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Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Hydrodynamic Simulation of the Columbia River, Hanford Reach, 1940–2004

S. R. Waichler
W. A. Perkins
M. C. Richmond

June 2005

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Executive Summary

Many hydrological and biological problems in the Columbia River corridor through the Hanford Site require estimates of river stage (water surface elevation) or river flow and velocity for their solution. Systematic collection of river stage data at locations in the Hanford Reach began in 1991, but many environmental projects need river stage information at unmeasured locations or over longer time periods. The Modular Aquatic Simulation System 1D (MASS1), a one-dimensional, unsteady hydrodynamic and water quality model, was used to simulate the Columbia River from Priest Rapids Dam to McNary Dam from 1940 to 2004 and estimate water surface elevation, volumetric flow rate, and flow velocity at 161 locations on the Hanford Reach.

The primary input data were bathymetric/topographic cross sections of the Columbia River channel, flow rates at Priest Rapids Dam, and stage at McNary Dam. Other inputs included Yakima River and Snake River inflows. A gaging station just below Priest Rapids Dam measured mean daily flow from 1940 to 1986 and hourly thereafter. McNary dam was completed in 1957, and hourly stage data are available beginning in 1975. MASS1 was run at an hourly timestep and calibrated and tested using 1991–2004 river stage data from six Hanford Reach locations (areas 100B, 100N, 100D, 100H, 100F, and 300). Manning's roughness coefficient in the Reach above each river recorder location was adjusted using an automated genetic algorithm and gradient search technique in three separate calibrations, corresponding to different data subsets, with minimization of mean absolute error as the objective. Manning's roughness coefficient (n) was the only parameter calibrated. The primary calibration was based on 1999, a representative year, and included all locations. The first alternative calibration also used all locations but was limited in time to a high-flow period during spring and early summer of 1997. The second alternative calibration was based on 1999 and included only 300 Area stage data. Model goodness-of-fit for all years with data was high with the primary calibration and indicated little bias caused by selecting 1999 data as the objective. The alternative calibrations led to improved goodness-of-fit for their limited time and locations, but degraded goodness-of-fit outside of the calibration set. For all years and locations, the mean absolute error in the primary calibration was 14.8 cm, the mean error was 1 mm, and model efficiency was 0.988. Overall, the simulations were very accurate and even highlighted some probable data problems, as evidenced by systematic shifts in the data. Further improvements in simulating the historic period would depend on correcting these inferred data problems.

The MASS1 output for 1940–2004 can be used to reconstruct historical river elevations at Hanford or to build scenarios of future river elevations for solving environmental problems such as groundwater-river interaction or fish habitat inventories. Longer-term scenarios extending more than a few decades from now should also consider the impacts of climate change and reservoir operation change. Once defined, these scenarios could be evaluated to drive new simulations with MASS1.

Acknowledgments

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This report is available in Portable Document Format (PDF) from the PNNL publications[a] public website. The electronic version contains hyperlinks to facilitate navigation between all cross-referenced material, including section headings, figures, tables, and references. Hyperlinks are not colored but become obvious when the mouse pointer is moved over them onscreen.

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Abbreviations and Acronyms

af	acre-feet
ACOE	Army Corps of Engineers
DEM	digital elevation model
GCPUD	Grant County Public Utility District
GIS	geographic information system
GPS	global positioning system
LIDAR	Light Detection and Ranging System
MAE	mean absolute error (see Appendix C)
MW	megawatts
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NGVD29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
PNNL	Pacific Northwest National Laboratory
RM	river mile
SHOALS	Scanning Hydrographic Operational Lidar Survey
SWS	surface water station
USGS	United States Geological Survey

Notation

E_1	first-degree efficiency (see Appendix C)
E'_1	baseline-adjusted first-degree efficiency (see Appendix C)

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1.0 Introduction

Knowledge of Columbia River water surface elevation (stage) and flow rates is needed for a wide variety of environmental projects at the Hanford Site, including studies of groundwater-river interaction and estimates of fish habitat duration and extent. Hourly river stage is measured at six locations along the Hanford Reach [areas 100B, 100N, 100D, 100H, 100F, and 300 (Figure 1.1)], but the longest record extends back to only 1991. Many Hanford projects require river stage information over the entire operating period of the Site, or at locations other than the recording stations. This study addressed those needs by simulating the Columbia River from Priest Rapids Dam to McNary Dam from 1940 to 2004 with the Modular Aquatic Simulation System 1D (MASS1), a one-dimensional unsteady hydrodynamic and water quality model. Model output includes hourly water surface elevation, volumetric flow rate, and average flow velocity at 161 cross-section locations within the Hanford Reach.

Previous studies simulated a limited historic period with MASS1 (Perkins et al. 2002, McMichael et al. 2003) or with MASS2, a 2D model capable of simulating temperature and dissolved gas distribution (Perkins et al. 2004, McMichael et al. 2003). MASS1 is applicable to any branched channel system and has been successfully applied to the lower Columbia and Snake Rivers to simulate water temperature and total dissolved gas (Richmond and Perkins 1999). It has also been used to simulate the difference between impounded and unimpounded temperature conditions in middle Columbia River (Perkins et al. 2002) and the lower Snake River (Perkins and Richmond 2001).

For this study, bathymetric and topographic elevations at river cross sections were updated with the best available data, a longer historical period was simulated, and an automated calibration technique was applied to MASS1 to yield model output with minimal error in simulated water surface elevation. For the first time, the entire operating period of the Hanford Site has been simulated and data, methods, and model output are documented in a report with unlimited distribution.

In the rest of this report, Section 2 provides an overview of historical Columbia River flow data at the site of Priest Rapids Dam and notes the changes caused by the development of the hydropower projects. Section 3 briefly describes MASS1. Section 4 describes the application of MASS1 to the Hanford Reach, including input data, data used for calibration and testing, and the calibration methods. Section 5 describes the goodness-of-fit of the simulations, and Section 6 discusses the limitations and implications of this study. Appendix A contains information about missing data, hydrographs of data, and various statistical plots concerning river stage at the 300 Area. Appendix B contains plots illustrating the bathymetry of the Columbia River. Appendix C contains definitions for the goodness-of-fit statistics used in this report. Appendix D contains hydrographs of observed and simulated river stage at the river recorder locations and goodness-of-fit statistics for an alternative calibration.

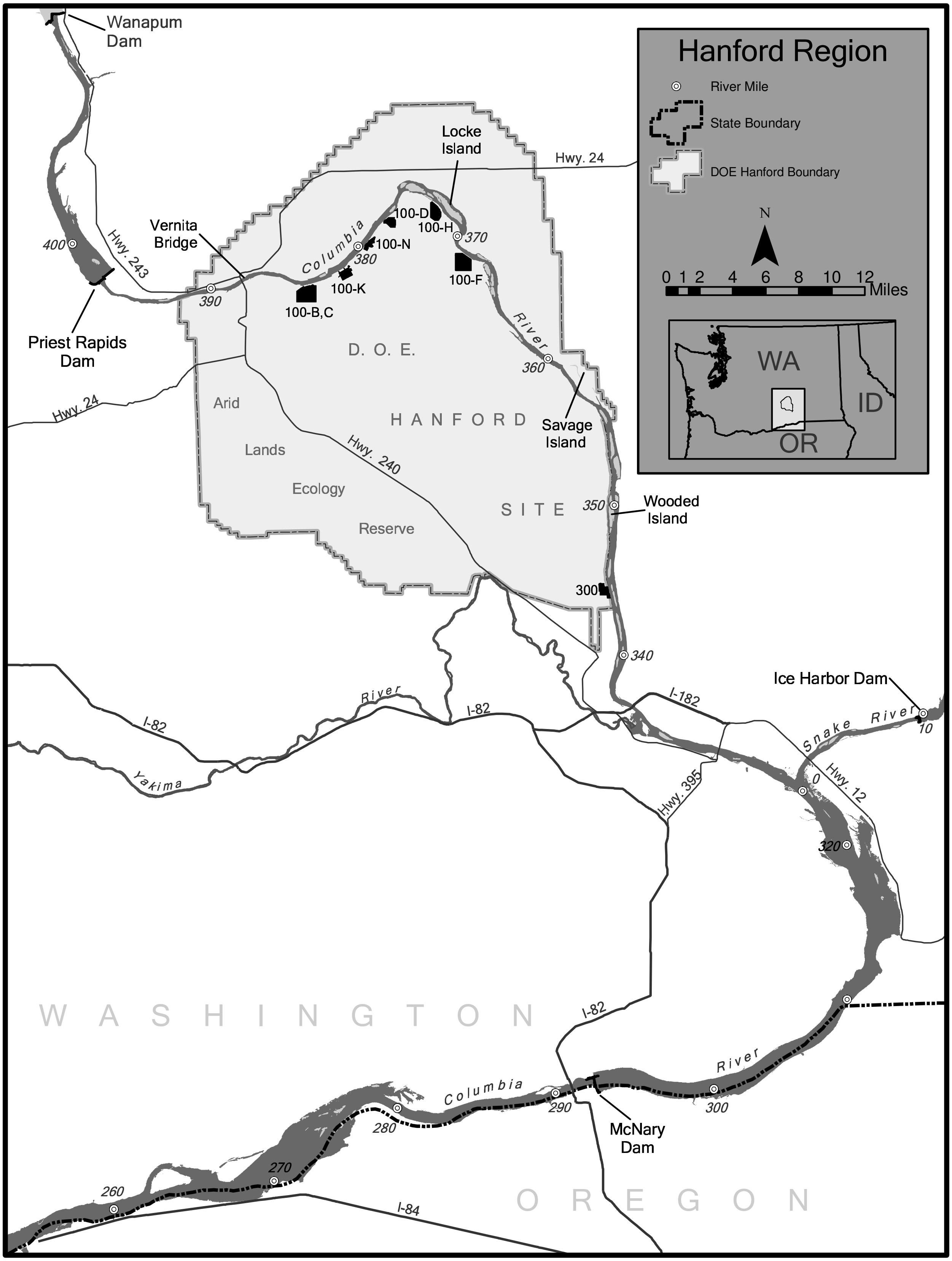

Figure 1.1. Mid-Columbia region and the Hanford Site.

2.0 Historical Columbia River Flow

Mean daily flow of the Columbia River has been measured at a site just below Priest Rapids Dam since 1917. The first dam on the mainstem Columbia River above Hanford was Rock Island, a run-of-river project with little storage that began operation in 1933 (Table 2.1). The first large storage project was Grand Coulee, and its operation increased fluctuations in the daily hydrograph during the fall and early winter baseflow period after its start in 1942 (Figure 2.1). More changes are visible in the hydrographs after the flood of record in 1948, with larger and more frequent fluctuations in the baseflow period after Priest Rapids Dam went online in 1961. Since 1974 there has been only one year with a relatively high annual maximum, 1997. The changes in flow at Priest Rapids over time are further illustrated in Figures 2.2 and 2.3. These figures show monthly means and standard deviations of the daily data by month, with a seasonal decomposition of the time series by locally weighted regression (Cleveland et al. 1990, R Development Core Team 2005). In this method the total flows are broken down into seasonal, trend, and remainder components. The seasonal component is the portion of water water flow fluctuation that recurs each year, and the trend component is the long-term mean of the data after removing the seasonal component. The total flows shown in the top panel indicate a rise in the minimum mean monthly flow over time (Figure 2.2). The seasonal component is the largest but exhibits a marked narrowing of its range after the mid-1970s. Similarly, the remainder com-

Table 2.1. Hydroelectric projects on the Columbia and Snake Rivers. Canadian projects are not included.

Dam	River mile	Start of operation	Generating capacity (MW)	Storage capacity (1000s af)
Columbia River				
Grand Coulee	596.6	1942	6,494	8,290
Chief Joseph	545.1	1961	2,069	588
Wells	515.8	1967	774	281
Rocky Reach	473.7	1961	1,347	440
Rock Island	453.4	1933	622	132
Wanapum	415.8	1963	1,038	710
Priest Rapids	397.1	1961	907	231
McNary	292.0	1957	980	1,295
John Day	215.6	1971	2,160	2,294
The Dalles	191.5	1960	1,780	311
Bonneville	146.1	1938	1,050	761
Snake River				
Lower Granite	107.5	1975	810	474
Little Goose	70.3	1970	810	541
Lower Monumental	41.6	1969	810	351
Ice Harbor	9.7	1962	603	400

ponent has smaller amplitudes after 1975. The standard deviations of daily flows (Figure 2.3) show a marked increase in the minimum variability after 1965 and a marked decrease in maximum variability in the mid-1970s. Daily flow variability apparently increased slightly during the 1990s and 2000s.

The mean and standard deviations of daily flow by month across all years is shown in Figures 2.4 and 2.5. Locally weighted regression lines (Cleveland 1981, Becker et al. 1988) in these plots gives a sense of the trends in the data over time. Again, the effect of increasing reservoir storage and water management is apparent in the increasing mean flows in the winter months and the decreasing mean flows in the spring and summer months. The year 1960 is an approximate inflection point for many of the months having large changes over time.

This historical perspective on river flows may be helpful when creating scenarios for simulation of future Hanford Site conditions. Many, if not all, of the Columbia River dams will reach the end of their design lives within 100 years, and the possibility of returning to a flow regime like that of the pre-1950s should be considered. The historical data may also be useful in developing methods to transfer predicted regional climate change impacts to actual river flows at short time scales.

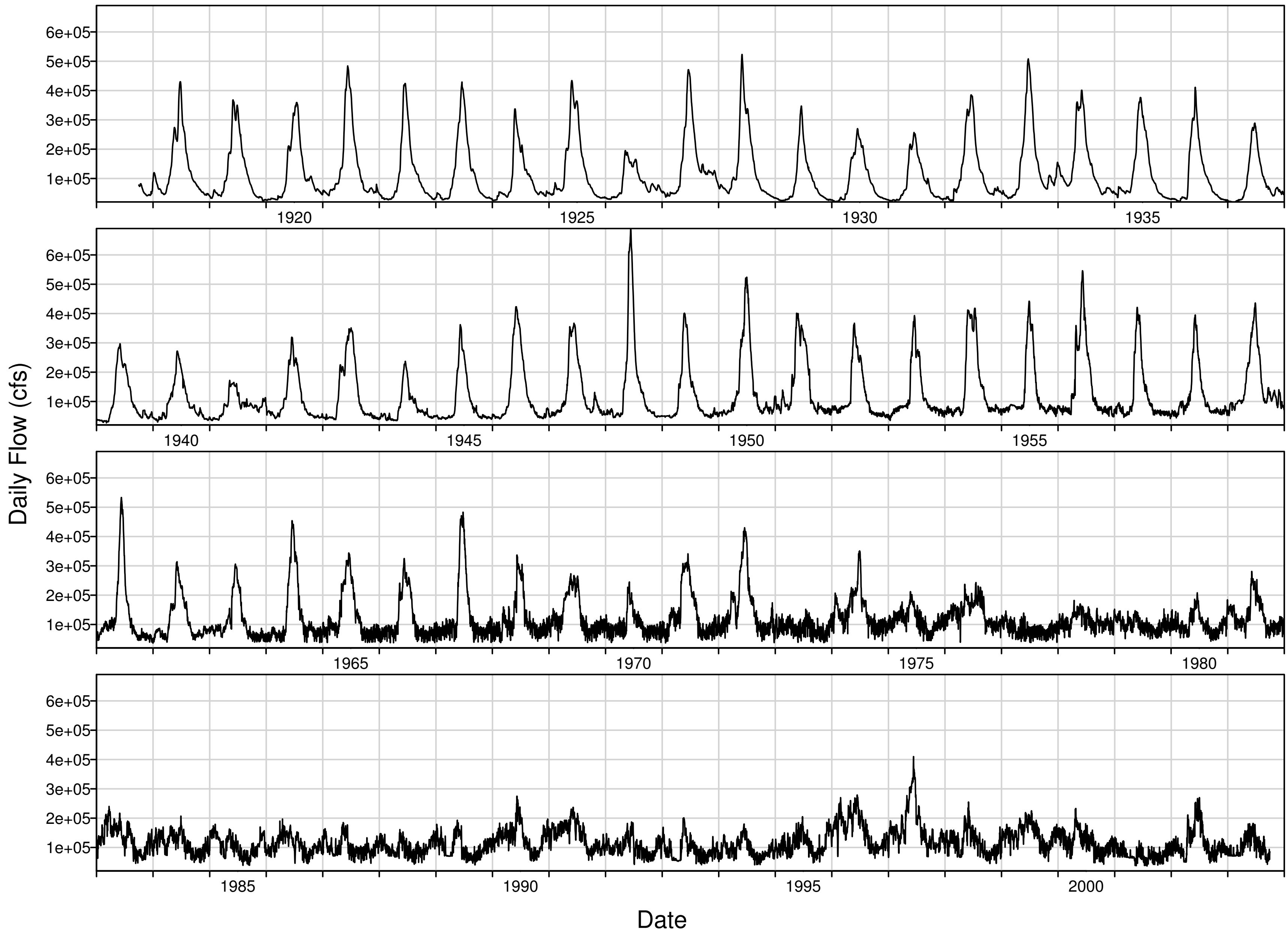

Figure 2.1. Columbia River daily flows at Priest Rapids, 1917–2004.

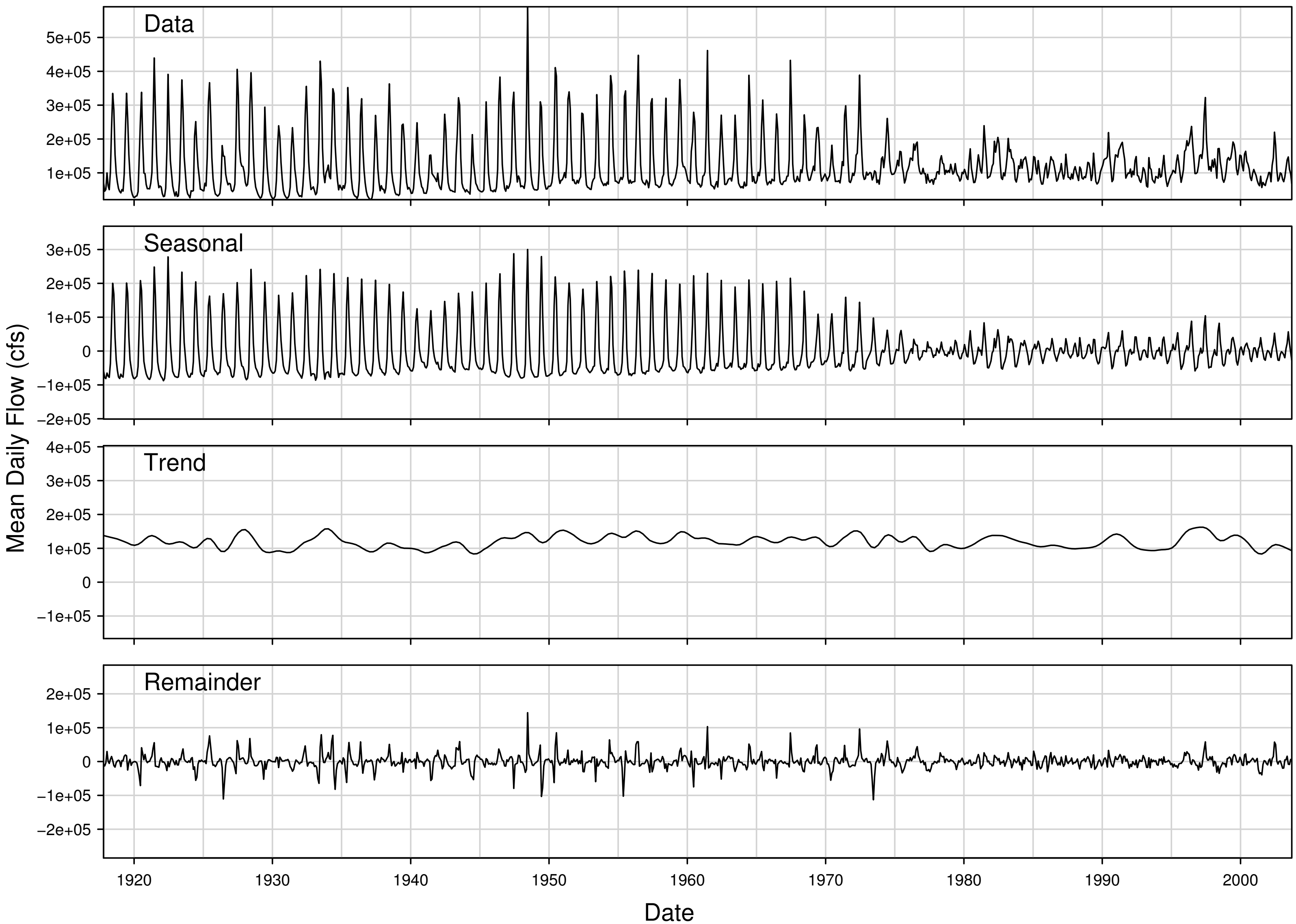

Figure 2.2. Mean of daily Columbia River flows by month at Priest Rapids, 1917–2004. Data are decomposed into seasonal, trend, and remainder components using seasonal decomposition by locally weighted regression (STL). The window for computing the seasonal component was five years. Vertical scale in each plot is the same.

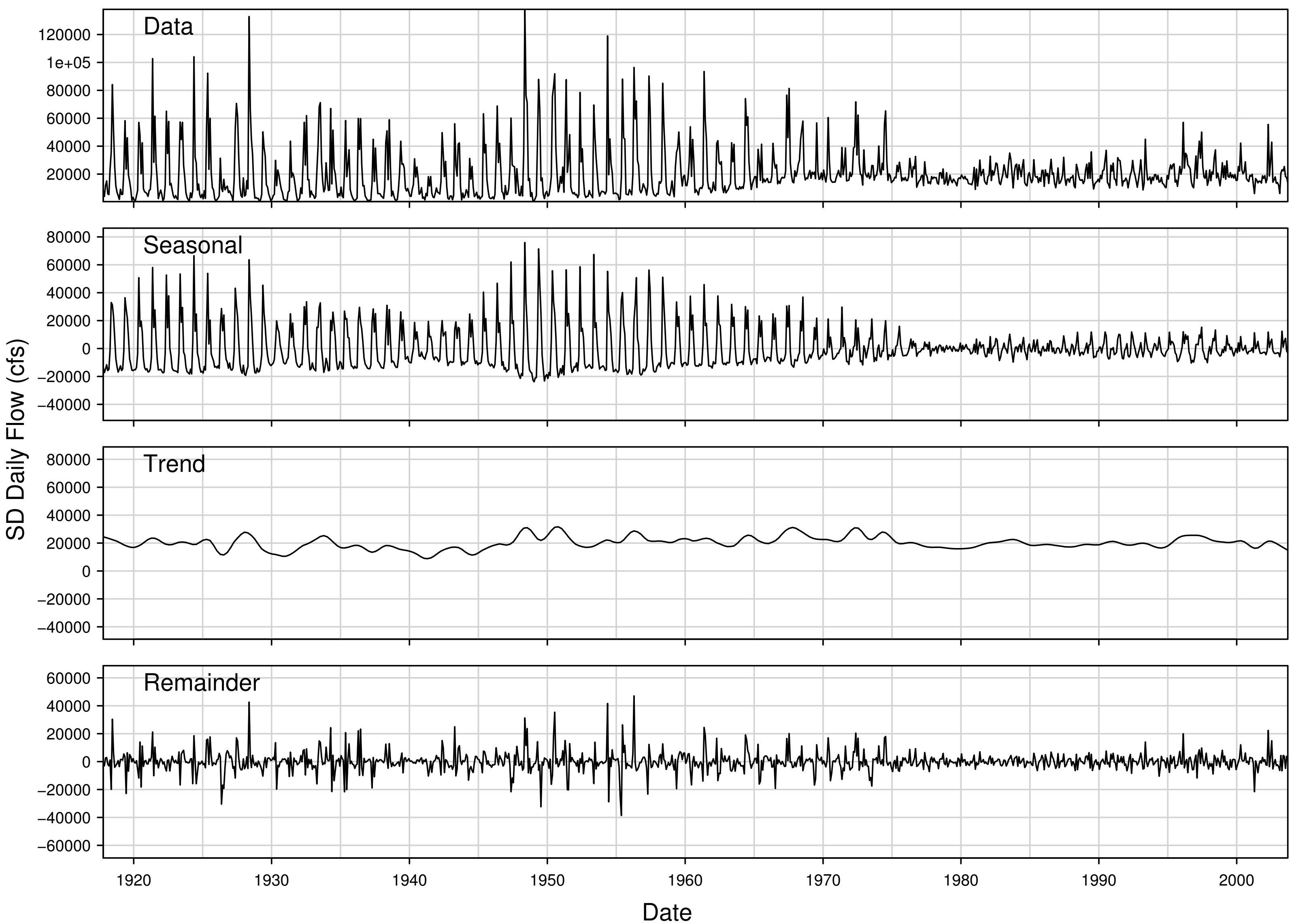

Figure 2.3. Standard deviation of daily Columbia River flows by month at Priest Rapids, 1917–2004.

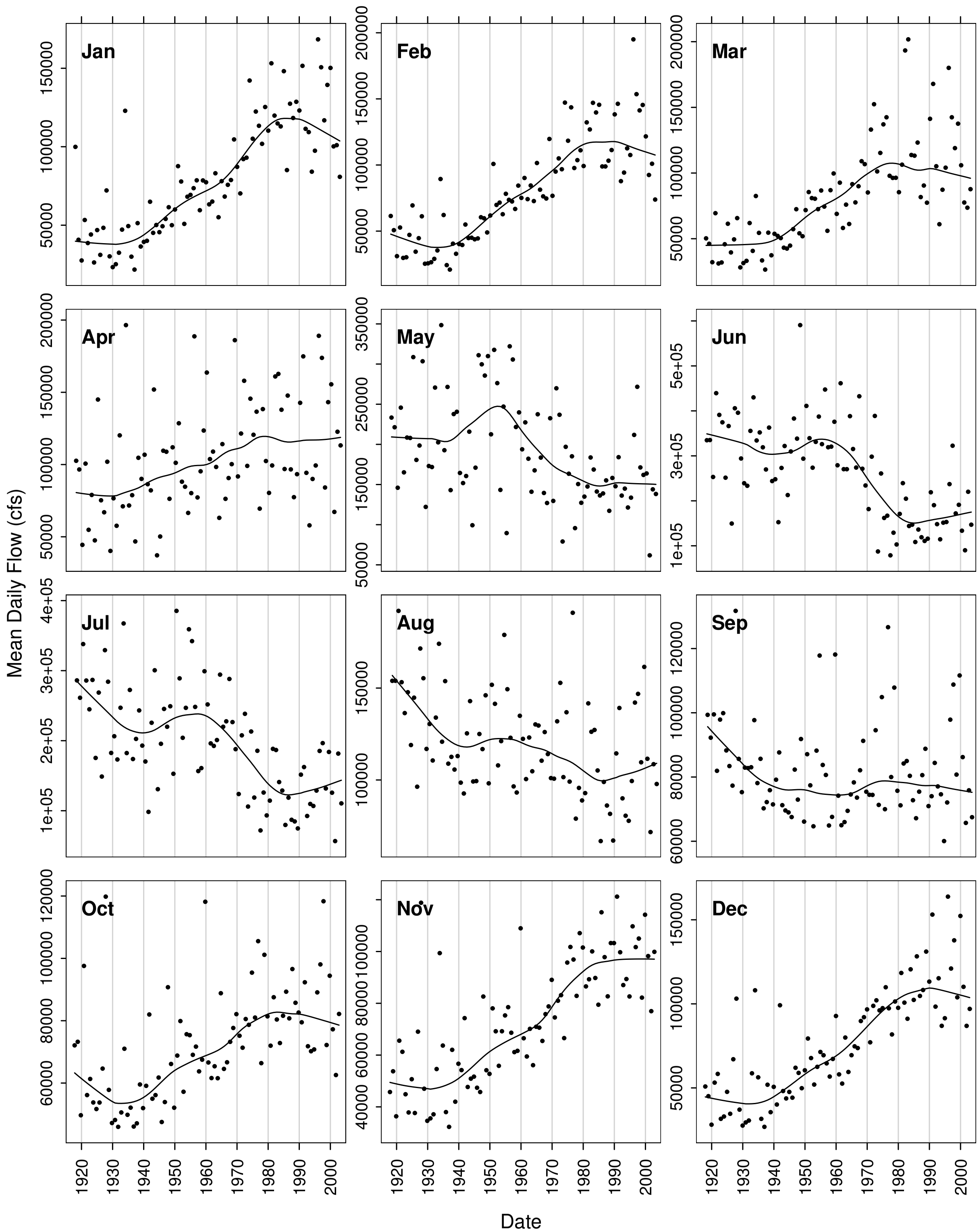

Figure 2.4. Mean of daily flows by month across years. Line is LOWESS based on nearest one-third of points.

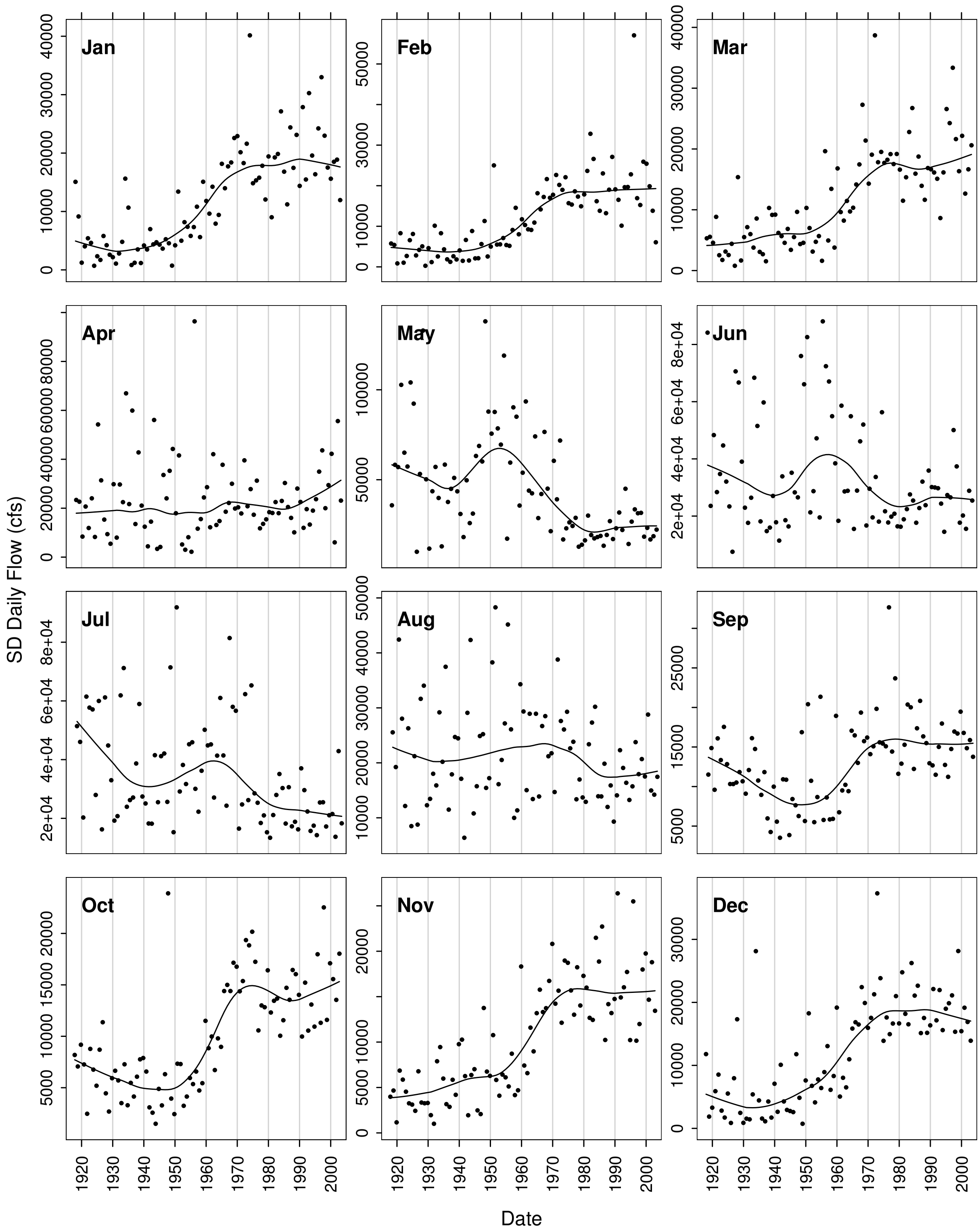

Figure 2.5. Standard deviation of daily flows by month across years. Line is LOWESS based on nearest one-third of points.

3.0 Description of MASS1

The Modular Aquatic Simulation System 1D (MASS1) is a one-dimensional, unsteady, cross-section averaged flow and water quality model. A single value of water surface elevation, discharge, velocity, concentration, and temperature is computed at each point in the model at each time interval. Lateral and vertical variations of these quantities are not simulated. Bathymetric data are a primary requirement of any surface water hydrodynamic and transport model. MASS1 requires bathymetry (bottom elevations) input as a series of cross sections. A cross section is a series of elevations along a line (not necessarily straight) extending laterally across the river. Cross sections can be either prismatic (rectangular, trapezoidal, etc.) or natural sections defined from topographic or bathymetric surveys.

The other primary data requirements of MASS1 are river inflows, which can include main stem flow at the upstream end of the network as well as distributed lateral inflows and tributary inflows, and river water surface elevation at the control section located at the downstream end of the network. MASS1 can be used only for subcritical flow (flow having a Froude number less than 1).

3.1 Hydrodynamics

Unsteady flow in rivers and canals is simulated in MASS1 by solving the one-dimensional equations of mass (Equation 3.1) and momentum (Equation 3.2) conservation. These equations are often referred to as the St. Venant equations.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial t} = 0 \tag{3.1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(\alpha \frac{Q^2}{A}) + gA\frac{\partial y}{\partial x} + gAS_f = 0 \tag{3.2}$$

where

A = river cross-sectional area, ft^2
Q = water discharge, ft^3/sec
y = water surface elevation, ft
S_f = friction slope, ft/ft, as defined in (3.3)
α = momentum friction correction factor
t = time, s
x = coordinate along the channel, ft.

The friction slope term can be computed using either the Manning or Chezy equations (see

Chow 1959). In MASS1, the friction slope is expressed in terms of the discharge and channel conveyance (K) as

$$S_f = \frac{Q \mid Q \mid}{K^2} \tag{3.3}$$

and the conveyance is computed using the Manning equation:

$$K = \frac{C_0}{n} A R^{2/3} \tag{3.4}$$

where

C_0 = 1.49 for English units and 1.0 for metric units
n = Manning channel roughness coefficient
R = hydraulic radius, ft
= A/P
P = channel wetted perimeter, ft.

Equations 3.3 and 3.4 represent the combined effects of variable channel geometry and resistance to flow (roughness) on the hydrodynamic simulation.

The average shear stress acting on the channel bottom can be computed from

$$\tau = \gamma R S_f \tag{3.5}$$

where

τ = bed shear stress, lb/ft^2
γ = unit weight of water, lb/ft^3.

MASS1 can simulate transport of general species and thermal energy (temperature), but these quantities were not included in this study.

3.2 Solution Methods

The foregoing equations are a coupled system of nonlinear partial differential equations. In general, analytical solutions to these equations can only be obtained for simplified channel geometries and boundary conditions. Therefore, numerical methods must be used to solve these equations for most practical situations. Finite difference methods are used in MASS1. The hydrodynamic Equations 3.1 and 3.2 are discretized using the Preissmann four-point implicit finite difference scheme, and the resulting system of nonlinear algebraic equations is solved using the double sweep method, as described in Cunge et al. (1980).

3.3 Model Topology

The first step in developing the numerical solution procedures implemented in MASS1 is to define the topology of the river systems that can be simulated. Here the topology defines how the channel system is connected, as well as the location and type of hydraulic control structures. The topology of the channel system is represented by dividing the river system into a series of links that are then further divided into a series of computational points along that link (Figure 3.1). Nodes occur at upstream or downstream boundary points and at the junction of two or more links.

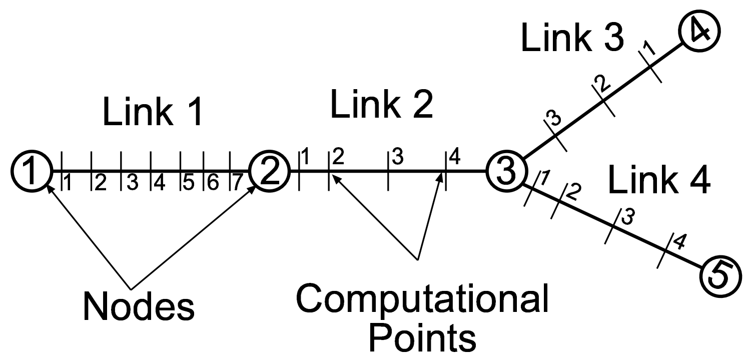

Figure 3.1. Typical MASS1 topological scheme.

4.0 Model Development

The key hydrodynamic components of the Hanford Reach, shown schematically in Figure 4.1, are the Columbia River between Priest Rapids Dam (Columbia River Mile (RM) 397.1) and McNary Dam (Columbia RM 292.5) and the Snake River and Yakima River inflows. The Hanford Reach (most of Segment 1) extends from Priest Rapids Dam to the 300 Area (Columbia RM 343.8), and the McNary pool extends from the 300 Area to McNary Dam (Segments 3 and 5). River miles of some reference points along the Hanford Reach are listed in Table 4.1.

Table 4.1. Reference points along the Hanford Reach.

Location	River mile
Priest Rapids Dam	397.1
Vernita Bridge	388.0
100-B recorder	384.09
100-N recorder	379.48
100-D recorder	377.65
100-H recorder	372.96
100-F recorder	368.68
300 Area recorder	344.34

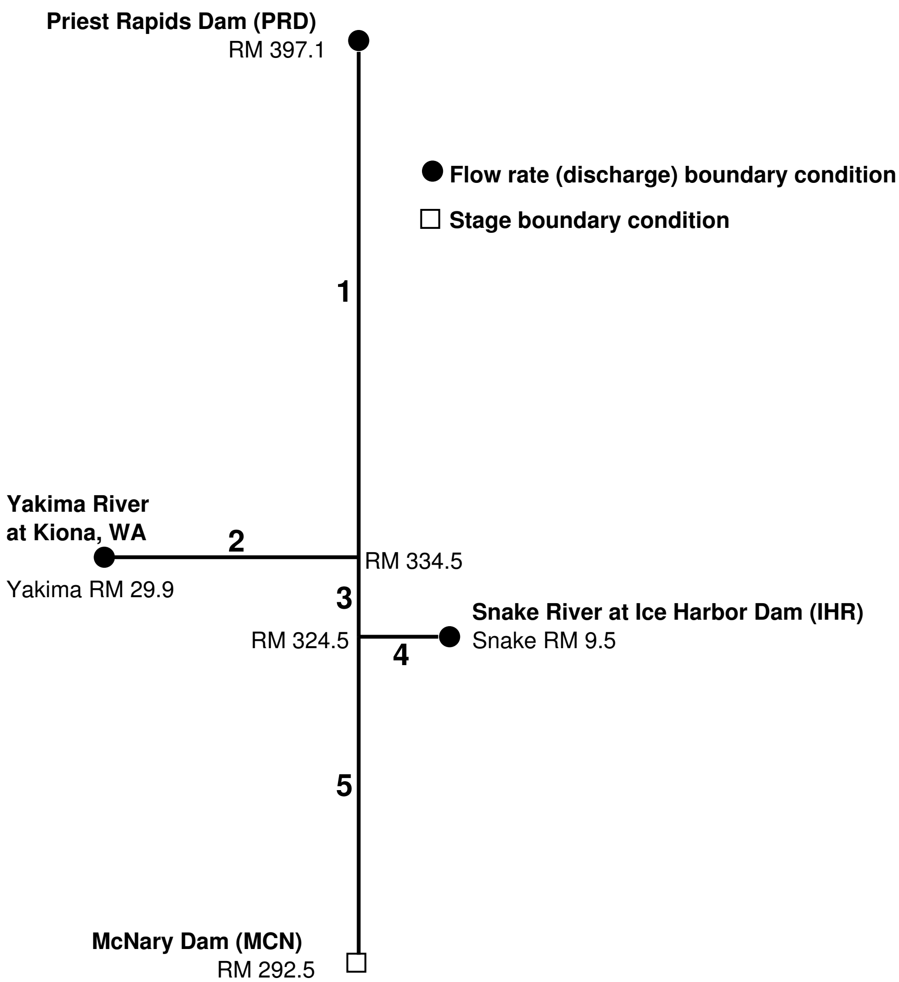

Figure 4.1. Channel network schematic. MASS1 uses a branched system, comprising nodes where volumetric flow rate or water surface elevation is specified and channel segments joining the nodes. Segment 1 includes the Hanford Reach, Segments 3 and 5 are mainstem McNary pool. River miles (RM) are Columbia River unless noted.

4.1 Bathymetry and Topography

Five data sources were used to construct elevation cross sections from Priest Rapids Dam to McNary Dam:

1. Cross sections surveyed by U.S. Army Corps of Engineers (ACOE) Seattle District (RM 337–394)

2. Priest Rapids Dam tailrace cross sections generated by Perkins et al. (2002) using the surveys performed by the Grant County Public Utility District (GCPUD) using echo sounder and GPS (RM 394–397)

3. High-resolution data collected in 1998 by the U.S. Geological Survey (USGS) using a Scanning Hydrographic Operational Lidar Survey (SHOALS) Light Detection and Ranging (LIDAR) System (Irish et al. 2000) (RM 355–377)

4. USGS 10-m digital elevation model (DEM) mosaic obtained from the Bureau of Land Management[a]

5. McNary Pool bathymetric surface created from various sources by Richmond and Perkins (1999) (RM 292–337)

Bathymetry input to MASS1 for the Hanford Reach was based on core data provided by the ACOE and GCPUD surveys, with the transects extended by DEM data. Most of the cross sections extend only to the shoreline under typical flows and in some cases fall short of that. Therefore, these cross sections were extended by sampling from the best available DEM, either the USGS 10-m or the one derived from LIDAR. First, gaps in the survey transects equal to or longer than 200 ft were filled. Cross sections within the SHOALS survey area were extended first using the SHOALS DEM, then further extended using the USGS 10-m DEM. A map of the SHOALS area and colored bathymetry maps therein are given in Appendix B. Outside of the SHOALS area, only the the USGS 10-m DEM was used. Both DEMs were sampled at 50-ft intervals along the cross-section line. Although the SHOALS LIDAR data were only collected for a portion of the modeled reach and the method can only penetrate into 15 ft of water, these data were an excellent complement to the ACOE and GCPUD survey data. More details about the SHOALS dataset can be found in Tiffan et al. (2002), and the method for extending cross sections is further described in McMichael et al. (2003). Cross-section locations in the Hanford Reach are shown in Figure 4.2, and an example cross section at the 300 Area is shown in Figure 4.3.

Bathymetry input to MASS1 for the McNary pool (see Figure B.5) was based on a combination of data sources and methods described briefly as follows and more extensively in Richmond and Perkins (1999). The following McNary pool bathymetry data were collected and converted to a consistent coordinate system and datum:

(a) http://www.or.blm.gov/gis/resources/library.asp

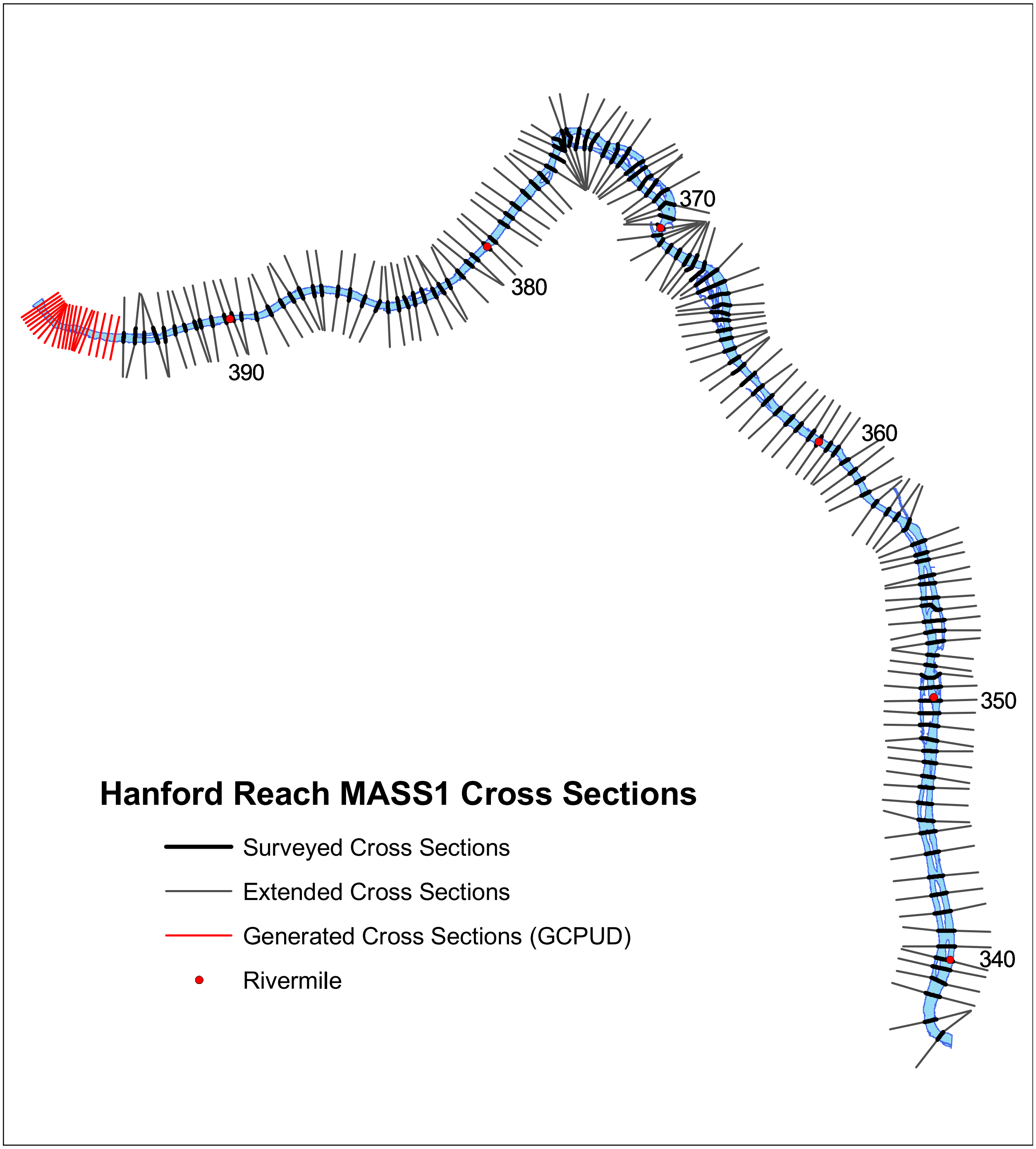

Figure 4.2. Hanford Reach cross sections.

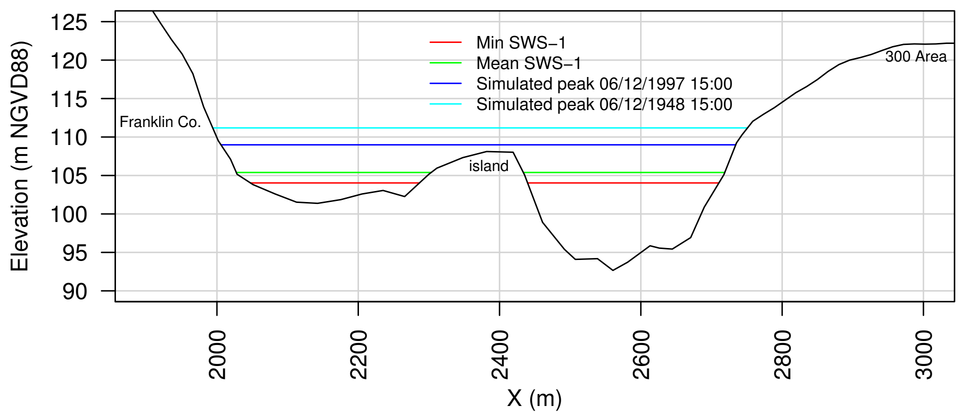

Figure 4.3. Example cross-section: RM 343.767, 300 Area. View is looking downstream. Water elevations shown are based on SWS-1 data from 11/7/91 to 3/31/04 and simulated elevations from the floods of 1997 and 1948. Minimum, mean, and maximum horizontal spacing between survey points were 4.8, 16.2, and 37.5 m, respectively.

- The 1997 ACOE bathymetric survey provided a dense set of elevations within the river from approximately RM 295 to 336,
- Digitized NOAA navigation charts provided distinct shoreline elevations and some sparse elevations in the river,
- The USGS 3-arcsecond (approximately 100-m spacing) DEM provided elevations on islands and shore allowing a good approximation of slopes near the shore.

A geographic information system (GIS) was used to render the above data as a triangular irregular network (TIN), a three-dimensional representation of the river bottom elevation. Transect lines at each desired cross section location were then processed with sampling of the TIN at regular intervals along the transects to derive the cross section elevations.

4.2 Discharge and Stage Data

Mainstem Columbia River and tributary river flow data and McNary Dam stage data were used to create the boundary condition inputs for MASS1. Stage data from six Department of Energy recorders in the Hanford Reach were used to calibrate and test the model.

4.2.1 Data Used for Model Input

The following discharge and stage inputs were the boundary conditions used to drive the MASS1 model: Columbia River flow at Priest Rapids Dam, Columbia River stage at McNary Dam, Snake River flow at Ice Harbor Dam (IHR), and Yakima River flow at Kiona (Figure 1.1). The primary data sources for these inputs were USGS, GCPUD, and ACOE (Table 4.2). Overall data availability is good, with relatively long records and gaps that are reasonably small (Figure 4.4).

Table 4.2. Data sources boundary conditions. These sources were tested and/or used to develop boundary conditions for MASS1.

