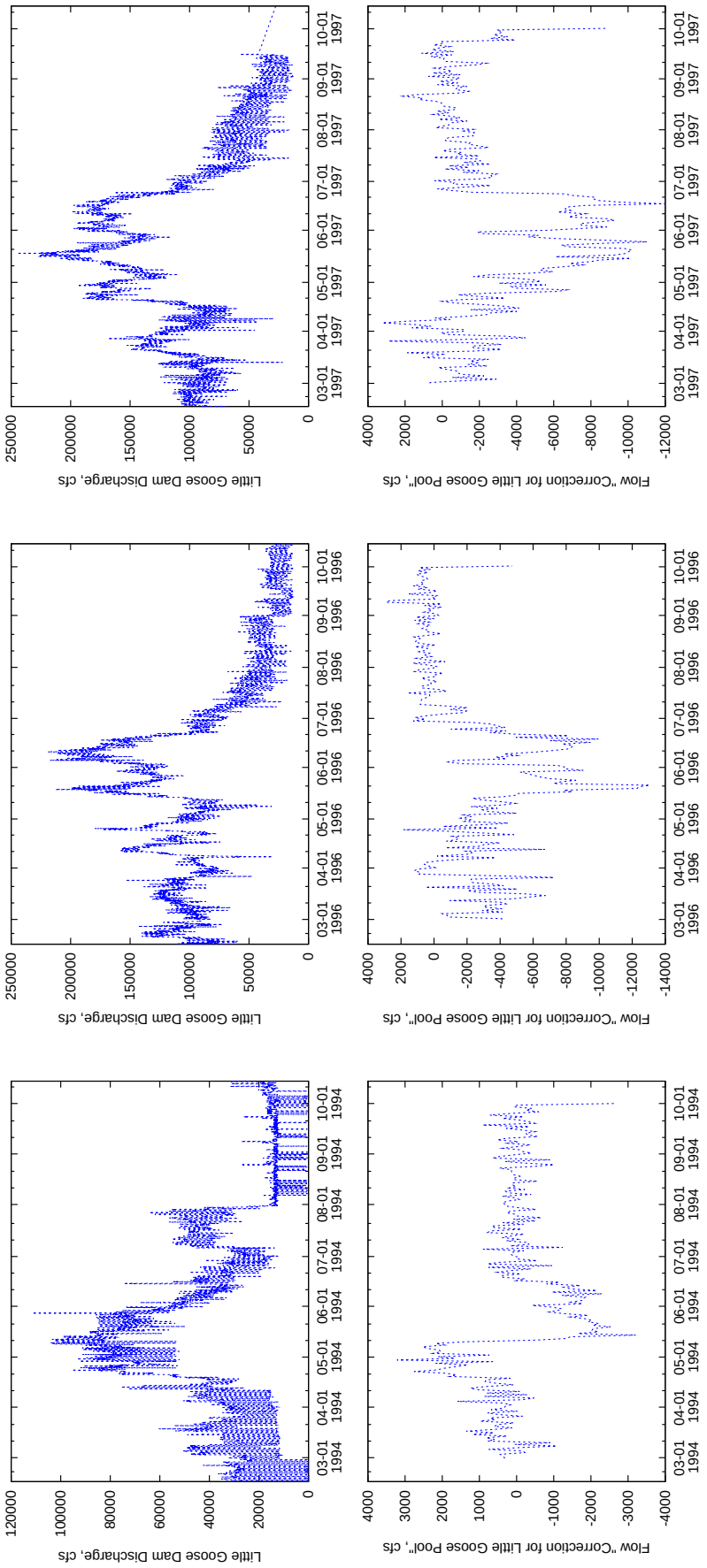

Figure A.7: Computed "flow corrections" applied as lateral inflow compared to total project flow for the Little Goose pool.

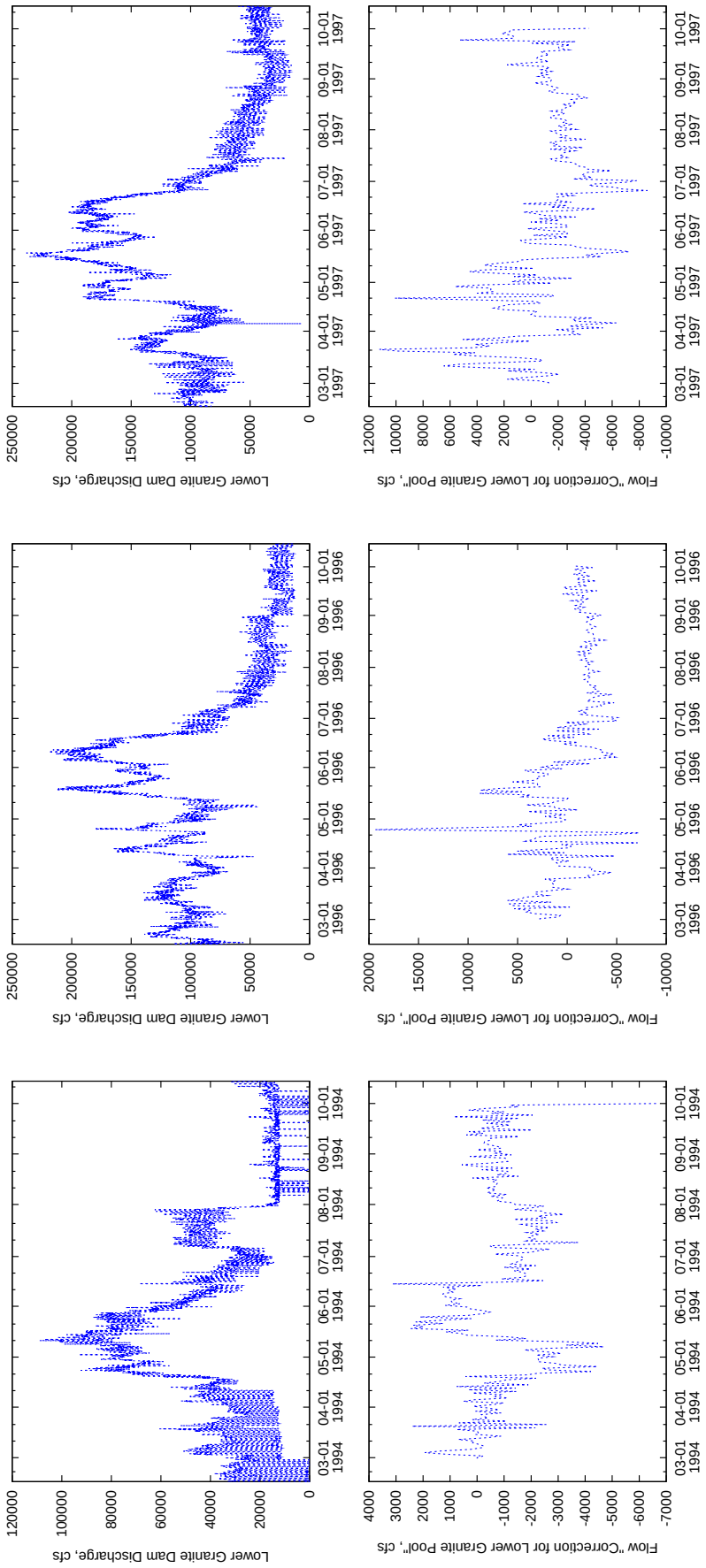

Figure A.8: Computed "flow corrections" applied as lateral inflow compared to total project flow for the Lower Granite pool.