Data Type	Name	Description	Gage No.	File in MASS1 Input Format
Columbia River flow below Priest Rapids Dam	Hourly GCPUD PRD	Grant County Public Utility District (GCPUD) mean hourly flows from Priest Rapids Dam (PRD)		PRD-GCPUD-discharge.dat
	Hourly ACOE PRD	Army Corps. of Engineers Water Management Division (ACOE) mean hourly flows below Priest Rapids Dam		PRD-WMD-discharge.dat
	Daily USGS PRD	U.S. Geological Survey (USGS) mean daily flows below Priest Rapids Dam	12472800	PRD-USGS-daily-discharge.dat
Snake River flow below Ice Harbor Dam	Hourly ACOE IHR	ACOE mean hourly flows from Ice Harbor Dam (IHR)		IHR-WMD-discharge.dat
	Daily USGS IHR	USGS mean daily flows from Ice Harbor Dam		IHR-USGS-discharge.dat
	Daily ACOE IHR	USGS mean daily flows from Ice Harbor Dam		IHR-daily-discharge.dat
McNary Pool Elevation	Hourly ACOE MCN	ACOE hourly water surface elevations from McNary Dam (MCN)		MCN-stage.dat
	Daily ACOE MCN	ACOE instantaneous daily water surface elevations at midnight from McNary Dam		MCN-daily-stage.dat
Yakima River flow at Kiona, WA	Daily USGS YAK	USGS daily flows	12510500	Yakima-USGS-discharge.dat
Snake River flow at Clarkston, WA	Daily USGS CLA	USGS daily flows	13344500	Clarkston-USGS-discharge.dat
Palouse River at Hooper, WA	Daily USGS PAL	USGS daily flows	13351000	Palouse-USGS-discharge.dat
Tucannon River near Starbuck, WA	Daily USGS TUC	USGS daily flows	13344500	Tucannon-USGS-discharge.dat

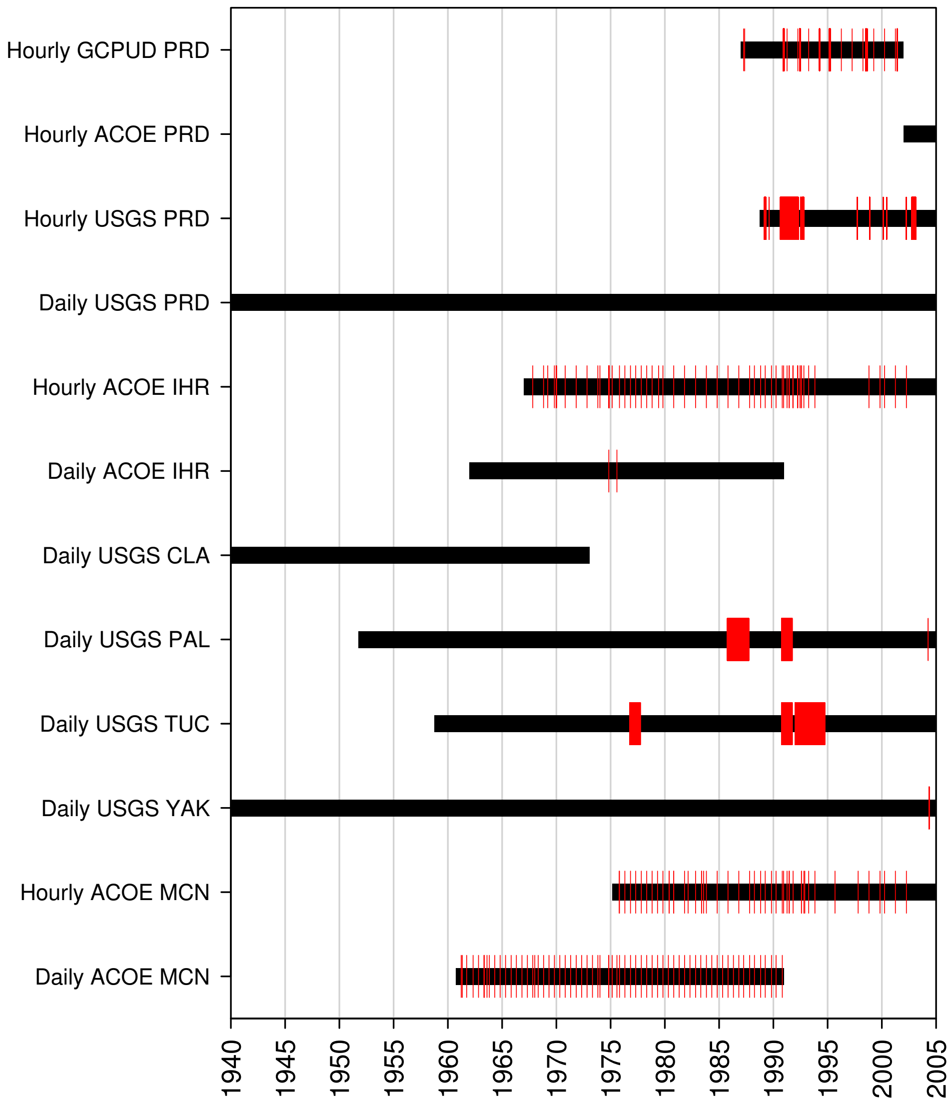

Figure 4.4. River flow and stage data availability. Red lines denote missing hours or days. See Table 4.2 for key to data sources.

Primary information about data sources and assumptions used in the MASS1 modeling is given in Tables 4.3 and 4.4. Further information and plots of river discharge and stage are given in Appendix A. The river stage data used in calibration and testing of MASS1 is discussed in Section 4.3.

Snake River flow at IHR includes the main-stem flow at Clarkston and inflow from the two largest tributaries below Clarkston, the Tucannon and Palouse Rivers. A number of linear regressions of Snake River flow at IHR on Snake flow at Clarkston and the flows of the tributaries were tested, including daily and annual averages. Flow at Clarkston was found to be a sufficient predictor all by itself, with no lagging and a slope of 0.987 in the simple linear regression with Clarkston as the explanatory variable and IHR flow as the dependent variable. The slope of less than one indicated a loss of some kind–perhaps evapotranspiration from the reservoirs below Clarkston, or irrigation withdrawals. For simplicity and to account for the fact that less development of water resources existed in the past, the (daily) flow at Clarkston was used as a surrogate for flow at IHR in the pre-IHR era (i.e., slope = 1).

4.2.2 Data Used for Model Calibration and Testing

Model calibration and testing ("validation") used all of the available river stage data from six Hanford Reach locations, 100B, 100N, 100D, 100H, 100F, and 300 Areas (Figure 4.5, Table 4.5). Gaps in the river stage datasets are listed in Appendix A, Table A.2. River stage hydrographs are given in Appendix D.

Cross-section and water surface elevations in MASS1 were in units of feet referenced to the National Geodetic Vertical Datum of 1929 (NGVD29). The river recorder data are in meters

Table 4.3. Data sources used for simulation with daily output. These sources were used for MASS1 simulation of historic periods. For all time periods, input data with the finest temporal resolution available (hourly or daily) was used. Daily Yakima River flows at Kiona (USGS) were used for all periods.

Period	Columbia River flow at Priest Rapids Dam	Snake River flow at Ice Harbor Dam	McNary Pool Elevation
12-31-1939 to 08-27-1953	Daily USGS PRD	Daily USGS CLA	assumed constant 270 ft
08-28-1953 to 12-01-1953	Daily USGS PRD	Daily USGS CLA	assumed rising linearly to 340 ft
12-02-1953 to 10-01-1960	Daily USGS PRD	Daily USGS CLA	assumed constant 340 ft
10-02-1960 to 12-24-1961	Daily USGS PRD	Daily USGS CLA	Daily ACOE MCN
12-25-1961 to 12-31-1966	Daily USGS PRD	Daily ACOE IHR	Daily ACOE MCN
01-01-1967 to 02-28-1975	Daily USGS PRD	Hourly ACOE IHR	Daily ACOE MCN
03-01-1975 to 12-31-1986	Daily USGS PRD	Hourly ACOE IHR	Hourly ACOE MCN
01-01-1987 to 12-06-2004	see Table 4.4	Hourly ACOE MCN	Hourly ACOE MCN

Table 4.4. Data sources used for hourly Columbia River flow at Priest Rapids Dam.

Start Time	End Time	Columbia River flow at Priest Rapids Dam
01-01-40 00:00	12-31-86 23:00	Daily USGS PRD
01-01-87 00:00	11-30-90 23:00	Hourly GCPUD PRD
12-01-90 00:00	12-31-90 23:00	Daily USGS PRD
01-01-91 00:00	05-31-92 23:00	Hourly GCPUD PRD
06-01-92 00:00	06-30-92 23:00	Daily USGS PRD
07-01-92 00:00	03-31-94 23:00	Hourly GCPUD PRD
04-01-94 00:00	04-09-94 23:00	Daily USGS PRD
04-10-94 00:00	02-28-95 23:00	Hourly GCPUD PRD
03-01-95 00:00	03-31-95 23:00	Hourly USGS PRD
04-01-95 00:00	07-04-98 07:30	Hourly GCPUD PRD
07-04-98 08:30	07-04-98 10:30	Hourly USGS PRD
07-04-98 11:30	07-06-98 10:30	Hourly GCPUD PRD
07-06-98 11:30	07-06-98 14:30	Hourly USGS PRD
07-06-98 15:30	07-10-98 18:30	Hourly GCPUD PRD
07-10-98 19:30	07-11-98 07:30	Hourly USGS PRD
07-11-98 08:30	07-20-98 14:30	Hourly GCPUD PRD
07-20-98 15:30	07-21-98 06:30	Hourly USGS PRD
07-21-98 07:30	07-23-98 14:30	Hourly GCPUD PRD
07-23-98 15:30	07-24-98 06:30	Hourly USGS PRD
07-24-98 07:30	07-24-98 14:30	Hourly GCPUD PRD
07-24-98 15:30	07-25-98 19:30	Hourly USGS PRD
07-25-98 20:30	07-27-98 06:30	Hourly GCPUD PRD
07-27-98 07:30	07-28-98 12:30	Hourly USGS PRD
07-28-98 13:30	07-28-98 23:30	Hourly GCPUD PRD
07-29-98 00:30	07-29-98 09:30	Hourly USGS PRD
07-29-98 10:30	07-30-98 01:30	Hourly GCPUD PRD
07-30-98 02:30	07-30-98 15:30	Hourly USGS PRD
07-30-98 16:30	08-30-98 23:30	Hourly GCPUD PRD
08-31-98 00:30	08-31-98 07:30	Hourly USGS PRD
08-31-98 08:30	05-31-01 23:00	Hourly GCPUD PRD
06-01-01 00:00	06-03-01 23:00	Hourly USGS PRD
06-04-01 00:00	12-31-01 23:00	Hourly GCPUD PRD
01-01-02 00:00	12-07-04 00:00	Hourly ACOE PRD

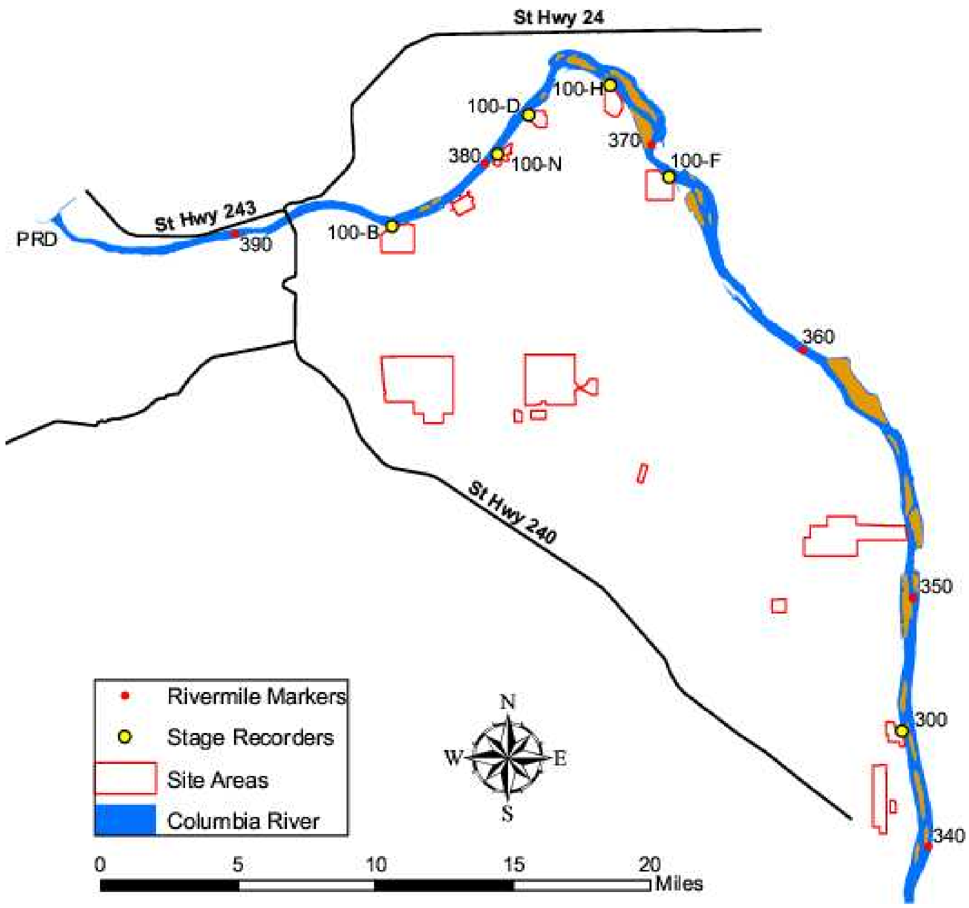

Figure 4.5. Columbia River stage recording sites in Hanford Reach.

Table 4.5. Hanford Reach river stage data availability (n = number of measurements available).

Location	RM	Start time	End time	n
100B	384.09	01/01/93 00:00	08/30/04 03:00	100,304
100N	379.48	07/19/93 15:00	10/31/04 23:00	96,311
100D	377.65	11/08/96 15:00	08/30/04 03:00	68,429
100H	372.96	01/01/93 00:00	08/30/04 03:00	96,435
100F	368.68	01/01/93 00:00	03/31/04 23:00	81,768
300	344.34	11/06/91 12:00	12/13/04 03:00	111,113

North American Vertical Datum of 1988 (NAVD88), so MASS1 elevations were converted to meters and then adjusted by the local correction factors listed in Table A.3. The correction factors ranged along the Hanford Reach ranged from 1.031 to 1.071 m, and the average value was 1.058 m. Simulated water surface elevations were also linearly interpolated to the river recorder locations (in river miles) from the adjacent cross sections.

4.3 Model Calibration

All MASS1 simulations were run at a 6-minute timestep, and model output was saved at an hourly timestep. The final 1940–2004 simulations discussed in Section 5 were performed after calibrating the model with a small subset of available river stage data. The model was calibrated by adjusting the six Manning's roughness coefficients (n_i) used in the Hanford Reach; no other parameters were adjusted. One value of n was used for each stretch of river above a river stage recorder. Candidate parameter sets consisting of the six n_i values each were determined and evaluated using an automatic calibration technique, GENetic Optimization Using Derivatives (GENOUD) (Sekhon and Mebane 1998). GENOUD was implemented using the rgenoud package in the R data analysis environment (Mebane and Sekhon 2005, R Development Core Team 2005). An R script was used to invoke GENOUD and execute the calibration of MASS1.

A primary and two alternative calibrations were performed, each with a different data subset. Minimization of mean absolute error (MAE) was the objective in all calibrations. The primary calibration was based on data at all locations in 1999, a typical year during the 1991–2004 period. The first alternative calibration also used all river recorder locations but was limited to a high-flow period during spring and early summer of 1997. The second alternative calibration was based on 1999 as in the primary calibration but included only 300 Area river stage data.

The GENOUD technique is a combination of genetic algorithm and gradient search methods. The genetic algorithm component ensures that a wide swath of the possible parameter space is sampled so that the optimization doesn't get stuck in local optima. The gradient search is used to refine the calibration once an optimum is found. The precision of n_i was limited to four decimal places, and the lower and upper bounds specified for n were 0.0210 and 0.0350, respectively. The lower bound was chosen by trial and error to eliminate model instability. The upper bound was set to speed calibration after trial and error indicated that no optimal model fits were obtained with values greater than 0.035. Multiple generations were run in the GENOUD method, and each generation had a large population of distinct parameter sets. Four separate executions of GENOUD having a total of 841 parameter sets were done for the primary calibration, and at the start of each GENOUD execution the goodness-of-fit for the different model runs (parameter sets) ranged from good to bad (Figure 4.6). Goodness-of-fit improved as the calibration continued, though there was still some sampling of the wider parameter space to check for other optimal values. Although the automatic calibration only dealt with minimizing MAE, the results of all calibration runs were inspected to ensure that bias was also as low as possible when choosing the best parameter set (see Appendix C for definitions of the statistics). The other goodness-of-fit statistic used in this report, baseline-adjusted first-degree efficiency E'_1, is closely related to MAE and tends to track it closely.

Figure 4.6 shows that improvement in MAE (and E_1') was asymptotic, with no further reduction of MAE to less than 0.08 m. These same best parameter sets tended to have bias clustered around 0.01 m. The suspected reason for this behavior is systematic error in part of the data, explained further in Section 5.

Goodness-of-fit versus roughness coefficient values is shown in Figure 4.7. For each of the six n_i there is a front of values that provide excellent goodness-of-fit, but a single value that provided the best fit. This indicates that although many parameter sets yielded about the same goodness-of-fit, only one or a few sets were optimal at the highest precision. The optimized roughness coefficient parameter sets for the three calibrations are listed in Table 4.6.

Hydrographs showing observed and simulated river stage during 1999 are shown in Figures D.1–D.6.

Table 4.6. Manning's roughness coefficients n_i.

Reach	Start RM	End RM	Calibration Primary	High Flow[a]	300 Area[b]
n_1	397.100	383.750	0.0231	0.0230	0.0221
n_2	383.750	378.690	0.0221	0.0229	0.0246
n_3	378.690	376.890	0.0275	0.0257	0.0237
n_4	376.890	372.520	0.0272	0.0253	0.0221
n_5	372.520	368.090	0.0281	0.0259	0.0220
n_6	368.090	343.000	0.0245	0.0252	0.0277
Fixed *a priori*, not calibrated in this study					
1[c]	343.000	334.500		0.0250	
2	Yakima River			0.0270	
3	334.500	324.500		0.0270	
4	Snake River			0.0236	

(a) High flow calibration based on 04/21/1997 12:00 to 06/29/1997 08:00.
(b) 300 Area calibration based on stage data from that location only.
(c) Lower part of segment 1, below 300 Area.

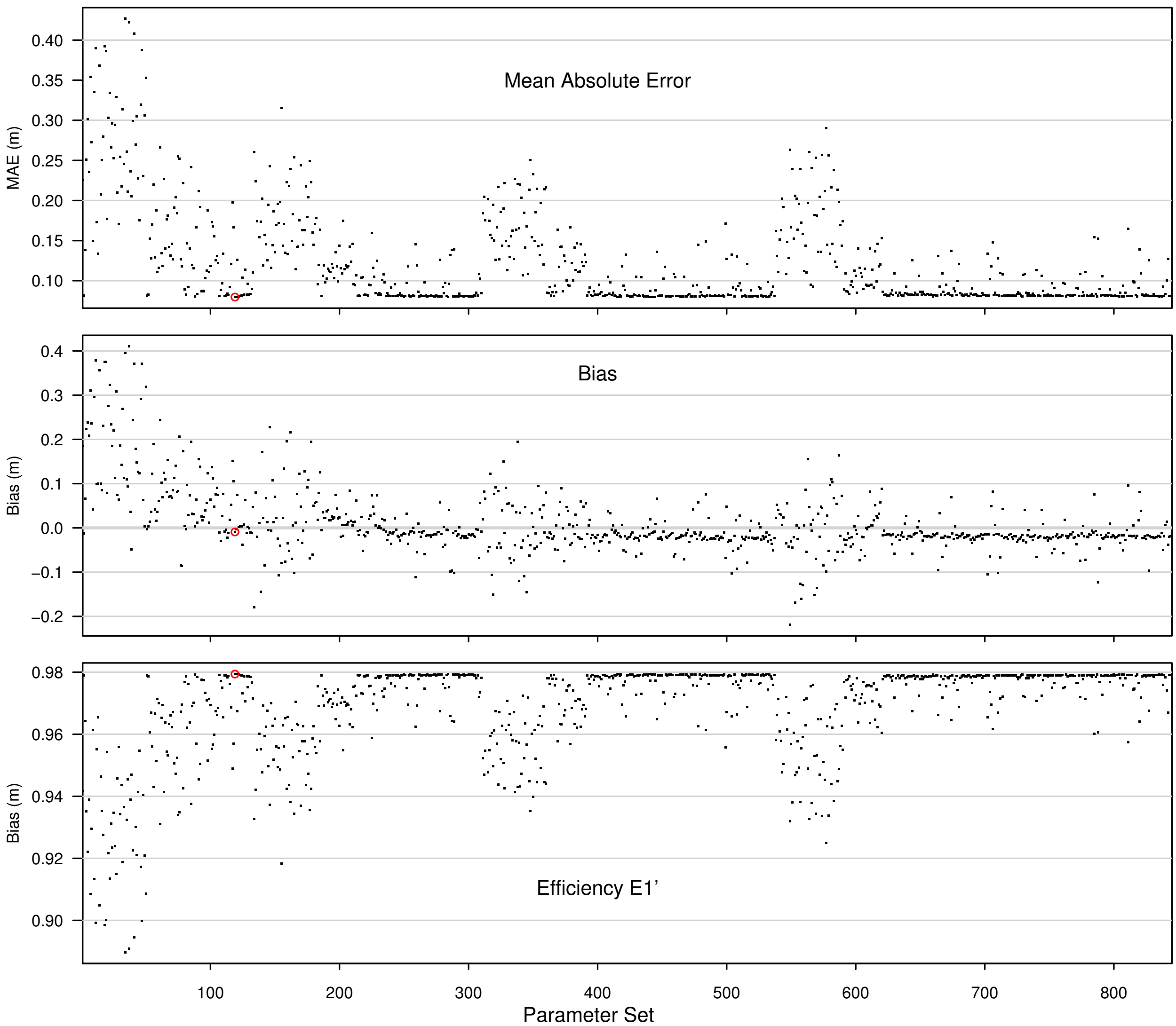

Figure 4.6. Goodness-of-fit for parameter sets in the primary calibration. Parameter set numbering is in chronological order, and the parameter sets from four separate calibration jobs are lumped together. The red circles indicate the parameter set that was ultimately selected as best.

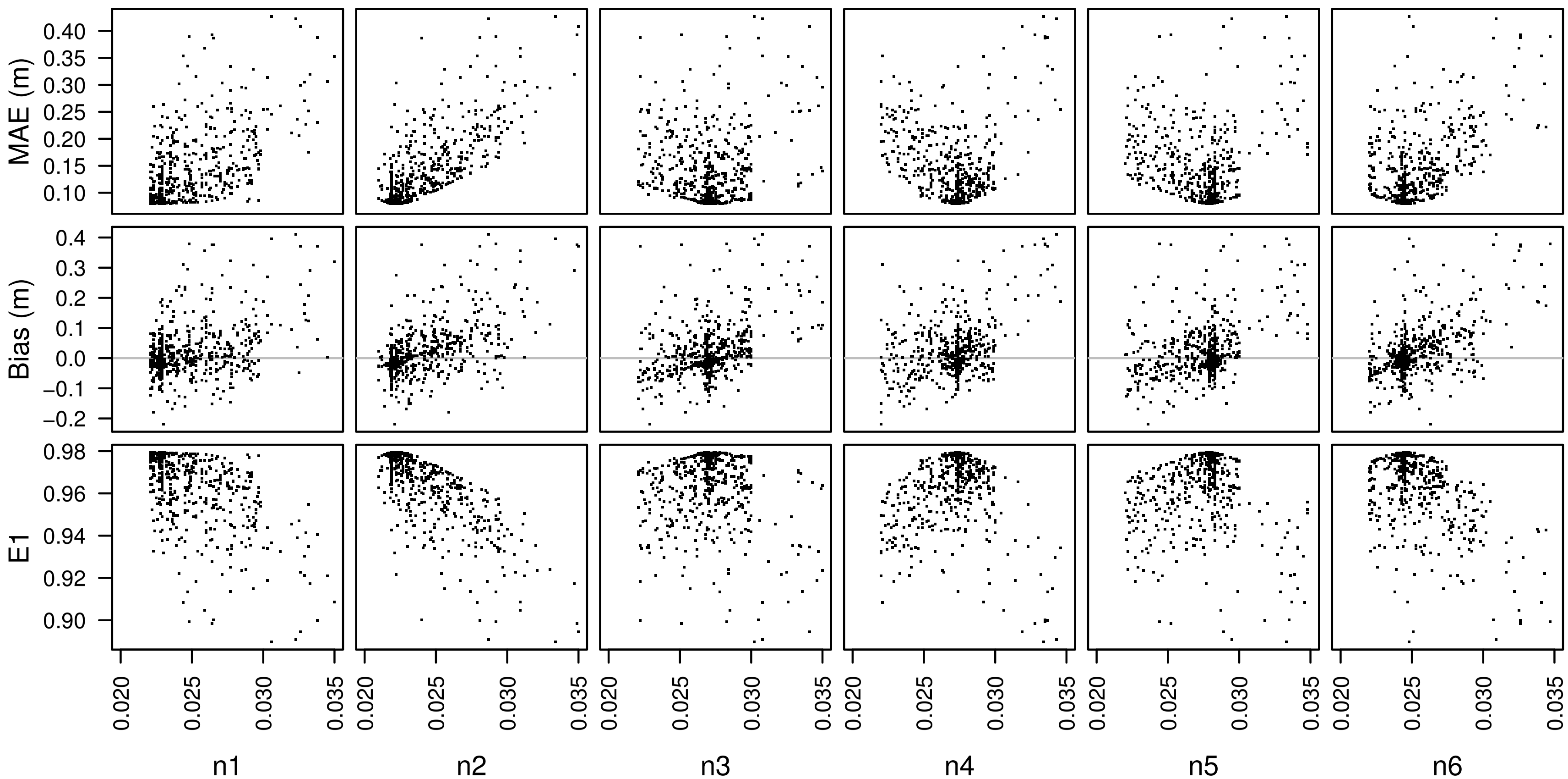

Figure 4.7. Goodness-of-fit for individual parameter values.

5.0 Model Results

Goodness-of-fit, or model skill in matching the available river stage data, is shown graphically in Figure 5.1 and tabulated in Table 5.1.

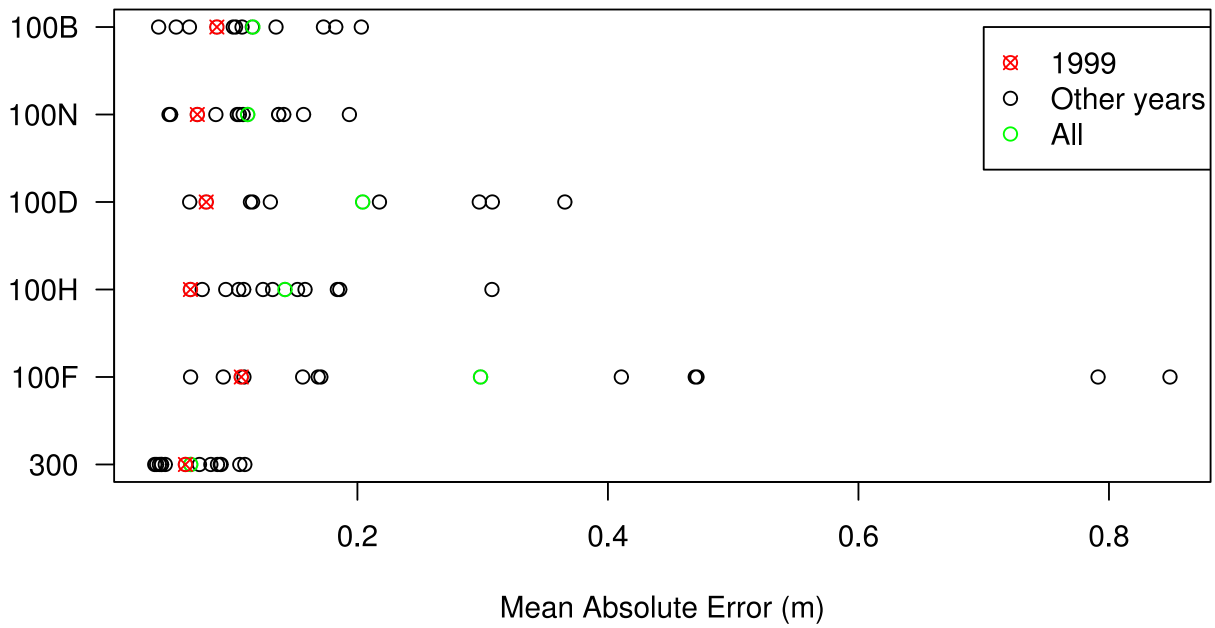

Figure 5.1. Mean absolute error (MAE) by year and location.

Table 5.1. Goodness-of-fit statistics, primary calibration (N_1 = number of hourly timesteps for Bias, MAE, R^2, E_2; MAE= mean absolute error, N_2 = number of hourly timesteps for E_1'; E_1'= baseline-adjusted first-degree efficiency [see Appendix C]).

Year	N_1	Bias (m)	MAE (m)	R^2	E_2	N_2	E_1'
			100-B				
1993	8658	-0.193	0.203	0.984	0.942	8640	0.797
1994	8759	-0.163	0.183	0.969	0.935	8736	0.806
1995	8661	-0.100	0.135	0.975	0.960	8616	0.856
1996	8783	0.088	0.173	0.963	0.955	8760	0.862
1997	8756	0.074	0.103	0.993	0.989	8736	0.924
1998	8706	0.055	0.108	0.982	0.979	8520	0.896
1999	8554	-0.014	0.088	0.978	0.977	8496	0.902
2000	7752	0.038	0.101	0.979	0.977	7536	0.892
2001	8344	0.076	0.116	0.968	0.954	7392	0.826
2002	8760	0.036	0.066	0.996	0.995	8760	0.949
2003	8759	0.017	0.055	0.995	0.993	8736	0.936

Table 5.1. (continued)

Year	N_1	Bias (m)	MAE (m)	R^2	E_2	N_2	E'_1
2004	5812	0.014	0.041	0.996	0.994	5808	0.945
All years	100304	-0.007	0.117	0.979	0.979	98736	0.899
			100-N				
1993	3425	-0.036	0.087	0.971	0.960	3384	0.872
1994	8760	0.033	0.106	0.968	0.964	8760	0.878
1995	8760	0.096	0.137	0.975	0.960	8760	0.849
1996	8784	0.117	0.157	0.990	0.965	8784	0.855
1997	8760	0.115	0.141	0.991	0.978	8760	0.889
1998	8104	-0.006	0.109	0.979	0.966	6672	0.886
1999	8454	-0.009	0.072	0.979	0.974	7824	0.907
2000	8438	-0.017	0.104	0.968	0.959	7728	0.884
2001	8206	-0.084	0.137	0.919	0.888	8088	0.785
2002	8540	0.001	0.050	0.996	0.996	8520	0.961
2003	8760	-0.033	0.051	0.996	0.994	8760	0.941
2004	7320	-0.194	0.194	0.996	0.929	7320	0.757
All years	96311	0.004	0.112	0.983	0.978	93360	0.905
			100-D				
1996	1281	-0.019	0.066	0.997	0.979	1272	0.880
1997	8760	0.058	0.116	0.996	0.978	8760	0.895
1998	8760	-0.035	0.115	0.986	0.966	8760	0.867
1999	8760	-0.021	0.079	0.986	0.973	8760	0.889
2000	8784	0.026	0.218	0.815	0.771	8784	0.740
2001	8760	-0.059	0.308	0.641	0.177	8760	0.365
2002	8758	0.007	0.366	0.839	0.718	8736	0.602
2003	8754	-0.110	0.297	0.794	0.638	8736	0.552
2004	5812	-0.118	0.131	0.997	0.928	5808	0.782
All years	68429	-0.027	0.204	0.922	0.887	68376	0.790
			100-H				
1993	8760	0.096	0.132	0.972	0.955	8760	0.829
1994	8759	0.267	0.307	0.897	0.766	8736	0.634
1995	8758	0.177	0.184	0.979	0.918	8736	0.768
1996	8783	0.156	0.158	0.995	0.965	8760	0.850
1997	8080	0.106	0.125	0.992	0.980	7944	0.880
1998	7677	0.139	0.152	0.980	0.944	6312	0.801
1999	8503	0.026	0.067	0.984	0.979	7992	0.903
2000	8313	0.050	0.076	0.986	0.978	7440	0.897
2001	6377	0.178	0.186	0.965	0.818	4536	0.622
2002	7853	0.099	0.109	0.993	0.980	6552	0.895
2003	8760	0.094	0.095	0.996	0.976	8760	0.865

Table 5.1. (continued)

Year	N_1	Bias (m)	MAE (m)	R^2	E_2	N_2	E'_1
2004	5812	0.105	0.105	0.996	0.962	5808	0.827
All years	96435	0.125	0.142	0.980	0.959	90336	0.856
			100-F				
1993	8669	-0.471	0.471	0.988	0.590	8640	0.414
1994	7855	-0.469	0.470	0.981	0.547	7848	0.400
1995	5824	-0.411	0.411	0.984	0.716	5784	0.522
1996	8784	-0.074	0.156	0.966	0.952	8784	0.855
1997	8584	0.024	0.067	0.995	0.994	8544	0.941
1998	8415	0.050	0.093	0.978	0.974	7800	0.894
1999	8760	0.012	0.107	0.952	0.951	8760	0.856
2000	1073	-0.066	0.109	0.922	0.898	1056	0.733
2001	5094	-0.166	0.169	0.972	0.895	4176	0.711
2002	8618	-0.162	0.171	0.991	0.959	8568	0.853
2003	7908	0.791	0.791	0.991	-0.461	7272	-0.141
2004	2184	0.849	0.849	0.998	-2.966	2184	-1.057
All years	81768	-0.052	0.298	0.855	0.852	79416	0.737
			300 Area				
1991	1332	-0.105	0.106	0.974	0.831	1320	0.608
1992	8784	-0.106	0.110	0.975	0.908	8784	0.748
1993	8759	-0.089	0.091	0.989	0.952	8736	0.817
1994	8760	-0.087	0.088	0.988	0.936	8760	0.791
1995	8760	-0.060	0.074	0.984	0.970	8760	0.868
1996	8722	-0.009	0.083	0.984	0.981	8664	0.908
1997	5901	0.007	0.043	0.993	0.993	5832	0.937
1998	8434	-0.021	0.047	0.990	0.989	7776	0.921
1999	8659	-0.051	0.063	0.989	0.977	8352	0.882
2000	8601	-0.074	0.090	0.947	0.922	8232	0.815
2001	8735	0.000	0.038	0.976	0.972	8688	0.870
2002	8731	-0.009	0.042	0.995	0.995	8616	0.944
2003	8603	-0.022	0.044	0.987	0.984	8448	0.915
2004	8185	-0.028	0.040	0.989	0.983	8184	0.903
All years	110966	-0.044	0.067	0.984	0.979	109152	0.900

At each location the fit was variable from year to year and did not exhibit any obvious long-term trends. Only one location, 100-H, had its best fit in the calibration year of 1999, indicating that the model performed consistently across calibration and noncalibration years. Location 100-N had the best fit for all years (E_1=0.905), and 100-F had the worst fit (E_1=0.737). Hydrographs showing both observed and simulated river stage using the primary calibration for all years are shown in Appendix D, Figures D.7–D.25. The best fit by year and location was 100-N during

2002 (Figure D.12), and the worst fit was 100-F during 2004 (Figure D.21).

Model efficiency at 100-F during 2003-2004 was negative, indicating that the mean of the daily data was a better predictor of hourly stage than the model, a highly undesirable outcome. Closer inspection of the river stage data suggests that there are probably some spurious shifts in the recorded water levels. Unless the river bathymetry has changed over time, or there are sustained errors in the boundary conditions, model errors should hover around a constant level over time. Instead, model error showed some significant excursions from the level trend at all locations, and extended and even step-like shifts for 100-F (Figure 5.2). These results strongly suggest that some problems exist in the data. Model error medians, inner quartiles, and extremes are shown by location with boxplots in Figure 5.3.

The alternative calibration based just the high-flow period (04/21/1997 12:00 to 06/29/1997 08:00) resulted in marginally better model fit for this period, though the goodness-of-fit values were not better than those of the primary calibration for all times (Table 5.2).

The alternative calibration based on just 300 Area led to higher goodness-of-fit at that location, but worse fit at the other locations, as expected (Table D.1 and Figure D.6).

Table 5.2. Model skill statistics, high-flow calibration (N_1 = number of hourly timesteps for Bias, MAE, R^2, E_2; MAE= mean absolute error, N_2 = number of hourly timesteps for E_1'; E_1'= baseline-adjusted first-degree efficiency [see Appendix C]).

Location	N_1	Bias (m)	MAE (m)	R^2	E_2	N_2	E_1'
100B	1653	0.010	0.071	0.981	0.980	1632	0.904
100N	1653	-0.001	0.052	0.989	0.988	1632	0.929
100D	1653	0.003	0.056	0.991	0.985	1632	0.915
100H	1347	-0.034	0.054	0.992	0.988	1296	0.921
100F	1645	0.021	0.054	0.991	0.988	1608	0.921
300	644	-0.065	0.068	0.992	0.961	600	0.839

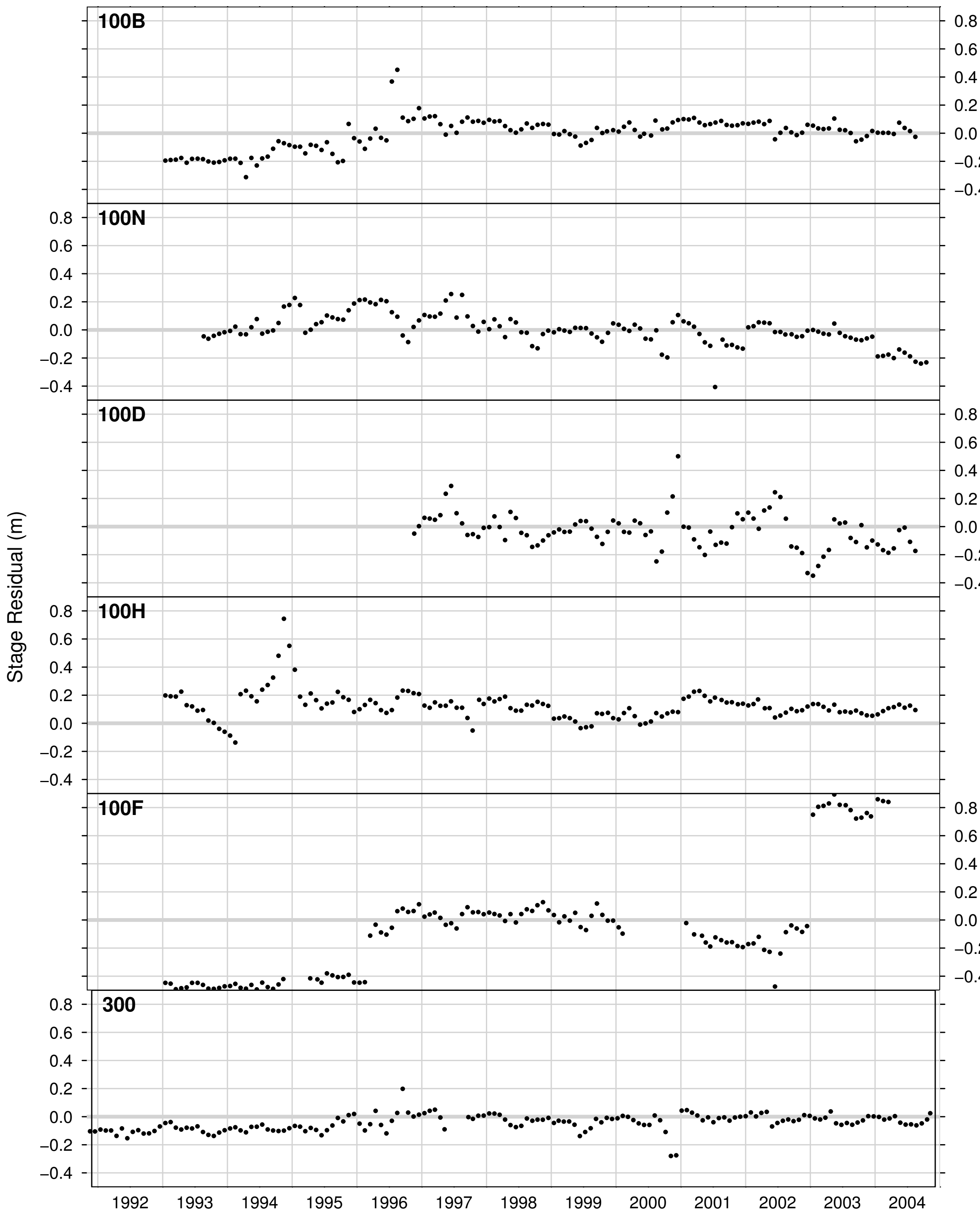

Figure 5.2. Mean monthly stage residuals for period of record.

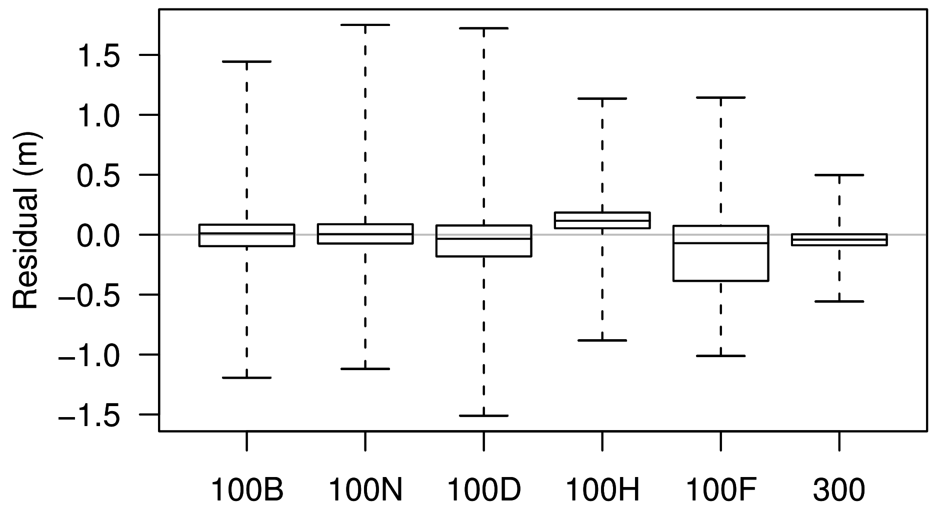

Figure 5.3. Boxplots of hourly stage residuals.

6.0 Discussion

The calibration was successful in finding a single best parameter set for each calibration objective, and the resulting values of Manning's roughness coefficient n_i were reasonable. The skill of the model in replicating observed water levels was high. Further improvement would probably result if more n_i zones or an island/curvature correction as suggested by Chow (1959) were used. However, the most significant improvement in model goodness-of-fit would probably result from improving the stage data used to calibrate the model. The large and/or persistent shifts in observed stage and model error indicate that the river stage data have some unresolved problems. At this time there is no evidence of any serious problems in the bathymetry or boundary condition data (Columbia, Snake, and Yakima inflows and McNary Dam stage). Over time, erosion and sedimentation will change the bathymetry, and such change is especially likely during high flows like that of 1997. Model skill tended to be greatest in reaches having smaller gradients, such as along the 300 Area and least in those reaches having relatively steep profiles, such as near 100-H and 100-F.

The need to know Columbia River water surface elevations at certain locations and times, or broad averages of them, has arisen at various times for many years in the era of Hanford cleanup operations. Previous efforts to simulate the Hanford Reach have met many of these ad hoc needs, but a comprehensive effort at simulating the entire historical period and documenting methods has been lacking. We hope this report and the electronic data underlying it will provide future Hanford projects the information they may need for a variety of environmental problems concerning the river. Scenarios of long-term future water levels could be based in part on these results, but should also consider effects of climate change and changes in dam operations.

7.0 References

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Appendix A

River Discharge and Stage Data

Appendix A – River Discharge and Stage Data

Table A.1. Timesteps missing from datasets. If a time gap is more than 1 timestep long, the number of timesteps is listed in column 1, and the start and end of the gap are noted in columns 2 and 3.

Number of Timesteps In Gap	From	To
Mean Hourly Columbia River Flow at PRD by GCPUD Total of 2652 missing timesteps in 28 different time gaps, or 2.02% of the full timeseries that begins 01-01-87 00:30 and ends 12-31-01 23:30.		
	04-05-87 02:30	
	05-11-87 21:30	
744	12-01-90 00:30	12-31-90 23:30
	04-07-91 01:30	
	04-05-92 01:30	
720	06-01-92 00:30	06-30-92 23:30
	04-04-93 01:30	
216	04-01-94 00:30	04-09-94 23:30
744	03-01-95 00:30	03-31-95 23:30
	04-02-95 01:30	
	04-07-96 01:30	
	04-06-97 01:30	
	04-05-98 01:30	
3	07-04-98 08:30	07-04-98 10:30
4	07-06-98 11:30	07-06-98 14:30
13	07-10-98 19:30	07-11-98 07:30
	07-11-98 23:30	
16	07-20-98 15:30	07-21-98 06:30
16	07-23-98 15:30	07-24-98 06:30
29	07-24-98 15:30	07-25-98 19:30
30	07-27-98 07:30	07-28-98 12:30
10	07-29-98 00:30	07-29-98 09:30
14	07-30-98 02:30	07-30-98 15:30
8	08-31-98 00:30	08-31-98 07:30
	04-04-99 01:30	
	04-02-00 01:30	
	04-01-01 01:30	
72	06-01-01 00:30	06-03-01 23:30
Mean Hourly Snake River Flow at IHR by ACOE Total of 96 missing timesteps in 66 different time gaps, or 0.03% of the full timeseries that begins 01-02-67 23:30 and ends 12-07-04 08:30.		
	10-29-6705:30	
	10-30-6715:30	
	10-27-6805:30	
	10-28-6814:30	
	03-17-6916:30	
	10-26-6905:30	
	10-27-6914:30	
	10-24-70 18:30	
	10-25-70 08:30	
	10-30-71 18:30	
	10-31-71 08:30	
	10-28-72 18:30	
	10-29-72 08:30	
	10-27-73 18:30	
	10-28-73 09:30	

Table A.1. (continued)

Number of Timesteps In Gap	From	To
	01-06-74 09:30	
	10-26-74 18:30	
	10-27-74 09:30	
25	11-06-74 19:30	11-07-74 19:30
	02-23-75 09:30	
	10-25-75 18:30	
	10-26-75 08:30	
	04-25-76 08:30	
	10-30-76 18:30	
	10-31-76 08:30	
	04-24-77 08:30	
	10-29-77 18:30	
	10-30-77 08:30	
	04-30-78 08:30	
	10-28-78 18:30	
	10-29-78 08:30	
	06-03-79 20:30	
	10-27-79 18:30	
	10-28-79 08:30	
	10-25-80 18:30	
	10-26-80 09:30	
	10-24-81 18:30	
	10-30-82 18:30	
	10-29-83 18:30	
	10-27-84 18:30	
	10-26-85 18:30	
	10-25-86 18:30	
	10-24-87 18:30	
	04-03-88 01:30	
	10-29-88 18:30	
	04-02-89 01:30	
	10-28-89 18:30	
	04-01-90 01:30	
	10-27-90 18:30	
	12-11-90 19:30	
	04-07-91 01:30	
3	06-19-91 12:30	06-19-91 14:30
2	10-21-91 13:30	10-21-91 14:30
	10-26-91 18:30	
2	03-23-92 10:30	03-23-92 11:30
	04-05-92 01:30	
2	06-20-92 17:30	06-20-92 18:30
2	08-03-92 09:30	08-03-92 10:30
	10-24-92 18:30	
	04-04-93 01:30	
	10-30-93 18:30	
	10-24-98 18:30	
	10-30-99 18:30	
	04-02-00 01:30	
	04-01-01 01:30	
	04-07-02 01:30	
Mean Daily Snake River Flow at IHR by USGS Total of 1826 missing timesteps in 1 different time gaps, or 13.33% of the full timeseries that begins 04-02-62 and ends 09-30-99.		
1826	10-01-90	09-30-95
Mean Daily Snake River Flow at IHR by ACOE Total of 2 missing timesteps in 2 different time gaps, or		

Table A.1. (continued)

Number of Timesteps In Gap	From	To
0.02% of the full timeseries that begins 12-26-61 and ends 12-29-90.		
	11-01-74	
	08-01-75	
Mean Daily Palouse River Flow at Hooper, WA by USGS Total of 1097 missing timesteps in 3 different time gaps, or 5.64% of the full timeseries that begins 10-02-51 and ends 01-06-05.		
730	10-01-85	09-30-87
365	10-01-90	09-30-91
2	04-06-04	04-07-04
Mean Daily Tucannon River Flow near Starbuck, WA by USGS Total of 1733 missing timesteps in 3 different time gaps, or 10.26% of the full timeseries that begins 10-02-58 and ends 01-06-05.		
365	10-01-76	09-30-77
365	10-01-90	09-30-91
1003	01-02-92	09-30-94
Mean Daily Yakima River Flow at Kiona, WA by USGS Total of 7 missing timesteps in 2 different time gaps, or 0.03% of the full timeseries that begins 01-02-40 and ends 01-09-05.		
2	05-04-04	05-05-04
5	05-13-04	05-17-04
Instantaneous Hourly Stage at McNary (on the hour) Total of 55 missing timesteps in 52 different time gaps, or 0.02% of the full timeseries that begins 03-01-75 00:00 and ends 12-07-04 09:00.		
	10-18-75 06:00	
	10-26-75 01:00	
	10-26-75 09:00	
	04-25-76 09:00	
	10-31-76 01:00	
	10-31-76 09:00	
	04-24-77 09:00	
	10-30-77 01:00	
	10-30-77 09:00	
	04-30-78 09:00	
	10-29-78 01:00	
	10-29-78 09:00	
	04-29-79 09:00	
	10-28-79 01:00	
	10-28-79 09:00	
	05-24-80 12:00	
	05-25-80 15:00	
	10-26-80 01:00	
	10-26-80 10:00	
	10-25-81 01:00	

Table A.1. (continued)

Number of Timesteps In Gap	From	To
	02-21-82 18:00	
	10-31-82 01:00	
	05-19-83 12:00	
	05-19-83 20:00	
	07-28-83 20:00	
	10-30-83 01:00	
	10-28-84 01:00	
	10-27-85 01:00	
	10-26-86 01:00	
	10-25-87 01:00	
	04-03-88 02:00	
	10-30-88 01:00	
	04-02-89 02:00	
	10-29-89 01:00	
	04-01-90 02:00	
	10-28-90 01:00	
	12-11-90 20:00	
	04-07-91 02:00	
3	06-19-91 13:00	06-19-91 15:00
	10-27-91 01:00	
2	08-03-92 10:00	08-03-92 11:00
	10-25-92 01:00	
	11-24-92 17:00	
	04-04-93 02:00	
	10-31-93 01:00	
	09-07-95 02:00	
	10-25-97 19:00	
	10-24-98 19:00	
	10-30-99 19:00	
	04-02-00 02:00	
	04-01-01 02:00	
	04-07-02 02:00	
Instantaneous Daily Stage at McNary (at midnight) Total of 6 missing timesteps in 6 different time gaps, or 0.05% of the full timeseries that begins 10-02-60 and ends 12-30-90.		
	03-25-61	
	05-13-63	
	08-11-63	
	01-05-68	
	11-02-74	
	08-02-75	

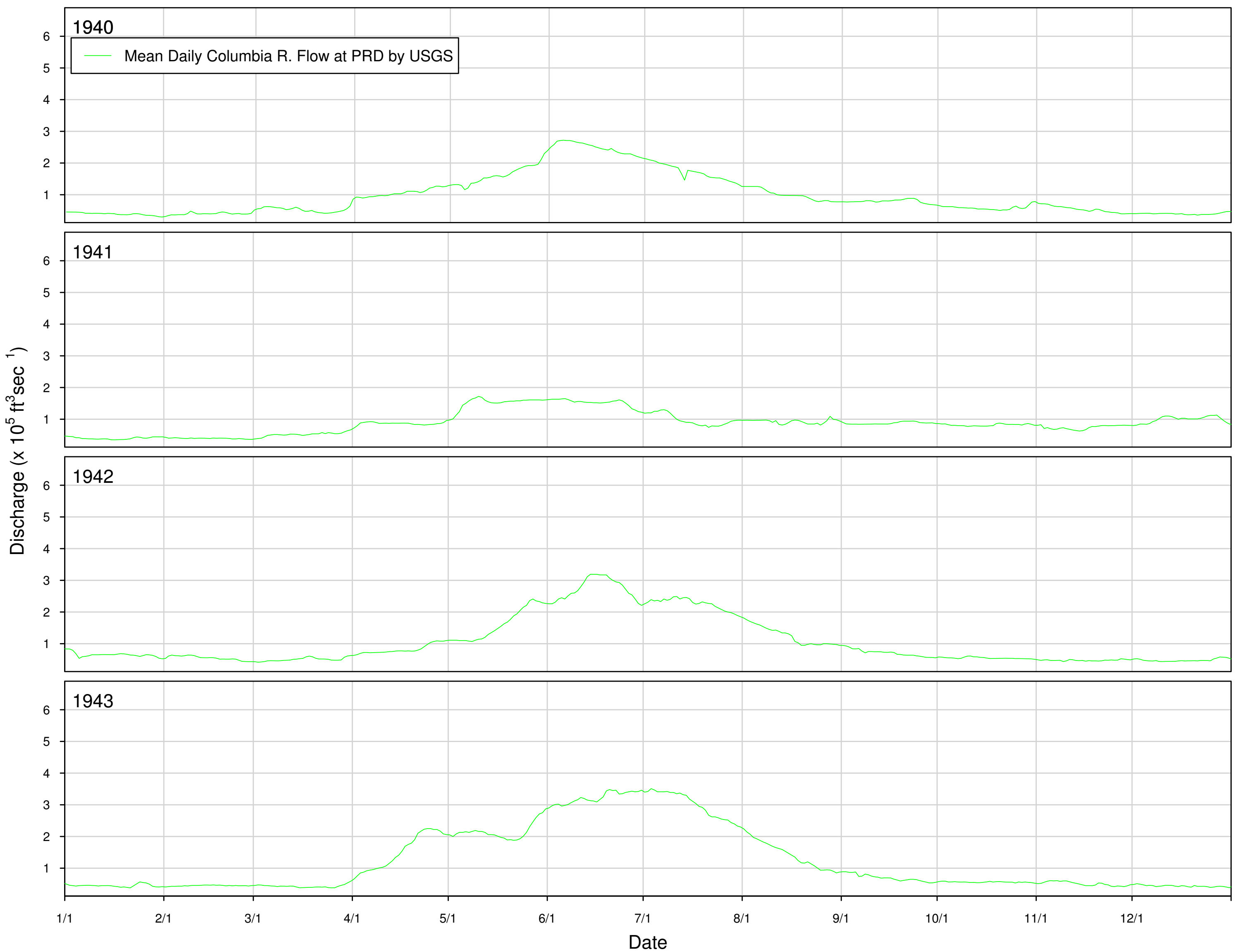

Figure A.1. Columbia River flow below Priest Rapids Dam, 1940–1943.