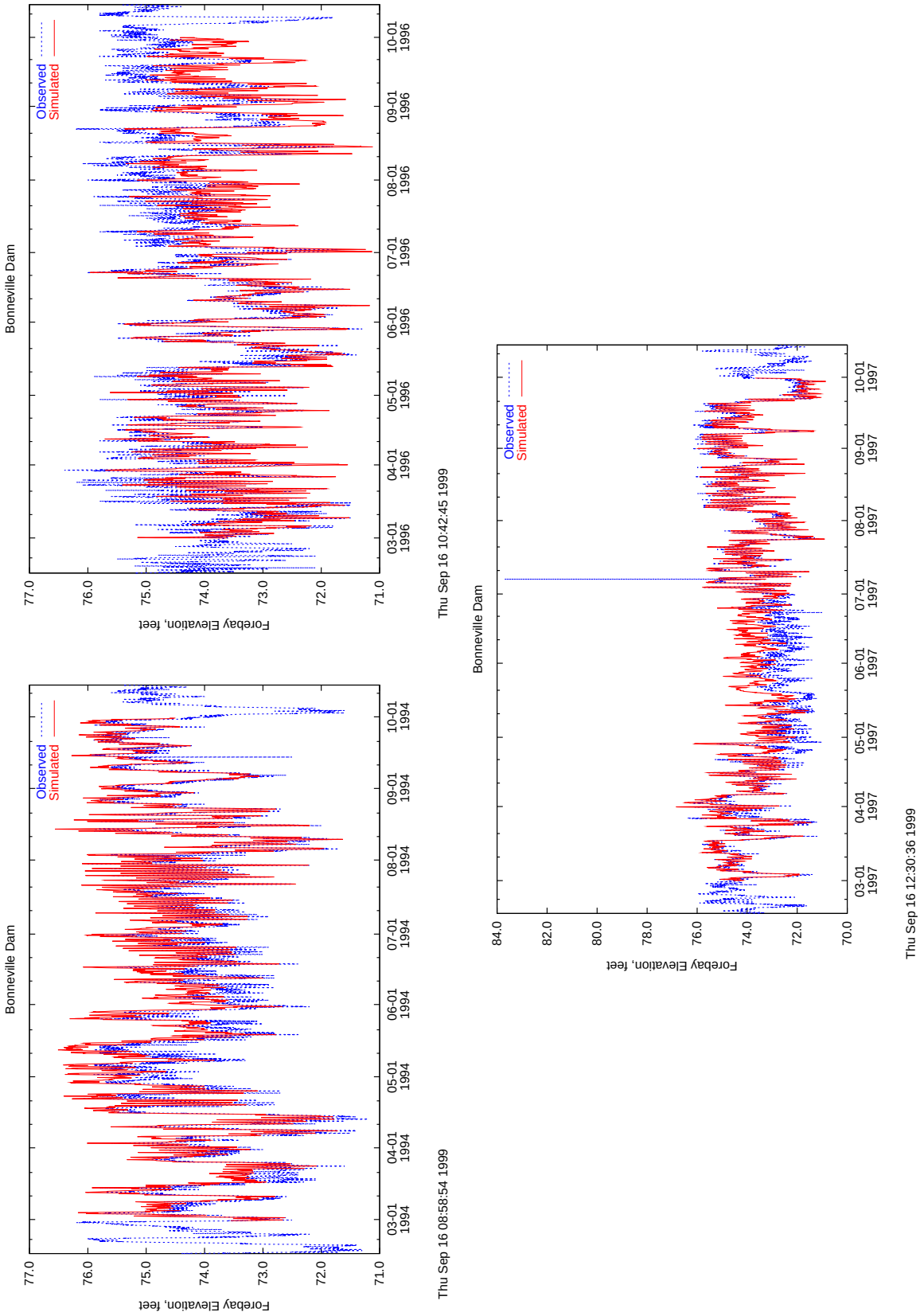

Figure A.9: Comparison of simulated and observed stage in the forebay Bonneville dam for the spill seasons of 1994, 1996, and 1997 while using flow boundary conditions at dams.

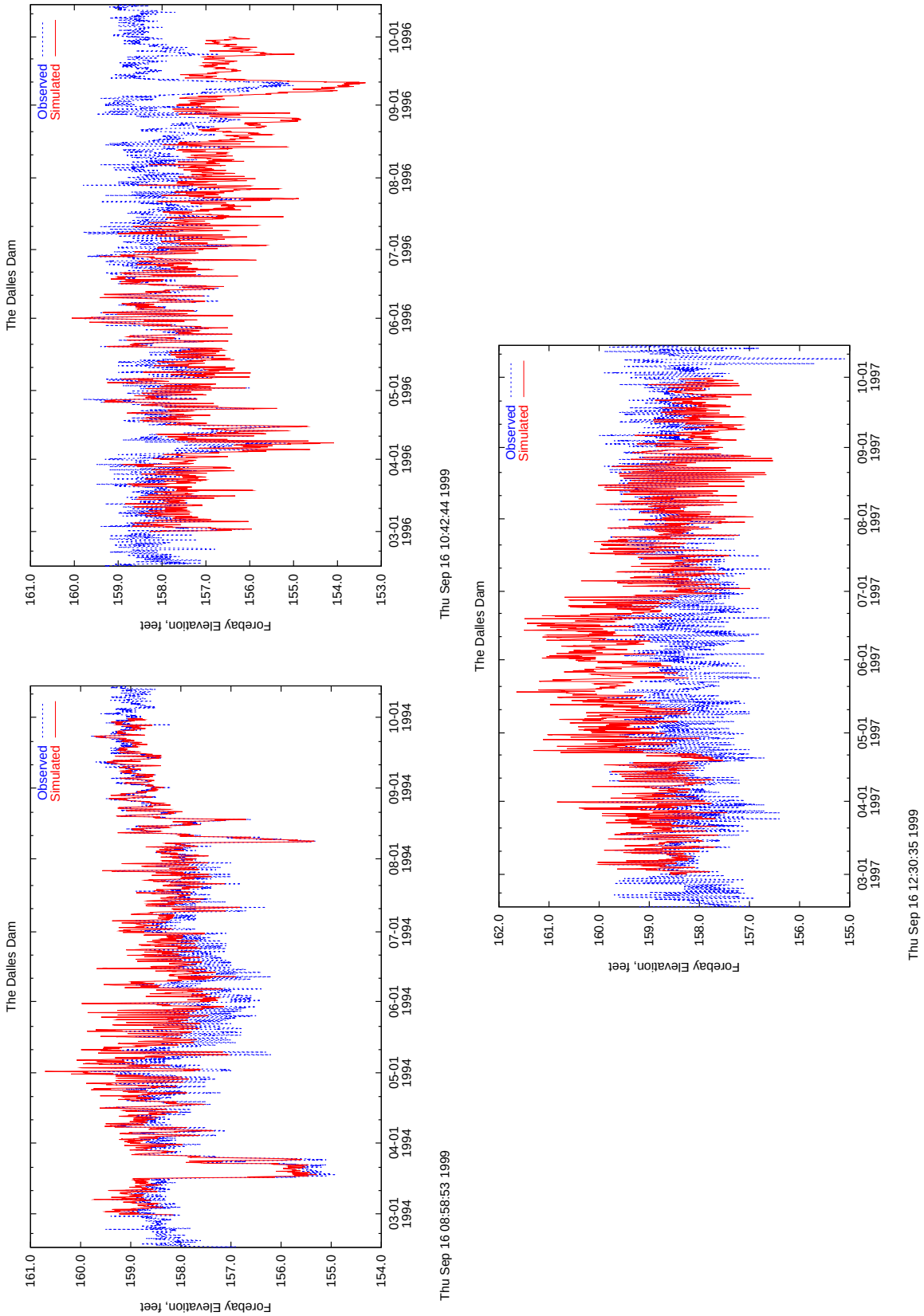

Figure A.10: Comparison of simulated and observed stage in the forebay The Dalles dam for the spill seasons of 1994, 1996, and 1997 while using flow boundary conditions at dams.

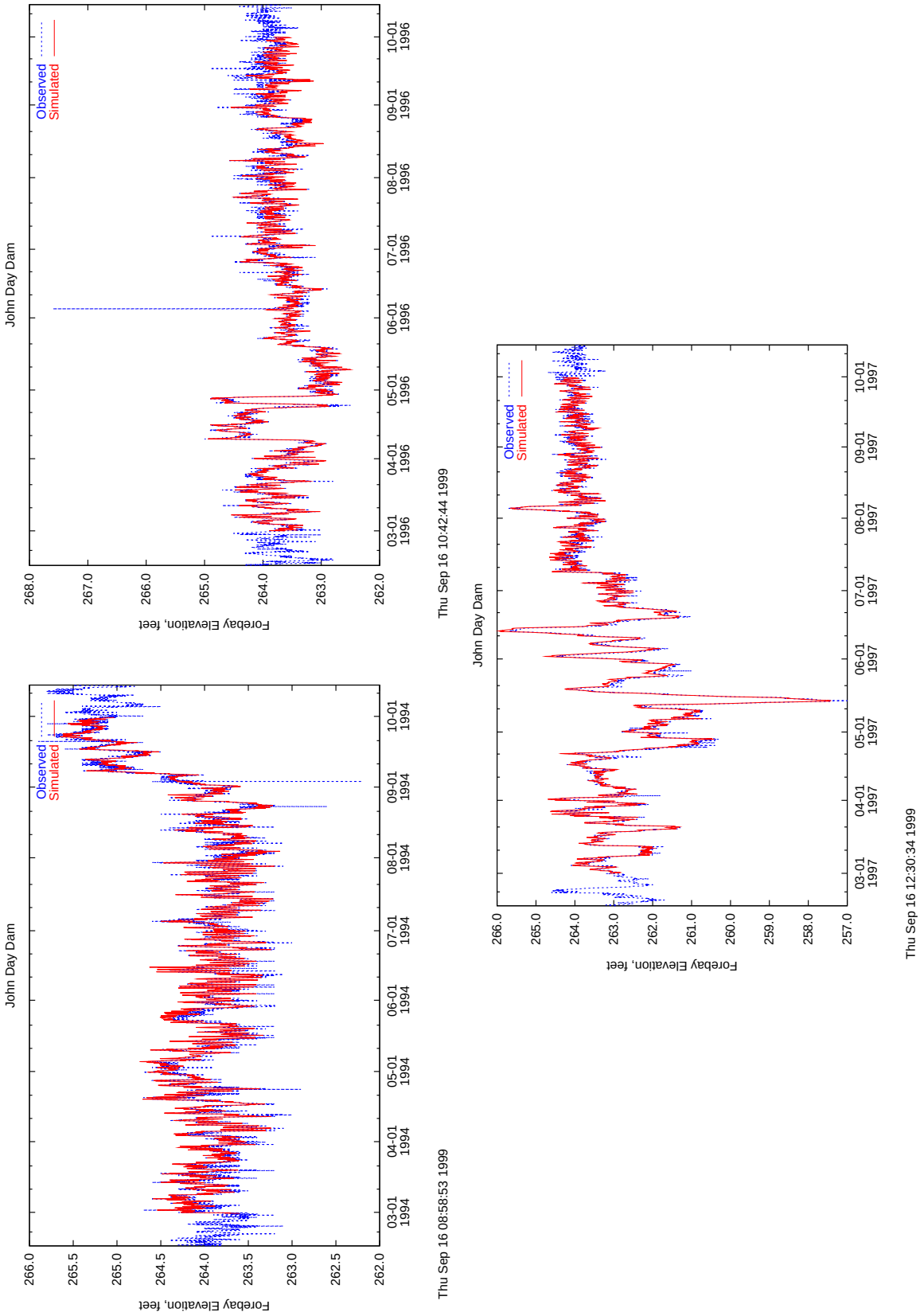

Figure A.11: Comparison of simulated and observed stage in the forebay John Day dam for the spill seasons of 1994, 1996, and 1997 while using flow boundary conditions at dams.