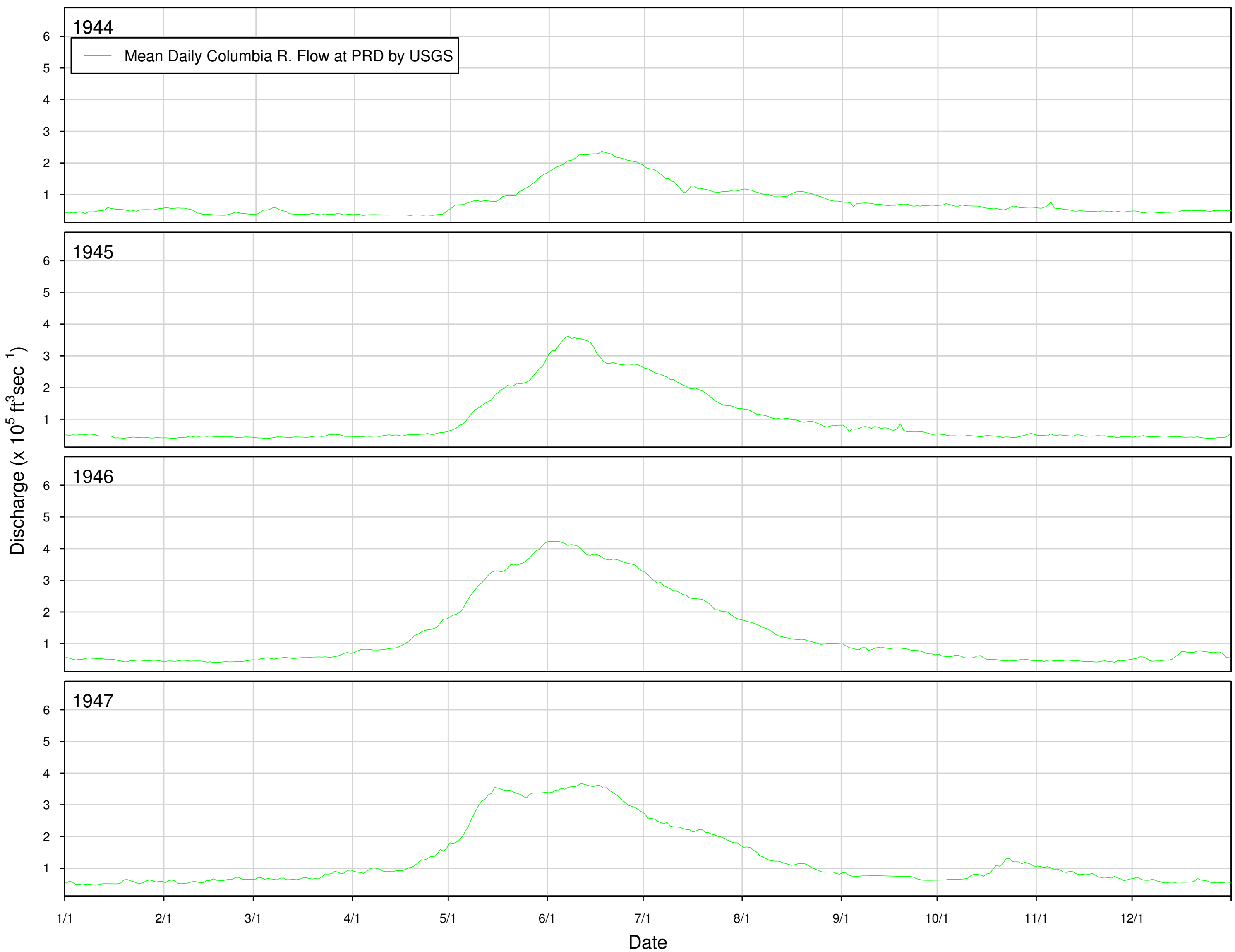

Figure A.2. Columbia River flow below Priest Rapids Dam, 1944–1947.

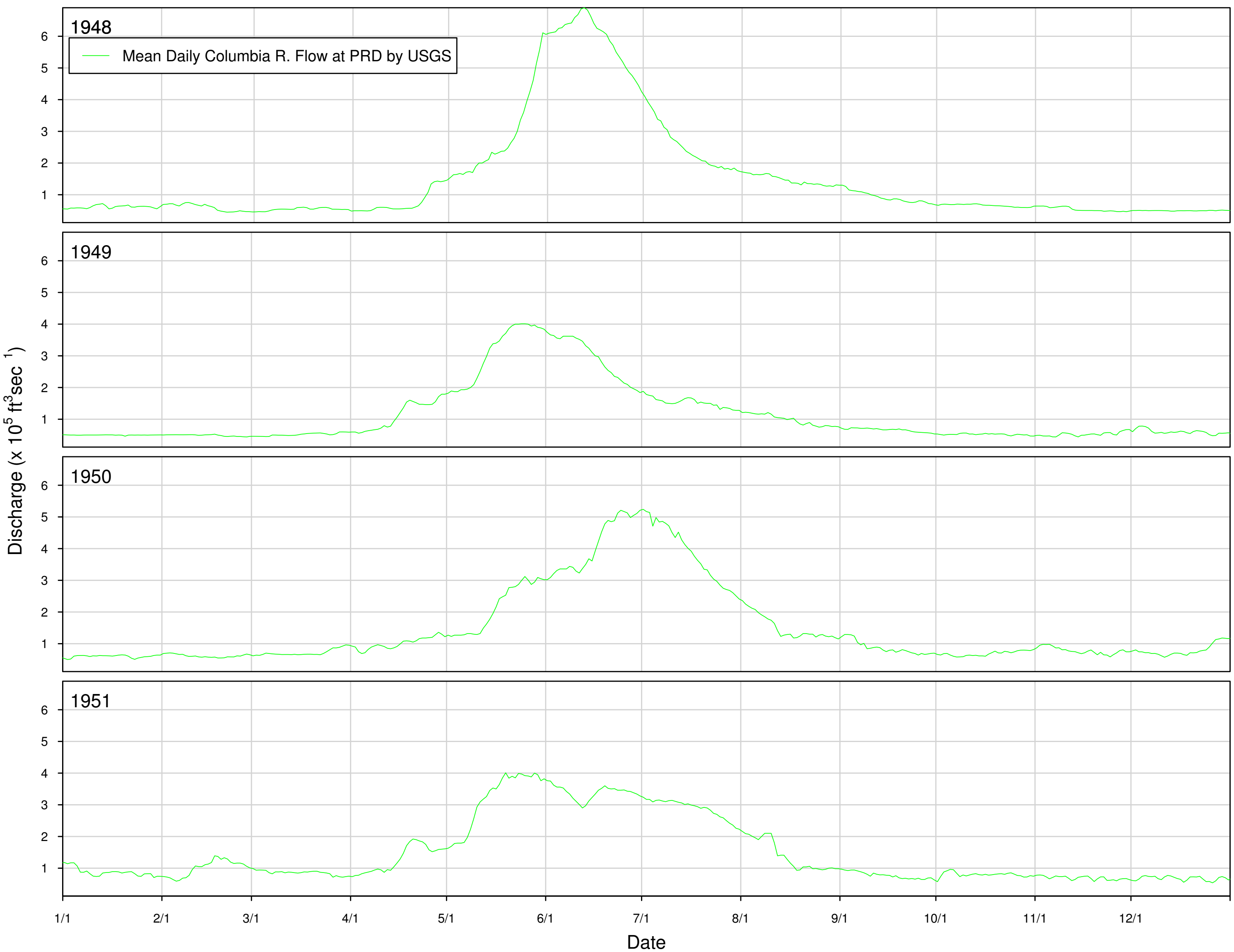

Figure A.3. Columbia River flow below Priest Rapids Dam, 1948–1951.

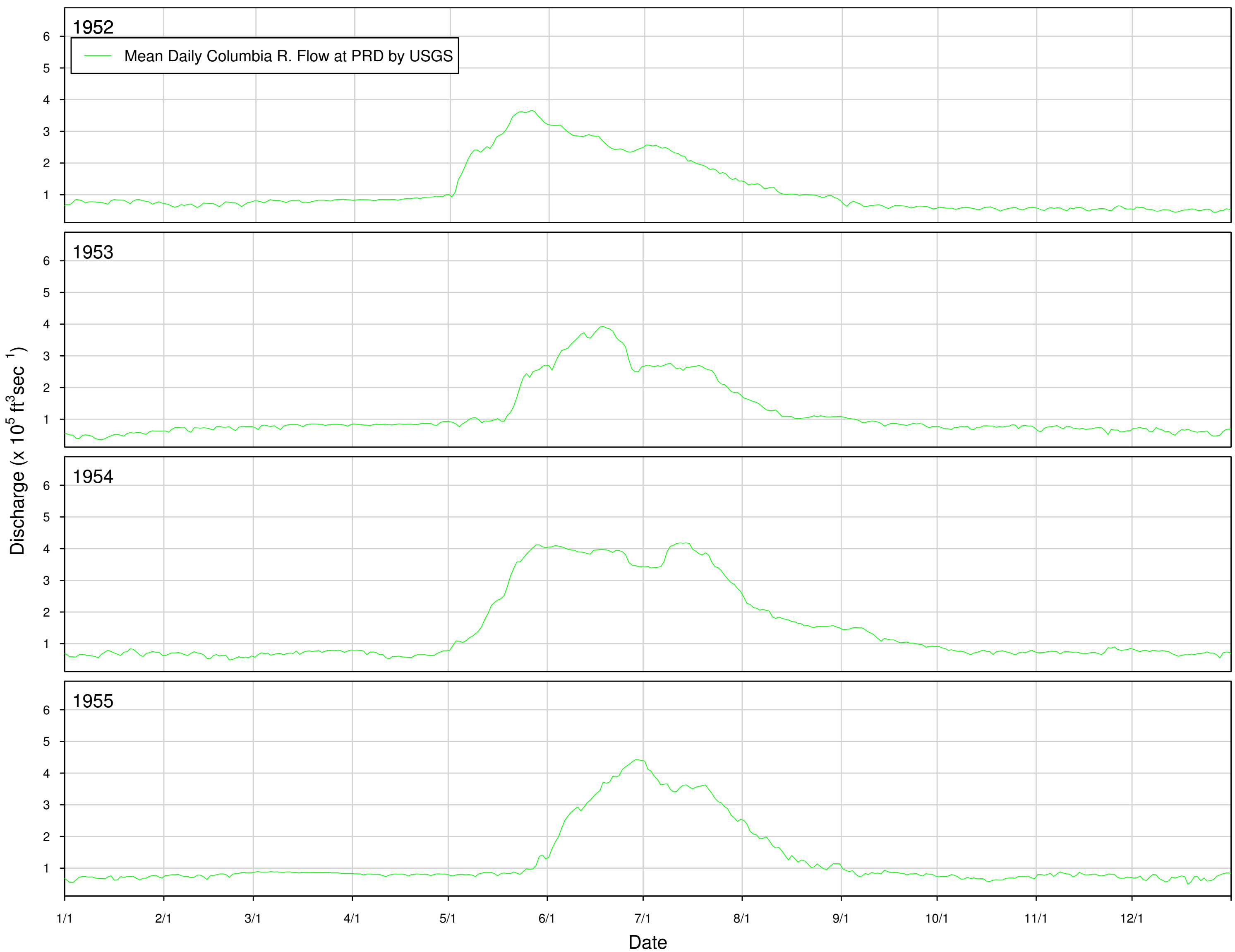

Figure A.4. Columbia River flow below Priest Rapids Dam, 1952–1955.

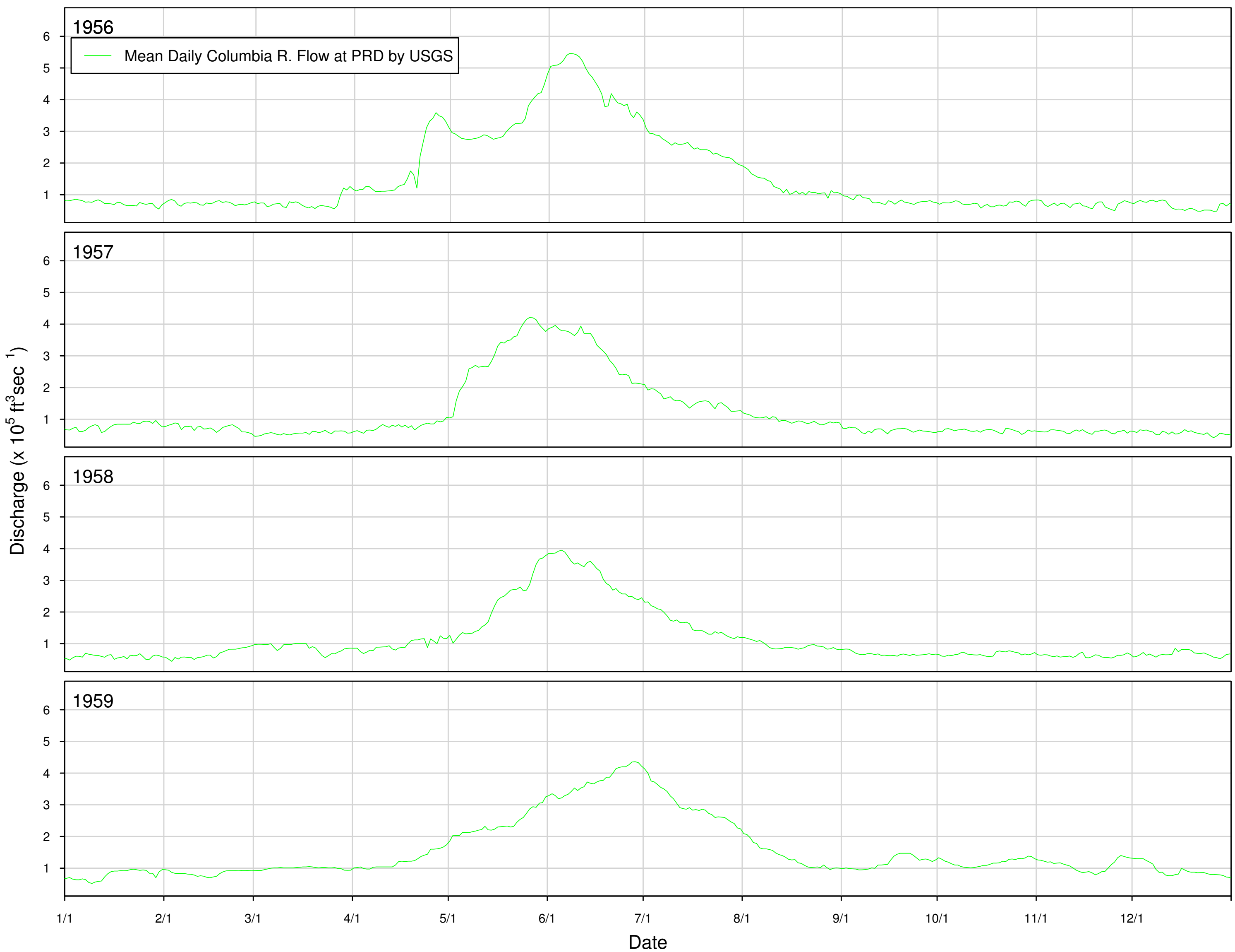

Figure A.5. Columbia River flow below Priest Rapids Dam, 1956–1959.

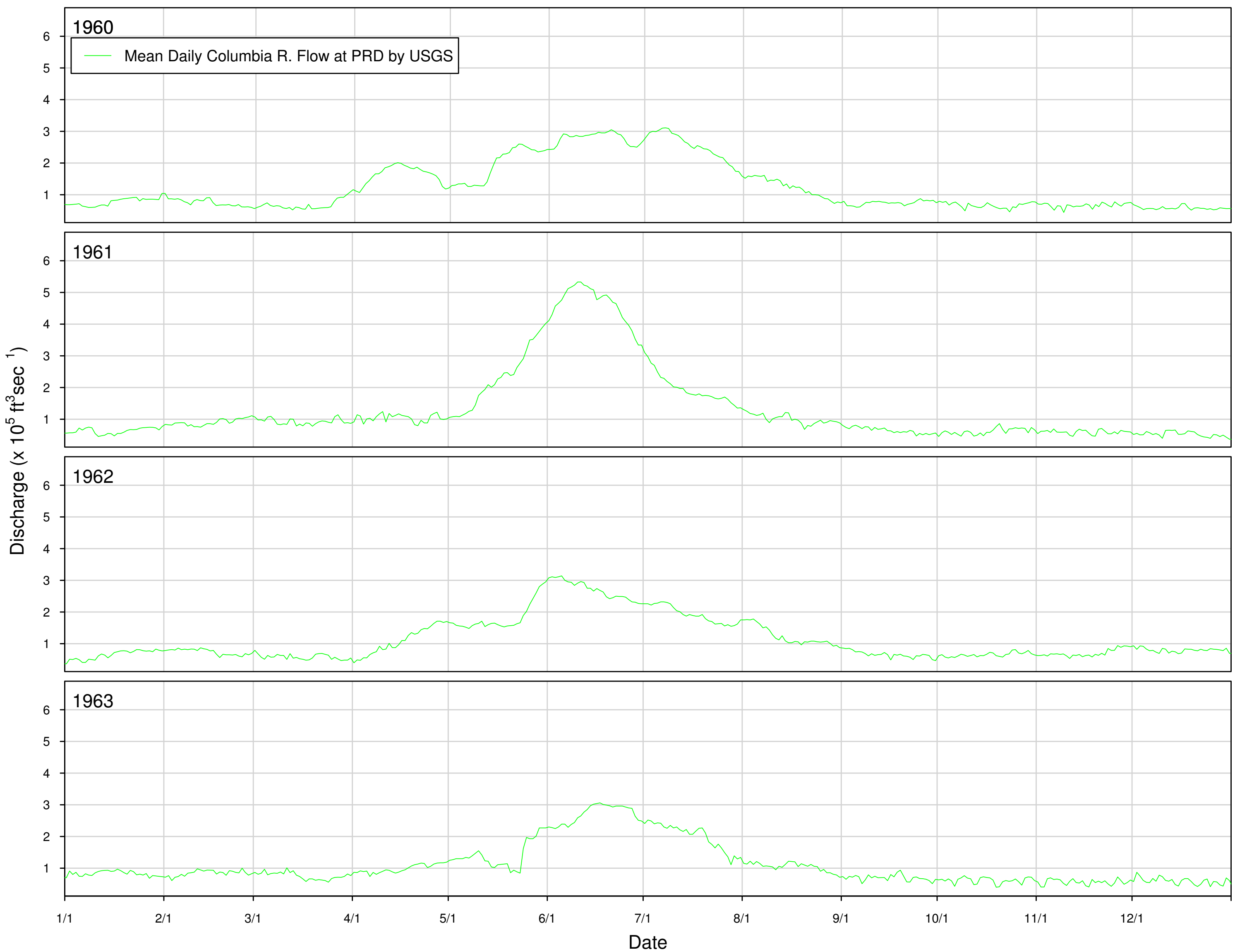

Figure A.6. Columbia River flow below Priest Rapids Dam, 1960–1963.

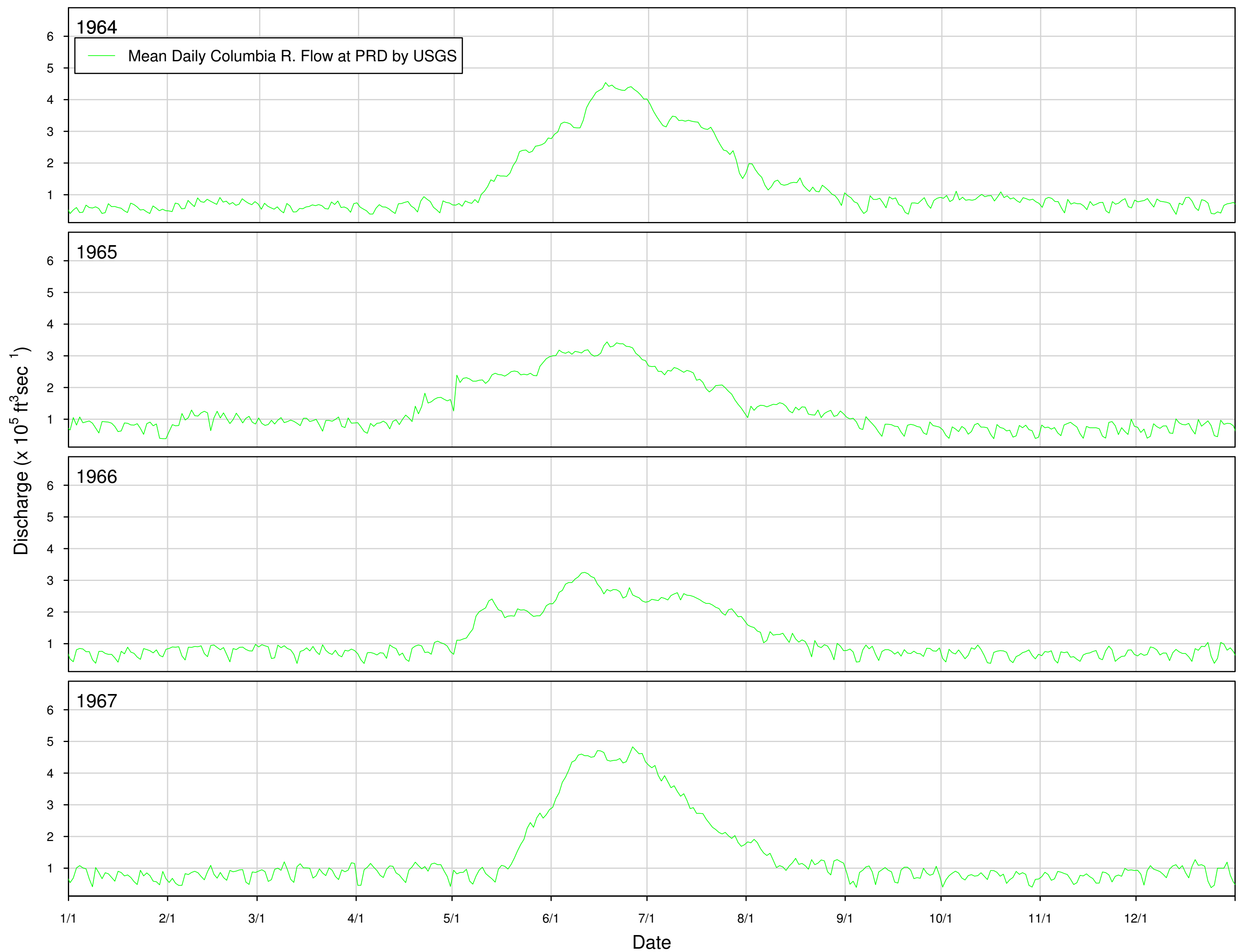

Figure A.7. Columbia River flow below Priest Rapids Dam, 1964–1967.

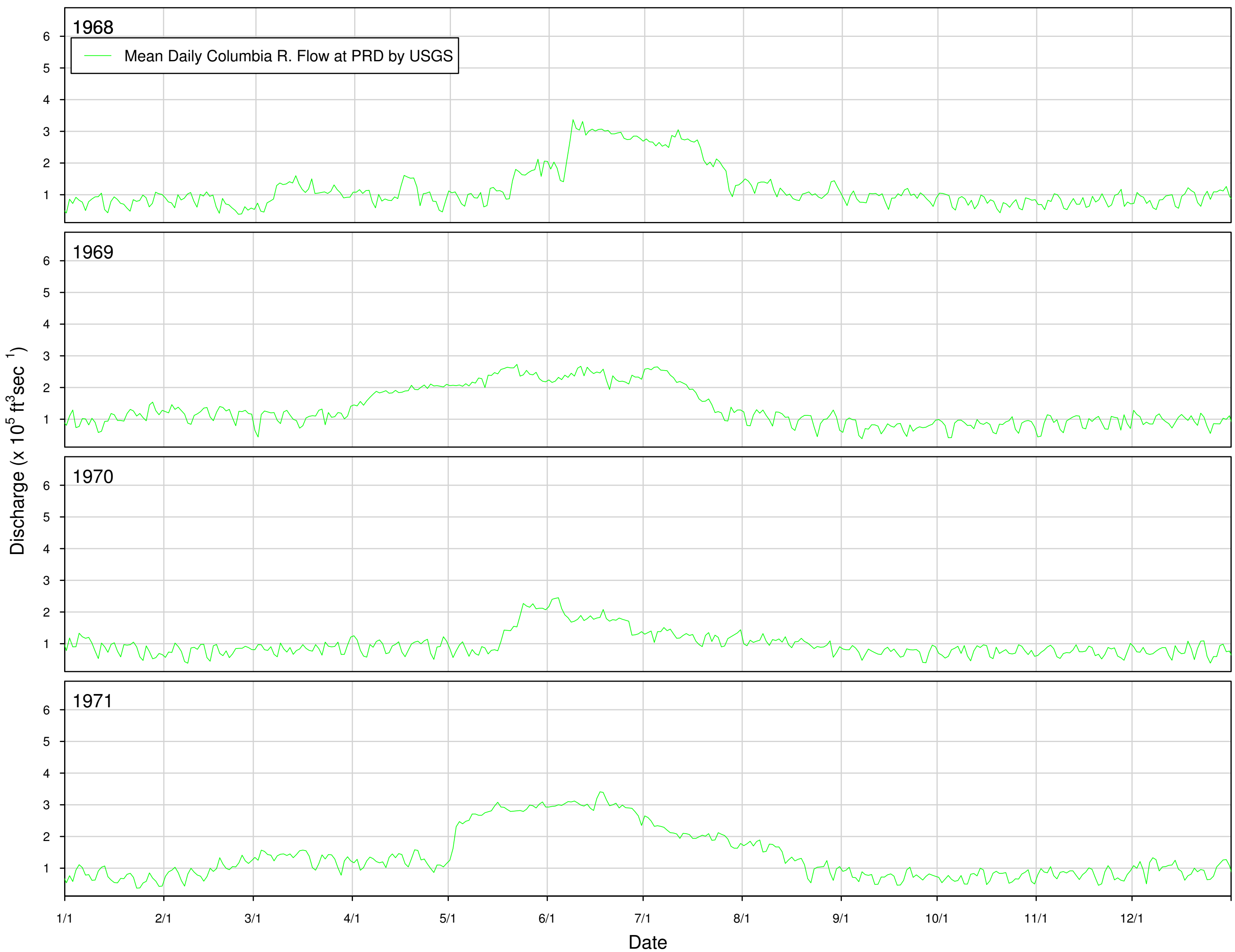

Figure A.8. Columbia River flow below Priest Rapids Dam, 1968–1971.

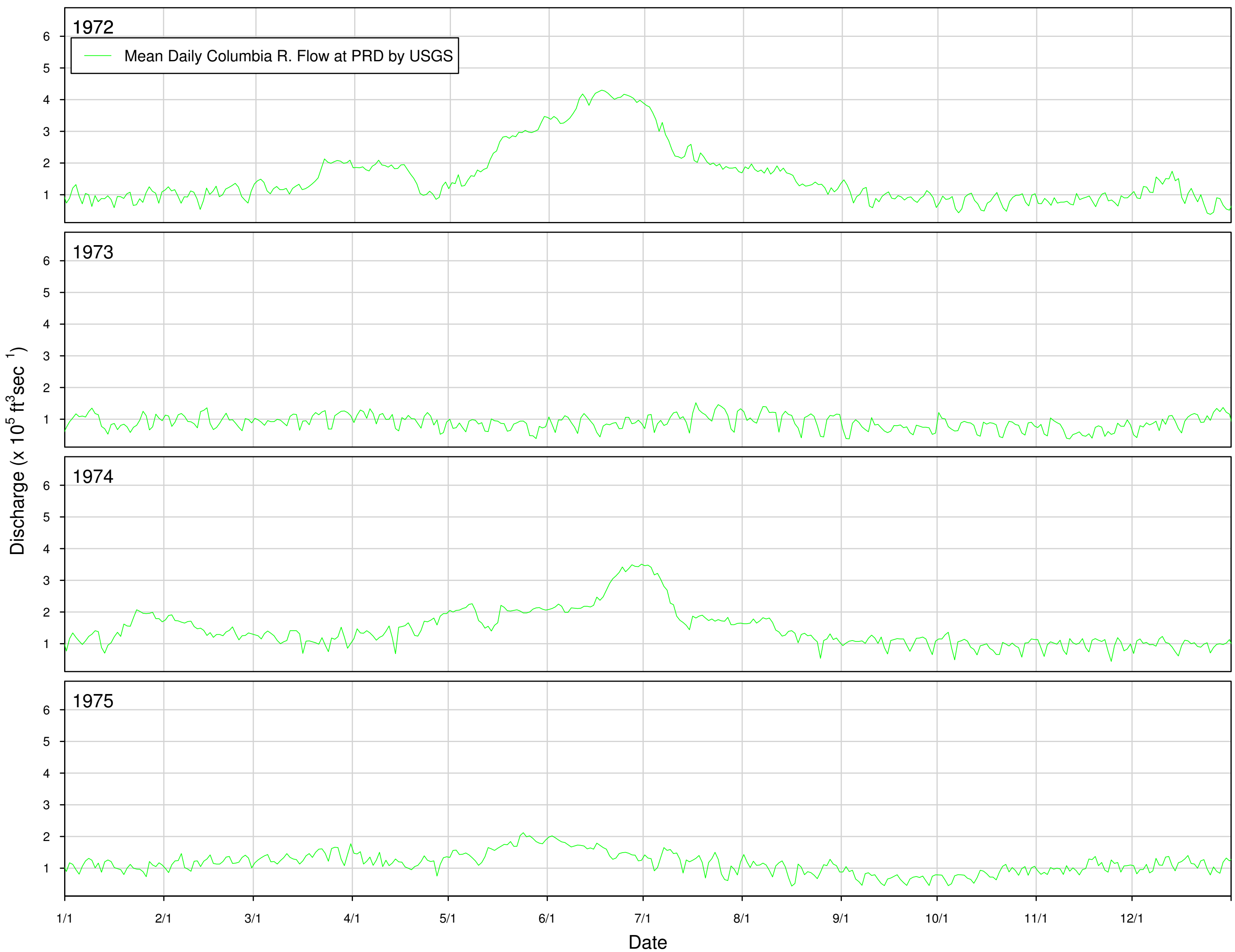

Figure A.9. Columbia River flow below Priest Rapids Dam, 1972–1975.

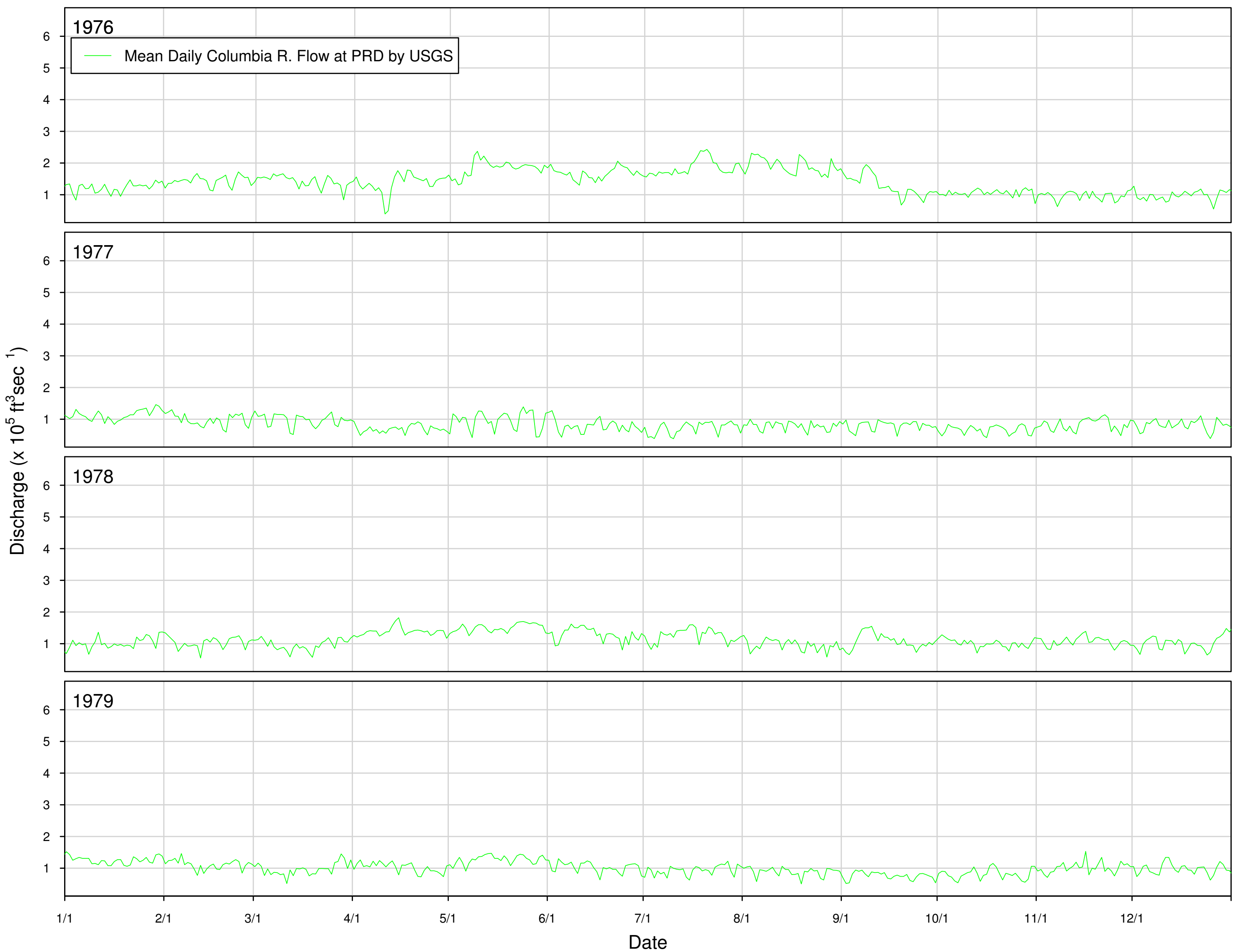

Figure A.10. Columbia River flow below Priest Rapids Dam, 1976–1979.

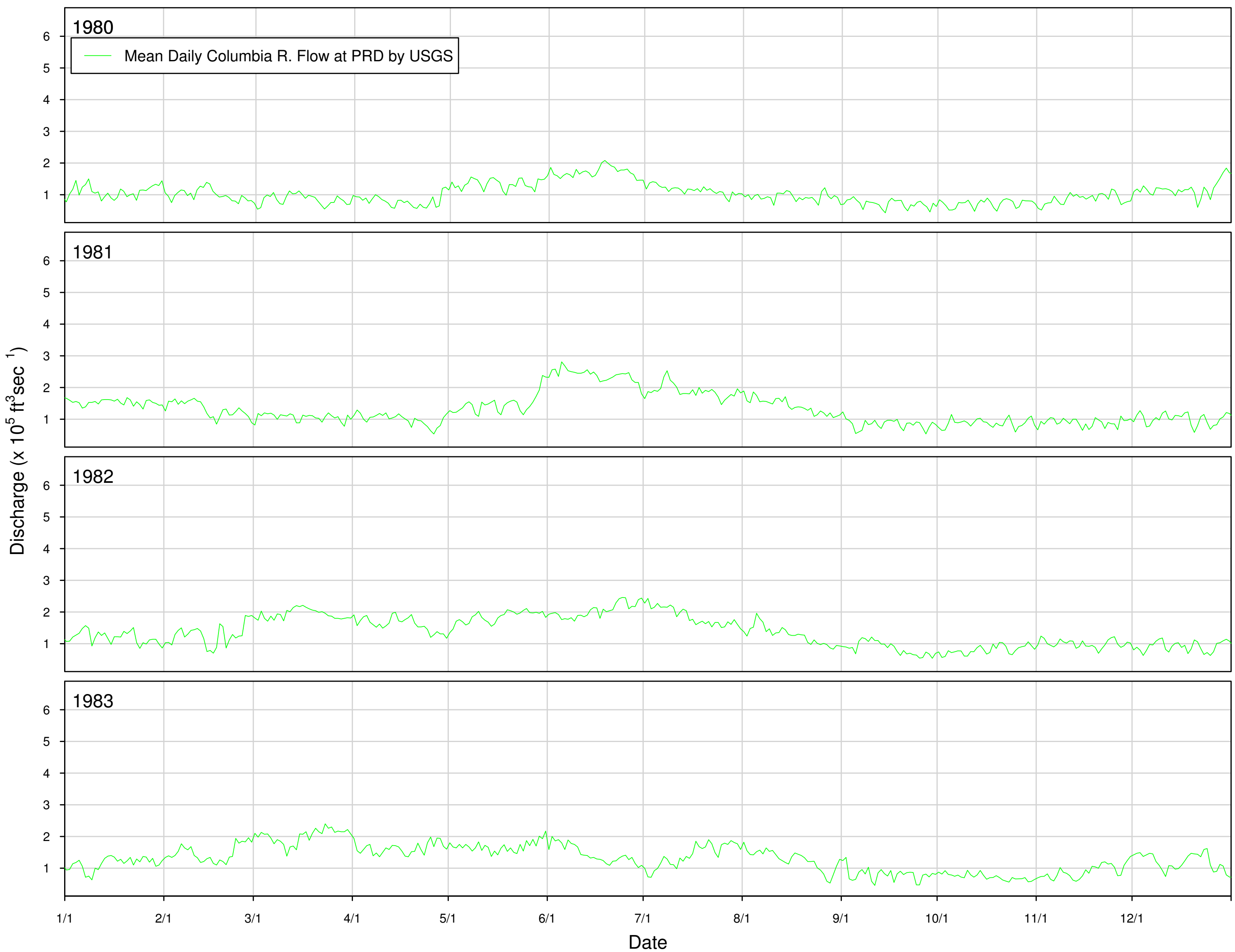

Figure A.11. Columbia River flow below Priest Rapids Dam, 1980–1983.

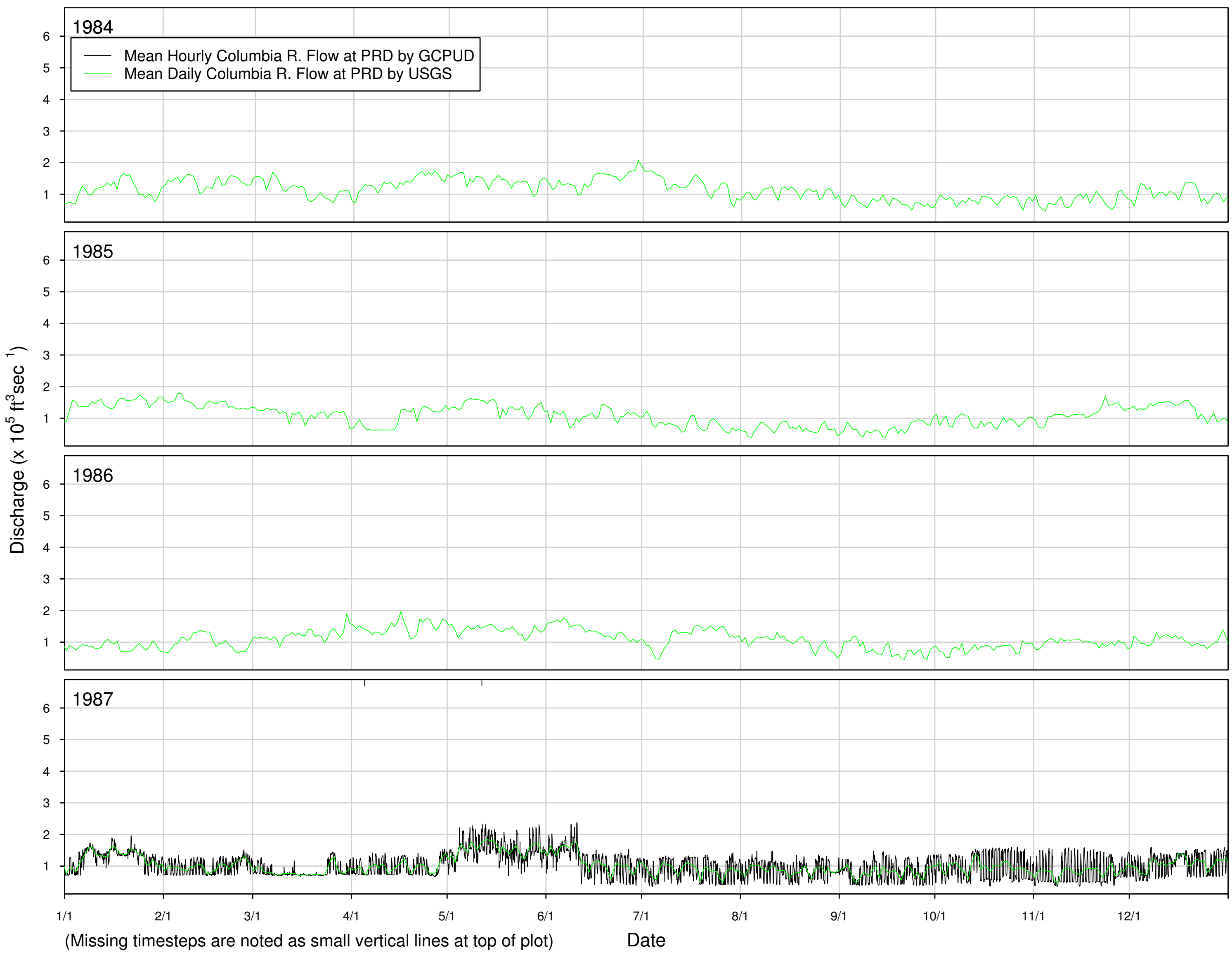

Figure A.12. Columbia River flow below Priest Rapids Dam, 1984–1987.

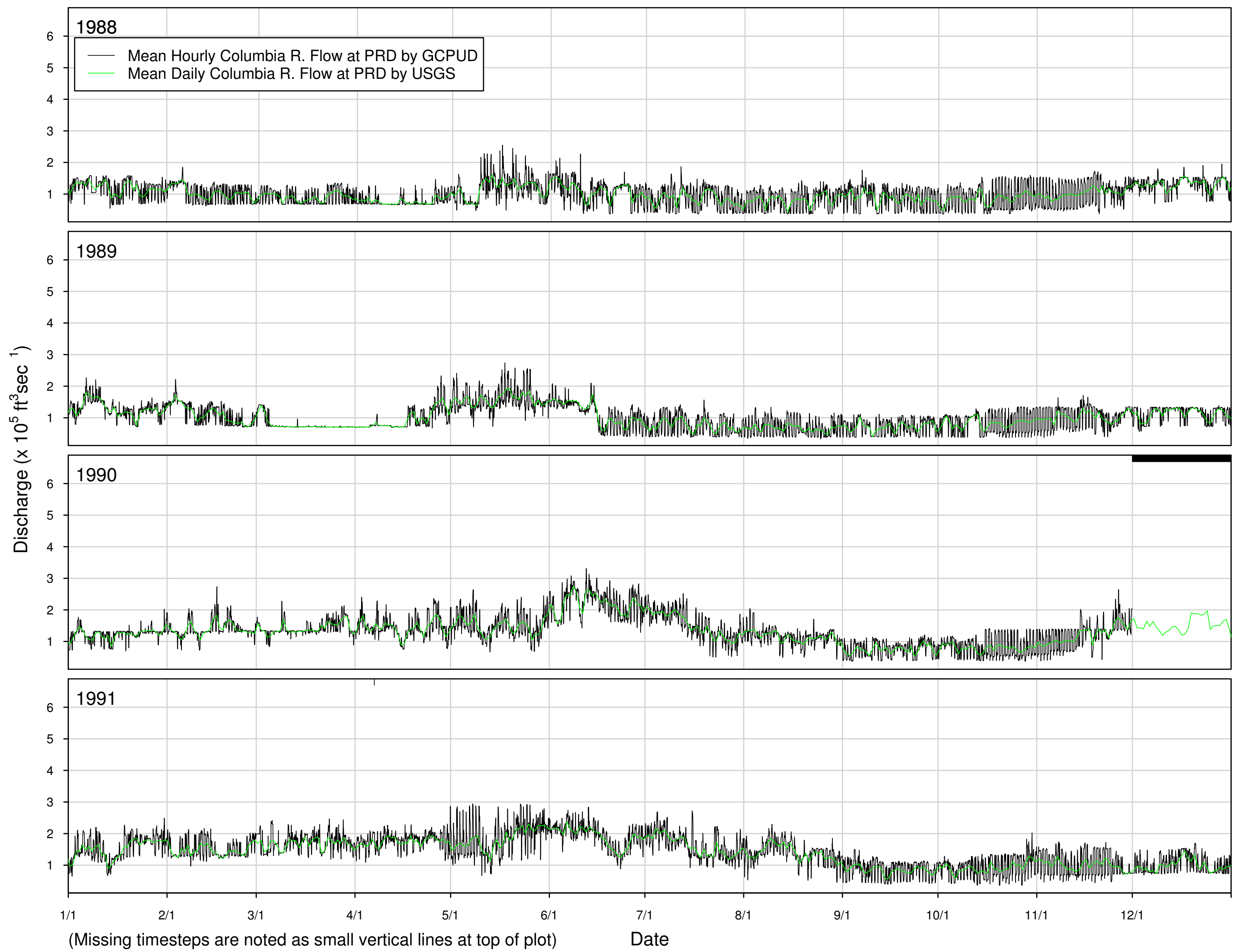

Figure A.13. Columbia River flow below Priest Rapids Dam, 1988–1991.