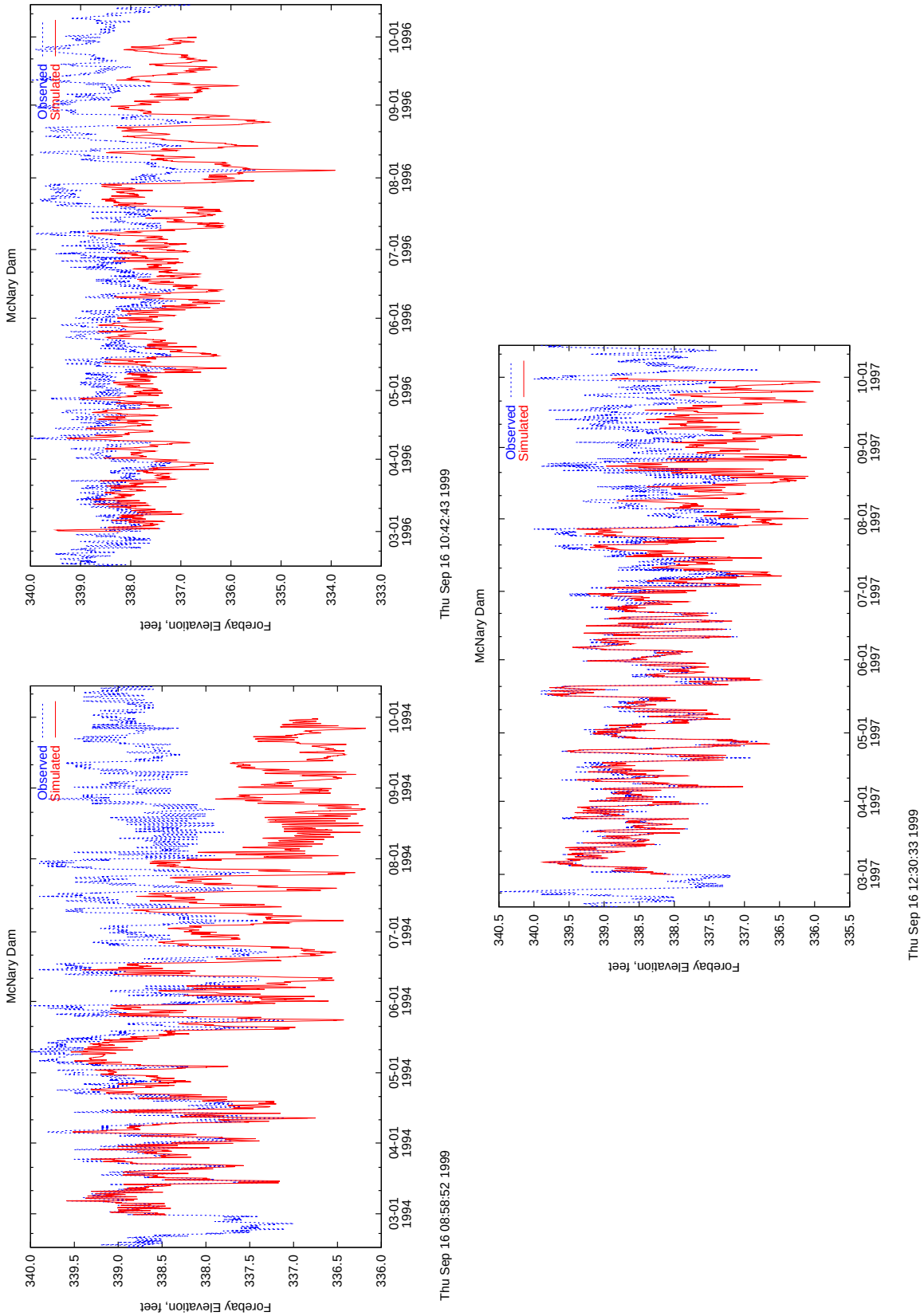

Figure A.12: Comparison of simulated and observed stage in the forebay McNary dam for the spill seasons of 1994, 1996, and 1997 while using flow boundary conditions at dams.

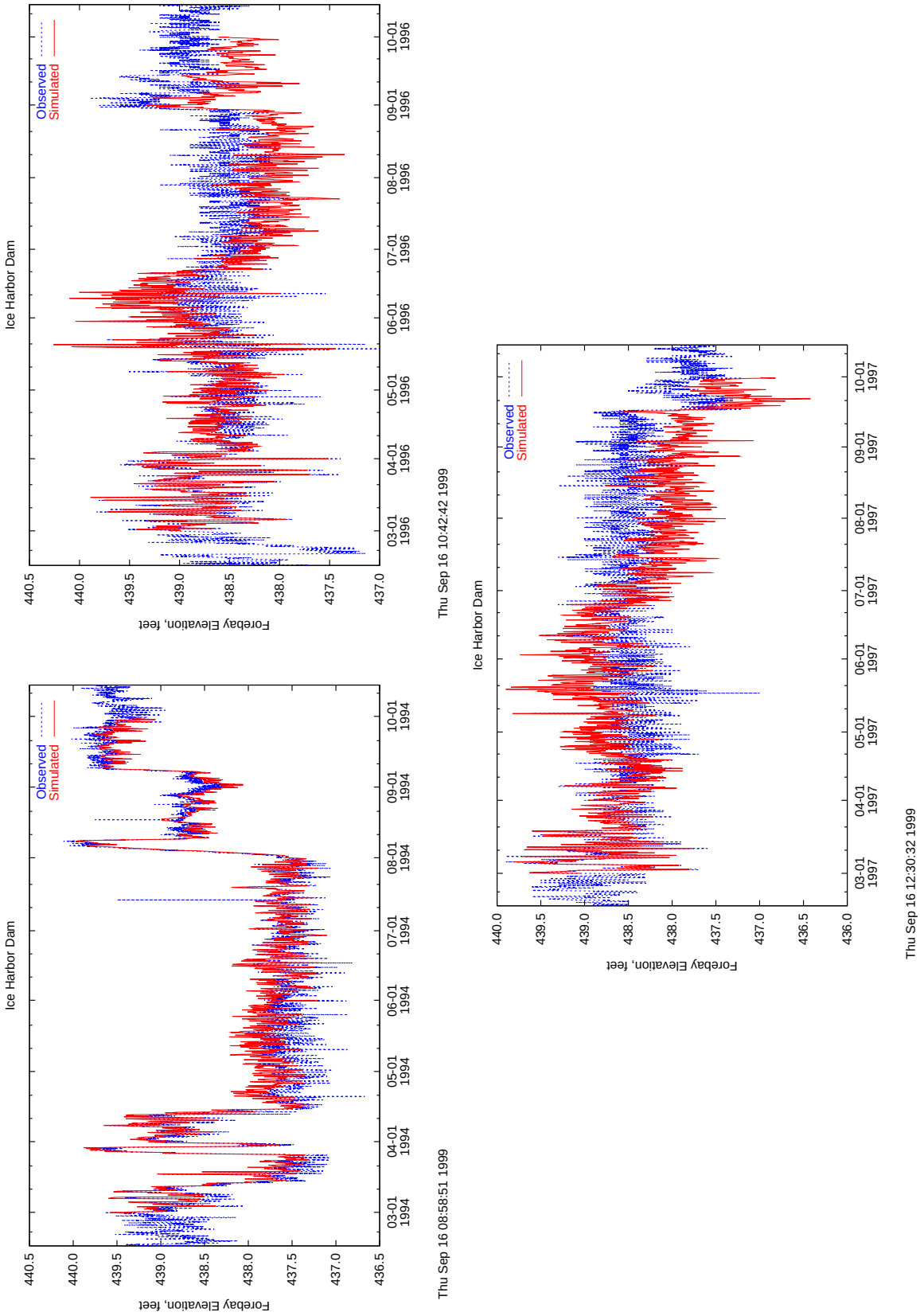

Figure A.13: Comparison of simulated and observed stage in the forebay Ice Harbor dam for the spill seasons of 1994, 1996, and 1997 while using flow boundary conditions at dams.