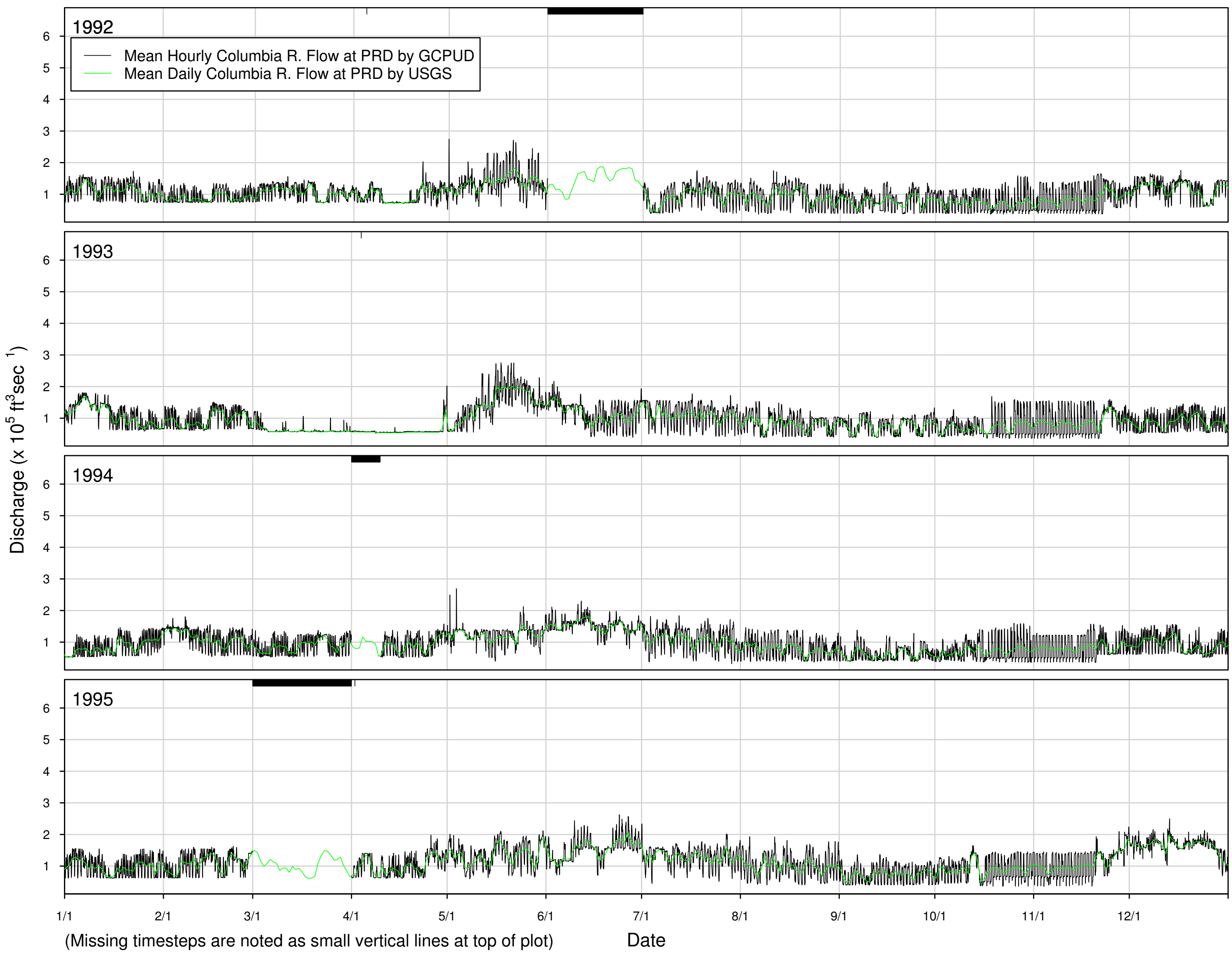

Figure A.14. Columbia River flow below Priest Rapids Dam, 1992–1995.

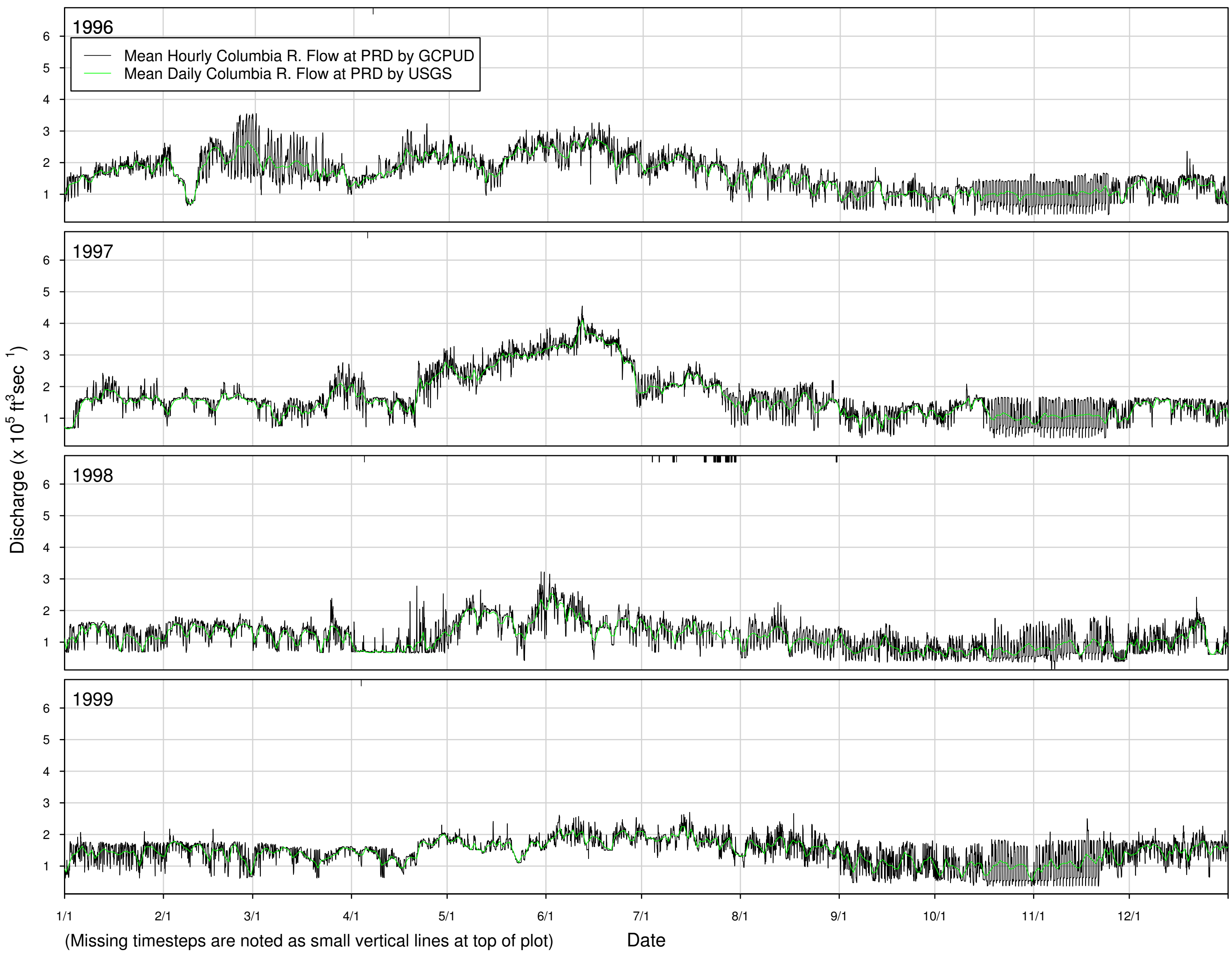

Figure A.15. Columbia River flow below Priest Rapids Dam, 1996–1999.

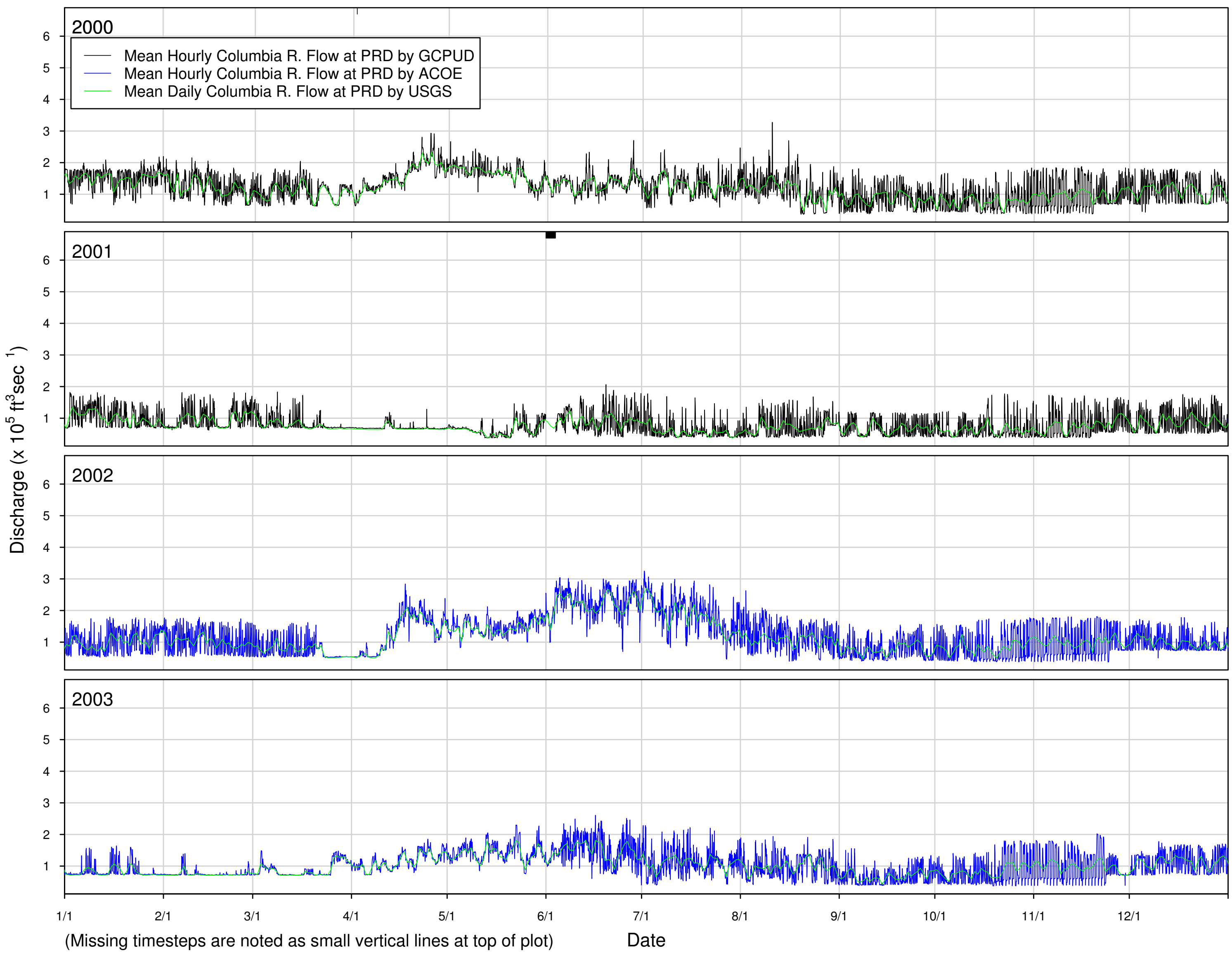

Figure A.16. Columbia River flow below Priest Rapids Dam, 2000–2003.

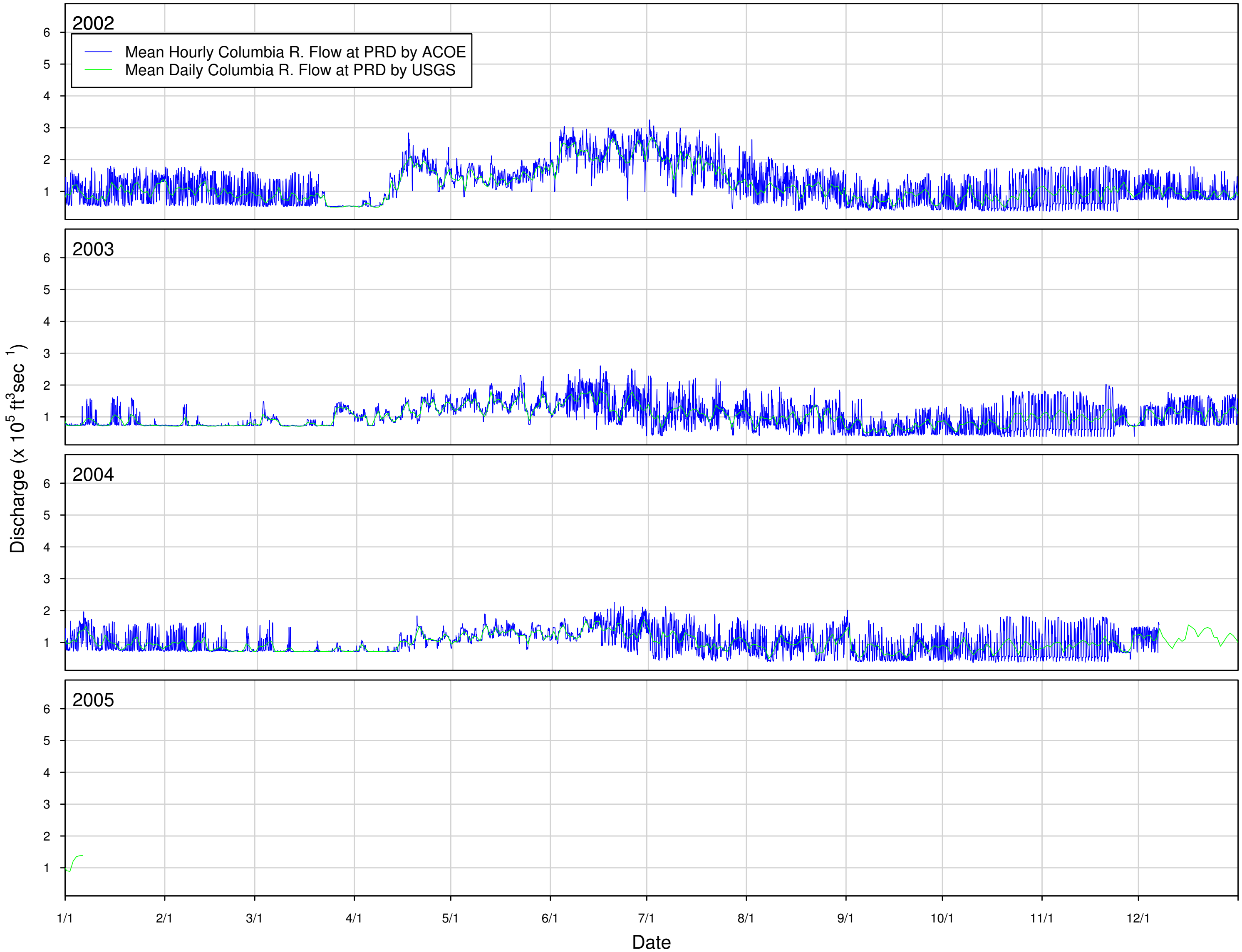

Figure A.17. Columbia River flow below Priest Rapids Dam, 2002–2005.

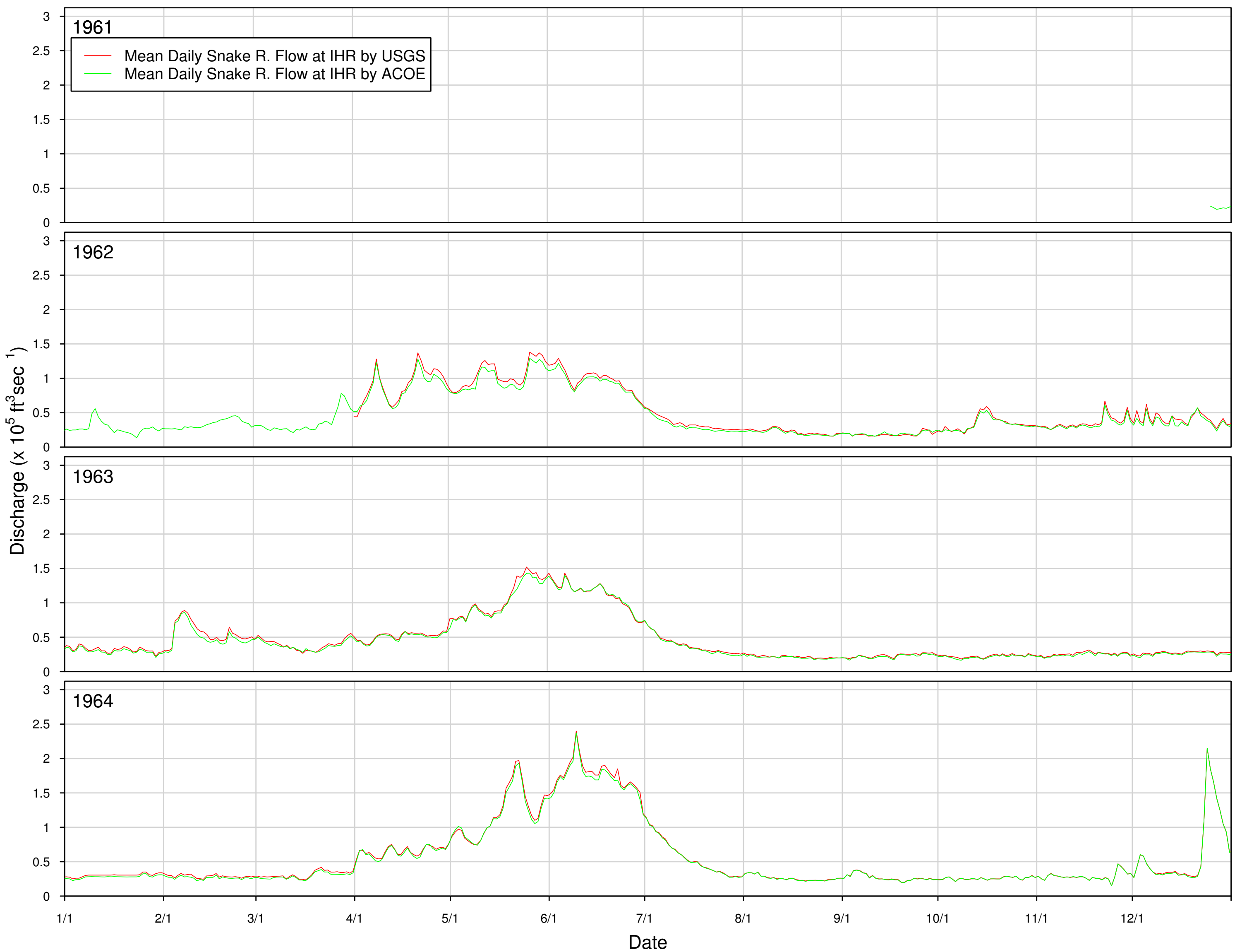

Figure A.18. Snake River flow below Ice Harbor Dam, 1961–1964.

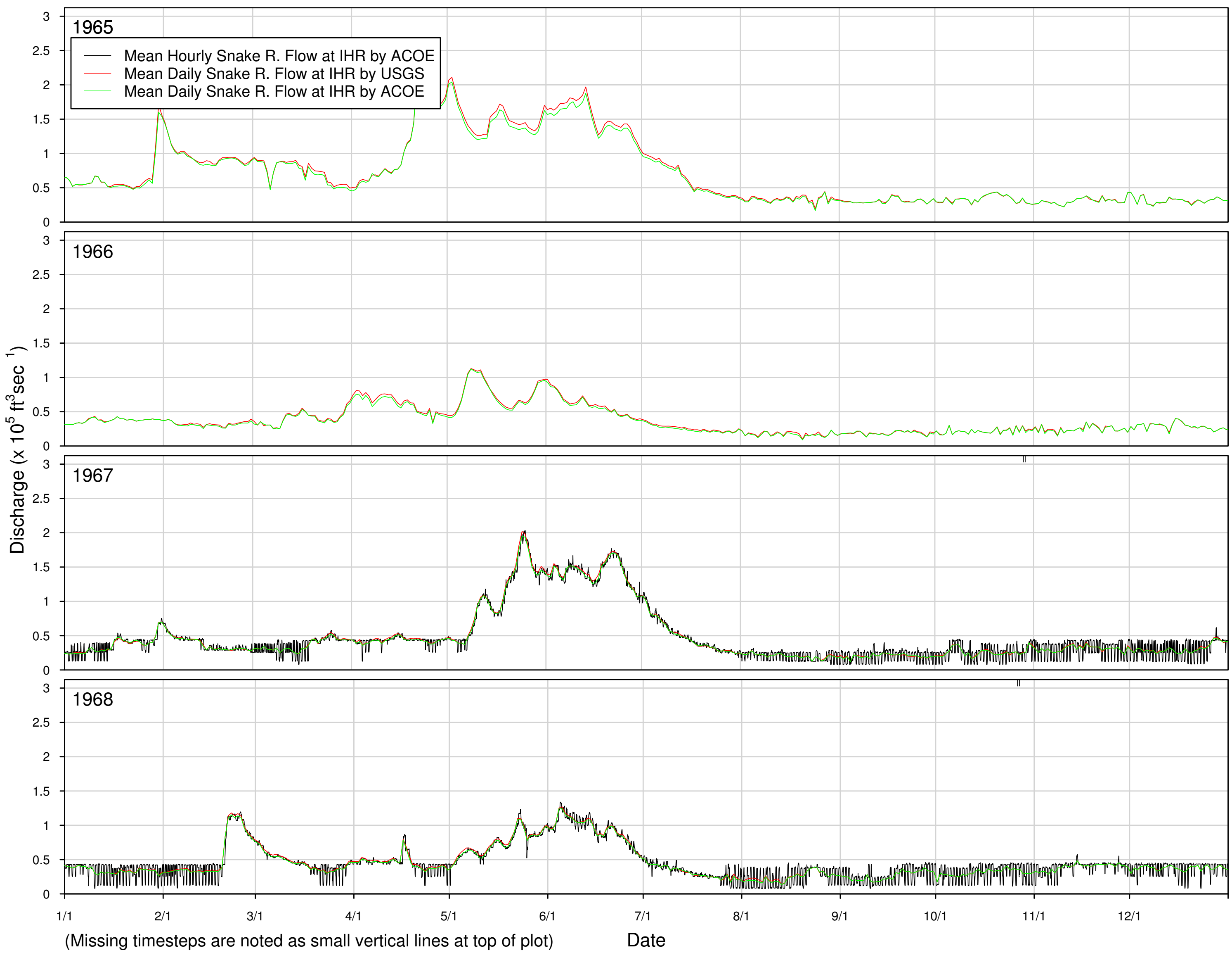

Figure A.19. Snake River flow below Ice Harbor Dam, 1965–1968.

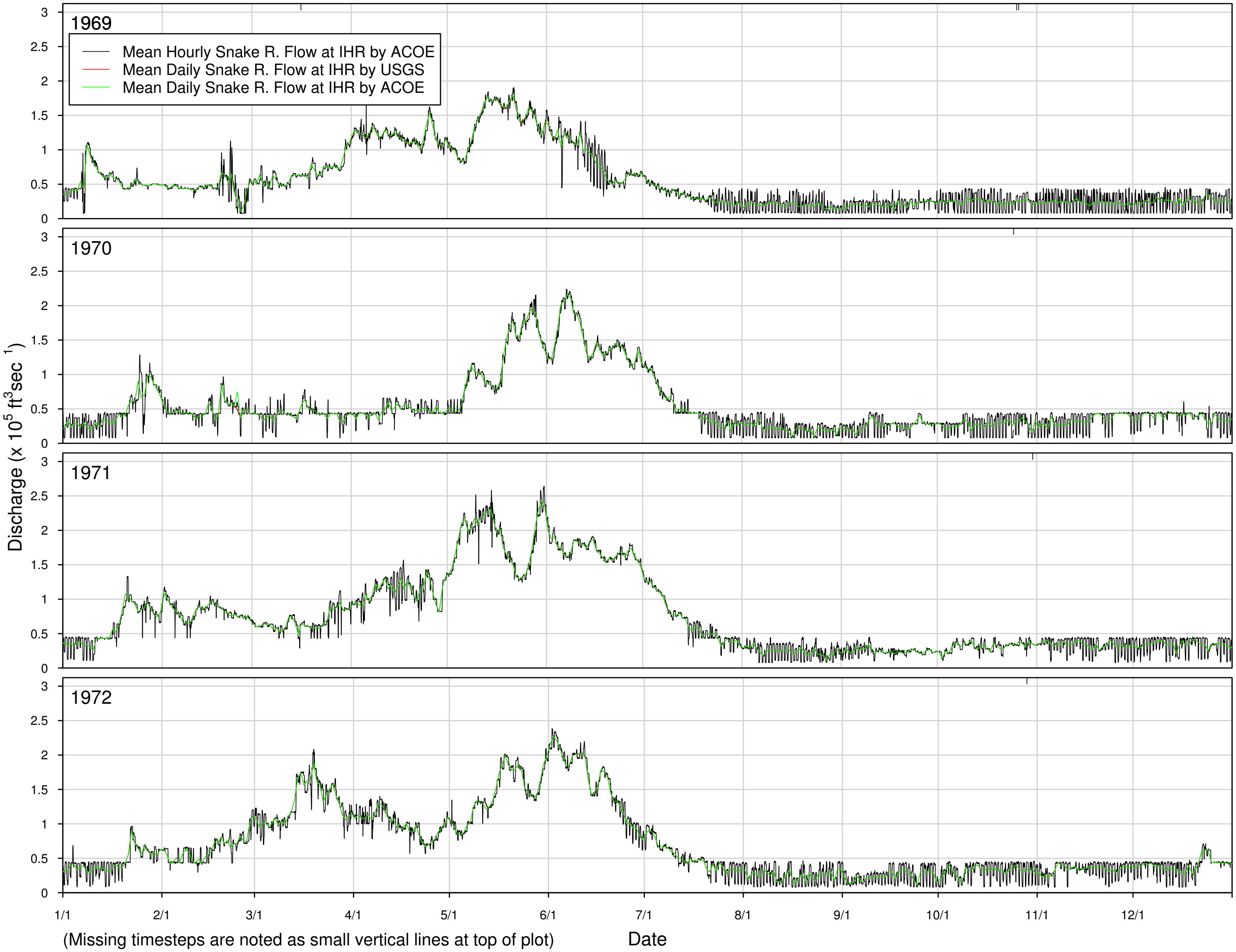

Figure A.20. Snake River flow below Ice Harbor Dam, 1969–1972.

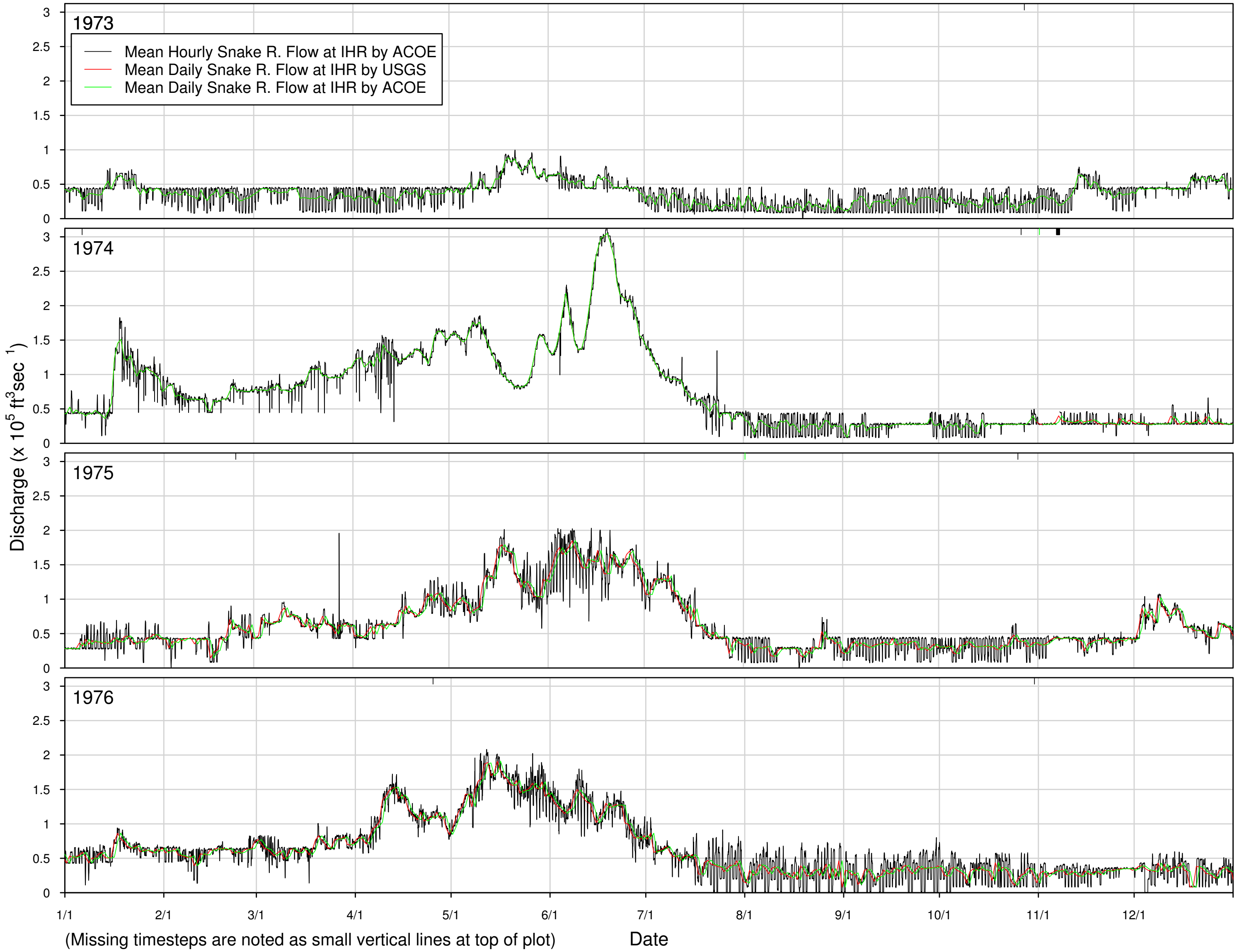

Figure A.21. Snake River flow below Ice Harbor Dam, 1973–1976.

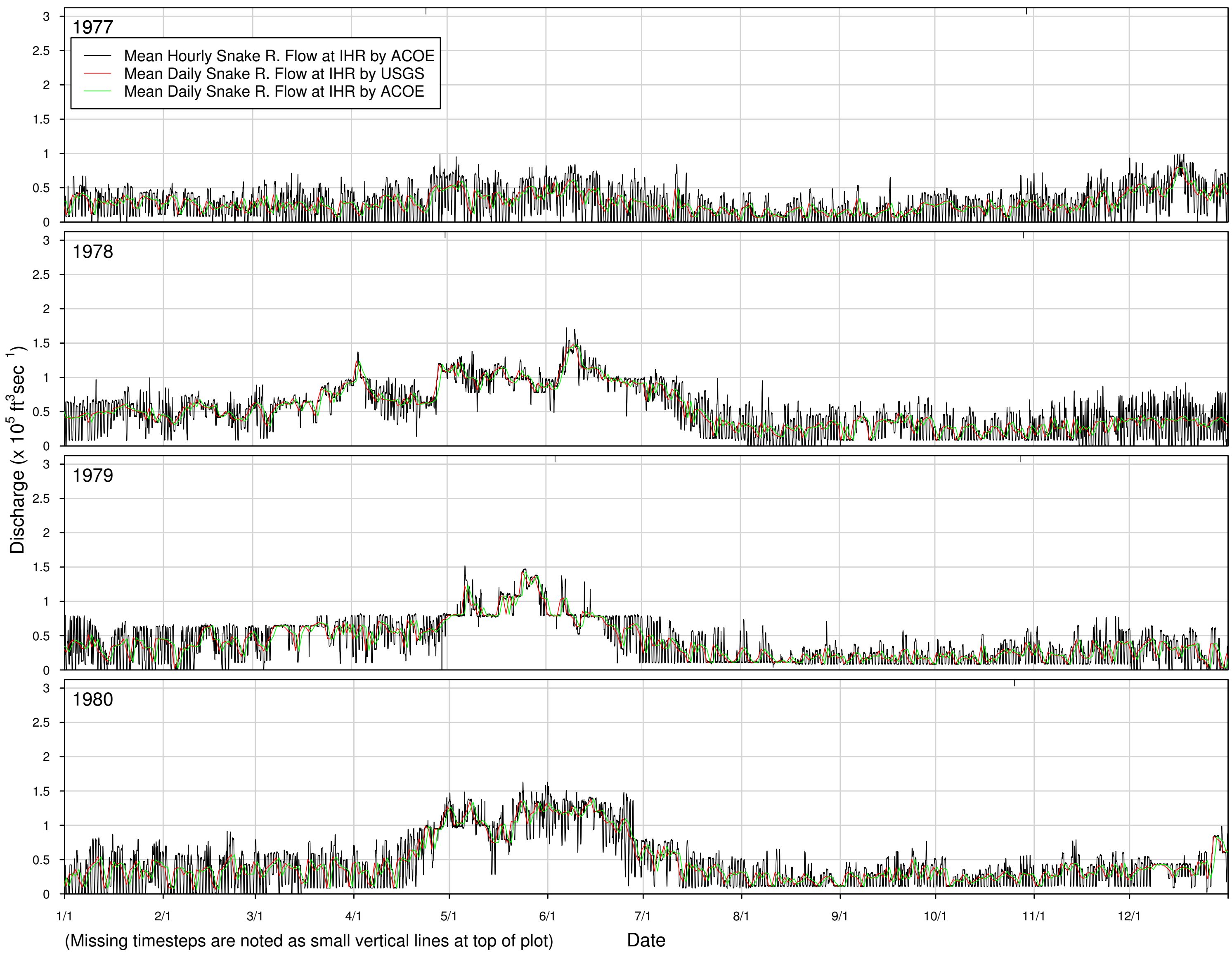

Figure A.22. Snake River flow below Ice Harbor Dam, 1977–1980.

Figure A.23. Snake River flow below Ice Harbor Dam, 1981–1984.

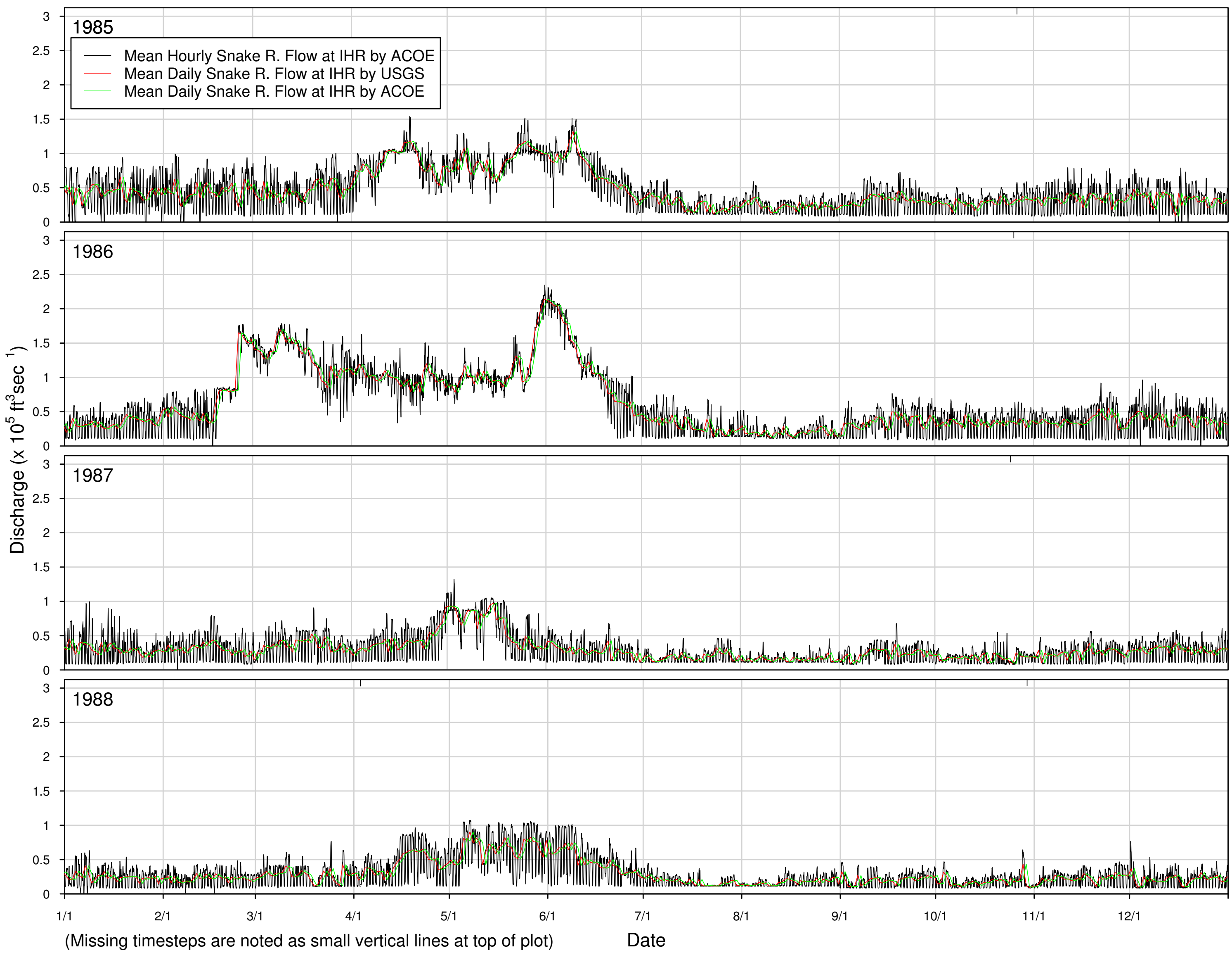

Figure A.24. Snake River flow below Ice Harbor Dam, 1985–1988.

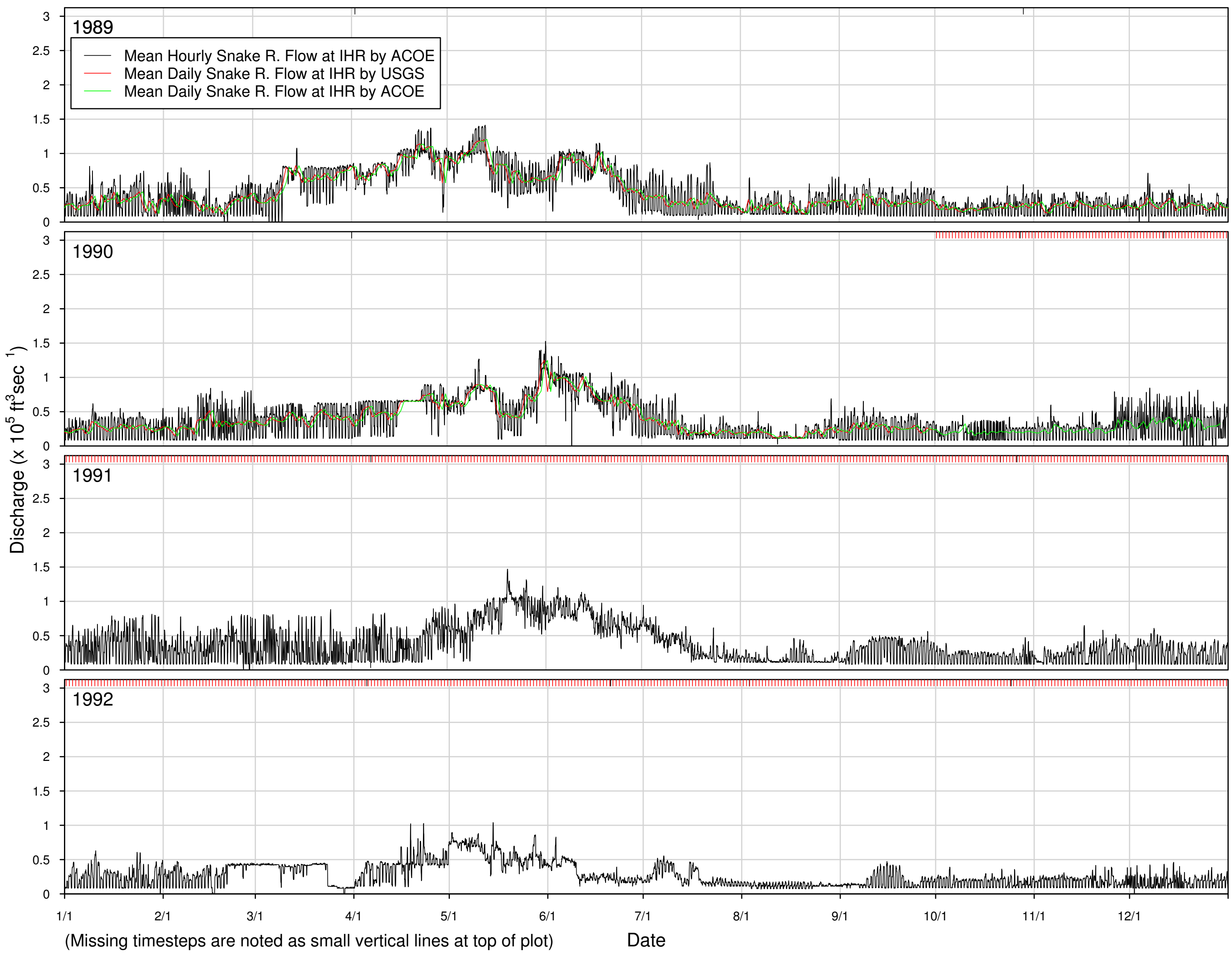

Figure A.25. Snake River flow below Ice Harbor Dam, 1989–1992.

Figure A.26. Snake River flow below Ice Harbor Dam, 1993–1996.

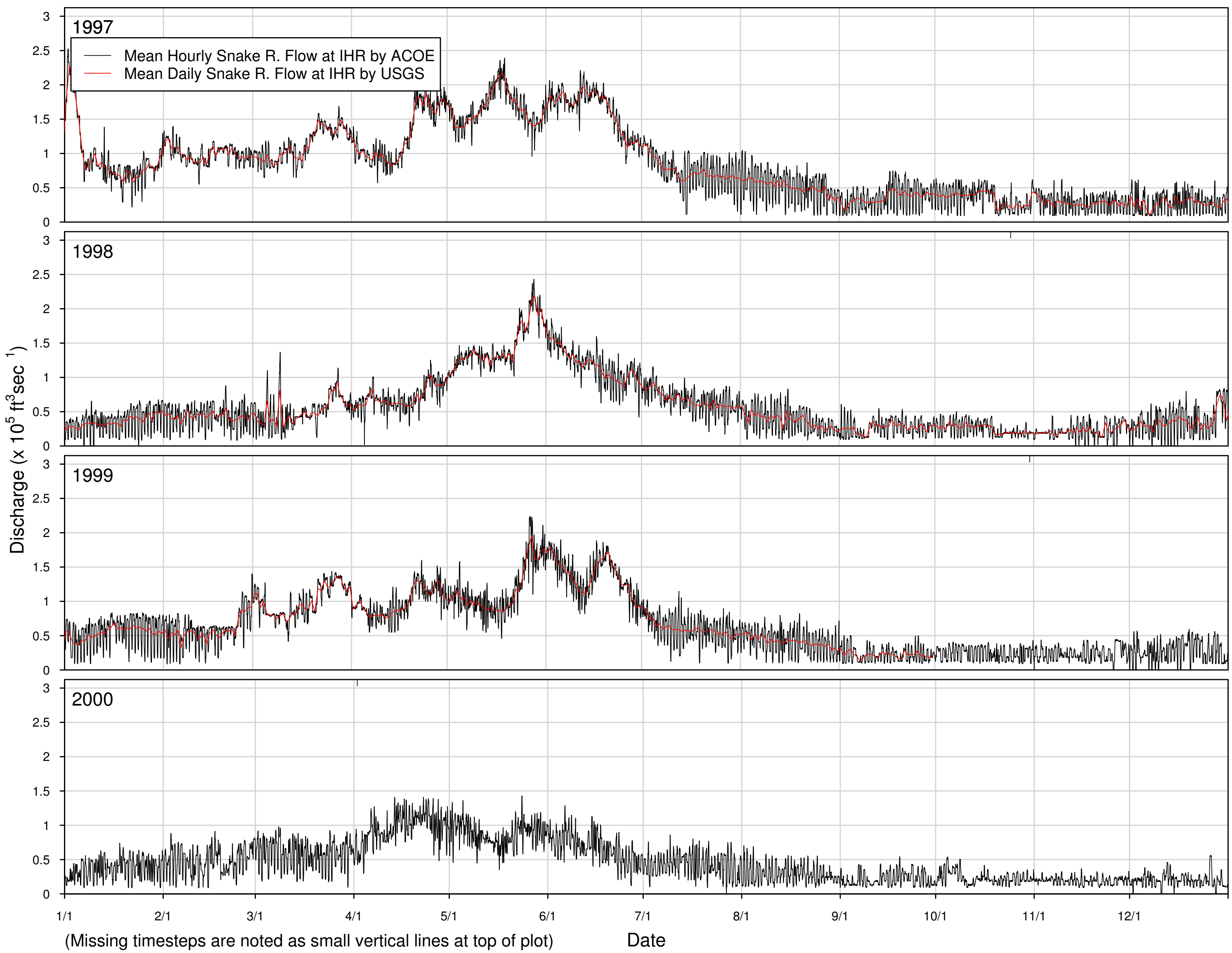

Figure A.27. Snake River flow below Ice Harbor Dam, 1997–2000.

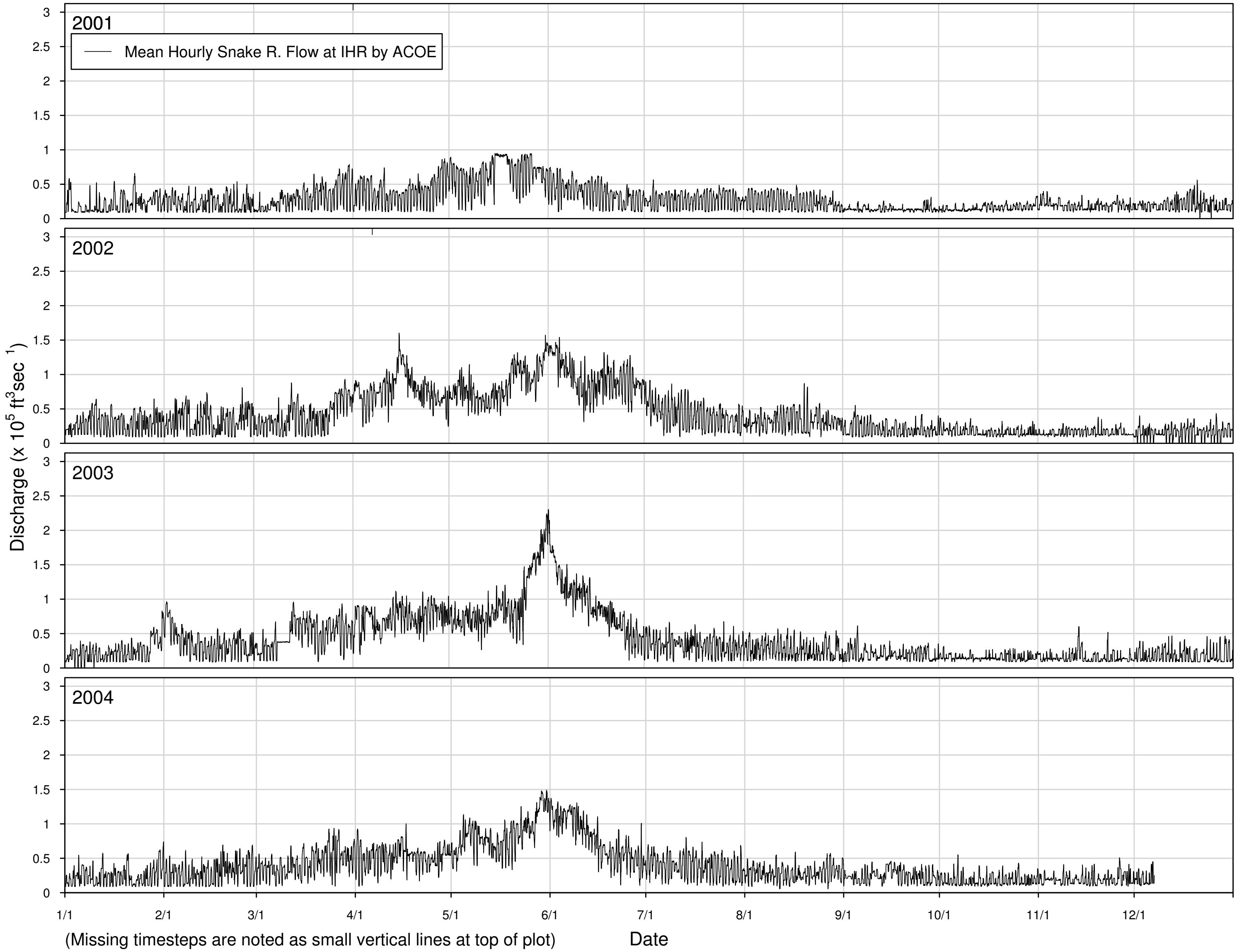

Figure A.28. Snake River flow below Ice Harbor Dam, 2001–2004.

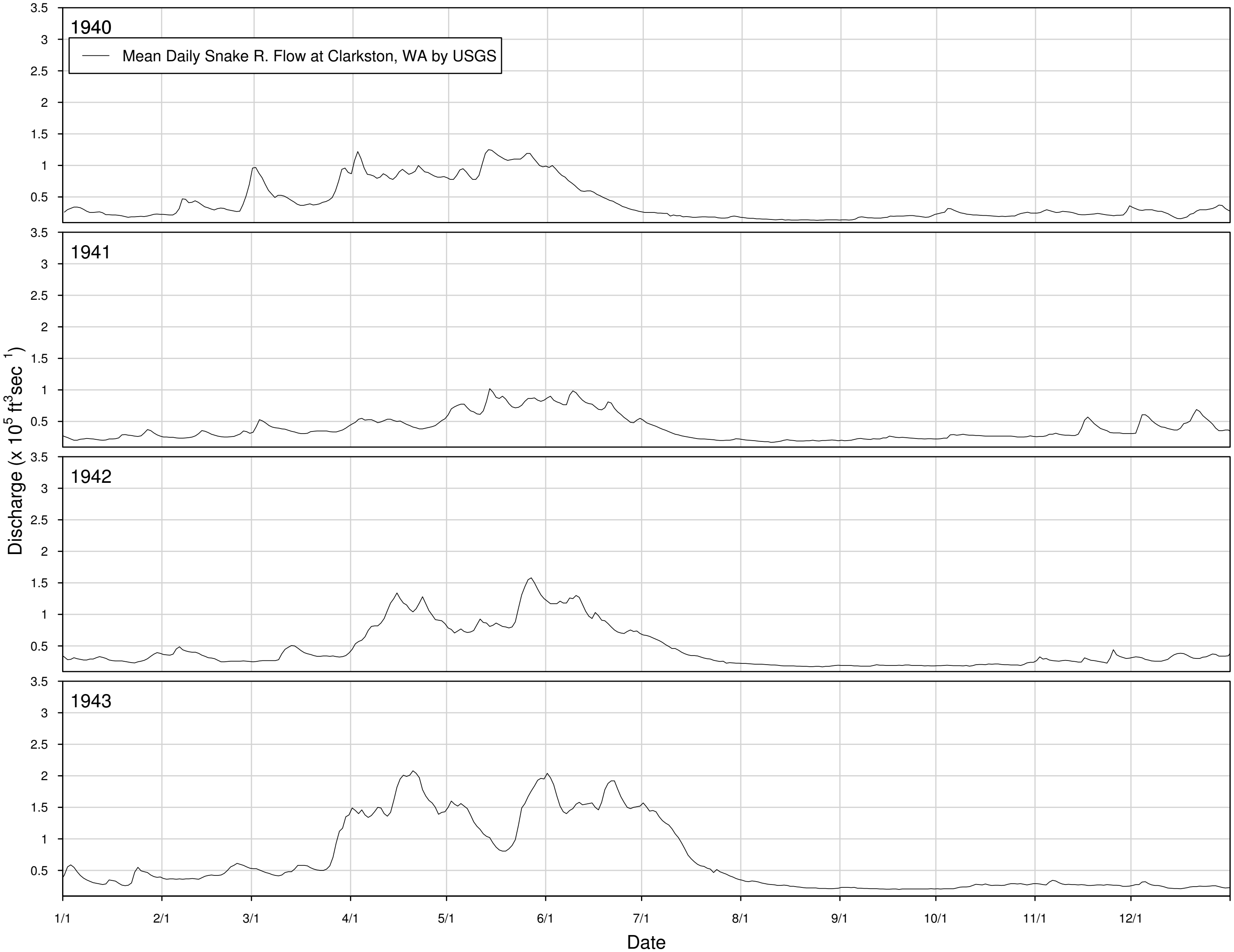

Figure A.29. Snake River flow at Clarkston, WA, 1940–1943.