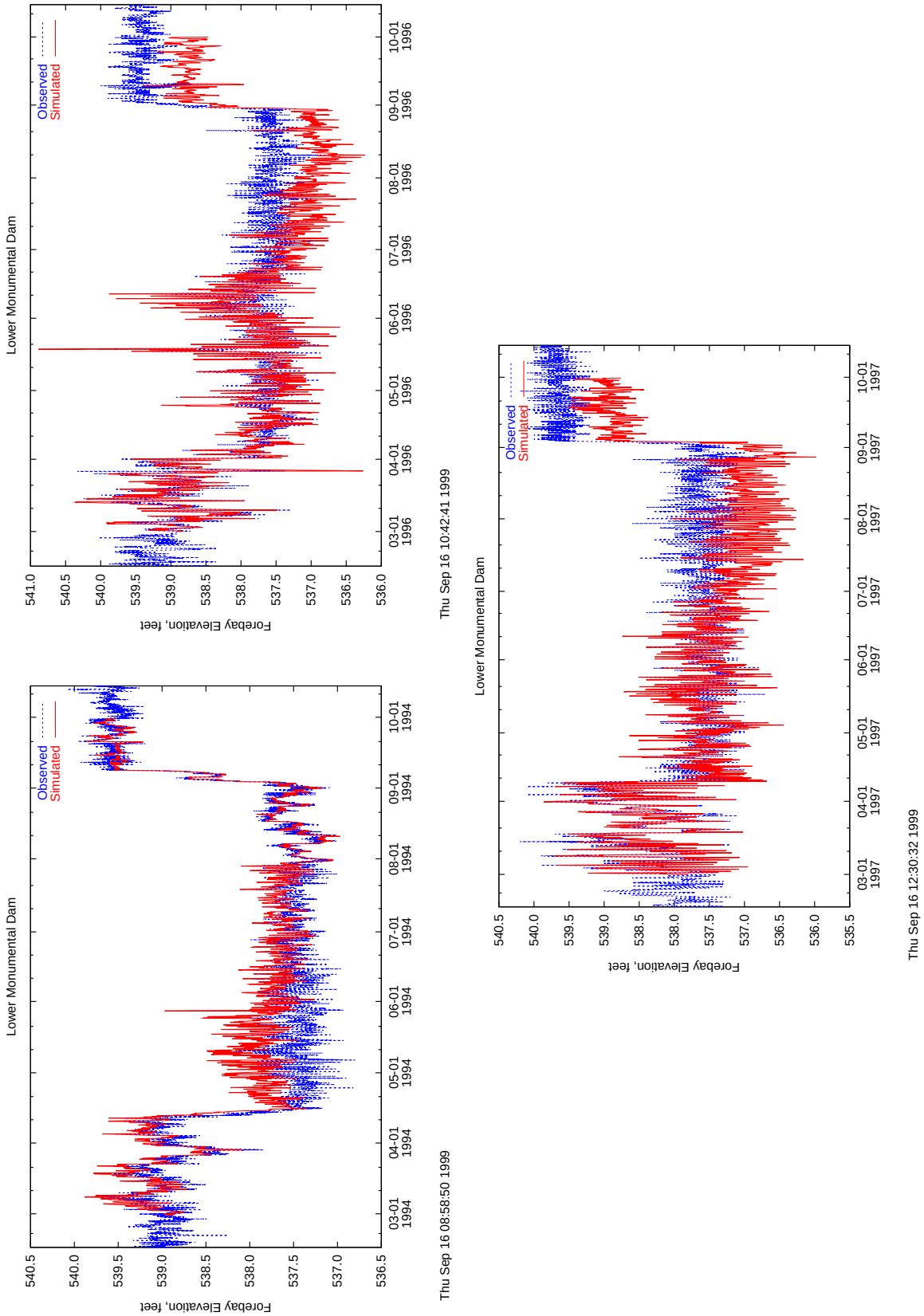

Figure A.14: Comparison of simulated and observed stage in the forebay Lower Monumental dam for the spill seasons of 1994, 1996, and 1997 while using flow boundary conditions at dams.