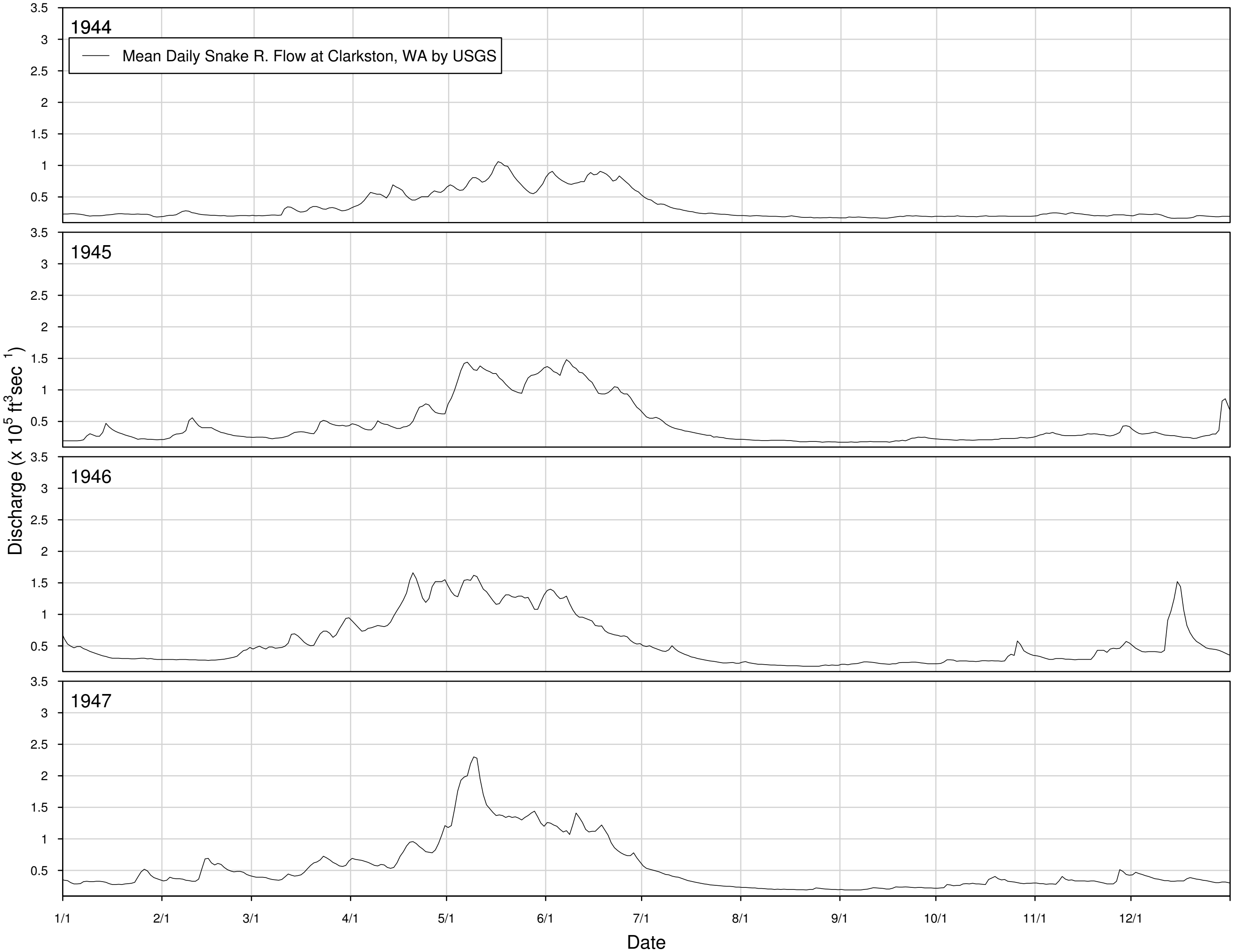

Figure A.30. Snake River flow at Clarkston, WA, 1944–1947.

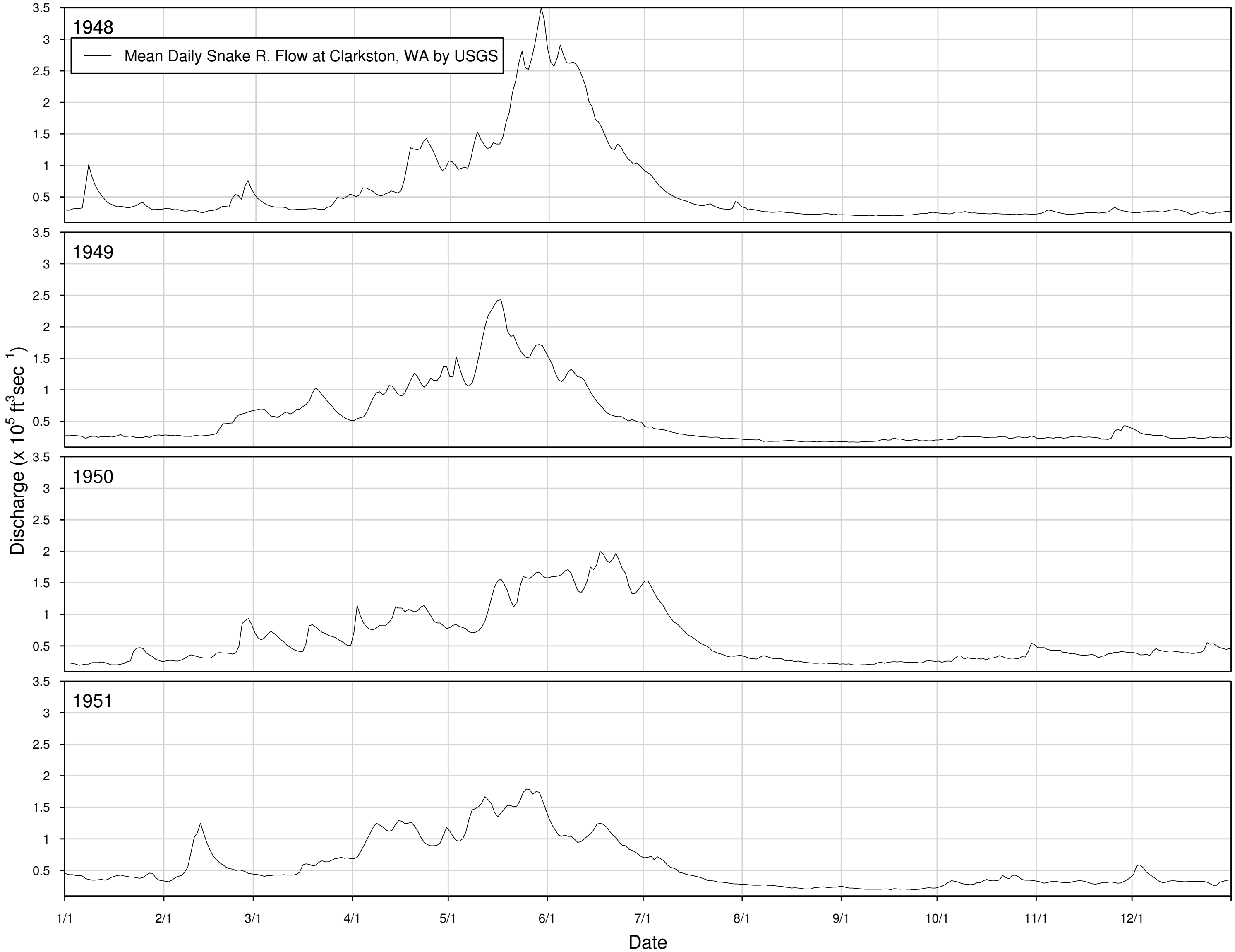

Figure A.31. Snake River flow at Clarkston, WA, 1948–1951.

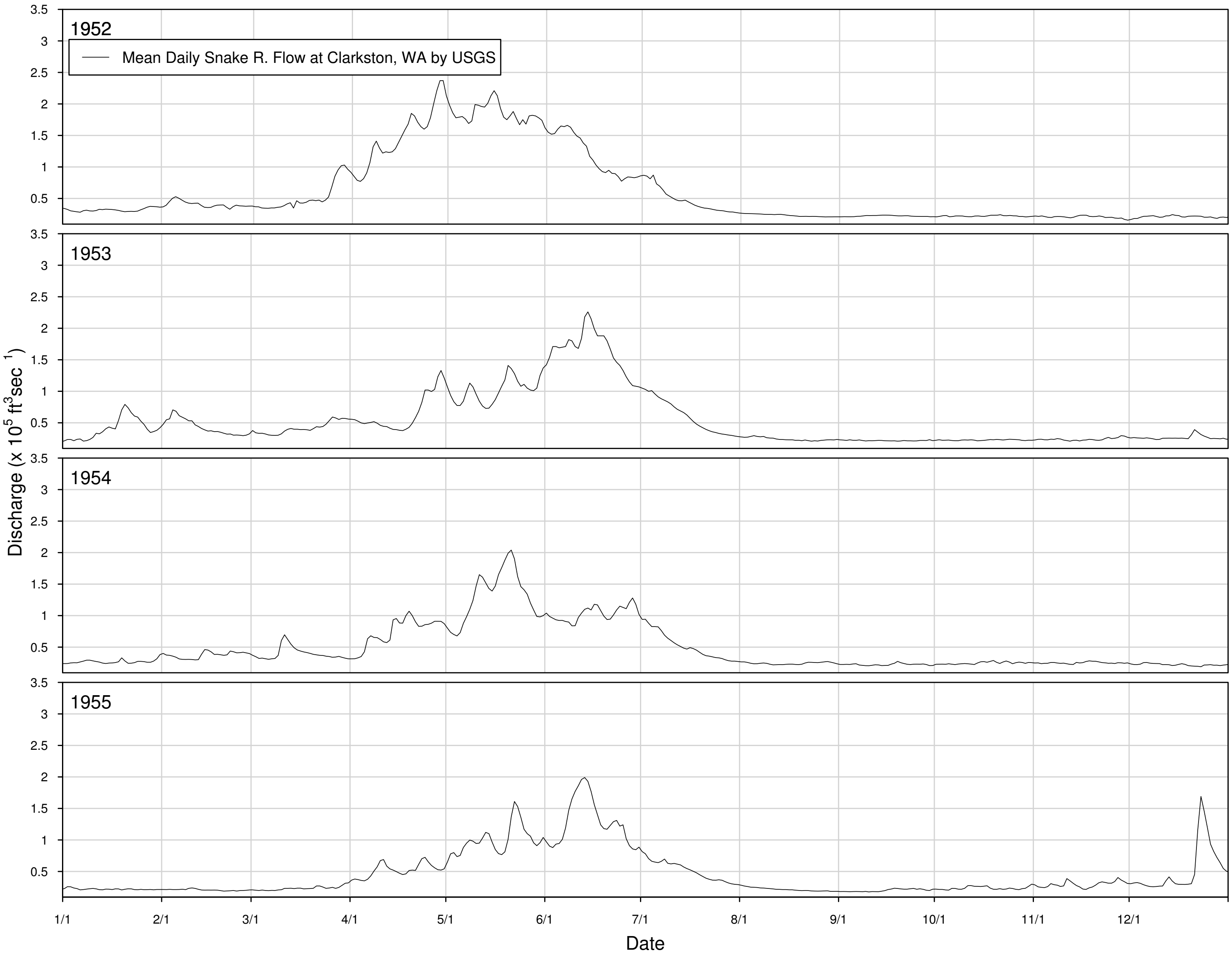

Figure A.32. Snake River flow at Clarkston, WA, 1952–1955.

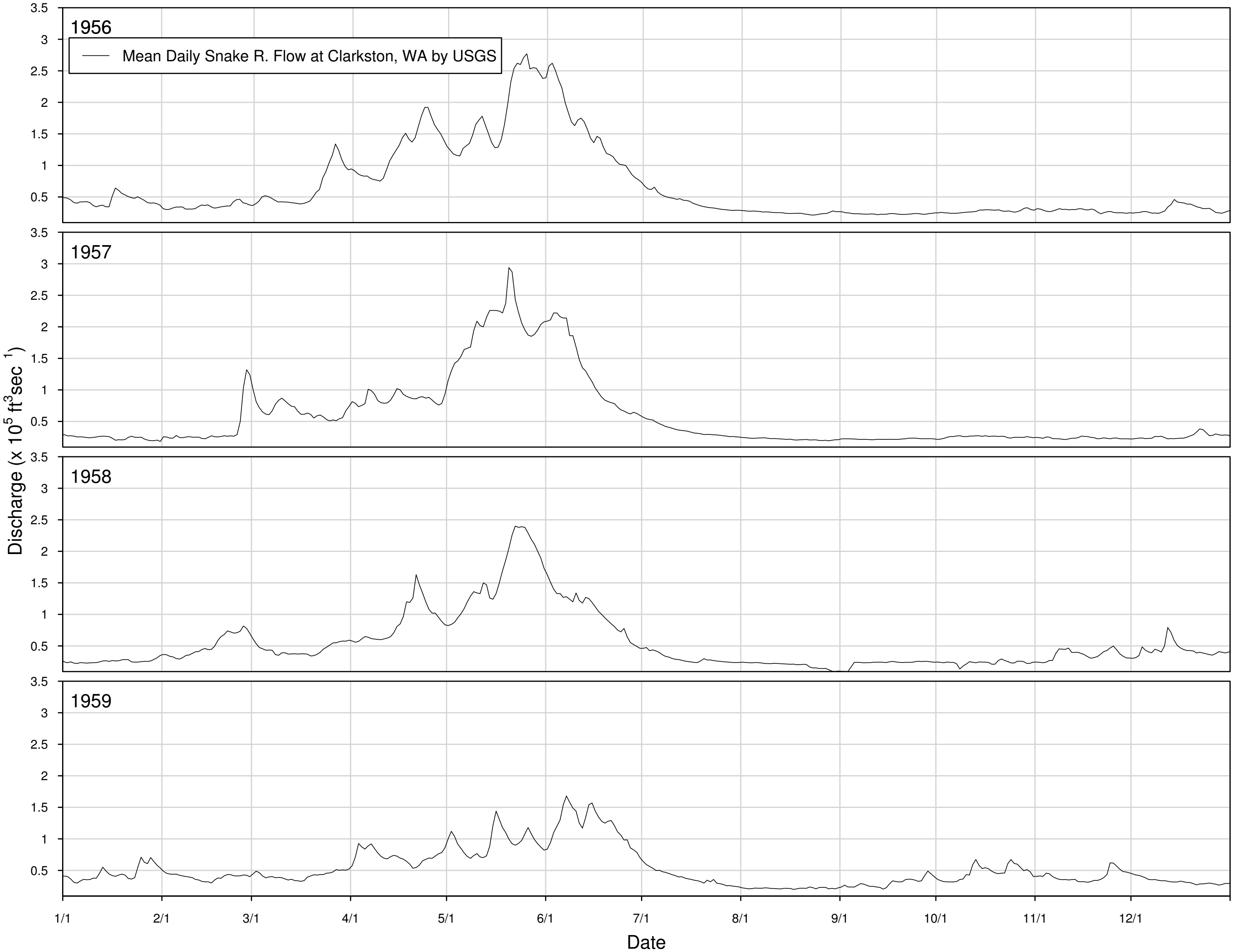

Figure A.33. Snake River flow at Clarkston, WA, 1956–1959.

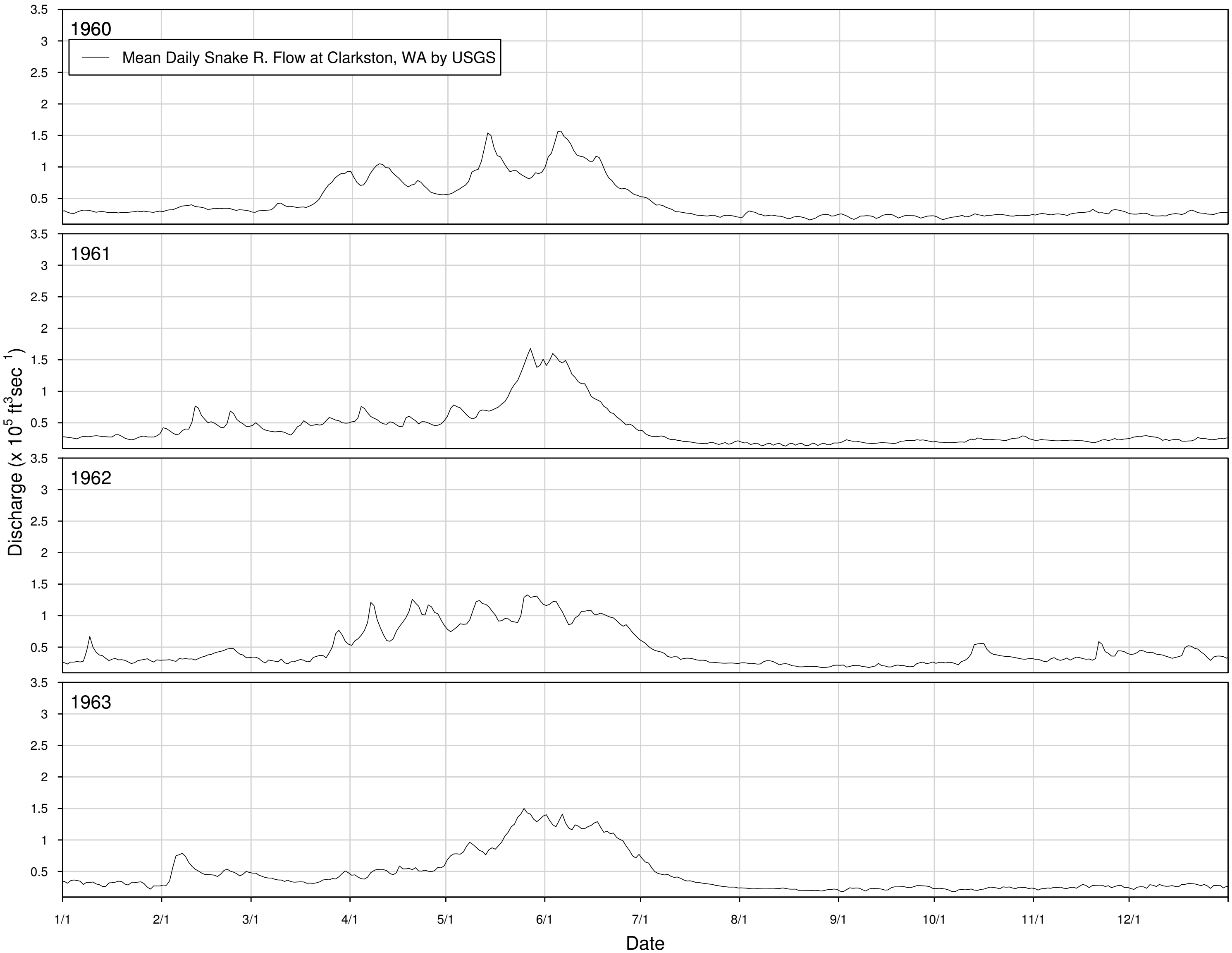

Figure A.34. Snake River flow at Clarkston, WA, 1960–1963.

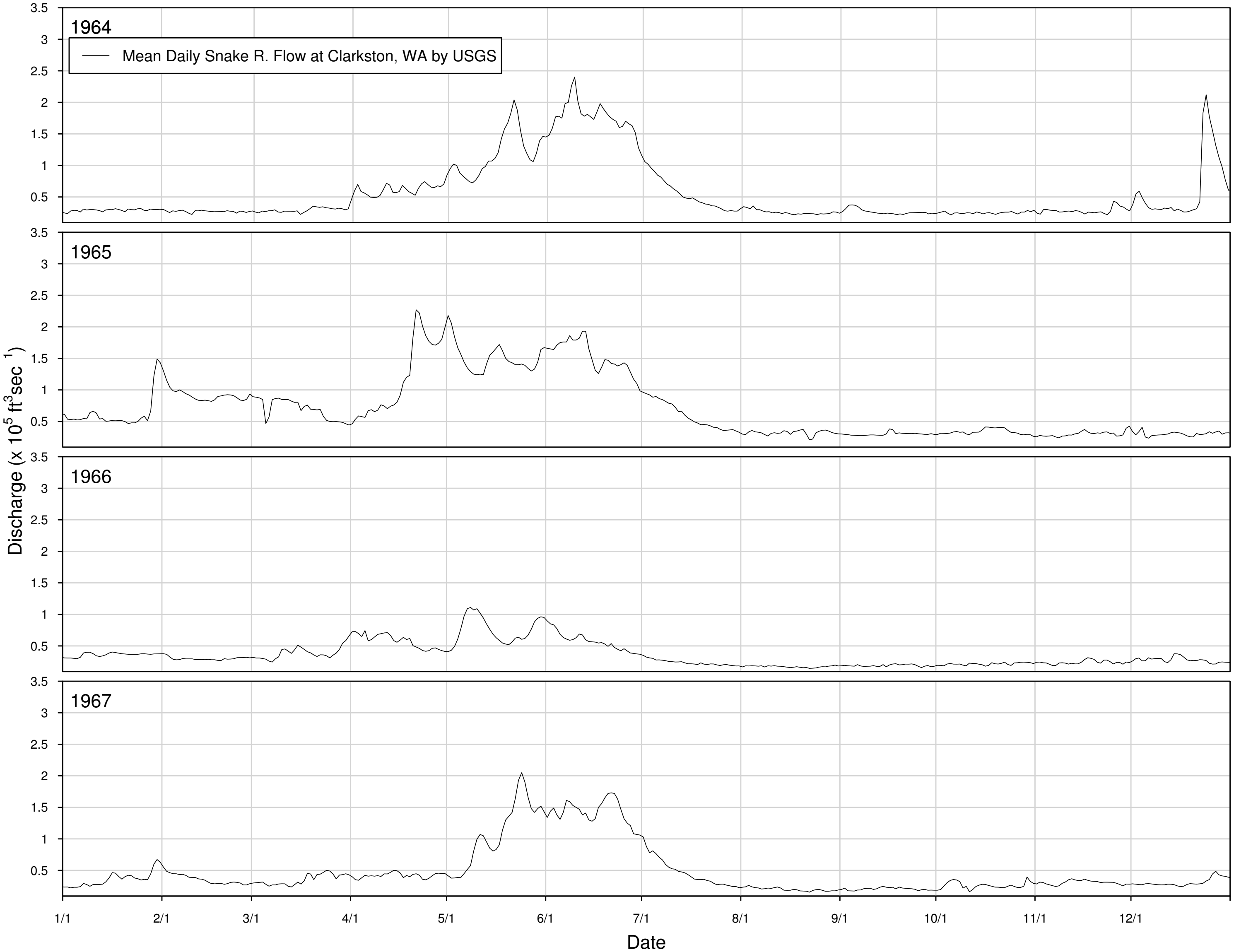

Figure A.35. Snake River flow at Clarkston, WA, 1964–1967.

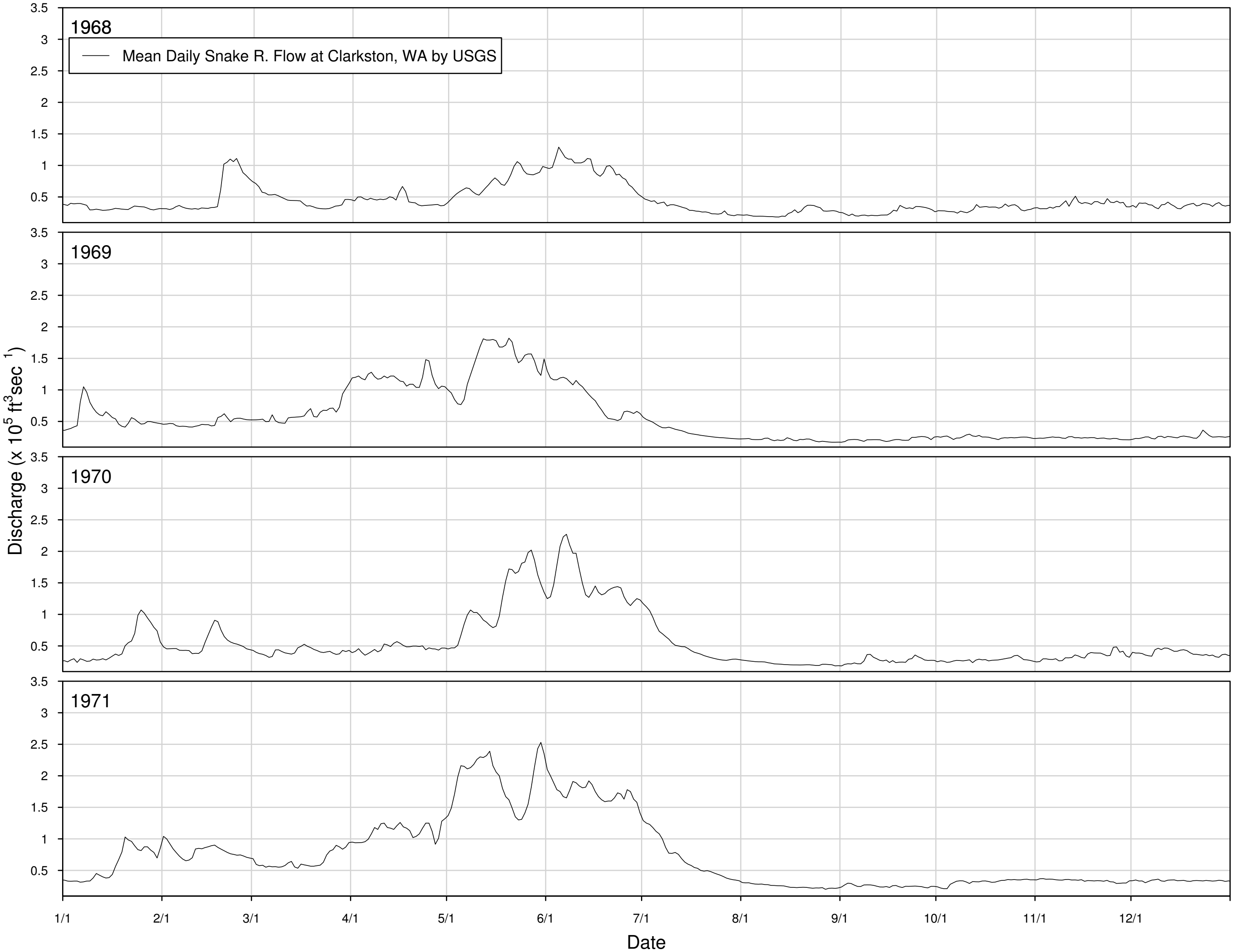

Figure A.36. Snake River flow at Clarkston, WA, 1968–1971.

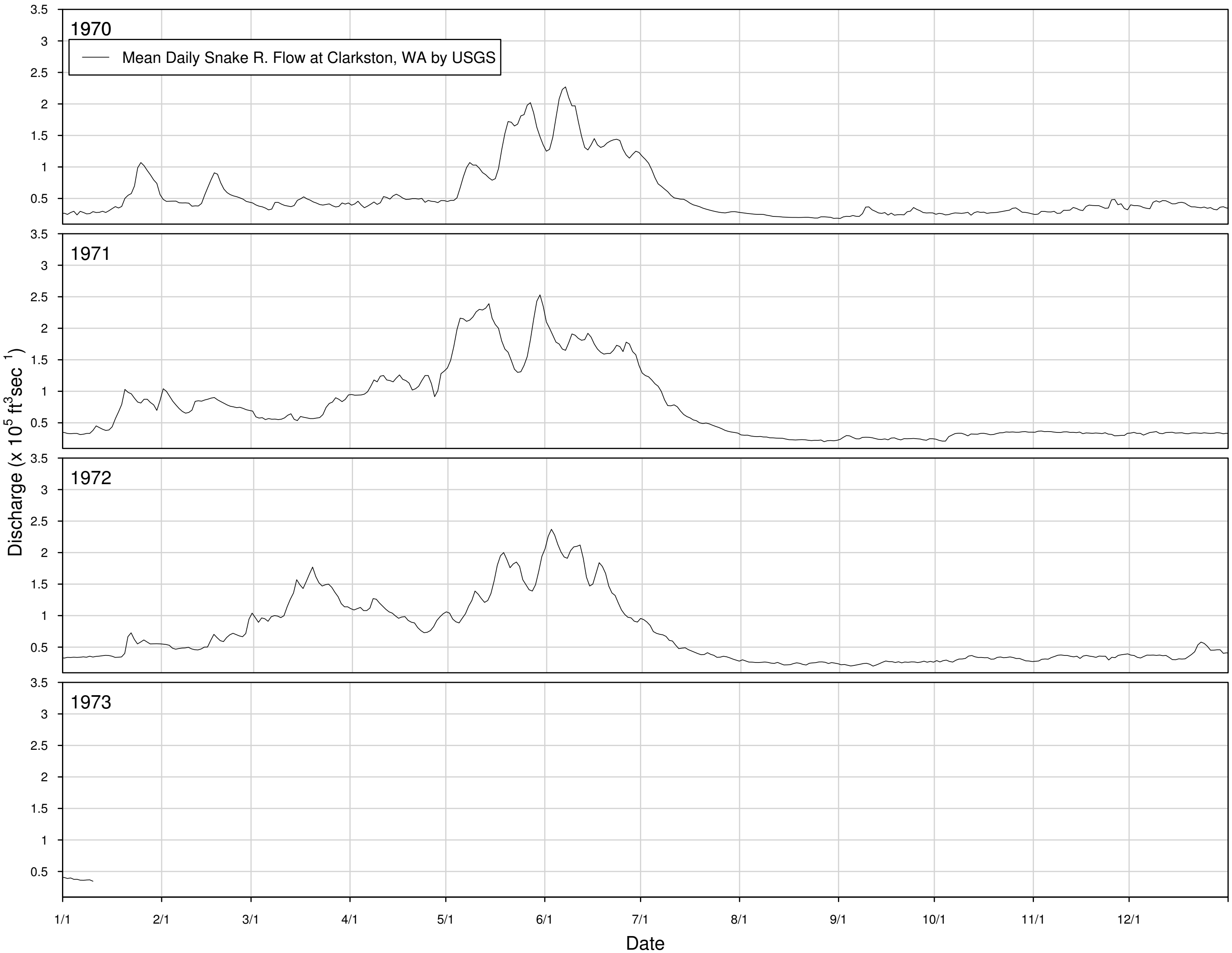

Figure A.37. Snake River flow at Clarkston, WA, 1970–1973.

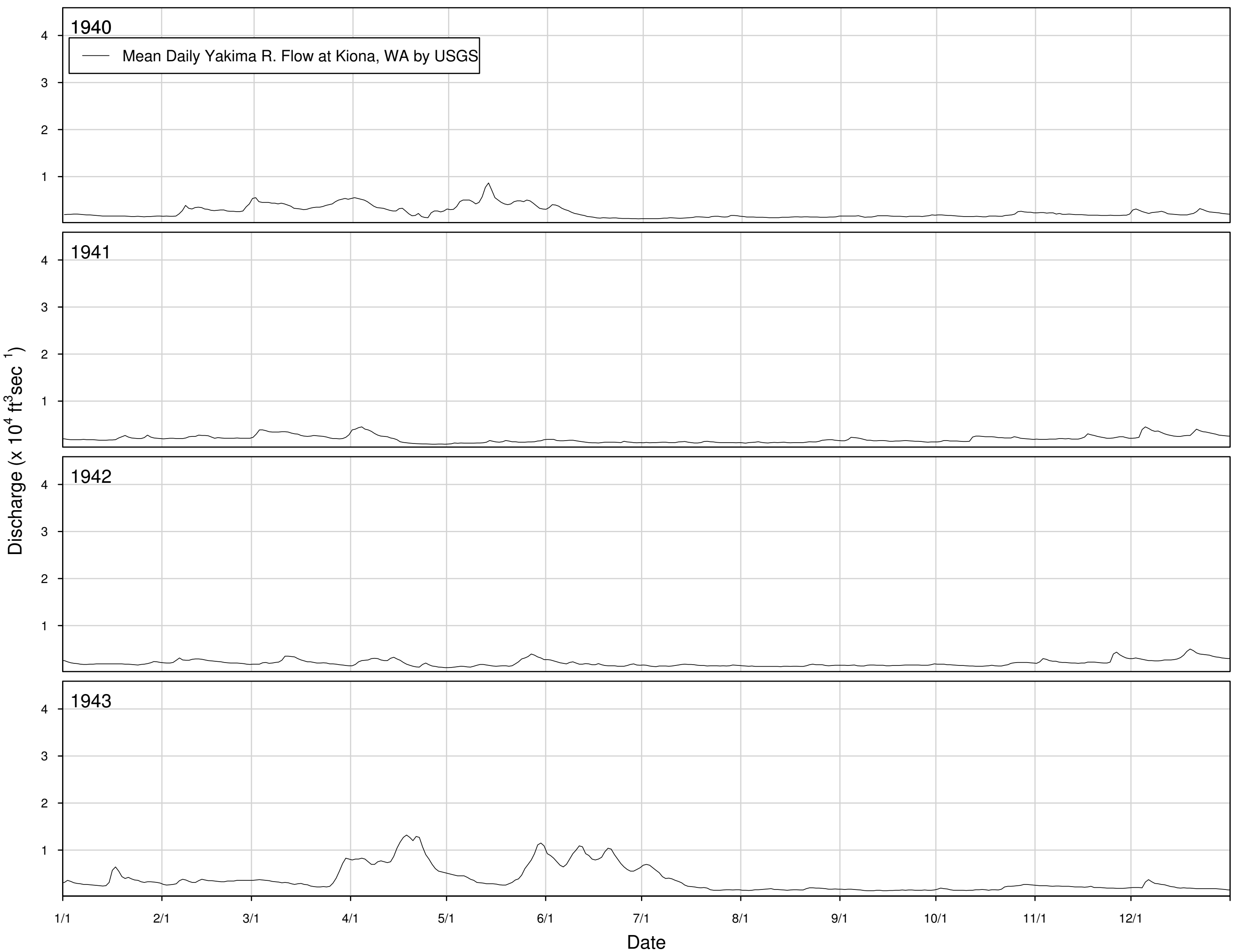

Figure A.38. Yakima River flow at Kiona, WA, 1940–1943.

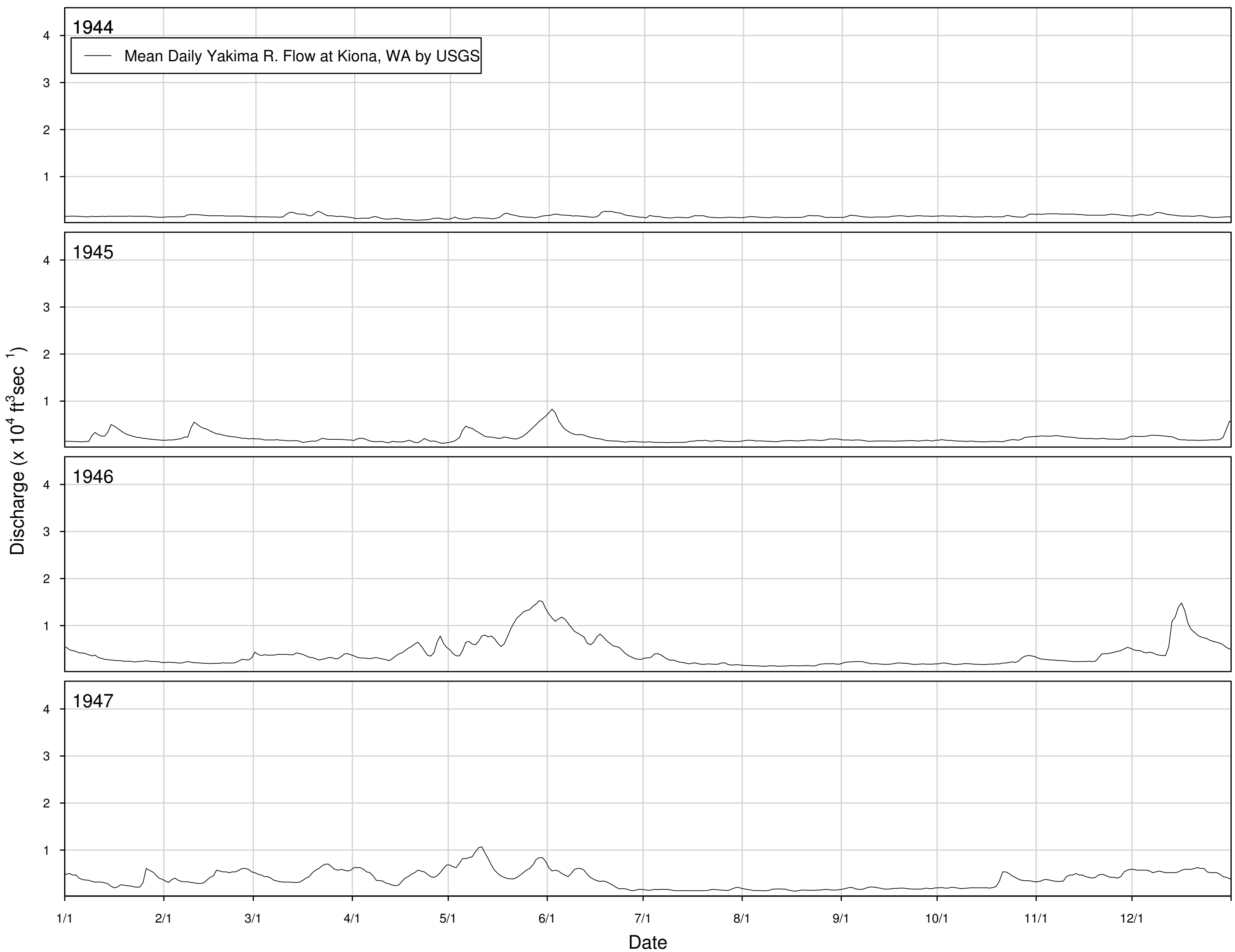

Figure A.39. Yakima River flow at Kiona, WA, 1944–1947.

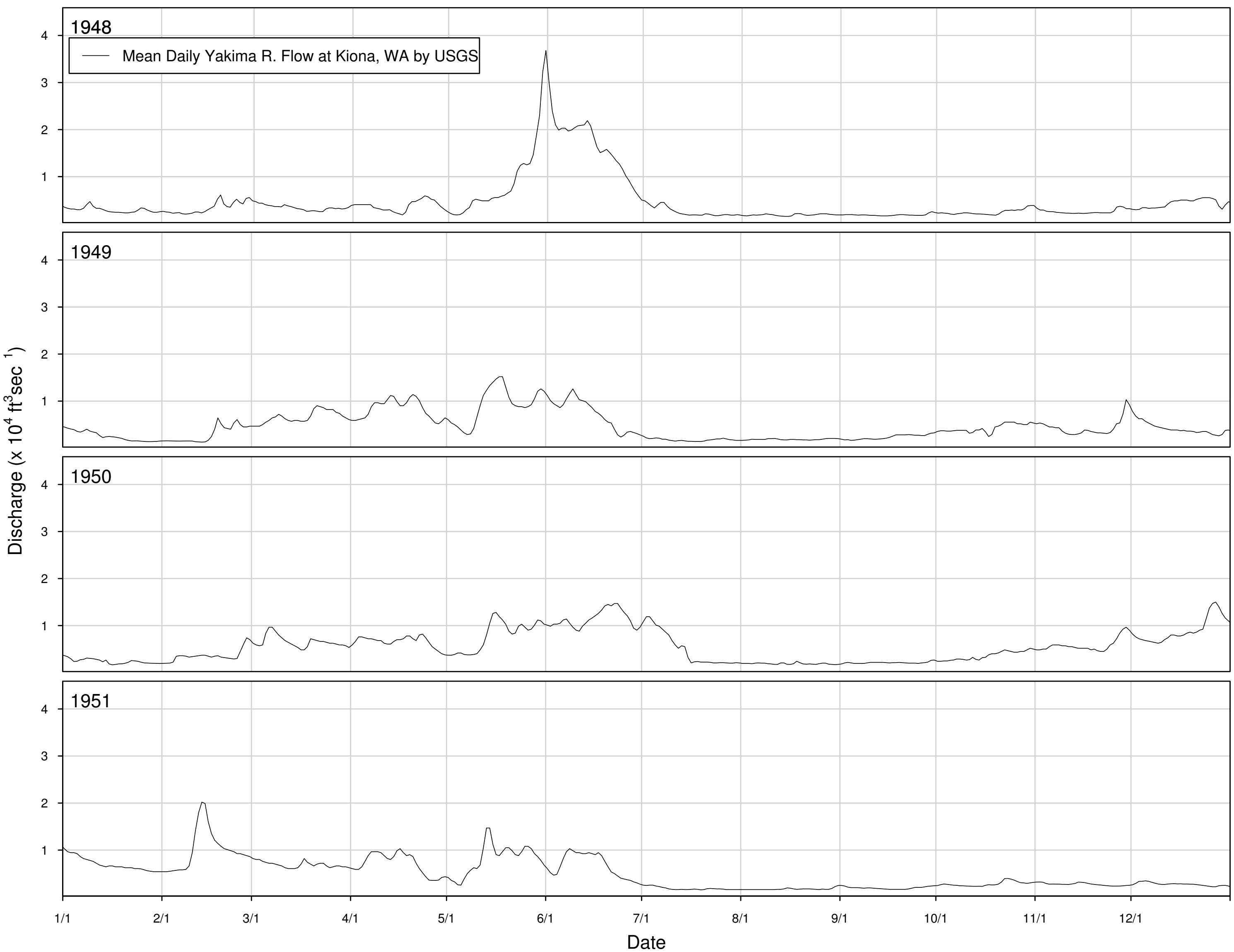

Figure A.40. Yakima River flow at Kiona, WA, 1948–1951.

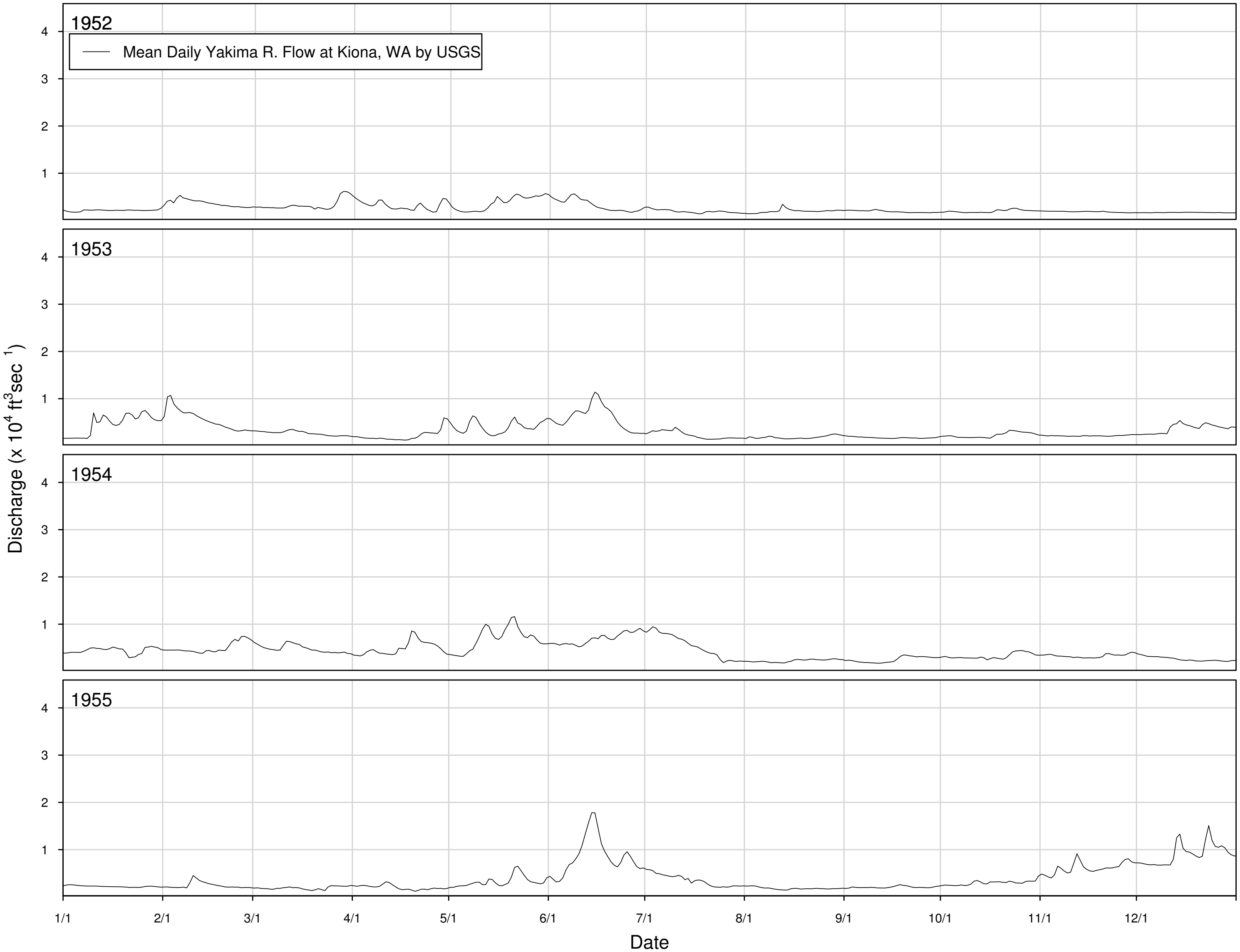

Figure A.41. Yakima River flow at Kiona, WA, 1952–1955.

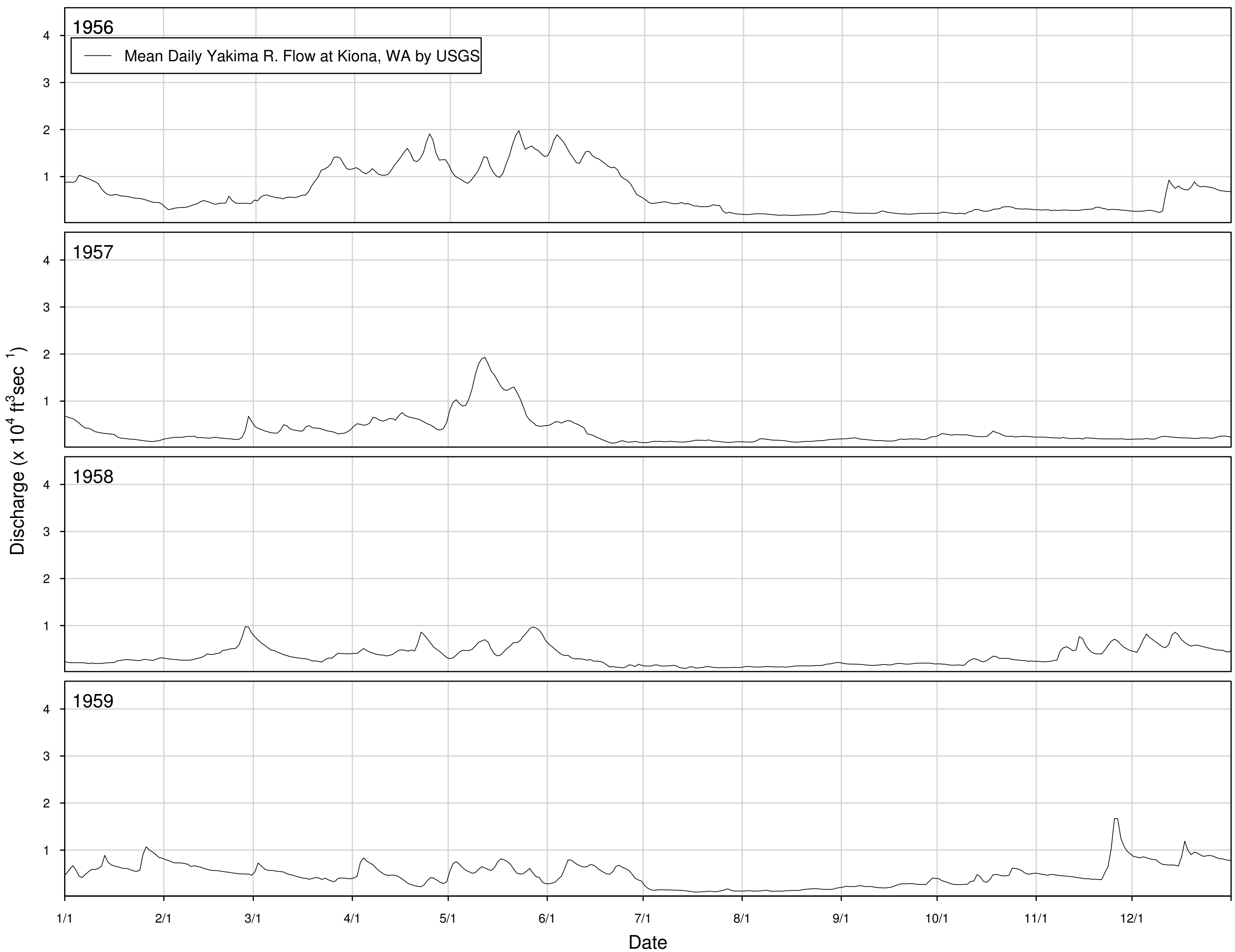

Figure A.42. Yakima River flow at Kiona, WA, 1956–1959.