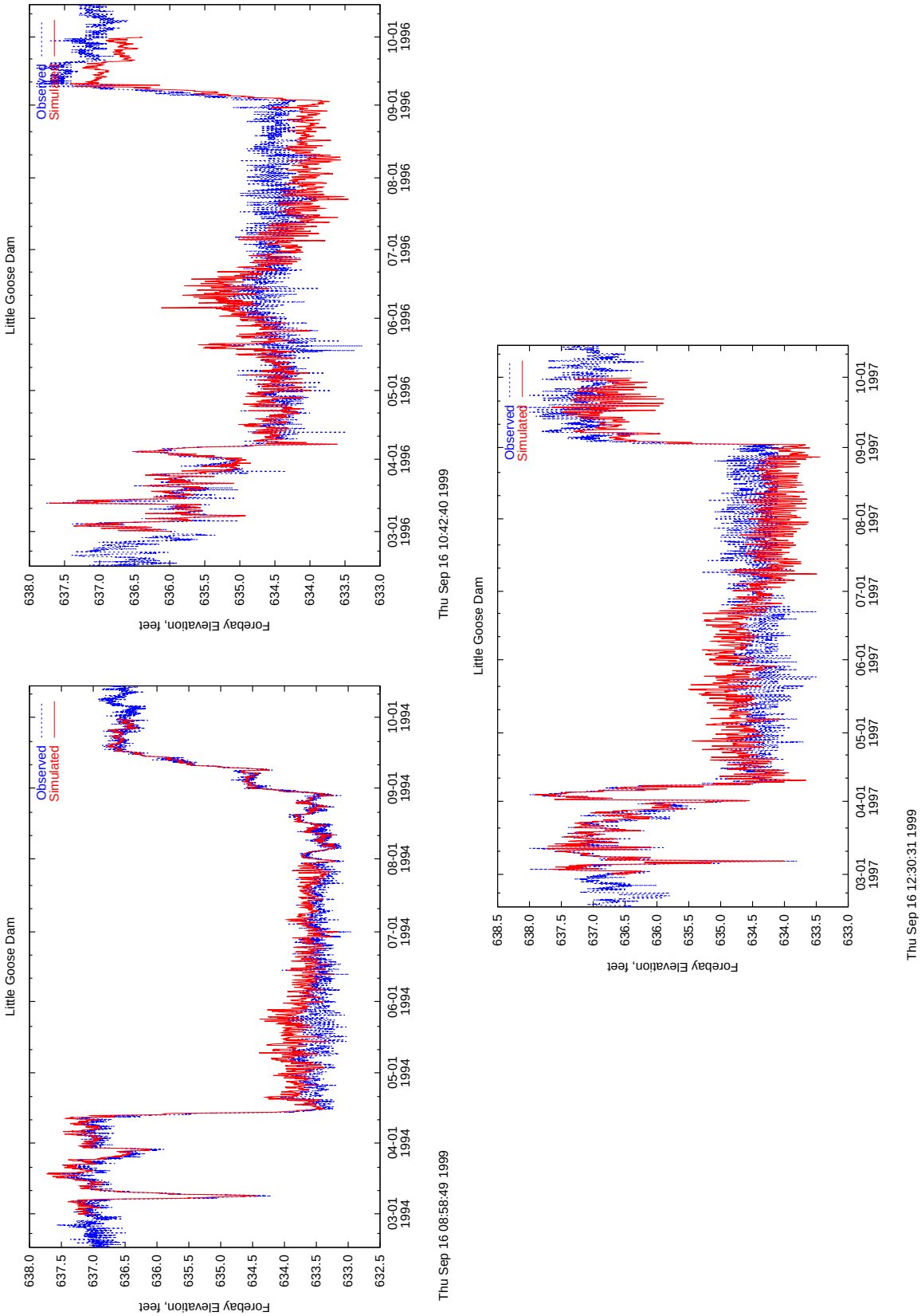

Figure A.15: Comparison of simulated and observed stage in the forebay Little Goose dam for the spill seasons of 1994, 1996, and 1997 while using flow boundary conditions at dams.

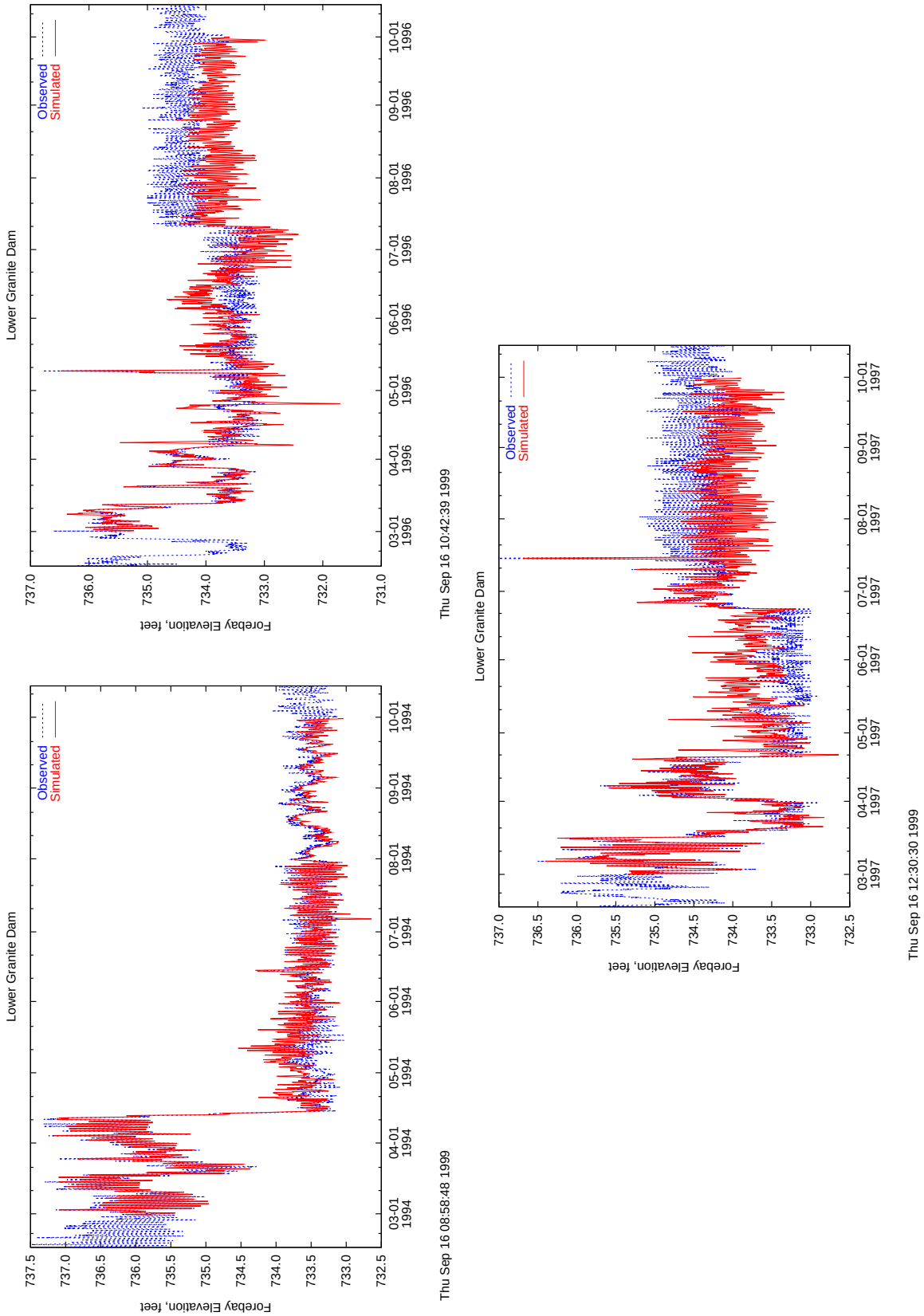

Figure A.16: Comparison of simulated and observed stage in the forebay Lower Granite dam for the spill seasons of 1994, 1996, and 1997 while using flow boundary conditions at dams.