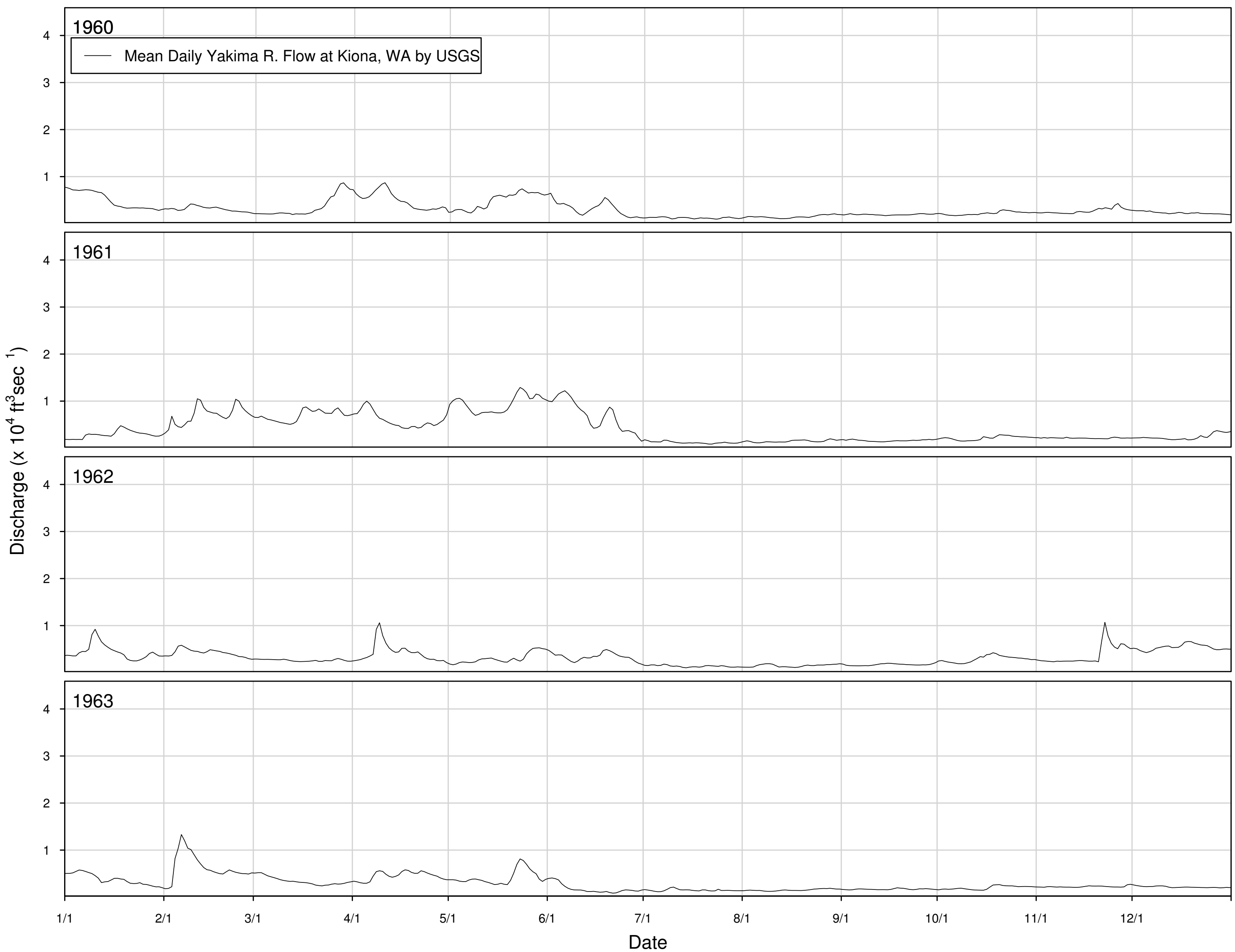

Figure A.43. Yakima River flow at Kiona, WA, 1960–1963.

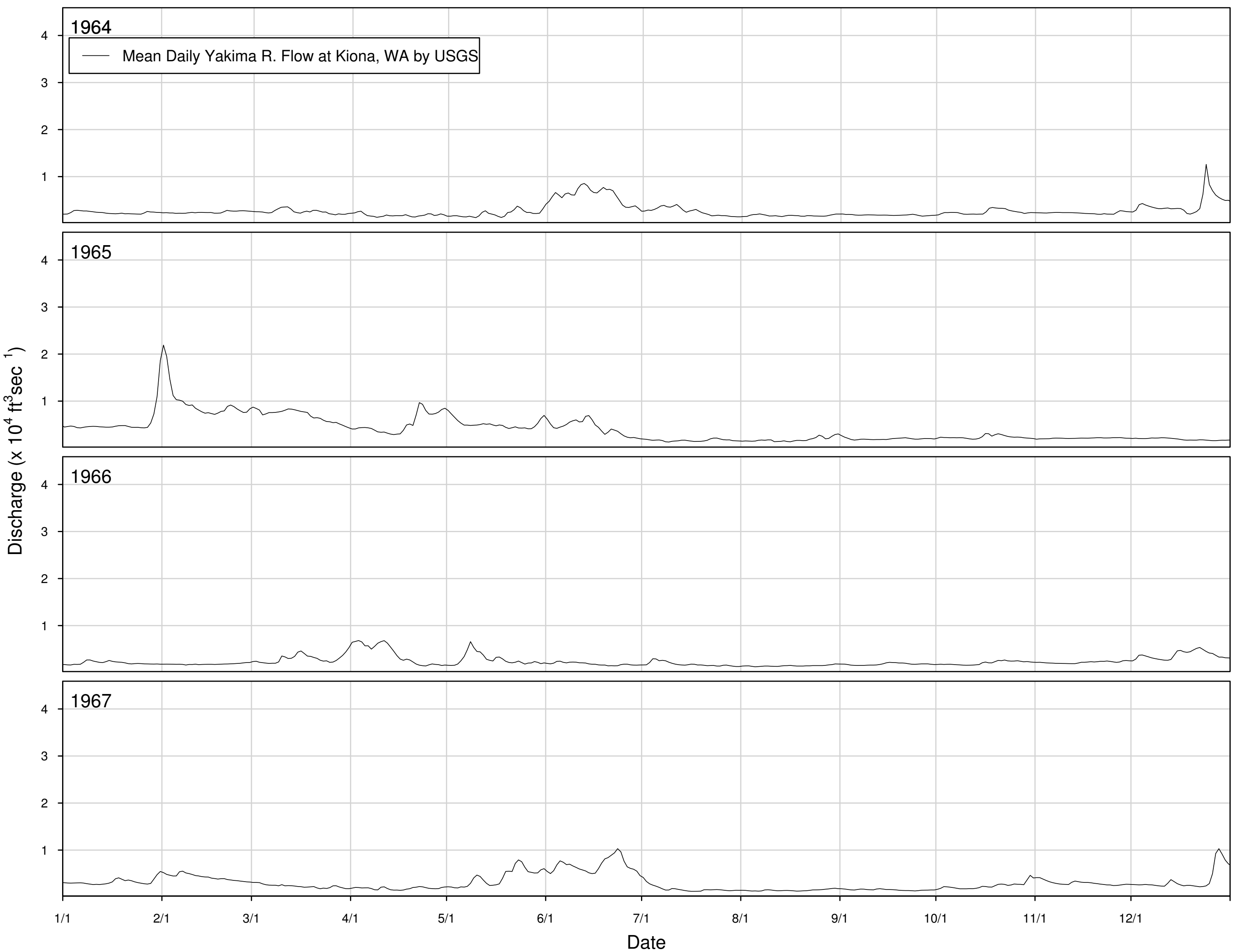

Figure A.44. Yakima River flow at Kiona, WA, 1964–1967.

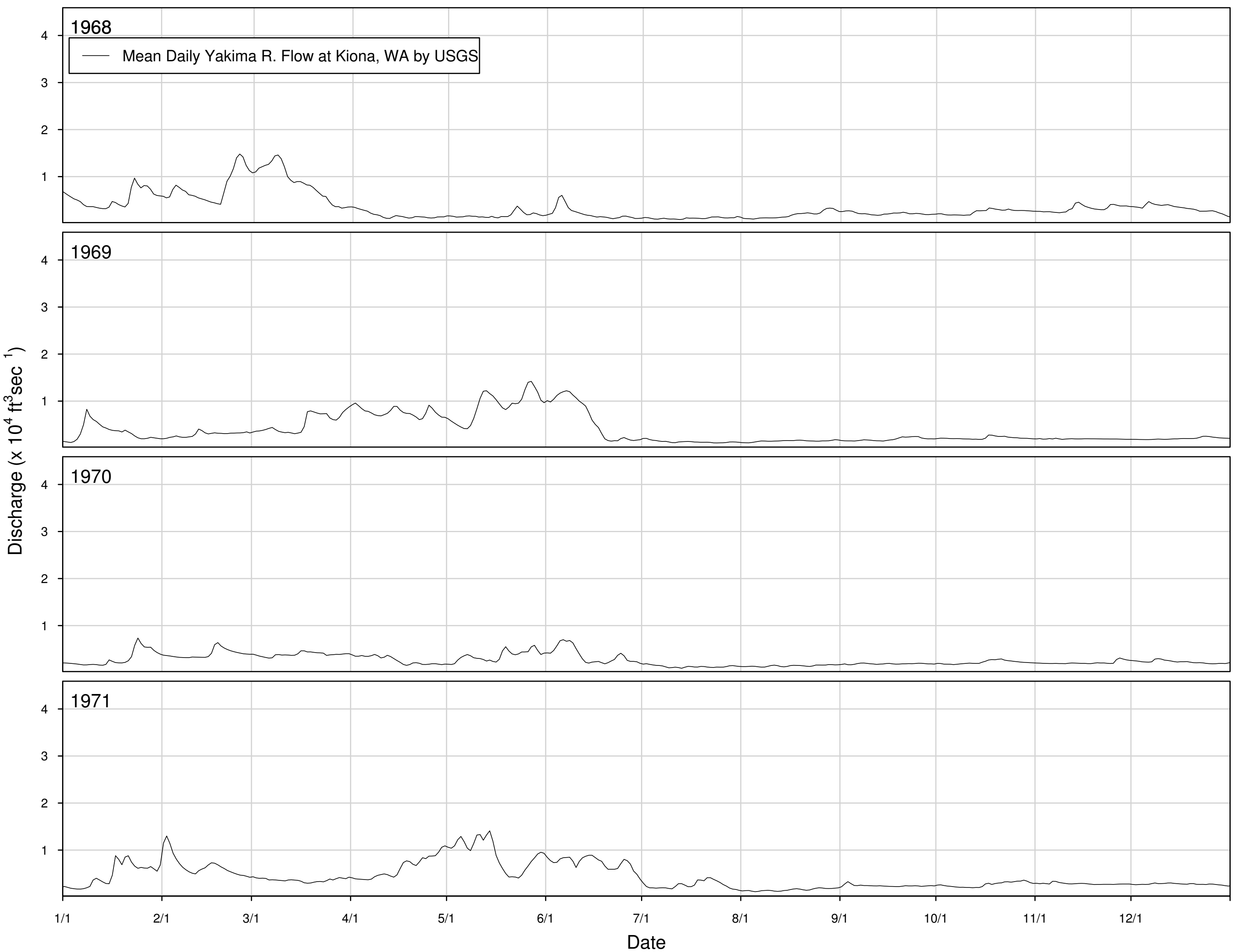

Figure A.45. Yakima River flow at Kiona, WA, 1968–1971.

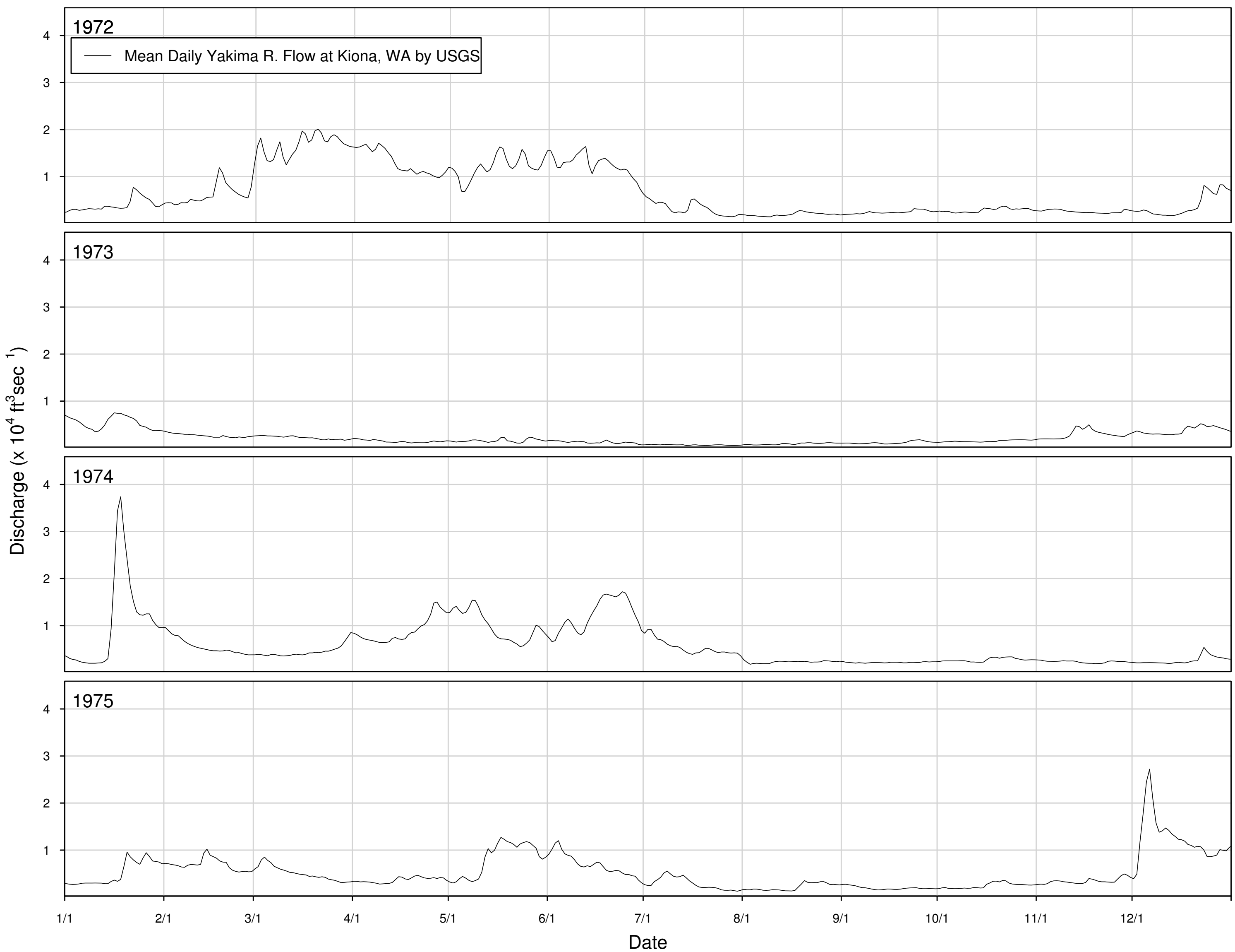

Figure A.46. Yakima River flow at Kiona, WA, 1972–1975.

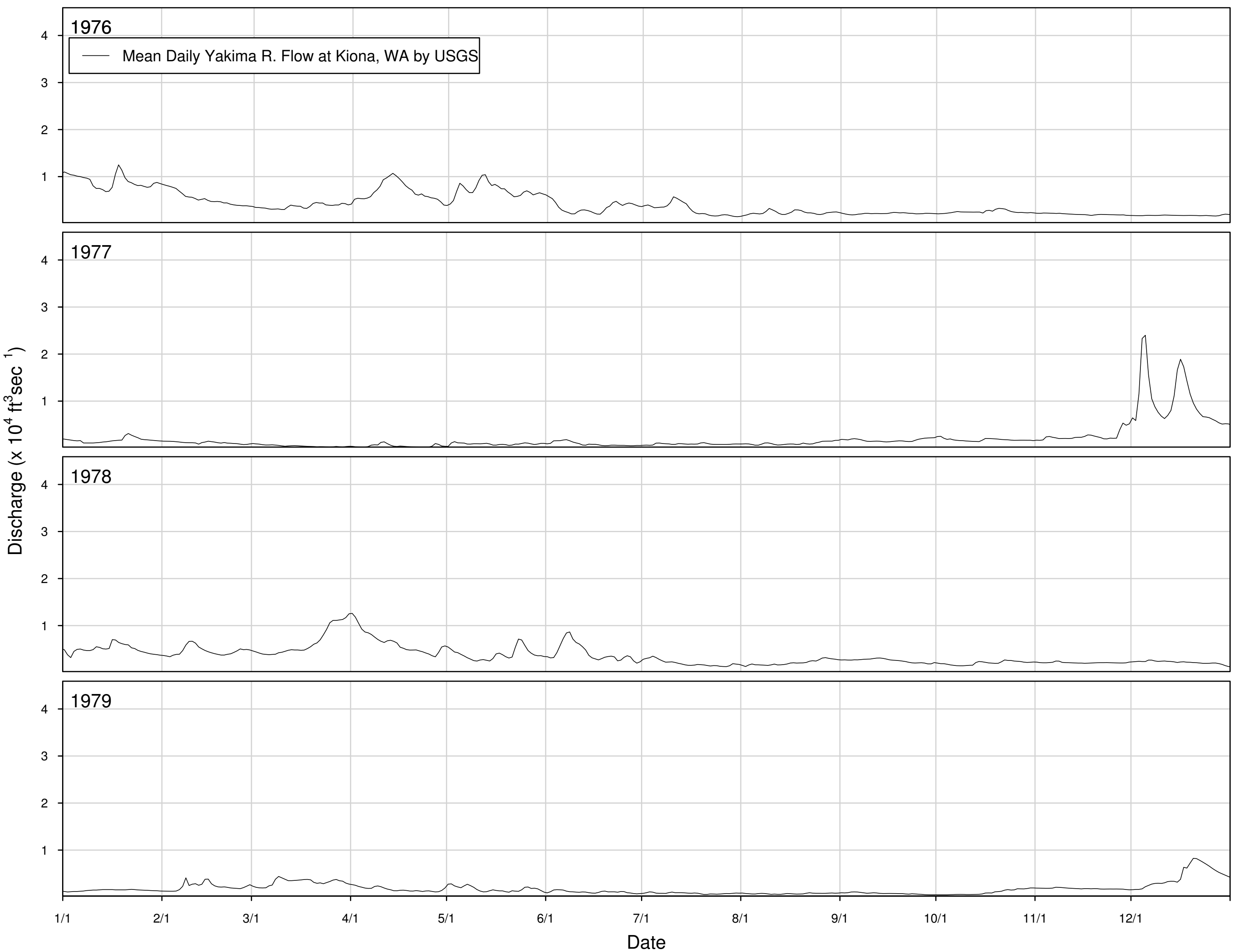

Figure A.47. Yakima River flow at Kiona, WA, 1976–1979.

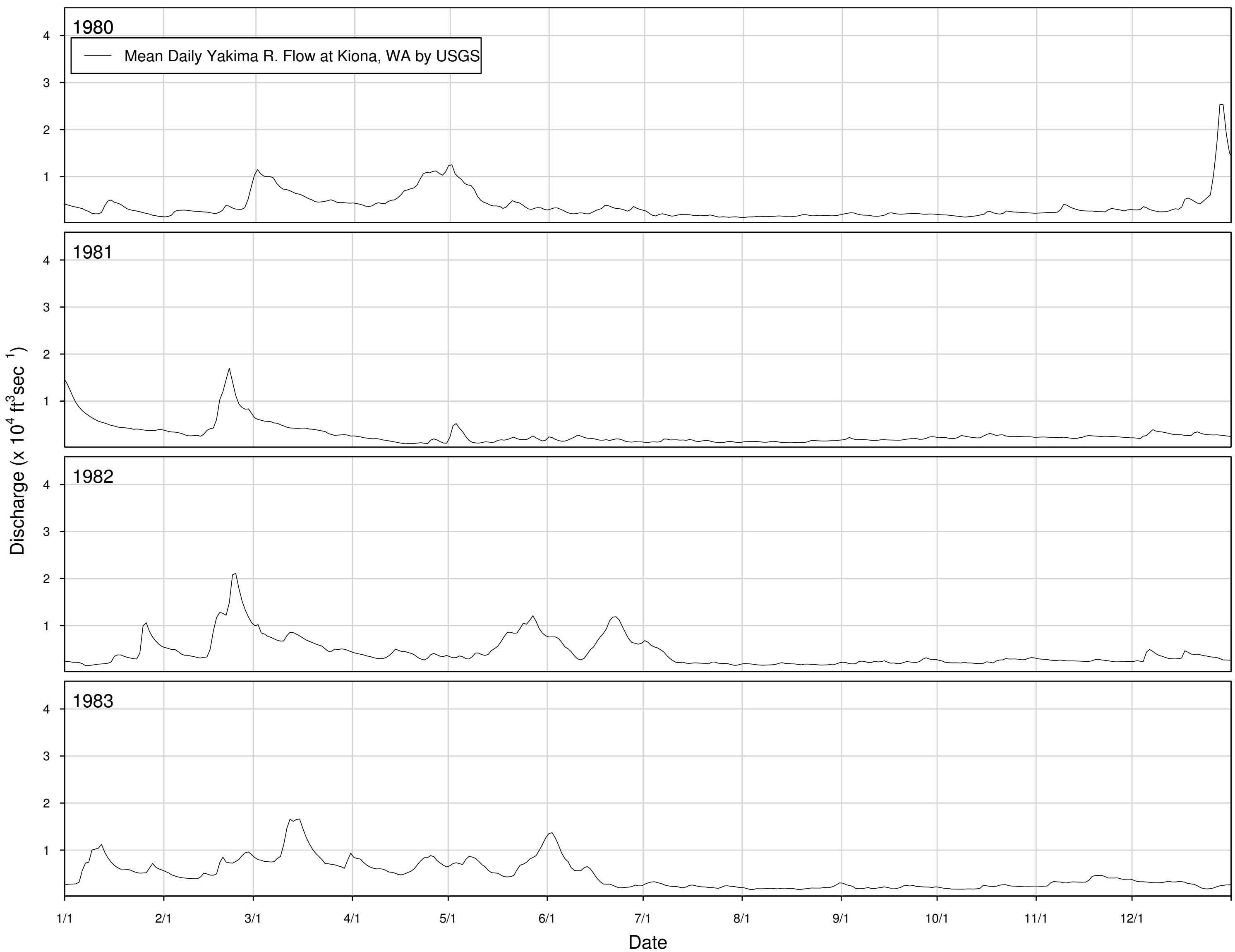

Figure A.48. Yakima River flow at Kiona, WA, 1980–1983.

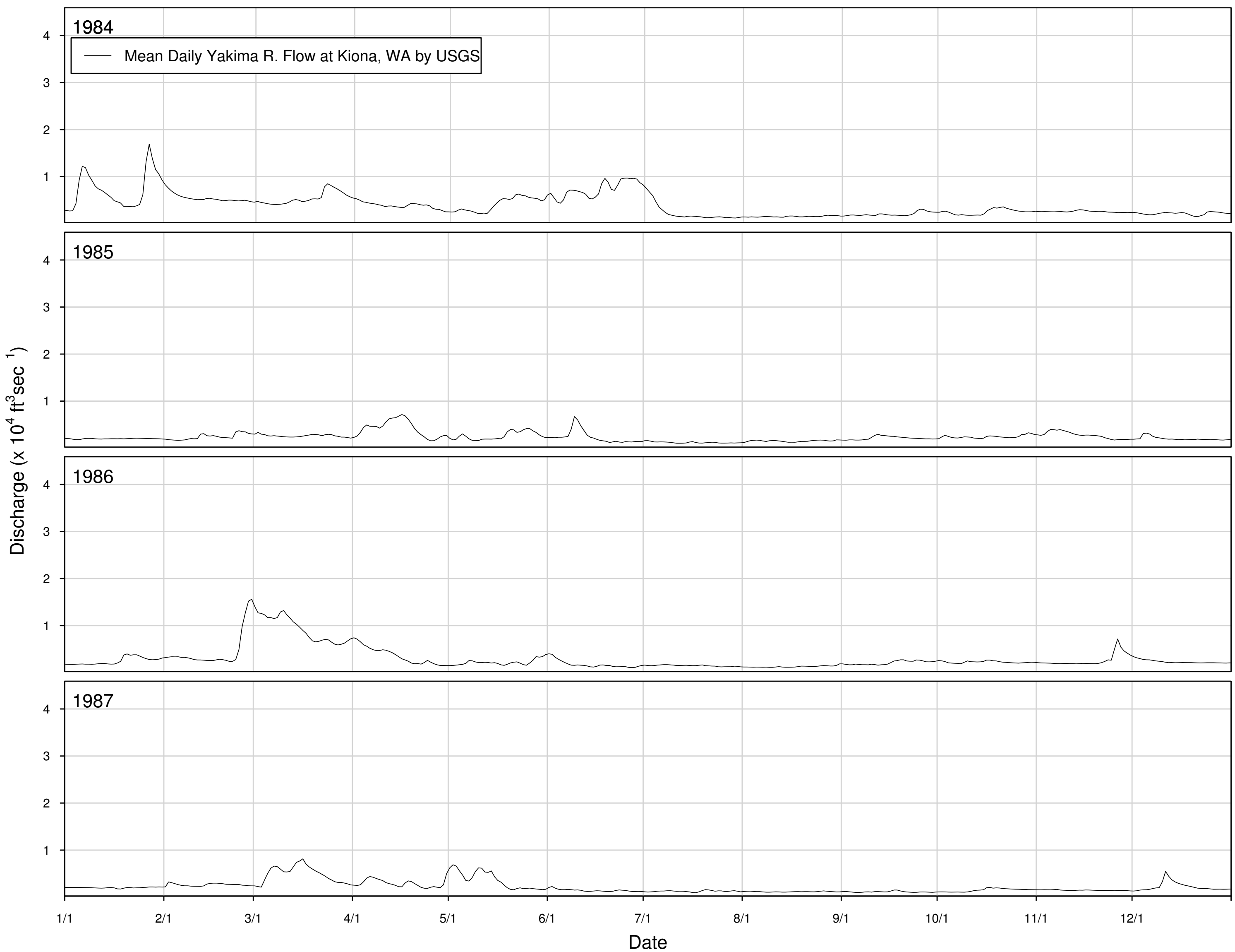

Figure A.49. Yakima River flow at Kiona, WA, 1984–1987.

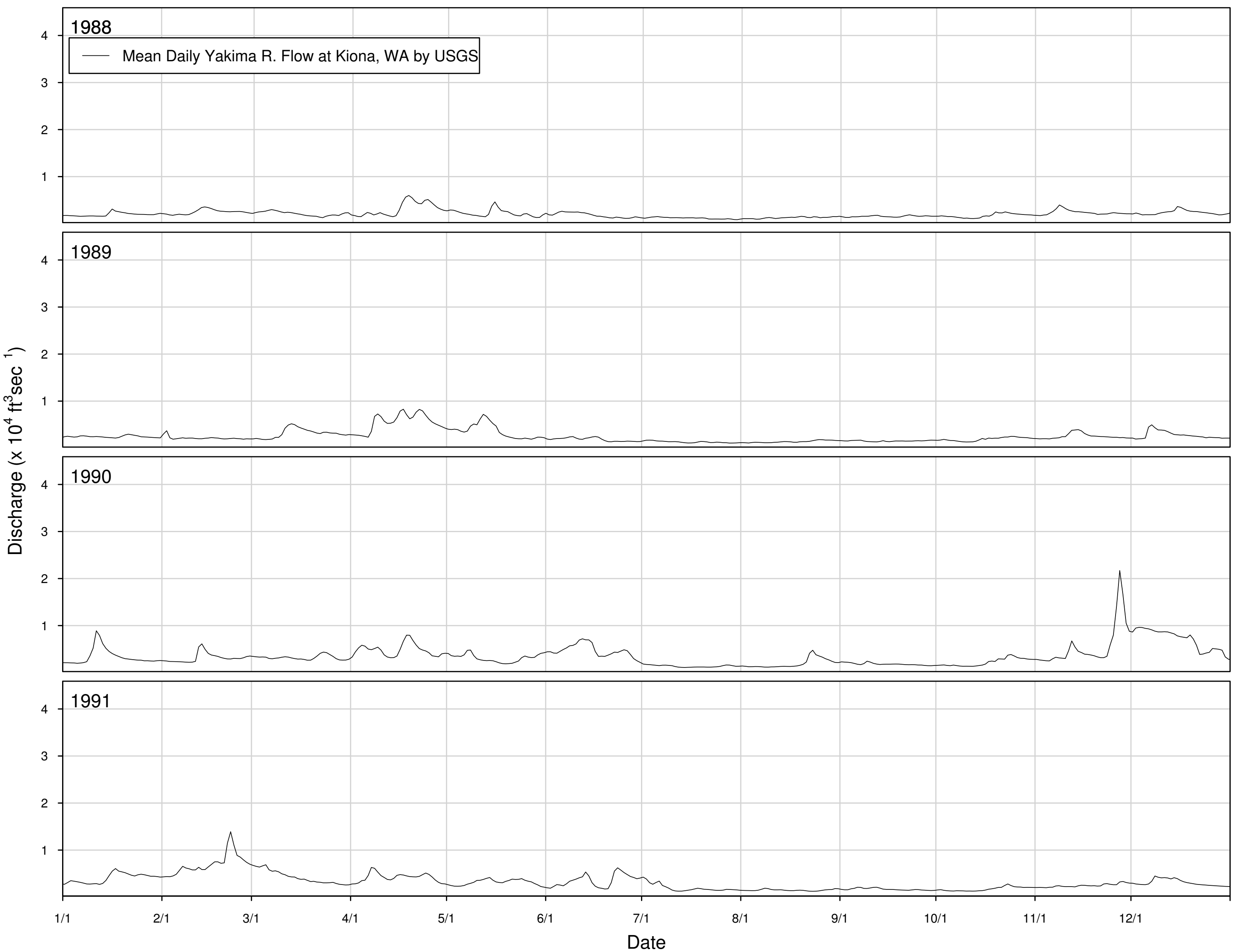

Figure A.50. Yakima River flow at Kiona, WA, 1988–1991.

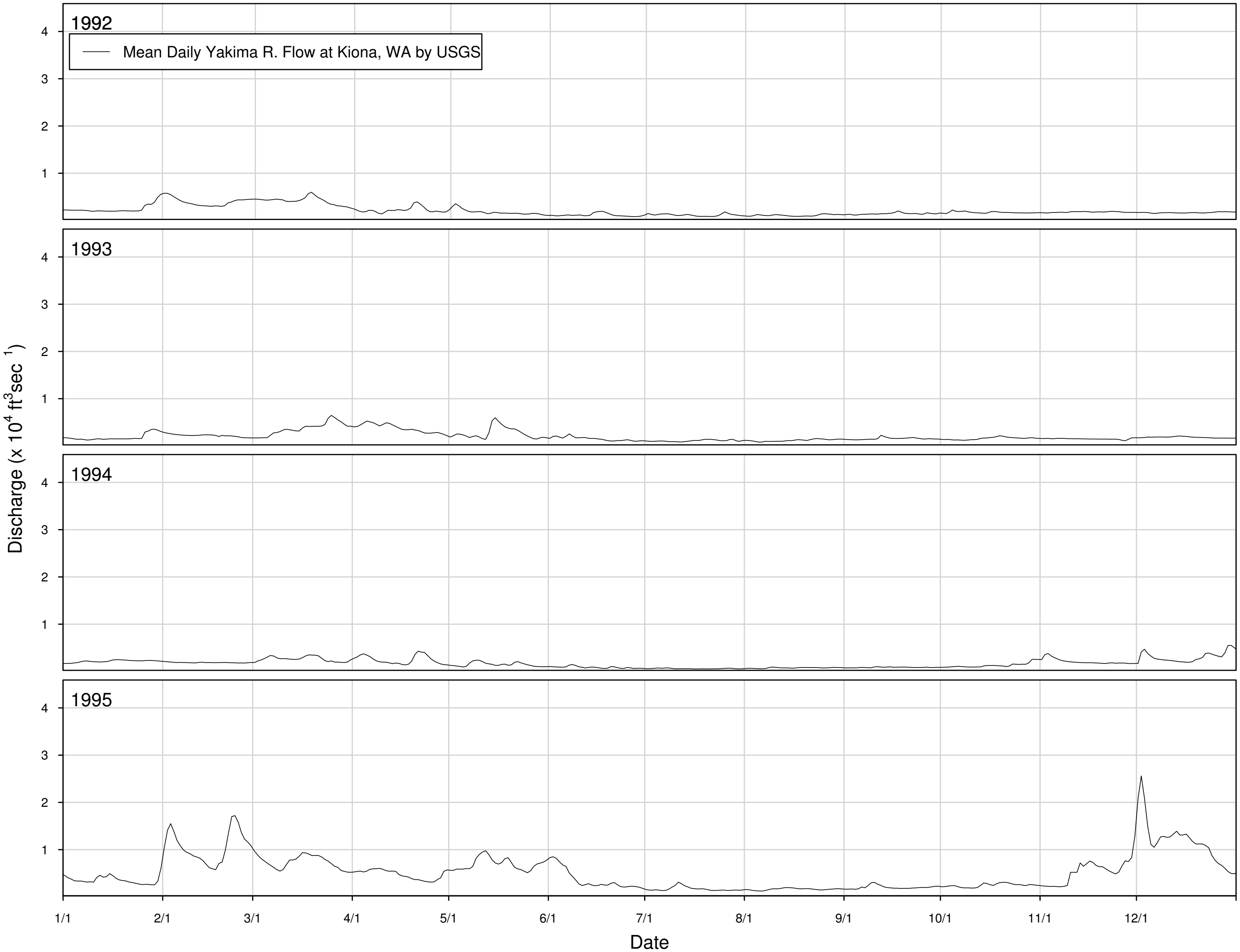

Figure A.51. Yakima River flow at Kiona, WA, 1992–1995.

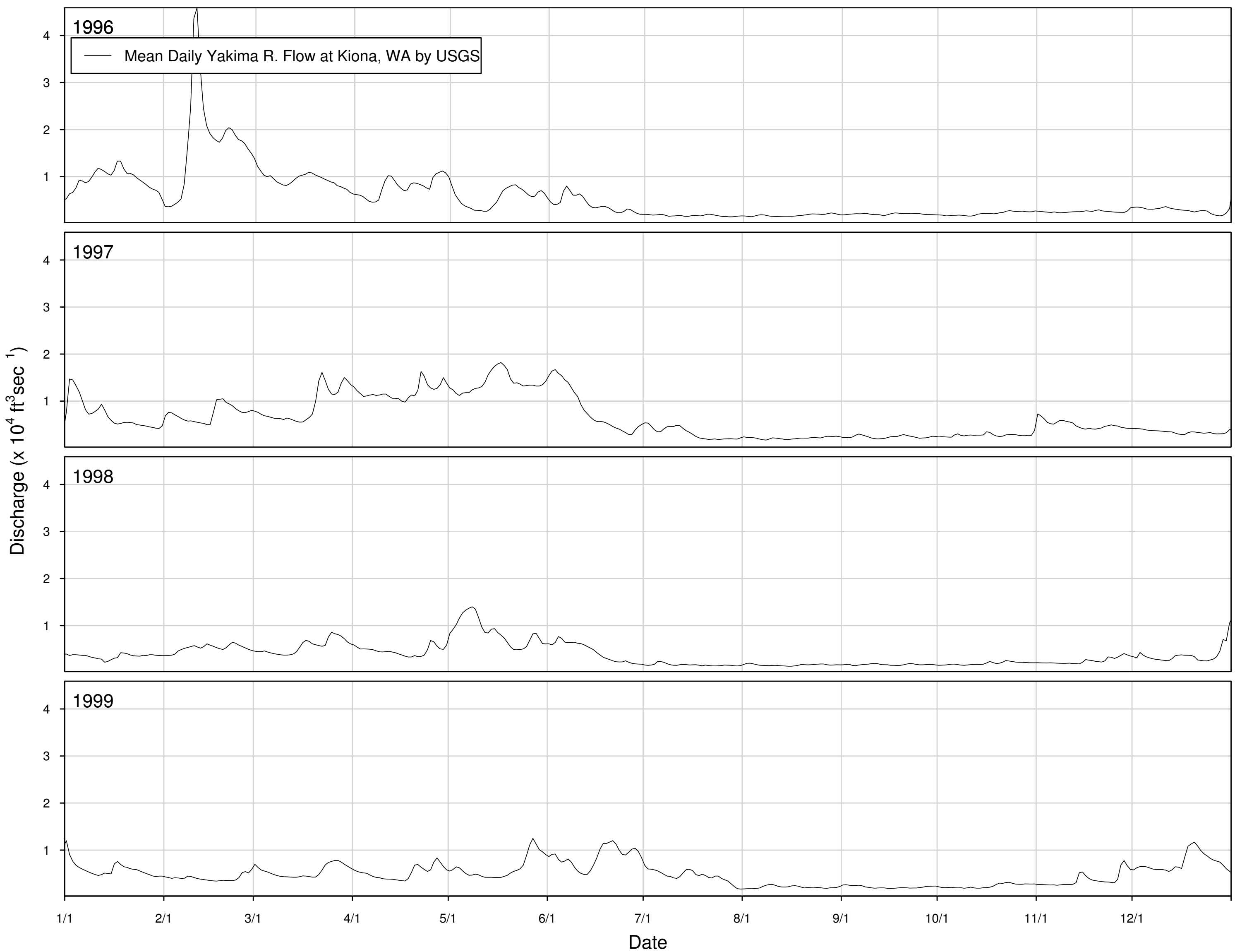

Figure A.52. Yakima River flow at Kiona, WA, 1996–1999.

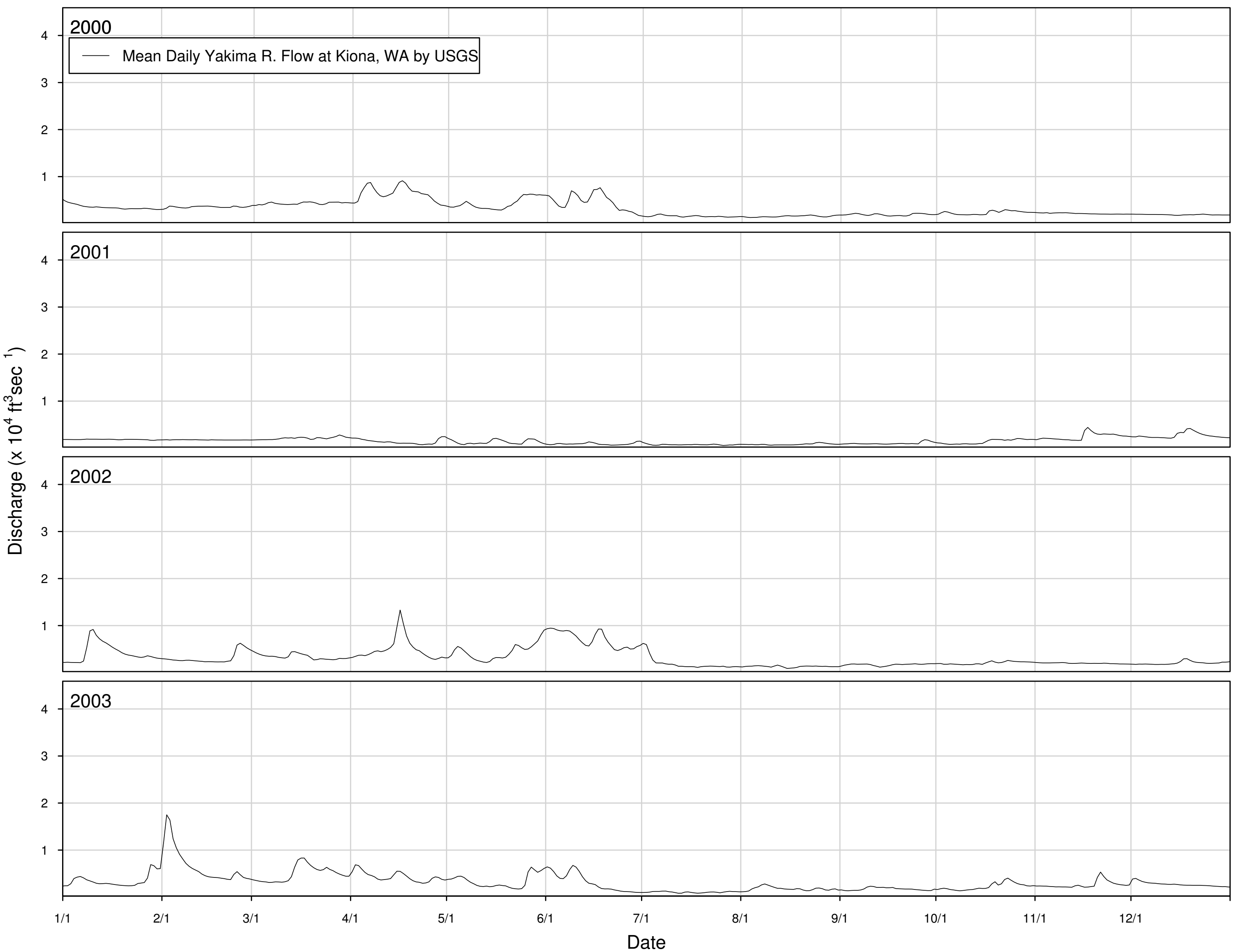

Figure A.53. Yakima River flow at Kiona, WA, 2000–2003.

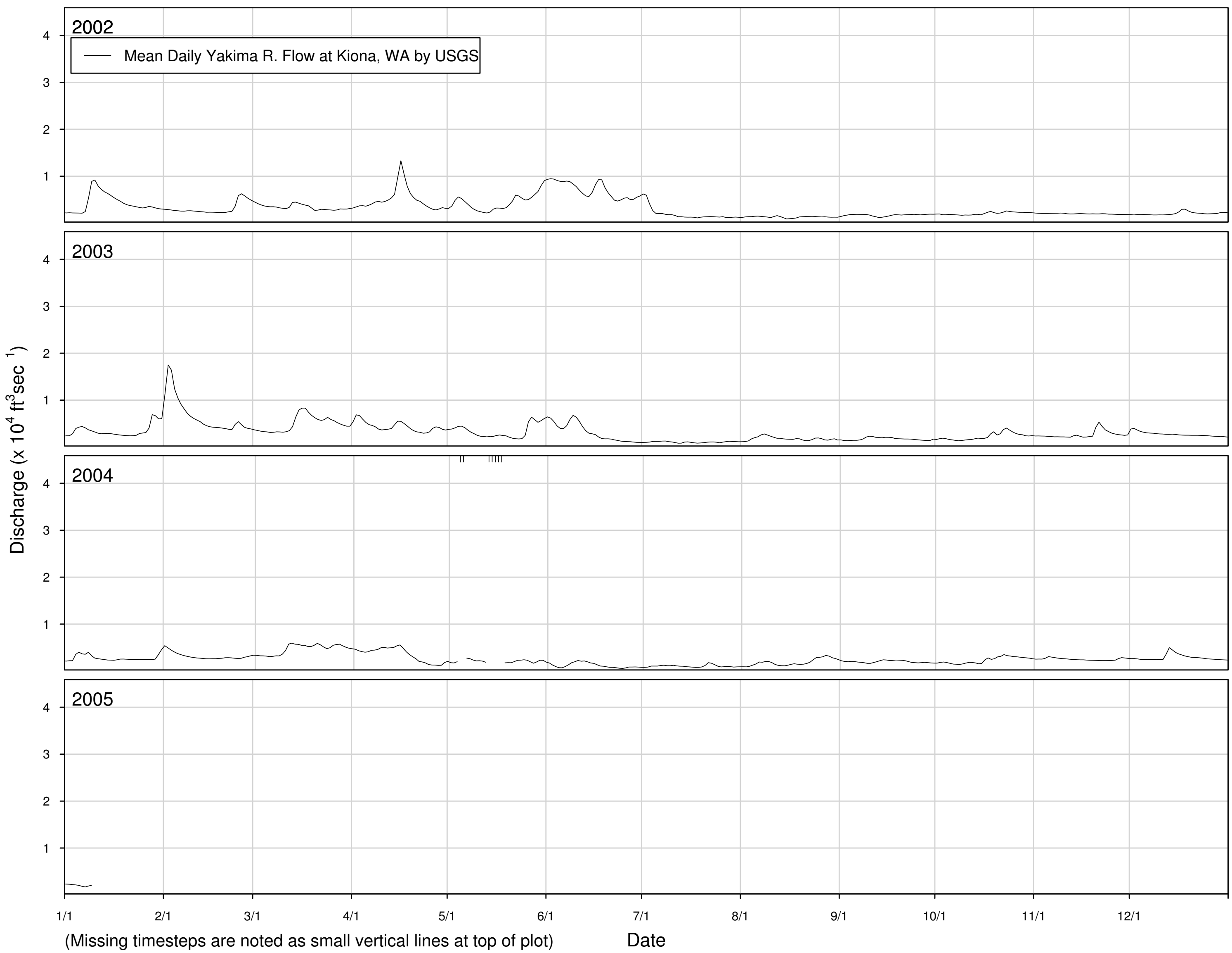

Figure A.54. Yakima River flow at Kiona, WA, 2002–2005.

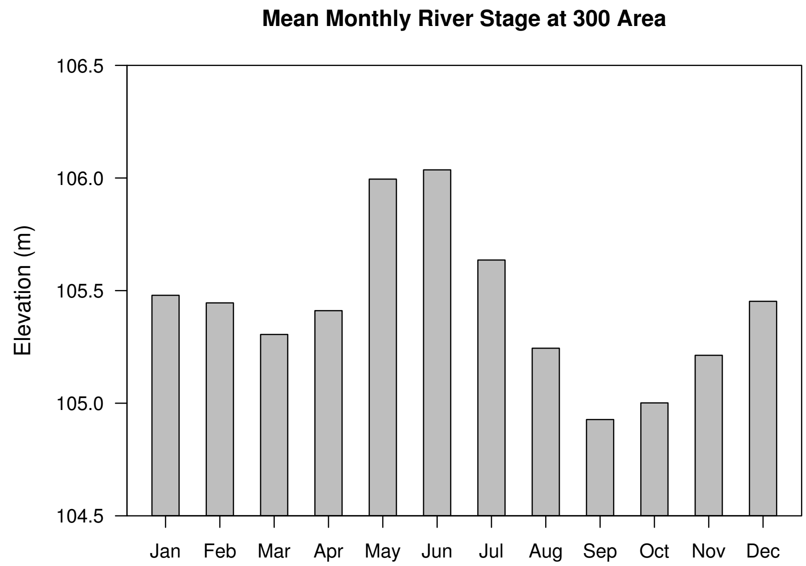

Figure A.55. Mean monthly river stage at SWS-1, 1991-2003.

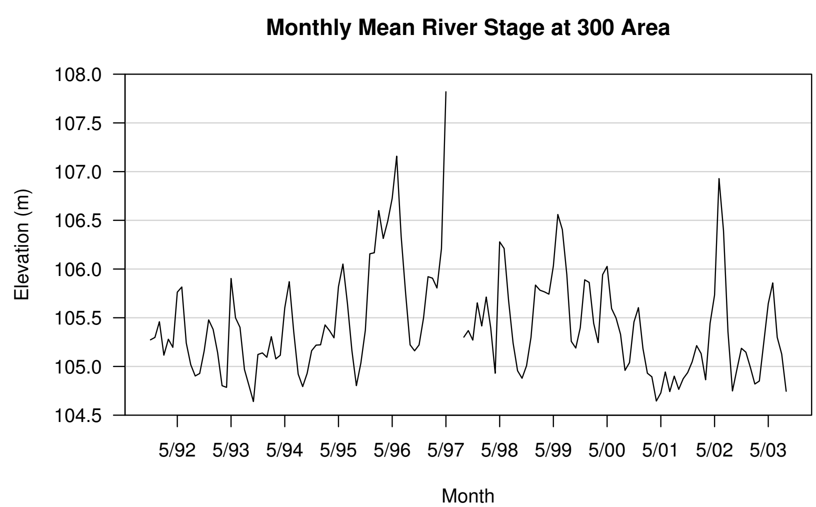

Figure A.56. Monthly mean stage, 1991-2003.

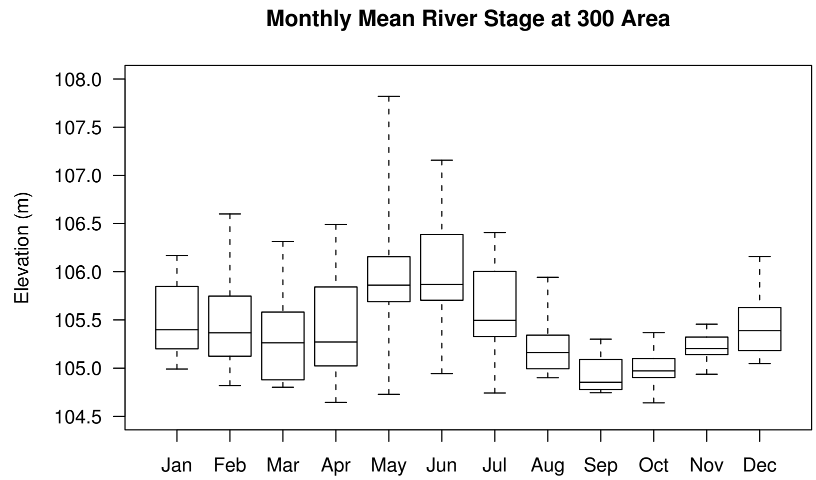

Figure A.57. Boxplot of mean monthly stages by month, 1991-2003.

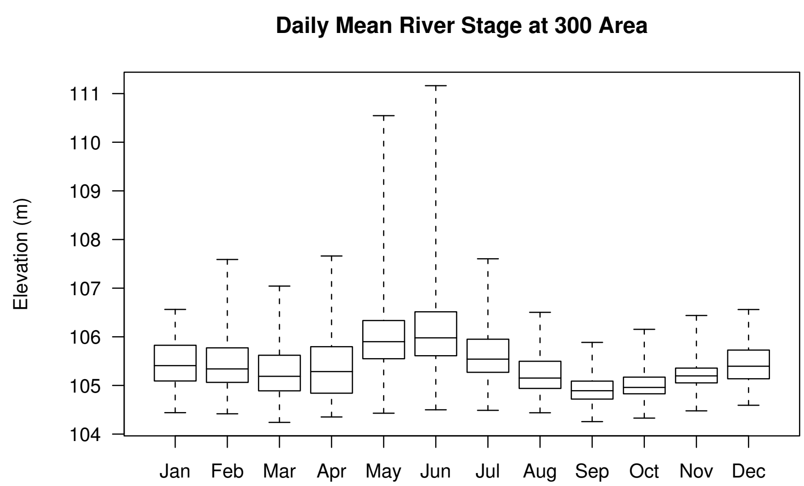

Figure A.58. Boxplot of mean daily stages by month, 1991-2003.

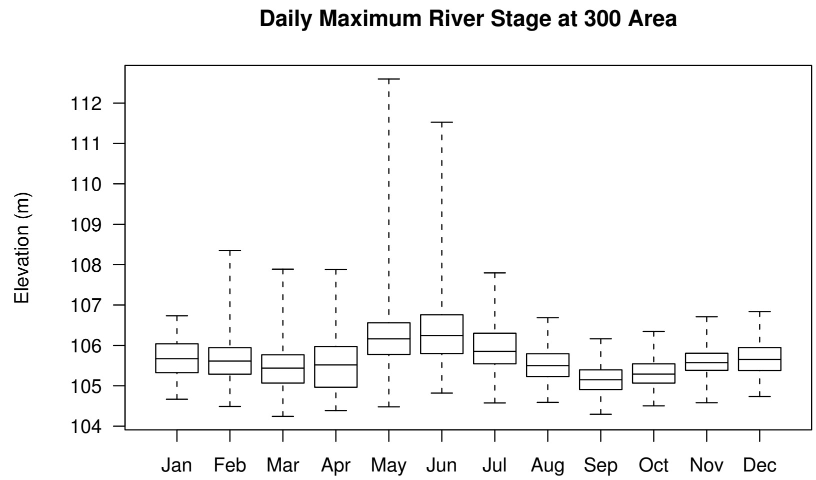

Figure A.59. Boxplot of maximum daily stages by month, 1991-2003.

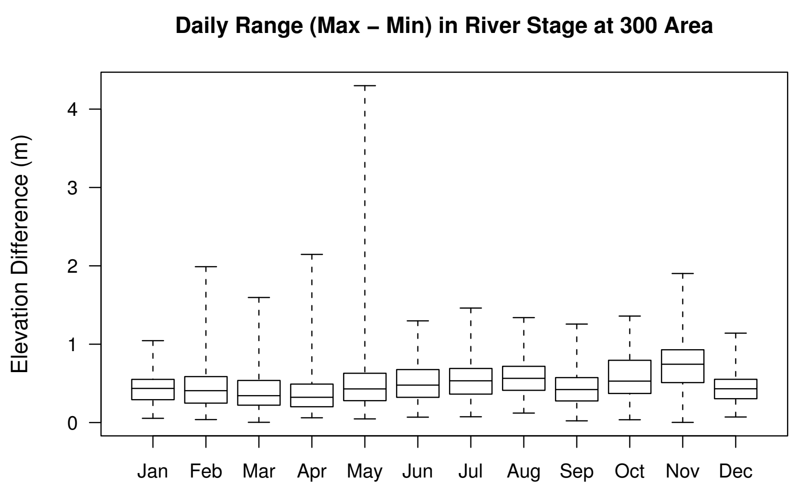

Figure A.60. Boxplot of daily stage ranges by month, 1991-2003.

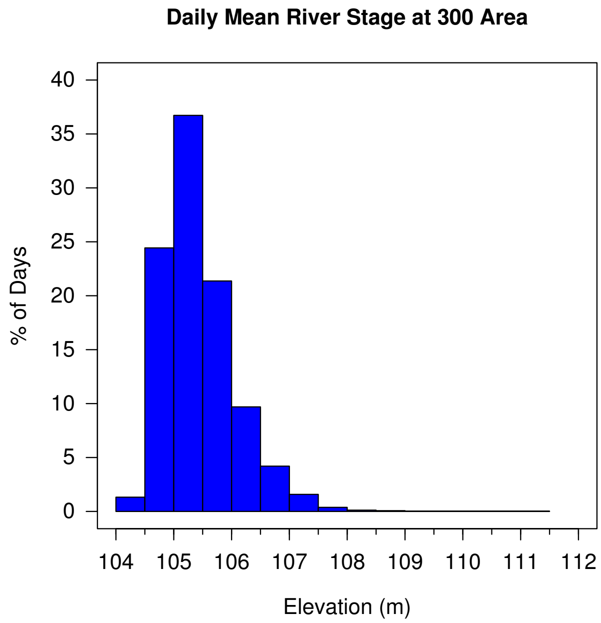

Figure A.61. Histogram of daily mean stage, 1991-2003.

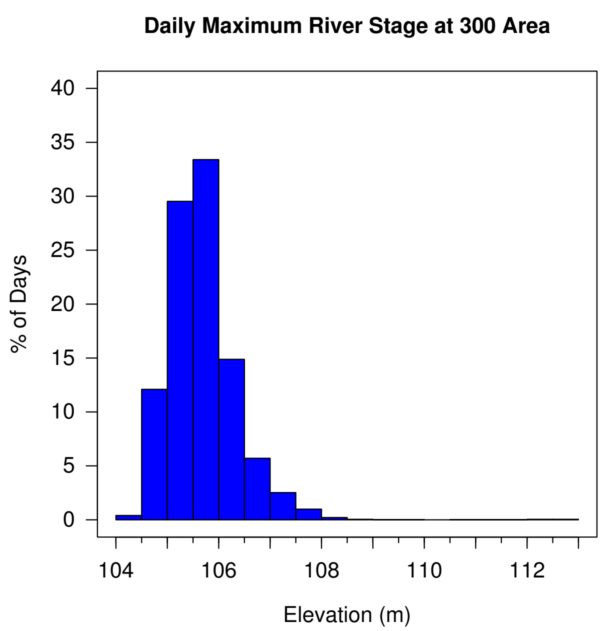

Figure A.62. Histogram of daily max stage, 1991-2003.

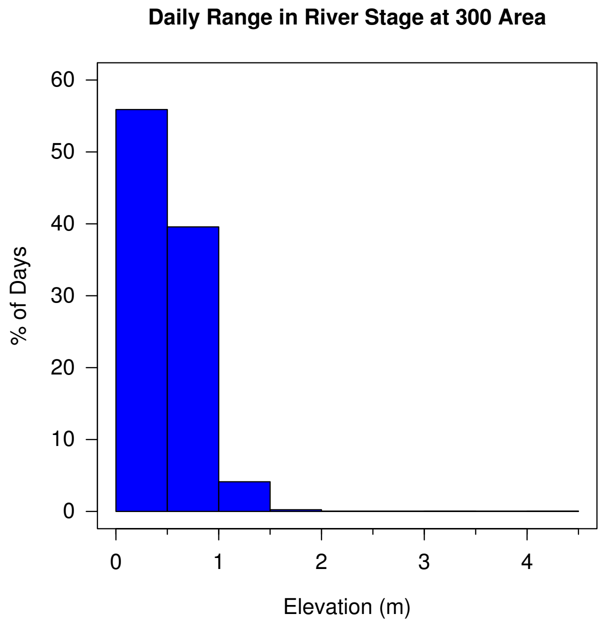

Figure A.63. Histogram of range in daily stage, 1991-2003.

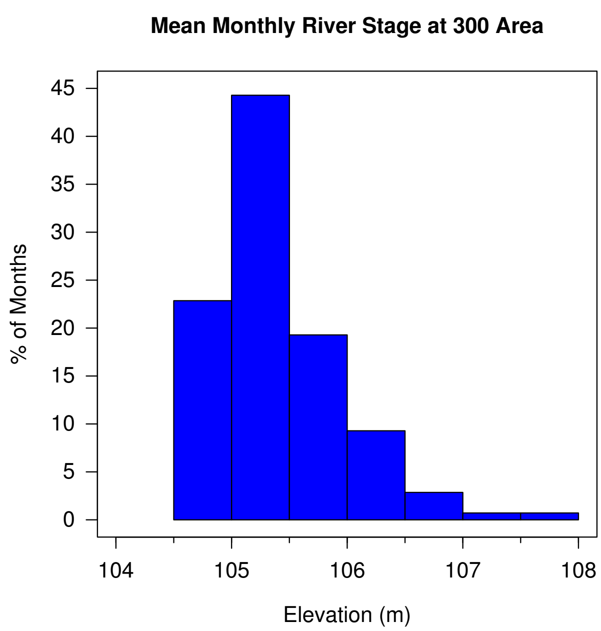

Figure A.64. Histogram of mean monthly stage, 1991-2003.

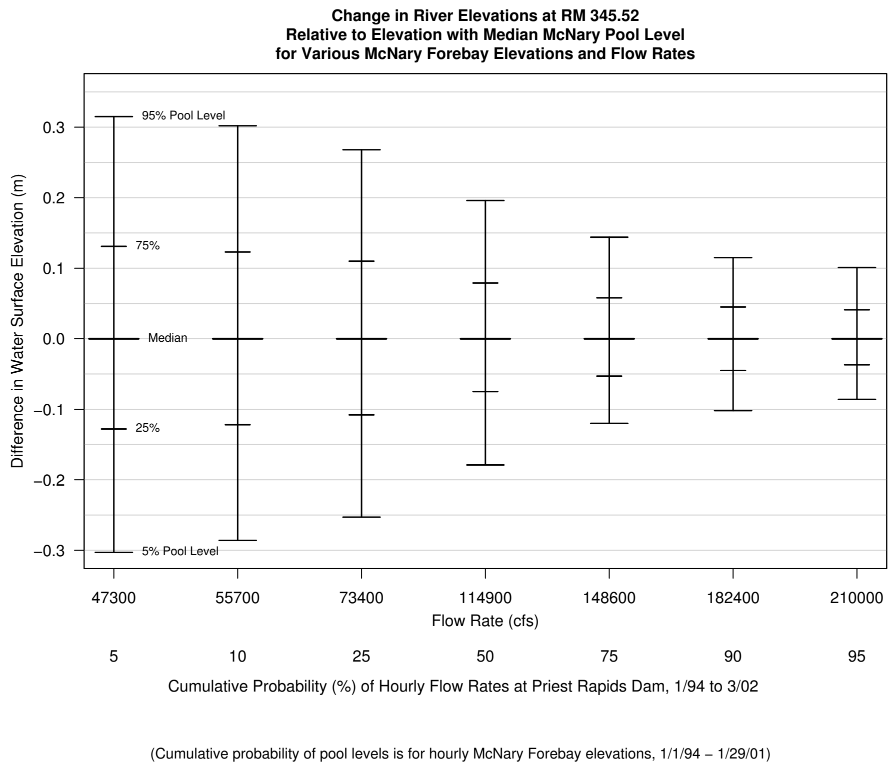

Figure A.65. Relative change in river stage at RM 345.48. Change in river stage at RM 345.48 relative to stage with median McNary pool level for various flow rates. Flow rates correspond to selected quantiles from cumulative probability of 1987–2004 hourly values at Priest Rapids Dam. Horizontal bars correspond to 5%, 25%, 50%, 75%, and 95% quantiles for hourly 1987–2004 McNary forebay elevations.

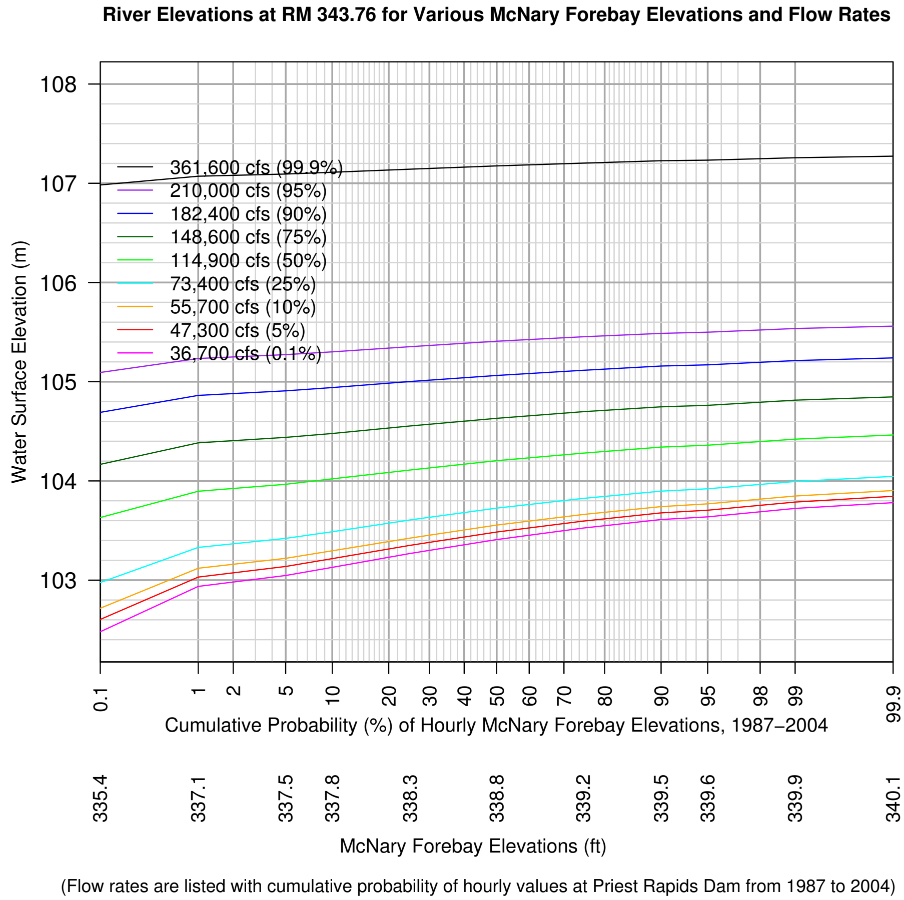

Figure A.66. Effect of McNary forebay water levels on river stage at RM 343.72. Flow rates correspond to selected quantiles from cumulative probability of 1987–2004 hourly values at Priest Rapids Dam.

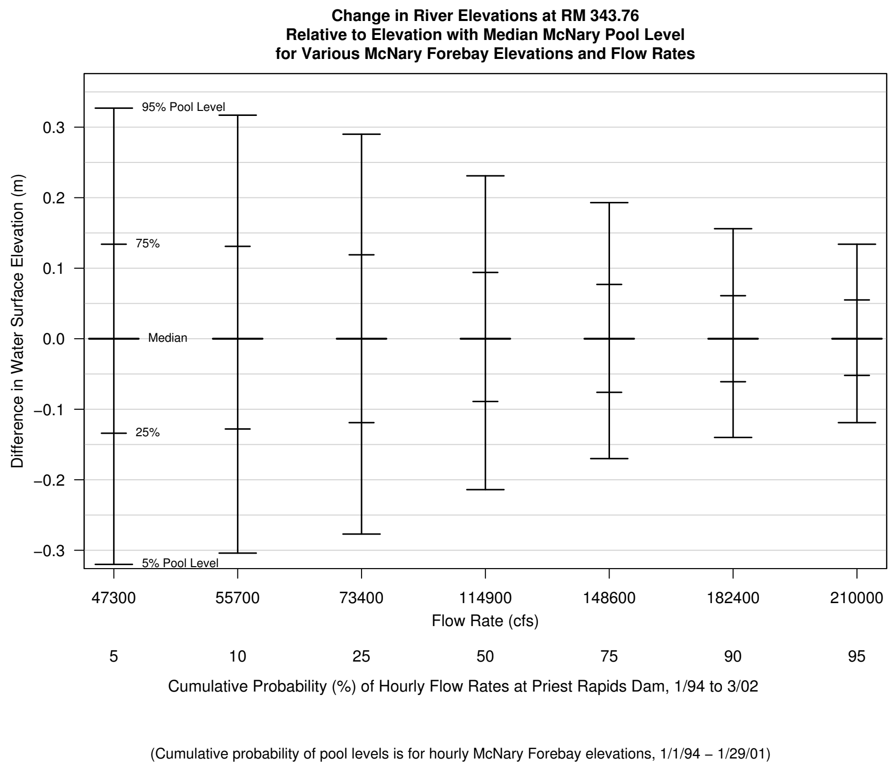

Figure A.67. Relative change in river stage at RM 343.72. Change in river stage at RM 343.72 relative to stage with median McNary pool level for various flow rates. Flow rates correspond to selected quantiles from cumulative probability of 1987–2004 hourly values at Priest Rapids Dam. Horizontal bars correspond to 5%, 25%, 50%, 75%, and 95% quantiles for hourly 1987–2004 McNary forebay elevations.

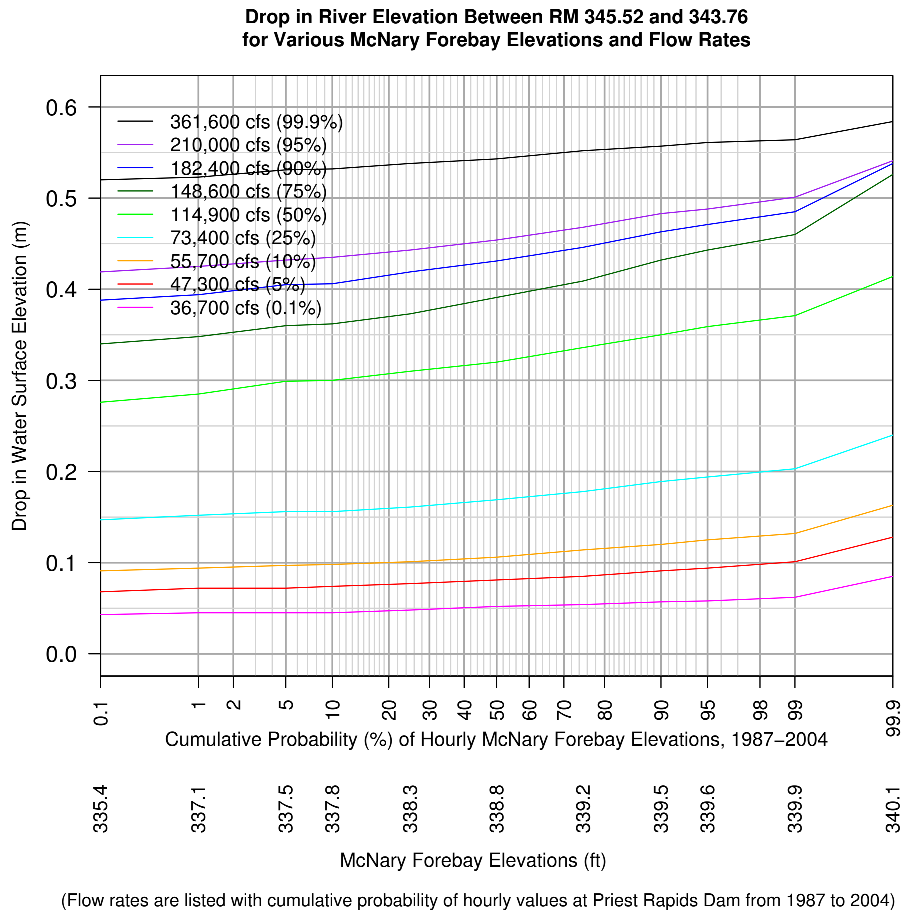

Figure A.68. Effect of McNary forebay water levels on drop in river elevation. Drop is between upstream and downstream points for various flow rates. Flow rates correspond to selected quantiles from cumulative probability of 1987–2004 hourly values at Priest Rapids Dam.

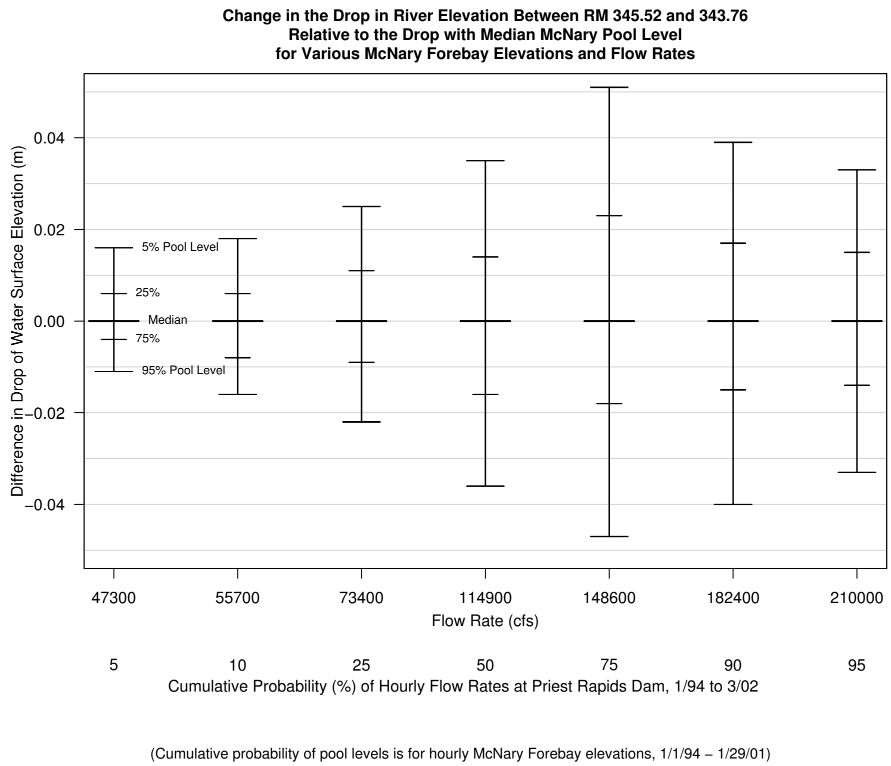

Figure A.69. Relative change in the drop of river elevation. Change is drop of river elevation relative to the drop with median McNary pool level for various flow rates. Flow rates correspond to selected quantiles from cumulative probability of 1987–2004 hourly values at Priest Rapids Dam. Horizontal bars correspond to 5%, 25%, 50%, 75%, and 95% quantiles for hourly 1987–2004 McNary forebay elevations.

Table A.2. Timesteps missing from river stage data. If a time gap is more than 1 timestep long, the number of timesteps is listed in column 1, and the start and end of the gap are noted in columns 2 and 3.

Number of Timesteps In Gap	From	To
	100-B	
Total of 1787 missing timesteps in 71 different time gaps, or 1.75% of the full timeseries that begins 01/01/93 00:00 and ends 08/30/04 03:00.		
102	07/08/93 09:00	07/12/93 14:00
	08/02/94 07:00	
	08/17/95 13:00	
98	10/26/95 08:00	10/30/95 09:00
	03/21/96 08:00	
202	11/22/99 07:00	11/30/99 16:00
19	03/12/00 18:00	03/13/00 12:00
498	06/14/00 22:00	07/05/00 15:00
106	07/24/00 05:00	07/28/00 14:00
2	08/10/00 13:00	08/10/00 14:00
9	08/20/00 09:00	08/20/00 17:00
368	08/21/00 07:00	09/05/00 14:00
5	10/15/00 08:00	10/15/00 12:00
10	10/22/00 07:00	10/22/00 16:00
6	10/29/00 13:00	10/29/00 18:00
4	11/19/00 12:00	11/19/00 15:00
20	05/13/01 00:00	05/13/01 19:00
13	05/13/01 23:00	05/14/01 11:00
13	05/15/01 20:00	05/16/01 08:00
6	05/16/01 19:00	05/17/01 00:00
7	05/19/01 03:00	05/19/01 09:00
3	05/19/01 14:00	05/19/01 16:00
21	05/20/01 03:00	05/20/01 23:00
2	05/21/01 03:00	05/21/01 04:00
8	05/27/01 23:00	05/28/01 06:00
6	07/08/01 06:00	07/08/01 11:00
19	07/11/01 20:00	07/12/01 14:00
2	07/13/01 04:00	07/13/01 05:00
	07/15/01 21:00	
2	07/16/01 03:00	07/16/01 04:00
2	07/16/01 15:00	07/16/01 16:00
	07/17/01 13:00	
11	07/21/01 17:00	07/22/01 03:00
3	07/22/01 07:00	07/22/01 09:00
18	07/22/01 12:00	07/23/01 05:00
3	07/24/01 18:00	07/24/01 20:00
16	07/28/01 15:00	07/29/01 06:00
10	07/29/01 20:00	07/30/01 05:00
3	07/30/01 16:00	07/30/01 18:00
3	07/31/01 02:00	07/31/01 04:00
2	08/03/01 16:00	08/03/01 17:00
2	08/05/01 05:00	08/05/01 06:00
5	08/05/01 11:00	08/05/01 15:00
2	08/10/01 01:00	08/10/01 02:00
2	08/12/01 15:00	08/12/01 16:00
3	08/17/01 23:00	08/18/01 01:00
2	08/20/01 18:00	08/20/01 19:00
4	08/26/01 19:00	08/26/01 22:00
6	09/02/01 00:00	09/02/01 05:00
3	09/08/01 15:00	09/08/01 17:00
	09/08/01 23:00	
3	09/09/01 02:00	09/09/01 04:00
4	09/09/01 16:00	09/09/01 19:00
2	09/16/01 07:00	09/16/01 08:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
8	09/16/01 12:00	09/16/01 19:00
16	10/06/01 04:00	10/06/01 19:00
13	10/07/01 18:00	10/08/01 06:00
3	10/14/01 10:00	10/14/01 12:00
6	10/19/01 17:00	10/19/01 22:00
2	10/20/01 17:00	10/20/01 18:00
5	10/21/01 10:00	10/21/01 14:00
8	10/28/01 06:00	10/28/01 13:00
6	10/29/01 13:00	10/29/01 18:00
2	10/30/01 17:00	10/30/01 18:00
9	11/03/01 03:00	11/03/01 11:00
6	11/04/01 12:00	11/04/01 17:00
6	11/05/01 13:00	11/05/01 18:00
4	11/06/01 15:00	11/06/01 18:00
2	11/10/01 17:00	11/10/01 18:00
20	11/10/01 22:00	11/11/01 17:00
5	11/18/01 14:00	11/18/01 18:00

100-N

Total of 2626 missing timesteps in 211 different time gaps, or 2.65% of the full timeseries that begins 07/19/93 15:00 and ends 10/31/04 23:00.

492	07/19/93 20:00	08/09/93 07:00
52	12/28/93 08:00	12/30/93 11:00
	08/02/98 10:00	
5	08/02/98 15:00	08/02/98 19:00
4	08/16/98 13:00	08/16/98 16:00
3	08/16/98 18:00	08/16/98 20:00
4	08/17/98 05:00	08/17/98 08:00
2	08/25/98 06:00	08/25/98 07:00
5	08/27/98 06:00	08/27/98 10:00
3	08/29/98 07:00	08/29/98 09:00
2	08/31/98 07:00	08/31/98 08:00
5	09/03/98 03:00	09/03/98 07:00
5	09/04/98 04:00	09/04/98 08:00
8	09/05/98 01:00	09/05/98 08:00
6	09/06/98 03:00	09/06/98 08:00
8	09/07/98 01:00	09/07/98 08:00
3	09/08/98 01:00	09/08/98 03:00
5	09/09/98 05:00	09/09/98 09:00
3	09/11/98 06:00	09/11/98 08:00
4	09/12/98 05:00	09/12/98 08:00
2	09/16/98 05:00	09/16/98 06:00
	09/17/98 15:00	
2	09/18/98 11:00	09/18/98 12:00
5	09/19/98 04:00	09/19/98 08:00
7	09/20/98 04:00	09/20/98 10:00
5	09/21/98 05:00	09/21/98 09:00
6	09/22/98 03:00	09/22/98 08:00
5	09/23/98 05:00	09/23/98 09:00
3	09/24/98 07:00	09/24/98 09:00
2	09/25/98 01:00	09/25/98 02:00
	09/25/98 10:00	
4	09/26/98 06:00	09/26/98 09:00
7	09/27/98 03:00	09/27/98 09:00
4	09/28/98 06:00	09/28/98 09:00
2	09/29/98 07:00	09/29/98 08:00
4	09/30/98 05:00	09/30/98 08:00
9	10/01/98 01:00	10/01/98 09:00
4	10/02/98 22:00	10/03/98 01:00
8	10/03/98 03:00	10/03/98 10:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
12	10/03/98 23:00	10/04/98 10:00
8	10/04/98 18:00	10/05/98 01:00
	10/05/98 06:00	
4	10/06/98 08:00	10/06/98 11:00
	10/07/98 07:00	
3	10/07/98 09:00	10/07/98 11:00
5	10/08/98 05:00	10/08/98 09:00
	10/08/98 12:00	
6	10/09/98 05:00	10/09/98 10:00
5	10/09/98 22:00	10/10/98 02:00
6	10/10/98 05:00	10/10/98 10:00
	10/10/98 13:00	
17	10/10/98 19:00	10/11/98 11:00
12	10/11/98 23:00	10/12/98 10:00
	10/13/98 06:00	
4	10/14/98 06:00	10/14/98 09:00
2	10/16/98 10:00	10/16/98 11:00
3	10/17/98 09:00	10/17/98 11:00
16	10/17/98 18:00	10/18/98 09:00
5	10/18/98 18:00	10/18/98 22:00
3	10/19/98 08:00	10/19/98 10:00
2	10/19/98 18:00	10/19/98 19:00
3	10/20/98 08:00	10/20/98 10:00
2	10/20/98 18:00	10/20/98 19:00
	10/21/98 10:00	
2	10/21/98 18:00	10/21/98 19:00
2	10/22/98 09:00	10/22/98 10:00
2	10/22/98 18:00	10/22/98 19:00
4	10/23/98 08:00	10/23/98 11:00
3	10/23/98 17:00	10/23/98 19:00
9	10/24/98 07:00	10/24/98 15:00
	10/24/98 18:00	
	10/24/98 20:00	
4	10/25/98 07:00	10/25/98 10:00
3	10/25/98 18:00	10/25/98 20:00
4	10/26/98 07:00	10/26/98 10:00
3	10/26/98 18:00	10/26/98 20:00
2	10/27/98 01:00	10/27/98 02:00
2	10/27/98 10:00	10/27/98 11:00
3	10/27/98 17:00	10/27/98 19:00
10	10/28/98 10:00	10/28/98 19:00
8	10/29/98 12:00	10/29/98 19:00
8	10/30/98 12:00	10/30/98 19:00
11	10/31/98 10:00	10/31/98 20:00
5	11/01/98 08:00	11/01/98 12:00
	11/01/98 15:00	
4	11/01/98 17:00	11/01/98 20:00
11	11/02/98 09:00	11/02/98 19:00
11	11/03/98 09:00	11/03/98 19:00
8	11/04/98 12:00	11/04/98 19:00
7	11/05/98 12:00	11/05/98 18:00
10	11/06/98 12:00	11/06/98 21:00
12	11/07/98 11:00	11/07/98 22:00
9	11/08/98 11:00	11/08/98 19:00
5	11/09/98 11:00	11/09/98 15:00
	11/09/98 18:00	
7	11/10/98 11:00	11/10/98 17:00
4	11/14/98 15:00	11/14/98 18:00
2	11/15/98 10:00	11/15/98 11:00
22	11/15/98 16:00	11/16/98 13:00
10	11/22/98 10:00	11/22/98 19:00
2	11/25/98 17:00	11/25/98 18:00
95	11/26/98 10:00	11/30/98 08:00
3	12/06/98 15:00	12/06/98 17:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
	12/26/98 00:00	
52	12/26/98 04:00	12/28/98 07:00
11	12/29/98 18:00	12/30/98 04:00
2	09/05/99 07:00	09/05/99 08:00
	09/05/99 15:00	
4	09/06/99 12:00	09/06/99 15:00
	09/11/99 15:00	
7	09/12/99 02:00	09/12/99 08:00
2	10/02/99 13:00	10/02/99 14:00
3	10/02/99 18:00	10/02/99 20:00
12	10/03/99 05:00	10/03/99 16:00
2	10/08/99 05:00	10/08/99 06:00
15	10/09/99 06:00	10/09/99 20:00
11	10/10/99 08:00	10/10/99 18:00
6	10/13/99 02:00	10/13/99 07:00
2	10/14/99 03:00	10/14/99 04:00
13	10/16/99 08:00	10/16/99 20:00
12	10/17/99 09:00	10/17/99 20:00
10	10/18/99 10:00	10/18/99 19:00
8	10/19/99 12:00	10/19/99 19:00
7	10/20/99 13:00	10/20/99 19:00
5	10/21/99 14:00	10/21/99 18:00
8	10/22/99 12:00	10/22/99 19:00
8	10/23/99 12:00	10/23/99 19:00
10	10/24/99 10:00	10/24/99 19:00
9	10/25/99 11:00	10/25/99 19:00
8	10/26/99 12:00	10/26/99 19:00
8	10/27/99 12:00	10/27/99 19:00
7	10/28/99 13:00	10/28/99 19:00
8	10/29/99 11:00	10/29/99 18:00
19	10/30/99 10:00	10/31/99 04:00
14	10/31/99 08:00	10/31/99 21:00
6	10/31/99 23:00	11/01/99 04:00
11	11/01/99 09:00	11/01/99 19:00
8	11/02/99 12:00	11/02/99 19:00
10	11/03/99 10:00	11/03/99 19:00
8	11/04/99 12:00	11/04/99 19:00
7	11/05/99 12:00	11/05/99 18:00
7	11/07/99 13:00	11/07/99 19:00
7	11/08/99 12:00	11/08/99 18:00
6	11/09/99 13:00	11/09/99 18:00
3	11/10/99 16:00	11/10/99 18:00
4	11/11/99 15:00	11/11/99 18:00
3	11/19/99 16:00	11/19/99 18:00
4	11/21/99 11:00	11/21/99 14:00
30	08/19/00 15:00	08/20/00 20:00
16	08/23/00 17:00	08/24/00 08:00
27	08/26/00 19:00	08/27/00 21:00
4	08/31/00 18:00	08/31/00 21:00
7	09/02/00 14:00	09/02/00 20:00
8	09/03/00 02:00	09/03/00 09:00
2	09/03/00 13:00	09/03/00 14:00
3	09/03/00 17:00	09/03/00 19:00
7	09/04/00 00:00	09/04/00 06:00
7	09/04/00 13:00	09/04/00 19:00
	09/06/00 12:00	
3	09/08/00 14:00	09/08/00 16:00
3	09/09/00 05:00	09/09/00 07:00
4	09/09/00 13:00	09/09/00 16:00
15	09/10/00 03:00	09/10/00 17:00
2	09/15/00 13:00	09/15/00 14:00
8	09/16/00 14:00	09/16/00 21:00
14	09/17/00 05:00	09/17/00 18:00
19	09/24/00 01:00	09/24/00 19:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
6	09/25/00 00:00	09/25/00 05:00
6	09/26/00 13:00	09/26/00 18:00
11	09/27/00 06:00	09/27/00 16:00
8	10/01/00 01:00	10/01/00 08:00
5	10/01/00 18:00	10/01/00 22:00
3	10/03/00 06:00	10/03/00 08:00
5	10/04/00 03:00	10/04/00 07:00
3	10/05/00 04:00	10/05/00 06:00
3	10/05/00 19:00	10/05/00 21:00
3	10/06/00 06:00	10/06/00 08:00
4	10/07/00 05:00	10/07/00 08:00
8	10/08/00 01:00	10/08/00 08:00
9	10/08/00 22:00	10/09/00 06:00
3	10/11/00 04:00	10/11/00 06:00
8	10/14/00 01:00	10/14/00 08:00
7	10/15/00 03:00	10/15/00 09:00
12	10/16/00 08:00	10/16/00 19:00
7	10/17/00 12:00	10/17/00 18:00
4	10/18/00 16:00	10/18/00 19:00
17	10/21/00 17:00	10/22/00 09:00
7	10/22/00 18:00	10/23/00 00:00
5	10/27/00 15:00	10/27/00 19:00
	10/28/00 12:00	
2	10/28/00 18:00	10/28/00 19:00
	10/29/00 11:00	
6	11/08/00 12:00	11/08/00 17:00
5	11/11/00 15:00	11/11/00 19:00
3	11/19/00 09:00	11/19/00 11:00
4	11/19/00 15:00	11/19/00 18:00
475	07/25/01 18:00	08/14/01 12:00
8	08/15/01 03:00	08/15/01 10:00
	08/15/01 16:00	
3	08/16/01 04:00	08/16/01 06:00
3	08/16/01 15:00	08/16/01 17:00
5	08/17/01 03:00	08/17/01 07:00
10	08/17/01 19:00	08/18/01 04:00
12	08/18/01 08:00	08/18/01 19:00
14	08/19/01 03:00	08/19/01 16:00
2	08/19/01 22:00	08/19/01 23:00
3	08/20/01 05:00	08/20/01 07:00
11	08/20/01 12:00	08/20/01 22:00
3	08/21/01 04:00	08/21/01 06:00
4	08/21/01 10:00	08/21/01 13:00
220	08/26/02 06:00	09/04/02 09:00
100-D Total of 8 missing timesteps in 2 different time gaps, or 0.01% of the full timeseries that begins 11/08/96 15:00 and ends 08/30/04 03:00.		
2	09/04/02 08:00	09/04/02 09:00
6	10/24/03 10:00	10/24/03 15:00
100-H Total of 5784 missing timesteps in 439 different time gaps, or 5.66% of the full timeseries that begins 01/01/93 00:00 and ends 08/30/04 03:00.		
	03/03/94 12:00	
2	08/17/95 09:00	08/17/95 10:00
163	06/02/97 10:00	06/09/97 04:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
50	06/23/97 09:00	06/25/97 10:00
128	06/25/97 12:00	06/30/97 19:00
3	06/30/97 23:00	07/01/97 01:00
16	07/01/97 11:00	07/02/97 02:00
17	07/09/97 17:00	07/10/97 09:00
303	10/28/97 23:00	11/10/97 13:00
203	07/13/98 05:00	07/21/98 15:00
9	08/01/98 10:00	08/01/98 18:00
11	08/02/98 10:00	08/02/98 20:00
9	08/16/98 14:00	08/16/98 22:00
6	08/17/98 05:00	08/17/98 10:00
2	08/25/98 07:00	08/25/98 08:00
5	08/27/98 07:00	08/27/98 11:00
5	08/29/98 08:00	08/29/98 12:00
3	08/31/98 08:00	08/31/98 10:00
6	09/03/98 04:00	09/03/98 09:00
5	09/04/98 05:00	09/04/98 09:00
17	09/05/98 01:00	09/05/98 17:00
7	09/06/98 04:00	09/06/98 10:00
9	09/07/98 02:00	09/07/98 10:00
6	09/08/98 02:00	09/08/98 07:00
5	09/09/98 06:00	09/09/98 10:00
4	09/11/98 07:00	09/11/98 10:00
10	09/12/98 06:00	09/12/98 15:00
5	09/13/98 15:00	09/13/98 19:00
2	09/16/98 06:00	09/16/98 07:00
3	09/17/98 15:00	09/17/98 17:00
4	09/18/98 12:00	09/18/98 15:00
6	09/19/98 05:00	09/19/98 10:00
13	09/20/98 04:00	09/20/98 16:00
11	09/21/98 05:00	09/21/98 15:00
10	09/22/98 04:00	09/22/98 13:00
8	09/23/98 05:00	09/23/98 12:00
7	09/24/98 07:00	09/24/98 13:00
3	09/25/98 02:00	09/25/98 04:00
4	09/25/98 10:00	09/25/98 13:00
9	09/26/98 07:00	09/26/98 15:00
18	09/27/98 03:00	09/27/98 20:00
4	09/28/98 07:00	09/28/98 10:00
3	09/29/98 08:00	09/29/98 10:00
5	09/30/98 06:00	09/30/98 10:00
13	10/01/98 02:00	10/01/98 14:00
16	10/02/98 23:00	10/03/98 14:00
28	10/04/98 00:00	10/05/98 03:00
2	10/05/98 06:00	10/05/98 07:00
5	10/06/98 09:00	10/06/98 13:00
11	10/07/98 08:00	10/07/98 18:00
9	10/08/98 06:00	10/08/98 14:00
6	10/09/98 06:00	10/09/98 11:00
5	10/09/98 23:00	10/10/98 03:00
9	10/10/98 06:00	10/10/98 14:00
18	10/10/98 19:00	10/11/98 12:00
12	10/12/98 00:00	10/12/98 11:00
	10/13/98 07:00	
	10/13/98 13:00	
4	10/14/98 07:00	10/14/98 10:00
5	10/16/98 10:00	10/16/98 14:00
38	10/17/98 10:00	10/18/98 23:00
12	10/19/98 09:00	10/19/98 20:00
12	10/20/98 09:00	10/20/98 20:00
10	10/21/98 11:00	10/21/98 20:00
12	10/22/98 09:00	10/22/98 20:00
12	10/23/98 09:00	10/23/98 20:00
14	10/24/98 08:00	10/24/98 21:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
14	10/25/98 08:00	10/25/98 21:00
14	10/26/98 08:00	10/26/98 21:00
3	10/27/98 02:00	10/27/98 04:00
10	10/27/98 11:00	10/27/98 20:00
10	10/28/98 11:00	10/28/98 20:00
7	10/29/98 13:00	10/29/98 19:00
8	10/30/98 13:00	10/30/98 20:00
10	10/31/98 12:00	10/31/98 21:00
13	11/01/98 09:00	11/01/98 21:00
11	11/02/98 10:00	11/02/98 20:00
10	11/03/98 10:00	11/03/98 19:00
7	11/04/98 13:00	11/04/98 19:00
7	11/05/98 13:00	11/05/98 19:00
10	11/06/98 13:00	11/06/98 22:00
12	11/07/98 12:00	11/07/98 23:00
8	11/08/98 12:00	11/08/98 19:00
8	11/09/98 12:00	11/09/98 19:00
7	11/10/98 12:00	11/10/98 18:00
2	11/13/98 17:00	11/13/98 18:00
5	11/14/98 15:00	11/14/98 19:00
29	11/15/98 11:00	11/16/98 15:00
12	11/22/98 11:00	11/22/98 22:00
2	11/24/98 17:00	11/24/98 18:00
3	11/25/98 17:00	11/25/98 19:00
96	11/26/98 10:00	11/30/98 09:00
	12/04/98 10:00	
3	12/06/98 16:00	12/06/98 18:00
	12/13/98 22:00	
56	12/26/98 01:00	12/28/98 08:00
12	12/29/98 18:00	12/30/98 05:00
6	10/02/99 15:00	10/02/99 20:00
10	10/03/99 07:00	10/03/99 16:00
13	10/09/99 08:00	10/09/99 20:00
11	10/10/99 09:00	10/10/99 19:00
5	10/13/99 04:00	10/13/99 08:00
11	10/16/99 10:00	10/16/99 20:00
11	10/17/99 11:00	10/17/99 21:00
10	10/18/99 11:00	10/18/99 20:00
8	10/19/99 13:00	10/19/99 20:00
6	10/20/99 14:00	10/20/99 19:00
5	10/21/99 15:00	10/21/99 19:00
7	10/22/99 14:00	10/22/99 20:00
8	10/23/99 13:00	10/23/99 20:00
9	10/24/99 12:00	10/24/99 20:00
9	10/25/99 12:00	10/25/99 20:00
8	10/26/99 13:00	10/26/99 20:00
7	10/27/99 14:00	10/27/99 20:00
6	10/28/99 14:00	10/28/99 19:00
7	10/29/99 13:00	10/29/99 19:00
18	10/30/99 12:00	10/31/99 05:00
14	10/31/99 09:00	10/31/99 22:00
5	11/01/99 00:00	11/01/99 04:00
10	11/01/99 11:00	11/01/99 20:00
8	11/02/99 13:00	11/02/99 20:00
8	11/03/99 12:00	11/03/99 19:00
7	11/04/99 13:00	11/04/99 19:00
6	11/05/99 13:00	11/05/99 18:00
7	11/07/99 14:00	11/07/99 20:00
6	11/08/99 14:00	11/08/99 19:00
2	11/09/99 15:00	11/09/99 16:00
2	11/10/99 18:00	11/10/99 19:00
3	11/11/99 17:00	11/11/99 19:00
4	11/21/99 12:00	11/21/99 15:00
4	03/19/00 18:00	03/19/00 21:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
10	03/20/00 00:00	03/20/00 09:00
	03/26/00 04:00	
9	03/27/00 01:00	03/27/00 09:00
	04/01/00 17:00	
30	08/19/00 16:00	08/20/00 21:00
15	08/23/00 19:00	08/24/00 09:00
27	08/26/00 20:00	08/27/00 22:00
4	08/31/00 19:00	08/31/00 22:00
6	09/02/00 16:00	09/02/00 21:00
6	09/03/00 04:00	09/03/00 09:00
2	09/03/00 14:00	09/03/00 15:00
6	09/04/00 02:00	09/04/00 07:00
6	09/04/00 14:00	09/04/00 19:00
2	09/08/00 15:00	09/08/00 16:00
2	09/09/00 07:00	09/09/00 08:00
8	09/09/00 14:00	09/09/00 21:00
15	09/10/00 04:00	09/10/00 18:00
	09/15/00 14:00	
2	09/16/00 08:00	09/16/00 09:00
7	09/16/00 15:00	09/16/00 21:00
13	09/17/00 07:00	09/17/00 19:00
19	09/24/00 02:00	09/24/00 20:00
5	09/25/00 02:00	09/25/00 06:00
5	09/26/00 14:00	09/26/00 18:00
2	09/27/00 07:00	09/27/00 08:00
5	09/27/00 13:00	09/27/00 17:00
22	10/01/00 02:00	10/01/00 23:00
5	10/03/00 08:00	10/03/00 12:00
5	10/04/00 04:00	10/04/00 08:00
3	10/05/00 06:00	10/05/00 08:00
10	10/05/00 12:00	10/05/00 21:00
2	10/06/00 08:00	10/06/00 09:00
14	10/07/00 07:00	10/07/00 20:00
16	10/08/00 02:00	10/08/00 17:00
7	10/09/00 00:00	10/09/00 06:00
3	10/09/00 11:00	10/09/00 13:00
2	10/11/00 05:00	10/11/00 06:00
8	10/14/00 02:00	10/14/00 09:00
19	10/15/00 04:00	10/15/00 22:00
11	10/16/00 10:00	10/16/00 20:00
7	10/17/00 13:00	10/17/00 19:00
8	10/18/00 13:00	10/18/00 20:00
5	10/19/00 15:00	10/19/00 19:00
4	10/20/00 14:00	10/20/00 17:00
35	10/21/00 16:00	10/23/00 02:00
7	10/27/00 15:00	10/27/00 21:00
9	10/28/00 12:00	10/28/00 20:00
10	10/29/00 11:00	10/29/00 20:00
6	10/30/00 13:00	10/30/00 18:00
3	11/01/00 17:00	11/01/00 19:00
7	11/08/00 13:00	11/08/00 19:00
6	11/11/00 15:00	11/11/00 20:00
6	11/12/00 13:00	11/12/00 18:00
2	11/16/00 17:00	11/16/00 18:00
3	11/17/00 16:00	11/17/00 18:00
3	11/18/00 16:00	11/18/00 18:00
10	11/19/00 10:00	11/19/00 19:00
12	05/08/01 05:00	05/08/01 16:00
71	05/08/01 19:00	05/11/01 17:00
74	05/12/01 08:00	05/15/01 09:00
151	05/15/01 15:00	05/21/01 21:00
5	05/26/01 09:00	05/26/01 13:00
63	05/26/01 16:00	05/29/01 06:00
3	05/29/01 15:00	05/29/01 17:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
6	06/03/01 15:00	06/03/01 20:00
9	06/10/01 22:00	06/11/01 06:00
7	06/16/01 11:00	06/16/01 17:00
7	06/17/01 09:00	06/17/01 15:00
	06/17/01 19:00	
5	06/18/01 05:00	06/18/01 09:00
2	06/18/01 11:00	06/18/01 12:00
5	06/22/01 20:00	06/23/01 00:00
3	06/23/01 18:00	06/23/01 20:00
10	06/24/01 14:00	06/24/01 23:00
6	06/25/01 04:00	06/25/01 09:00
5	06/30/01 14:00	06/30/01 18:00
3	07/02/01 06:00	07/02/01 08:00
3	07/02/01 17:00	07/02/01 19:00
2	07/04/01 08:00	07/04/01 09:00
22	07/04/01 13:00	07/05/01 10:00
17	07/05/01 17:00	07/06/01 09:00
19	07/06/01 17:00	07/07/01 11:00
33	07/07/01 13:00	07/08/01 21:00
13	07/09/01 05:00	07/09/01 17:00
3	07/10/01 06:00	07/10/01 08:00
2	07/10/01 15:00	07/10/01 16:00
3	07/11/01 06:00	07/11/01 08:00
56	07/11/01 12:00	07/13/01 19:00
18	07/14/01 03:00	07/14/01 20:00
63	07/15/01 04:00	07/17/01 18:00
4	07/18/01 06:00	07/18/01 09:00
24	07/18/01 19:00	07/19/01 18:00
17	07/20/01 03:00	07/20/01 19:00
56	07/21/01 02:00	07/23/01 09:00
5	07/23/01 17:00	07/23/01 21:00
32	07/24/01 11:00	07/25/01 18:00
8	07/26/01 01:00	07/26/01 08:00
19	07/26/01 13:00	07/27/01 07:00
9	07/27/01 14:00	07/27/01 22:00
76	07/28/01 05:00	07/31/01 08:00
9	07/31/01 13:00	07/31/01 21:00
23	07/31/01 23:00	08/01/01 21:00
4	08/02/01 04:00	08/02/01 07:00
8	08/02/01 12:00	08/02/01 19:00
18	08/03/01 05:00	08/03/01 22:00
59	08/04/01 10:00	08/06/01 20:00
5	08/09/01 05:00	08/09/01 09:00
12	08/09/01 20:00	08/10/01 07:00
2	08/10/01 14:00	08/10/01 15:00
8	08/11/01 15:00	08/11/01 22:00
14	08/12/01 06:00	08/12/01 19:00
12	08/13/01 06:00	08/13/01 17:00
3	08/14/01 05:00	08/14/01 07:00
6	08/15/01 05:00	08/15/01 10:00
	08/16/01 06:00	
5	08/17/01 04:00	08/17/01 08:00
10	08/17/01 20:00	08/18/01 05:00
12	08/18/01 09:00	08/18/01 20:00
12	08/19/01 05:00	08/19/01 16:00
11	08/20/01 13:00	08/20/01 23:00
	08/21/01 06:00	
8	08/21/01 12:00	08/21/01 19:00
5	08/22/01 03:00	08/22/01 07:00
8	08/22/01 12:00	08/22/01 19:00
5	08/23/01 04:00	08/23/01 08:00
5	08/23/01 16:00	08/23/01 20:00
13	08/24/01 06:00	08/24/01 18:00
7	08/25/01 20:00	08/26/01 02:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
12	08/26/01 15:00	08/27/01 02:00
23	09/01/01 15:00	09/02/01 13:00
18	09/02/01 15:00	09/03/01 08:00
5	09/03/01 15:00	09/03/01 19:00
77	09/06/01 19:00	09/09/01 23:00
17	09/10/01 01:00	09/10/01 17:00
75	09/14/01 17:00	09/17/01 19:00
15	09/18/01 01:00	09/18/01 15:00
5	09/19/01 03:00	09/19/01 07:00
6	09/19/01 15:00	09/19/01 20:00
3	09/20/01 03:00	09/20/01 05:00
3	09/21/01 13:00	09/21/01 15:00
3	09/22/01 05:00	09/22/01 07:00
8	09/22/01 13:00	09/22/01 20:00
6	09/23/01 01:00	09/23/01 06:00
12	09/23/01 09:00	09/23/01 20:00
5	09/24/01 05:00	09/24/01 09:00
4	09/24/01 18:00	09/24/01 21:00
6	09/26/01 15:00	09/26/01 20:00
2	09/27/01 05:00	09/27/01 06:00
5	09/27/01 13:00	09/27/01 17:00
3	09/28/01 04:00	09/28/01 06:00
4	09/28/01 14:00	09/28/01 17:00
5	09/29/01 04:00	09/29/01 08:00
15	09/29/01 13:00	09/30/01 03:00
10	09/30/01 10:00	09/30/01 19:00
16	10/02/01 19:00	10/03/01 10:00
26	10/03/01 17:00	10/04/01 18:00
70	10/05/01 14:00	10/08/01 11:00
5	10/08/01 17:00	10/08/01 21:00
4	10/09/01 04:00	10/09/01 07:00
7	10/09/01 14:00	10/09/01 20:00
7	10/11/01 01:00	10/11/01 07:00
6	10/11/01 16:00	10/11/01 21:00
3	10/12/01 05:00	10/12/01 07:00
13	10/13/01 03:00	10/13/01 15:00
28	10/13/01 18:00	10/14/01 21:00
4	10/15/01 03:00	10/15/01 06:00
8	10/16/01 01:00	10/16/01 08:00
3	10/17/01 03:00	10/17/01 05:00
11	10/18/01 10:00	10/18/01 20:00
83	10/19/01 10:00	10/22/01 20:00
9	10/23/01 11:00	10/23/01 19:00
13	10/24/01 09:00	10/24/01 21:00
14	10/25/01 07:00	10/25/01 20:00
11	10/26/01 10:00	10/26/01 20:00
12	10/27/01 09:00	10/27/01 20:00
20	10/28/01 03:00	10/28/01 22:00
2	10/29/01 03:00	10/29/01 04:00
12	10/29/01 10:00	10/29/01 21:00
12	10/30/01 11:00	10/30/01 22:00
	10/31/01 05:00	
10	10/31/01 11:00	10/31/01 20:00
11	11/01/01 10:00	11/01/01 20:00
36	11/02/01 10:00	11/03/01 21:00
26	11/04/01 03:00	11/05/01 04:00
13	11/05/01 08:00	11/05/01 20:00
10	11/06/01 11:00	11/06/01 20:00
6	11/07/01 14:00	11/07/01 19:00
7	11/08/01 14:00	11/08/01 20:00
8	11/09/01 12:00	11/09/01 19:00
38	11/10/01 09:00	11/11/01 22:00
7	11/12/01 00:00	11/12/01 06:00
11	11/12/01 11:00	11/12/01 21:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
9	11/13/01 11:00	11/13/01 19:00
10	11/14/01 11:00	11/14/01 20:00
11	11/15/01 10:00	11/15/01 20:00
8	11/16/01 13:00	11/16/01 20:00
10	11/17/01 13:00	11/17/01 22:00
10	11/18/01 12:00	11/18/01 21:00
2	11/19/01 18:00	11/19/01 19:00
4	11/20/01 01:00	11/20/01 04:00
	11/20/01 17:00	
2	11/22/01 18:00	11/22/01 19:00
4	11/23/01 17:00	11/23/01 20:00
14	11/24/01 21:00	11/25/01 10:00
3	11/25/01 16:00	11/25/01 18:00
2	11/26/01 05:00	11/26/01 06:00
33	12/02/01 00:00	12/03/01 08:00
5	12/03/01 16:00	12/03/01 20:00
5	12/07/01 04:00	12/07/01 08:00
2	12/08/01 04:00	12/08/01 05:00
34	12/09/01 00:00	12/10/01 09:00
4	12/14/01 17:00	12/14/01 20:00
4	12/15/01 16:00	12/15/01 19:00
2	12/16/01 17:00	12/16/01 18:00
6	12/17/01 03:00	12/17/01 08:00
3	12/17/01 16:00	12/17/01 18:00
2	12/22/01 16:00	12/22/01 17:00
	12/24/01 06:00	
3	12/24/01 18:00	12/24/01 20:00
15	12/25/01 18:00	12/26/01 08:00
5	12/31/01 04:00	12/31/01 08:00
	12/31/01 18:00	
5	01/08/02 04:00	01/08/02 08:00
2	01/08/02 17:00	01/08/02 18:00
6	01/11/02 03:00	01/11/02 08:00
	01/11/02 17:00	
	01/12/02 06:00	
5	01/13/02 15:00	01/13/02 19:00
	01/21/02 06:00	
	02/02/02 18:00	
	02/10/02 19:00	
3	02/15/02 04:00	02/15/02 06:00
5	02/23/02 05:00	02/23/02 09:00
3	02/24/02 17:00	02/24/02 19:00
3	02/26/02 06:00	02/26/02 08:00
	03/01/02 06:00	
4	03/02/02 16:00	03/02/02 19:00
6	03/03/02 17:00	03/03/02 22:00
17	03/04/02 16:00	03/05/02 08:00
	03/06/02 17:00	
3	03/07/02 17:00	03/07/02 19:00
9	03/10/02 04:00	03/10/02 12:00
5	03/11/02 05:00	03/11/02 09:00
5	03/11/02 11:00	03/11/02 15:00
3	03/12/02 04:00	03/12/02 06:00
	03/13/02 06:00	
12	03/14/02 05:00	03/14/02 16:00
	03/15/02 05:00	
5	03/15/02 17:00	03/15/02 21:00
15	03/16/02 17:00	03/17/02 07:00
3	03/17/02 17:00	03/17/02 19:00
2	03/18/02 05:00	03/18/02 06:00
	03/20/02 04:00	
277	03/23/02 07:00	04/03/02 19:00
4	04/03/02 23:00	04/04/02 02:00
6	04/04/02 16:00	04/04/02 21:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
16	04/05/02 02:00	04/05/02 17:00
93	04/06/02 06:00	04/10/02 02:00
3	07/27/02 20:00	07/27/02 22:00
4	08/17/02 17:00	08/17/02 20:00
4	08/18/02 13:00	08/18/02 16:00
12	08/25/02 18:00	08/26/02 05:00
13	09/01/02 10:00	09/01/02 22:00
6	09/02/02 17:00	09/02/02 22:00
2	09/04/02 08:00	09/04/02 09:00
13	09/04/02 17:00	09/05/02 05:00
6	09/06/02 13:00	09/06/02 18:00
2	09/07/02 08:00	09/07/02 09:00
8	09/07/02 13:00	09/07/02 20:00
15	09/08/02 08:00	09/08/02 22:00
11	09/09/02 00:00	09/09/02 10:00
5	09/10/02 17:00	09/10/02 21:00
11	09/11/02 14:00	09/12/02 00:00
3	09/12/02 18:00	09/12/02 20:00
3	09/13/02 04:00	09/13/02 06:00
3	09/13/02 15:00	09/13/02 17:00
16	09/14/02 20:00	09/15/02 11:00
26	09/15/02 17:00	09/16/02 18:00
8	09/18/02 18:00	09/19/02 01:00
11	09/27/02 17:00	09/28/02 03:00
	09/28/02 05:00	
3	09/28/02 09:00	09/28/02 11:00
22	09/28/02 22:00	09/29/02 19:00
	09/30/02 02:00	
12	09/30/02 06:00	09/30/02 17:00
	10/02/02 15:00	
	10/03/02 05:00	
2	10/03/02 16:00	10/03/02 17:00
	10/04/02 07:00	
3	10/04/02 15:00	10/04/02 17:00
15	10/05/02 08:00	10/05/02 22:00
6	10/06/02 08:00	10/06/02 13:00
2	10/06/02 19:00	10/06/02 20:00
4	10/07/02 03:00	10/07/02 06:00
	10/10/02 14:00	
8	10/12/02 11:00	10/12/02 18:00
16	10/13/02 03:00	10/13/02 18:00
6	10/14/02 02:00	10/14/02 07:00
10	10/15/02 11:00	10/15/02 20:00
10	10/16/02 12:00	10/16/02 21:00
10	10/17/02 12:00	10/17/02 21:00
11	10/18/02 11:00	10/18/02 21:00
13	10/19/02 12:00	10/20/02 00:00
	10/20/02 05:00	
13	10/20/02 10:00	10/20/02 22:00
11	10/21/02 10:00	10/21/02 20:00
10	10/22/02 11:00	10/22/02 20:00
	12/28/02 15:00	

100-F

Total of 16824 missing timesteps in 146 different time gaps, or 17.06% of the full timeseries that begins 01/01/93 00:00 and ends 03/31/04 23:00.

91	07/08/93 14:00	07/12/93 08:00
3217	11/24/94 07:00	04/07/95 07:00
624	04/19/95 09:00	05/15/95 08:00
166	03/17/97 09:00	03/24/97 06:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
	03/24/97 09:00	
	03/24/97 11:00	
8	06/04/97 09:00	06/04/97 16:00
5	10/01/98 05:00	10/01/98 09:00
2	10/01/98 13:00	10/01/98 14:00
7	10/03/98 07:00	10/03/98 13:00
3	10/04/98 12:00	10/04/98 14:00
2	10/05/98 00:00	10/05/98 01:00
4	10/07/98 15:00	10/07/98 18:00
8	10/08/98 07:00	10/08/98 14:00
3	10/09/98 09:00	10/09/98 11:00
2	10/10/98 11:00	10/10/98 12:00
12	10/11/98 00:00	10/11/98 11:00
6	10/12/98 03:00	10/12/98 08:00
9	10/17/98 14:00	10/17/98 22:00
20	10/18/98 04:00	10/18/98 23:00
7	10/19/98 14:00	10/19/98 20:00
8	10/20/98 13:00	10/20/98 20:00
6	10/21/98 15:00	10/21/98 20:00
12	10/22/98 10:00	10/22/98 21:00
12	10/23/98 10:00	10/23/98 21:00
13	10/24/98 10:00	10/24/98 22:00
13	10/25/98 09:00	10/25/98 21:00
9	10/26/98 13:00	10/26/98 21:00
11	10/27/98 12:00	10/27/98 22:00
8	10/28/98 13:00	10/28/98 20:00
6	10/30/98 15:00	10/30/98 20:00
8	10/31/98 14:00	10/31/98 21:00
12	11/01/98 10:00	11/01/98 21:00
10	11/02/98 11:00	11/02/98 20:00
8	11/03/98 13:00	11/03/98 20:00
4	11/04/98 17:00	11/04/98 20:00
6	11/05/98 15:00	11/05/98 20:00
8	11/06/98 16:00	11/06/98 23:00
10	11/07/98 14:00	11/07/98 23:00
6	11/08/98 14:00	11/08/98 19:00
8	11/15/98 14:00	11/15/98 21:00
5	11/16/98 07:00	11/16/98 11:00
5	11/22/98 14:00	11/22/98 18:00
4	11/26/98 15:00	11/26/98 18:00
6	11/27/98 02:00	11/27/98 07:00
7	11/27/98 16:00	11/27/98 22:00
21	11/28/98 01:00	11/28/98 21:00
29	11/29/98 01:00	11/30/98 05:00
8446	02/14/00 17:00	01/31/01 14:00
787	01/31/01 16:00	03/05/01 10:00
552	03/05/01 12:00	03/28/01 11:00
793	03/28/01 13:00	04/30/01 13:00
212	04/30/01 15:00	05/09/01 10:00
43	05/13/01 01:00	05/14/01 19:00
15	05/15/01 23:00	05/16/01 13:00
8	05/16/01 21:00	05/17/01 04:00
20	05/19/01 01:00	05/19/01 20:00
26	05/20/01 06:00	05/21/01 07:00
10	05/28/01 02:00	05/28/01 11:00
8	07/08/01 08:00	07/08/01 15:00
	07/08/01 20:00	
38	07/11/01 20:00	07/13/01 09:00
2	07/13/01 17:00	07/13/01 18:00
14	07/15/01 20:00	07/16/01 09:00
8	07/16/01 13:00	07/16/01 20:00
6	07/17/01 13:00	07/17/01 18:00
38	07/21/01 19:00	07/23/01 08:00
4	07/24/01 20:00	07/24/01 23:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
42	07/28/01 16:00	07/30/01 09:00
7	07/30/01 16:00	07/30/01 22:00
4	07/31/01 04:00	07/31/01 07:00
3	08/03/01 18:00	08/03/01 20:00
6	08/04/01 19:00	08/05/01 00:00
17	08/05/01 06:00	08/05/01 22:00
5	08/10/01 02:00	08/10/01 06:00
	08/11/01 22:00	
4	08/12/01 16:00	08/12/01 19:00
3	08/18/01 02:00	08/18/01 04:00
3	08/20/01 20:00	08/20/01 22:00
5	08/26/01 21:00	08/27/01 01:00
10	09/02/01 00:00	09/02/01 09:00
3	09/02/01 22:00	09/03/01 00:00
2	09/07/01 05:00	09/07/01 06:00
11	09/07/01 10:00	09/07/01 20:00
20	09/08/01 16:00	09/09/01 11:00
5	09/09/01 17:00	09/09/01 21:00
3	09/15/01 19:00	09/15/01 21:00
17	09/16/01 07:00	09/16/01 23:00
	09/29/01 20:00	
4	10/04/01 05:00	10/04/01 08:00
	10/04/01 16:00	
24	10/06/01 02:00	10/07/01 01:00
2	10/07/01 09:00	10/07/01 10:00
16	10/07/01 18:00	10/08/01 09:00
2	10/14/01 01:00	10/14/01 02:00
7	10/14/01 11:00	10/14/01 17:00
14	10/19/01 18:00	10/20/01 07:00
5	10/20/01 17:00	10/20/01 21:00
8	10/21/01 13:00	10/21/01 20:00
3	10/25/01 15:00	10/25/01 17:00
9	10/28/01 09:00	10/28/01 17:00
5	10/29/01 16:00	10/29/01 20:00
5	10/30/01 17:00	10/30/01 21:00
15	11/03/01 06:00	11/03/01 20:00
10	11/04/01 14:00	11/04/01 23:00
6	11/05/01 15:00	11/05/01 20:00
4	11/06/01 17:00	11/06/01 20:00
28	11/10/01 18:00	11/11/01 21:00
	11/14/01 19:00	
5	11/18/01 17:00	11/18/01 21:00
2	09/04/02 08:00	09/04/02 09:00
140	12/25/02 15:00	12/31/02 10:00
3	01/31/03 13:00	01/31/03 15:00
9	07/02/03 22:00	07/03/03 06:00
244	07/05/03 04:00	07/15/03 07:00
8	07/27/03 22:00	07/28/03 05:00
6	08/28/03 12:00	08/28/03 17:00
7	08/31/03 23:00	09/01/03 05:00
3	09/03/03 16:00	09/03/03 18:00
24	09/06/03 15:00	09/07/03 14:00
2	09/07/03 21:00	09/07/03 22:00
9	09/08/03 12:00	09/08/03 20:00
7	09/09/03 09:00	09/09/03 15:00
16	09/10/03 08:00	09/10/03 23:00
7	09/11/03 15:00	09/11/03 21:00
7	09/12/03 16:00	09/12/03 22:00
4	09/13/03 21:00	09/14/03 00:00
27	09/14/03 07:00	09/15/03 09:00
4	09/15/03 18:00	09/15/03 21:00
	09/16/03 07:00	
6	09/18/03 16:00	09/18/03 21:00
10	09/19/03 14:00	09/19/03 23:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
8	09/20/03 14:00	09/20/03 21:00
8	09/21/03 14:00	09/21/03 21:00
4	09/23/03 17:00	09/23/03 20:00
	09/24/03 18:00	
7	09/27/03 20:00	09/28/03 02:00
7	09/28/03 16:00	09/28/03 22:00
3	09/29/03 05:00	09/29/03 07:00
6	10/05/03 12:00	10/05/03 17:00
8	10/12/03 15:00	10/12/03 22:00
10	10/20/03 11:00	10/20/03 20:00
7	10/26/03 14:00	10/26/03 20:00
3	11/11/03 15:00	11/11/03 17:00
4	11/23/03 15:00	11/23/03 18:00
372	12/16/03 01:00	12/31/03 12:00
300 Area		
Total of 3423 missing timesteps in 98 different time gaps, or 2.98% of the full timeseries that begins 11/06/91 12:00 and ends 12/13/04 03:00.		
	01/15/93 16:00	
44	08/23/96 13:00	08/25/96 08:00
11	09/30/96 13:00	09/30/96 23:00
72	04/11/97 11:00	04/14/97 10:00
4	05/30/97 23:00	05/31/97 02:00
3	05/31/97 05:00	05/31/97 07:00
2	05/31/97 11:00	05/31/97 12:00
16	05/31/97 15:00	06/01/97 06:00
2449	06/01/97 10:00	09/11/97 10:00
4	08/01/98 20:00	08/01/98 23:00
14	08/02/98 15:00	08/03/98 04:00
7	08/03/98 10:00	08/03/98 16:00
5	08/07/98 13:00	08/07/98 17:00
4	08/17/98 12:00	08/17/98 15:00
3	09/03/98 12:00	09/03/98 14:00
4	09/04/98 11:00	09/04/98 14:00
9	09/05/98 10:00	09/05/98 18:00
36	09/06/98 10:00	09/07/98 21:00
7	09/08/98 08:00	09/08/98 14:00
11	09/09/98 10:00	09/09/98 20:00
8	09/18/98 17:00	09/19/98 00:00
9	09/19/98 09:00	09/19/98 17:00
8	09/20/98 10:00	09/20/98 17:00
7	09/21/98 12:00	09/21/98 18:00
3	09/22/98 14:00	09/22/98 16:00
6	10/04/98 14:00	10/04/98 19:00
2	10/11/98 10:00	10/11/98 11:00
2	10/13/98 19:00	10/13/98 20:00
3	10/14/98 13:00	10/14/98 15:00
16	10/18/98 10:00	10/19/98 01:00
2	10/19/98 22:00	10/19/98 23:00
4	10/21/98 20:00	10/21/98 23:00
4	10/22/98 21:00	10/23/98 00:00
5	10/23/98 19:00	10/23/98 23:00
2	10/24/98 20:00	10/24/98 21:00
10	10/25/98 17:00	10/26/98 02:00
12	10/26/98 15:00	10/27/98 02:00
3	10/27/98 21:00	10/27/98 23:00
6	11/09/98 18:00	11/09/98 23:00
5	11/10/98 19:00	11/10/98 23:00
35	11/15/98 16:00	11/17/98 02:00
6	11/17/98 19:00	11/18/98 00:00

Table A.2. (continued)

Number of Timesteps In Gap	From	To
8	11/18/98 16:00	11/18/98 23:00
3	11/19/98 21:00	11/19/98 23:00
2	11/27/98 23:00	11/28/98 00:00
7	11/28/98 08:00	11/28/98 14:00
44	11/28/98 21:00	11/30/98 16:00
5	02/28/99 17:00	02/28/99 21:00
	04/17/99 14:00	
15	09/05/99 09:00	09/05/99 23:00
3	09/06/99 18:00	09/06/99 20:00
26	09/11/99 22:00	09/12/99 23:00
5	09/13/99 17:00	09/13/99 21:00
6	09/18/99 15:00	09/18/99 20:00
3	09/19/99 19:00	09/19/99 21:00
11	09/25/99 08:00	09/25/99 18:00
8	09/26/99 17:00	09/27/99 00:00
5	09/27/99 05:00	09/27/99 09:00
	10/17/99 23:00	
	10/18/99 23:00	
2	11/03/99 22:00	11/03/99 23:00
6	11/04/99 19:00	11/05/99 00:00
3	11/05/99 20:00	11/05/99 22:00
28	03/19/00 18:00	03/20/00 21:00
2	04/02/00 18:00	04/02/00 19:00
	08/20/00 08:00	
	08/20/00 12:00	
	08/20/00 14:00	
10	08/20/00 16:00	08/21/00 01:00
18	08/24/00 02:00	08/24/00 19:00
24	08/27/00 05:00	08/28/00 04:00
2	09/03/00 22:00	09/03/00 23:00
6	09/04/00 08:00	09/04/00 13:00
7	09/04/00 18:00	09/05/00 00:00
	09/10/00 21:00	
3	09/17/00 20:00	09/17/00 22:00
30	09/24/00 07:00	09/25/00 12:00
5	09/26/00 19:00	09/26/00 23:00
10	09/27/00 13:00	09/27/00 22:00
15	10/01/00 12:00	10/02/00 02:00
	10/16/00 00:00	
6	10/16/00 19:00	10/17/00 00:00
12	10/22/00 19:00	10/23/00 06:00
4	06/11/01 02:00	06/11/01 05:00
13	09/02/01 04:00	09/02/01 16:00
6	09/03/01 00:00	09/03/01 05:00
2	09/03/01 21:00	09/03/01 22:00
	09/05/02 09:00	
2	09/07/02 22:00	09/07/02 23:00
16	09/08/02 10:00	09/09/02 01:00
4	09/30/02 18:00	09/30/02 21:00
6	10/28/02 06:00	10/28/02 11:00
104	03/08/03 22:00	03/13/03 05:00
	08/28/03 21:00	
47	12/15/03 12:00	12/17/03 10:00
	12/19/03 16:00	
2	12/20/03 12:00	12/20/03 13:00
2	12/22/03 14:00	12/22/03 15:00

Table A.3. Horizontal coordinates and NAVD88 offsets for cross sections. All values except river mile (RM) in meters. Horizontal datum is State Plane, NAD83 and horizontal zone is Washington South/4602. Offset is correction to convert from NGVD29 to NAVD88.

RM	Easting	Northing	Offset
396.76	545536.1	145388.7	1.068
396.49	545752.4	145011.1	1.068
396.26	545992.6	144746.2	1.068
395.96	546417.6	144572.7	1.067
395.58	547013.2	144474.9	1.067
395.19	547631.2	144280.4	1.066
394.75	548299.2	144079.1	1.065
394.30	549008.3	143932.5	1.064
394.00	549472.2	143836.6	1.064
393.70	549975.1	143844.2	1.064
393.31	550613.4	143853.9	1.064
393.00	551122.2	143813.9	1.064
392.60	551765.0	143969.4	1.064
392.28	552262.8	144089.8	1.064
391.92	552851.4	144232.3	1.064
391.57	553412.8	144368.5	1.063
391.20	554000.0	144511.0	1.063
391.03	554281.7	144579.3	1.063
390.62	554920.0	144703.4	1.062
390.15	555666.7	144846.0	1.061
389.89	556074.0	144906.6	1.061
389.57	556560.8	144948.8	1.061
389.00	557435.0	145024.6	1.060
388.52	558104.6	145400.3	1.059
388.00	558831.1	145807.8	1.058
387.63	559388.9	146046.6	1.057
387.27	559911.6	146270.5	1.057
386.84	560578.0	146496.8	1.056
386.55	561040.6	146476.0	1.056
386.00	561948.1	146515.9	1.056
385.57	562596.0	146265.7	1.057
385.04	563393.2	145957.8	1.057
384.46	564253.4	145786.4	1.058
384.14	564720.2	145693.3	1.058
383.75	565313.2	145744.3	1.058
383.46	565753.5	145849.9	1.058
383.16	566214.7	145960.5	1.058
382.81	566729.8	146164.5	1.058
382.41	567275.3	146459.3	1.058
382.14	567661.0	146667.7	1.058
381.81	568090.5	146967.0	1.058
381.31	568711.3	147475.6	1.058
380.85	569279.6	147976.4	1.058
380.55	569616.7	148320.1	1.057
380.00	570251.4	148967.2	1.057
379.69	570550.0	149357.9	1.056
379.03	571198.8	150206.6	1.055
378.69	571536.9	150645.1	1.055
378.28	571896.5	151188.6	1.054
377.74	572438.9	151870.7	1.054
377.30	572928.2	152383.0	1.054
376.89	573357.8	152885.5	1.057
376.52	573683.3	153399.6	1.059
376.11	574041.2	153964.9	1.060
375.78	574367.3	154387.6	1.062
375.65	574505.0	154548.8	1.062
375.55	574602.7	154663.0	1.062
375.24	574917.3	155030.9	1.063
374.85	575383.1	155258.3	1.064
374.51	575854.5	155124.6	1.065
374.18	576326.5	154990.6	1.066

Table A.3. (continued)

RM	Easting	Northing	Offset
373.67	576962.5	154549.3	1.067
373.27	577432.4	154101.0	1.067
372.95	577798.5	153737.5	1.068
372.52	578238.8	153178.5	1.068
372.29	578466.5	152889.4	1.068
371.87	578910.8	152374.8	1.068
371.53	579305.5	152002.4	1.068
371.19	579709.7	151621.0	1.067
370.85	580057.8	151227.3	1.066
370.44	580144.6	150634.4	1.065
370.04	579961.1	150054.9	1.064
369.76	579827.7	149576.6	1.063
369.53	580027.0	149228.8	1.063
369.21	580422.8	148804.6	1.062
368.85	580901.2	148474.8	1.063
368.41	581424.6	148195.6	1.065
368.09	581808.9	147990.5	1.066
367.69	582332.0	147662.0	1.068
367.38	582759.4	147383.7	1.070
366.91	583301.8	146920.9	1.071
366.51	583421.3	146298.6	1.070
366.11	583605.9	145702.6	1.069
365.78	583650.7	145202.9	1.068
365.55	583645.9	144841.0	1.067
365.21	583638.9	144313.3	1.066
364.88	583686.1	143802.4	1.065
364.47	583930.4	143223.1	1.064
364.08	584161.8	142674.2	1.062
363.70	584492.7	142233.4	1.062
363.18	584985.9	141659.8	1.062
362.66	585477.7	141039.6	1.063
362.14	585964.8	140399.2	1.065
361.65	586548.6	139795.9	1.065
361.18	587146.7	139225.5	1.066
360.81	587648.7	138820.7	1.065
360.32	588327.4	138358.9	1.065
360.00	588777.2	138052.8	1.065
359.63	589294.4	137695.7	1.065
359.36	589686.1	137425.2	1.065
358.92	590270.3	136953.3	1.064
358.52	590659.5	136365.6	1.062
358.15	591017.6	135824.7	1.060
357.70	591517.1	135193.1	1.059
357.28	591990.2	134645.2	1.059
356.80	592598.7	134086.5	1.059
356.46	593097.6	133764.6	1.060
355.98	593773.1	133306.4	1.061
355.38	594288.0	132373.5	1.061
355.02	594577.0	131804.0	1.060
354.78	594702.9	131419.6	1.060
354.27	594978.2	130579.5	1.059
354.00	595122.2	130139.8	1.058
353.47	595081.6	129330.5	1.057
353.20	595061.7	128935.4	1.057
352.61	595074.4	128026.7	1.056
352.23	595102.3	127434.4	1.056
351.85	595103.0	126827.8	1.055
351.44	595058.0	126134.0	1.055
351.09	595020.5	125556.7	1.054
350.67	595073.9	124874.1	1.053
350.34	595139.4	124324.1	1.053
349.87	595212.3	123588.0	1.052
349.39	595241.2	122870.8	1.051
348.93	595249.2	122194.0	1.050
348.38	595130.4	121401.7	1.049
347.94	595034.6	120770.4	1.048
347.48	594931.8	120137.7	1.046

Table A.3. (continued)

RM	Easting	Northing	Offset
346.92	594834.4	119354.4	1.045
346.49	594898.5	118734.3	1.044
345.85	594964.4	117824.7	1.042
345.17	594796.7	116894.3	1.040
344.65	594781.2	116225.5	1.039
343.77	594940.4	115048.0	1.037
343.00	595296.1	113806.6	1.034
342.32	595697.5	112809.8	1.033
341.67	595971.3	111812.9	1.032
341.00	596138.9	110752.0	1.031
340.44	596136.9	109851.0	1.031
339.95	596122.0	109062.2	1.031
339.62	595893.9	108589.3	1.031
339.14	595562.4	107901.9	1.031
338.61	595273.5	107115.4	1.031
337.69	595156.7	105746.0	1.032
337.07	595560.2	104875.9	1.031
337.06	595646.9	104893.1	
336.00	597098.5	104137.2	
335.50	597643.9	103517.4	
335.00	598153.1	102940.6	
334.50	598608.1	102401.7	

Appendix B

Bathymetry and Topography Data

Appendix B – Bathymetry and Topography Data

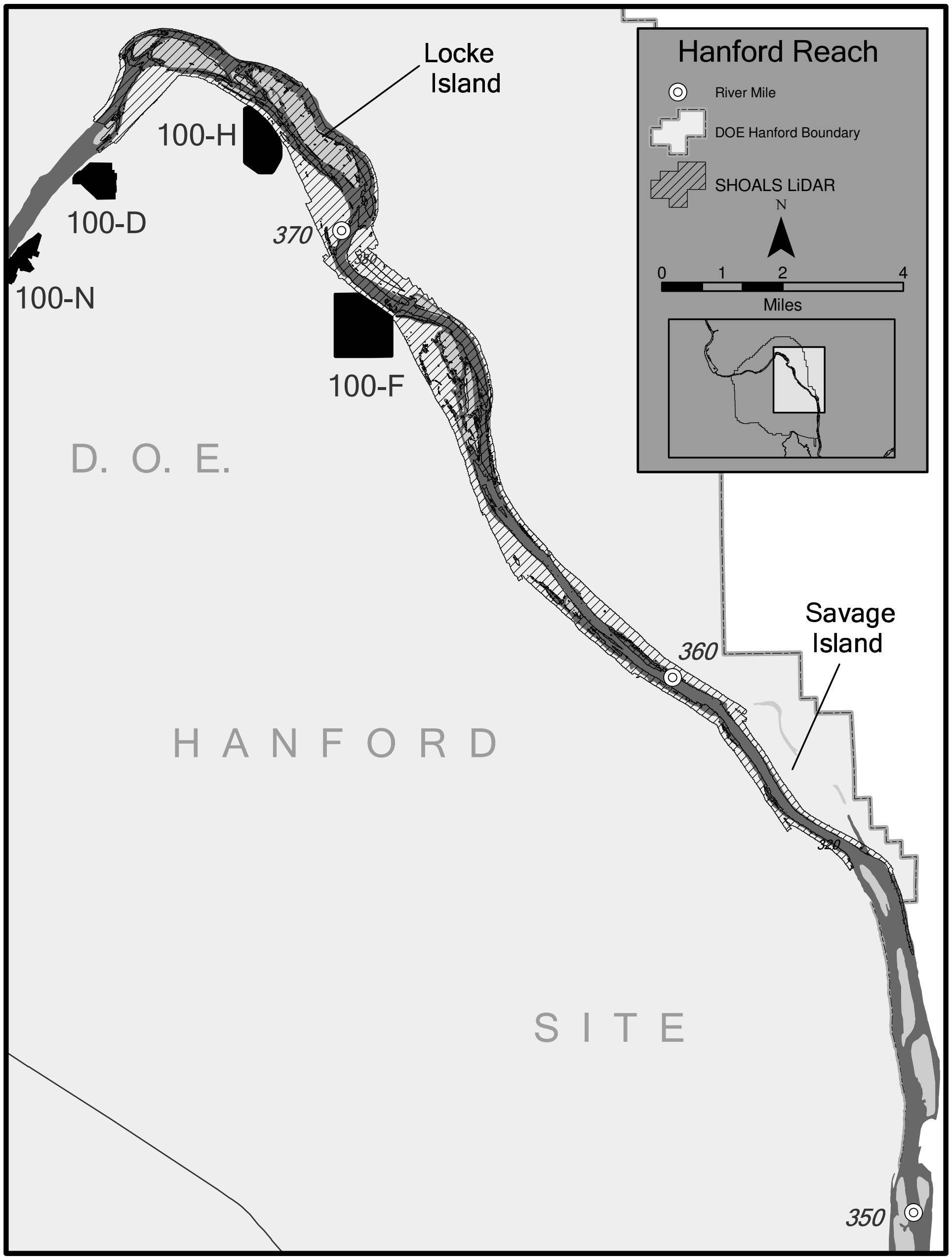

Figure B.1. Area where LIDAR data are available for the Hanford Reach.

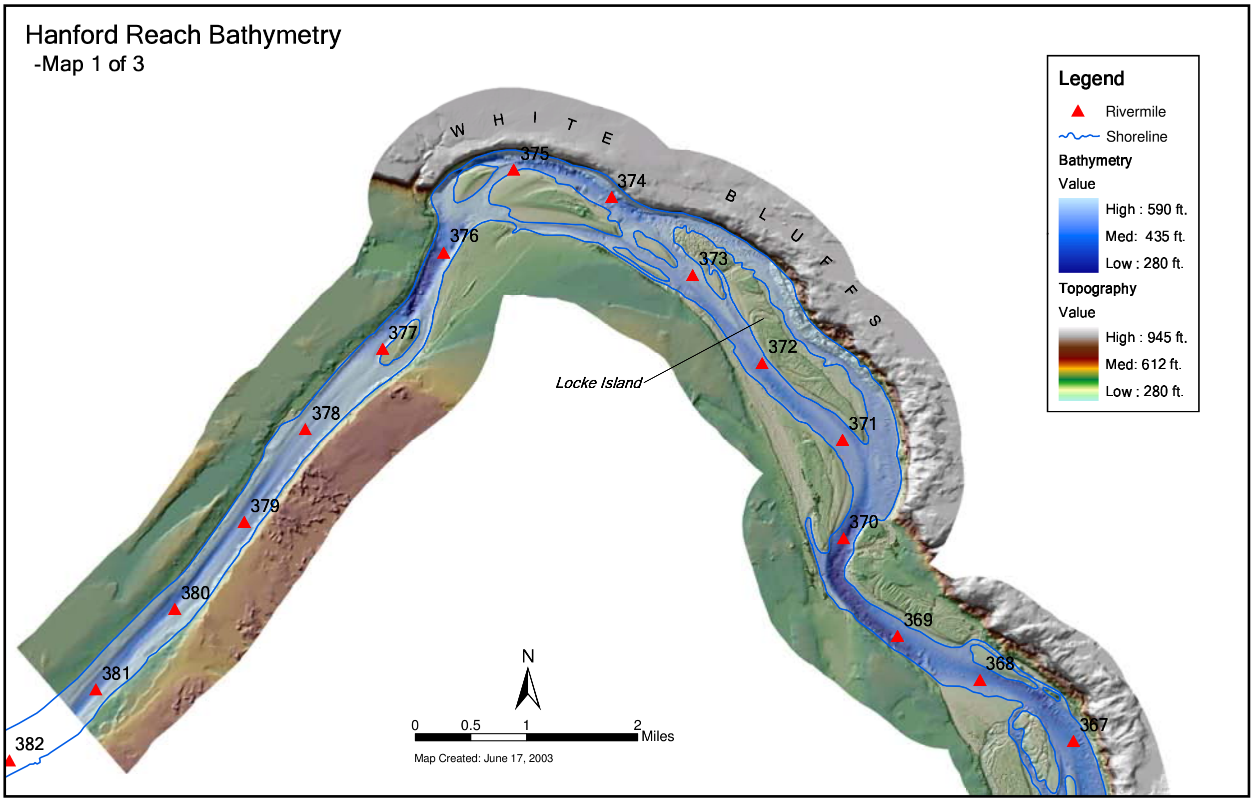

Figure B.2. Hanford Reach bathymetry map 1 of 3. From LIDAR data (McMichael et al. 2003).

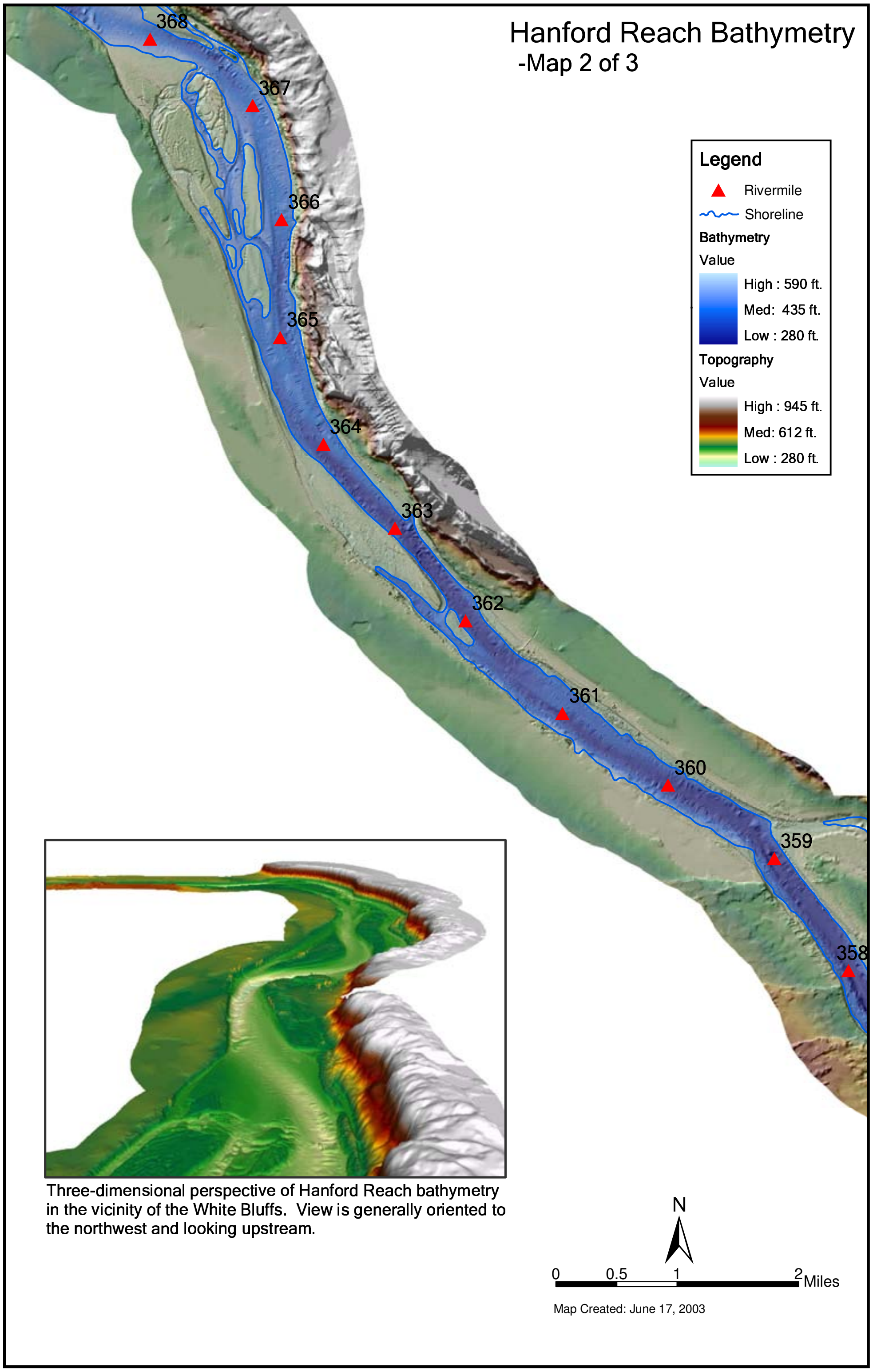

Figure B.3. Hanford Reach bathymetry map 2 of 3. From LIDAR data (McMichael et al. 2003).

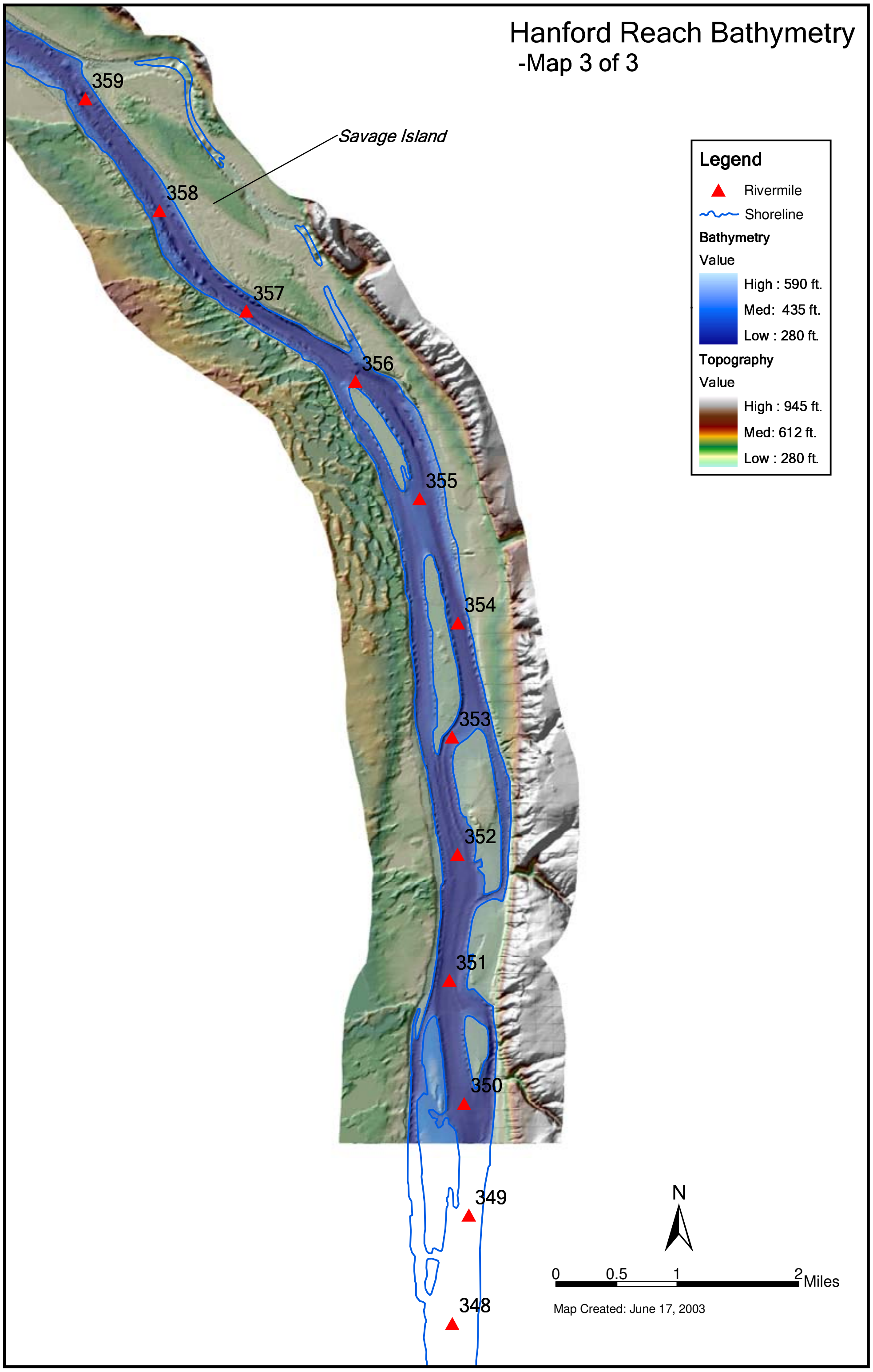

Figure B.4. Hanford Reach bathymetry map 3 of 3. From LIDAR data (McMichael et al. 2003).

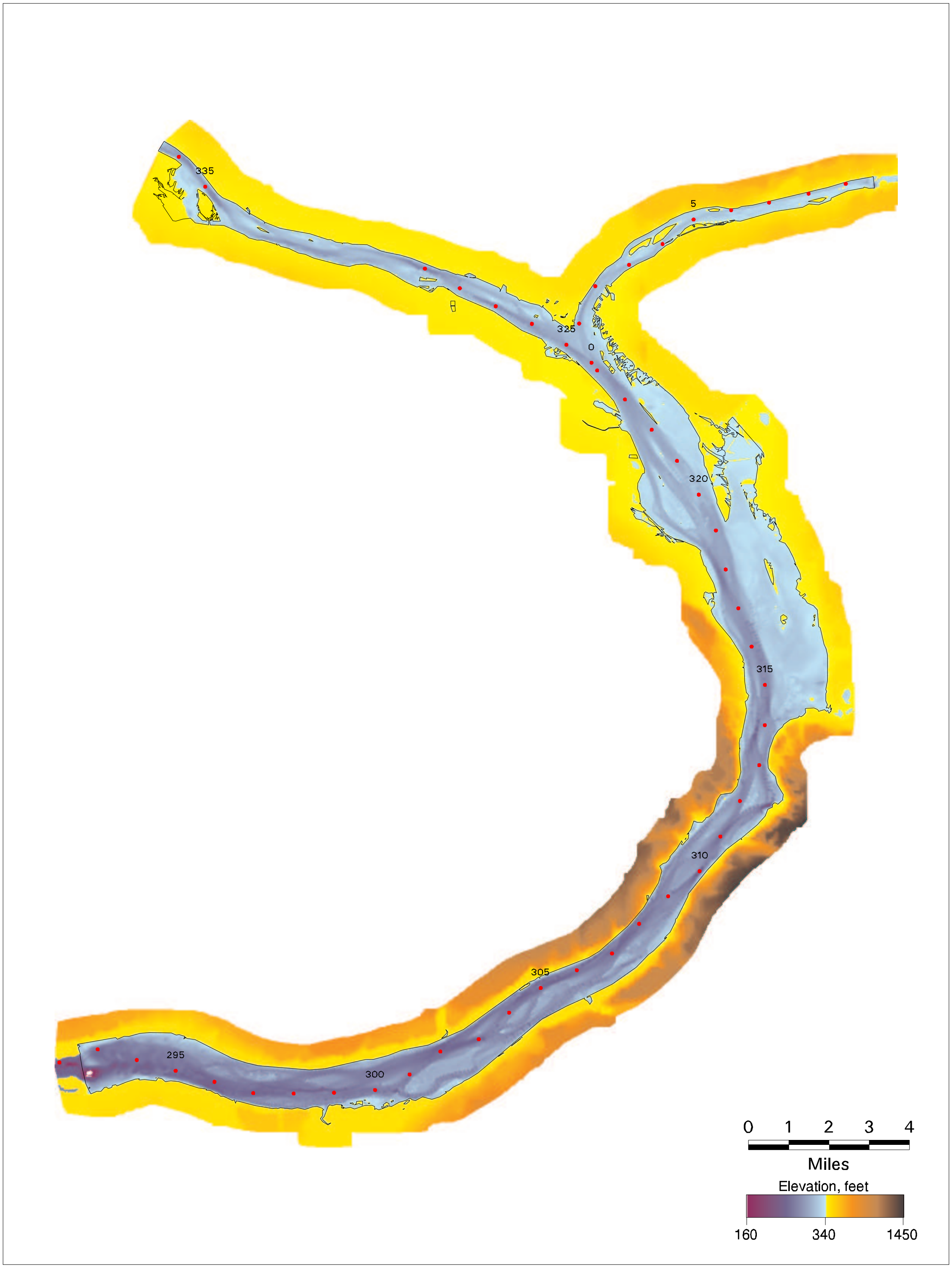

Figure B.5. McNary Pool bathymetric surface (Richmond and Perkins 1999).

B.1 References

McMichael GA, WA Perkins, CJ McMurray, YJ Chien, CL Rakowski, A Coleman, MC Richmond, J Vucelick, EV Arntzen, RP Mueller, CA Duberstein, and J Lukas. 2003. *Subyearling Chinook Salmon Stranding in the Hanford Reach of the Columbia River*. PNWD-3308, Prepared for Grant County Public Utility District No. 2 by Battelle – Pacific Northwest Division, Richland, Washington.

Richmond MC and WA Perkins. 1999. *McNary Reservoir. Part 6 in Two-Dimensional Hydrodynamic, Water Quality, and Fish Exposure Modeling of the Columbia and Snake Rivers*. Prepared for the U.S. Army Corps of Engineers, Walla Walla District by Battelle – Pacific Northwest Division, Richland, Washington.

Appendix C

Definitions for Goodness-of-Fit Statistics

Appendix C – Definitions for Goodness-of-Fit Statistics

Mean absolute error (MAE) and Bias (B) were the primary goodness-of-fit measures used in calibration of MASS1. These and other goodness-of-fit statistics defined below were also used to evaluate model output in all years with data. Bias B is defined as the ratio of predicted (simulated) mean to observed mean

MAE is defined as

$$\mathrm{MAE} = \frac{1}{N}\sum_{i=1}^{N} |P_i - O_i| \tag{C.1}$$

where

N = number of timesteps
P = predictions
O = observations

Bias is defined as

$$B = \frac{1}{N}\sum_{i=1}^{N} P_i - O_i \tag{C.2}$$

The familiar R^2, or square of Pearson's product-moment correlation coefficient, describes the portion of total variance in the observed data that can be explained by the model and ranges from 0.0 to 1.0:

$$R^2 = \left\{ \frac{\sum_{i=1}^{N} (O_i - \overline{O})(P_i - \overline{P})}{\left[\sum_{i=1}^{N} (O_i - \overline{O})^2\right]^{0.5} \left[\sum_{i=1}^{N} (P_i - \overline{P})^2\right]^{0.5}} \right\}^2 \tag{C.3}$$

where

$overlineP$ = mean of the predictions
$\overline{O}$ = mean of the observations

There are two disadvantages of R^2 for describing model skill: 1) any linear relationship between the observations and the predictions, not necessarily a 1:1 relationship, results in a high value of R^2; 2) the squaring of terms gives too much weight to large values. In the case of river stage, a high R^2 value may indicate good fit at high flow conditions but mask poor model skill during low flow periods.

Efficiency E_2 (Nash and Sutcliffe 1970) is a tougher test than R^2 and casts the mean of the observations as a benchmark for the model:

$$E_2 = 1.0 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \overline{O})^2}. \tag{C.4}$$

Values of E_2 tend to be somewhat less than R^2.

A further discrimination can be made by using the absolute value instead of the square of the difference between simulated and observed, and by comparing to a baseline mean that involves some kind of seasonal or other categorical variation inherent in the data. Baseline-adjusted, first-degree efficiency E_1' is defined as (Legates and McCabe 1999)

$$E_1' = 1.0 - \frac{\sum_{i=1}^{N} \mid O_i - P_i \mid}{\sum_{i=1}^{N} \mid O_i - \bar{O}' \mid}. \tag{C.5}$$

where

$\bar{O}'$ = baseline mean of the observations

Here the baseline mean was the daily mean of river stage, and E_1' was computed only from data where O_i was available for complete days. When applied to a single location (stage recorder), $\bar{O}'$ was the daily mean for data at that location. When applied to multiple locations, $\bar{O}'$ was the daily mean for each day-location of the corresponding i. Efficiency has a possible range of $-\infty$ to 1.0. When efficiency=0, the model is no better or worse than the observed mean as a predictor. The closer the baseline mean is to the individual observations, the lower the efficiency is likely to be.

C.1 References

Legates DR and GJ McCabe. 1999. "Evaluating the use of goodness-of-fit measures in hydrologic and hydroclimatic model validation." *Water Resources Research* 35(1):233–241.

Nash JE and JV Sutcliffe. 1970. "River flow forecasting through conceptual models, Part 1—A discussion of principles." *Journal of Hydrology* 10:282–290.

Appendix D

Simulated and Observed River Stage, 1991–2004

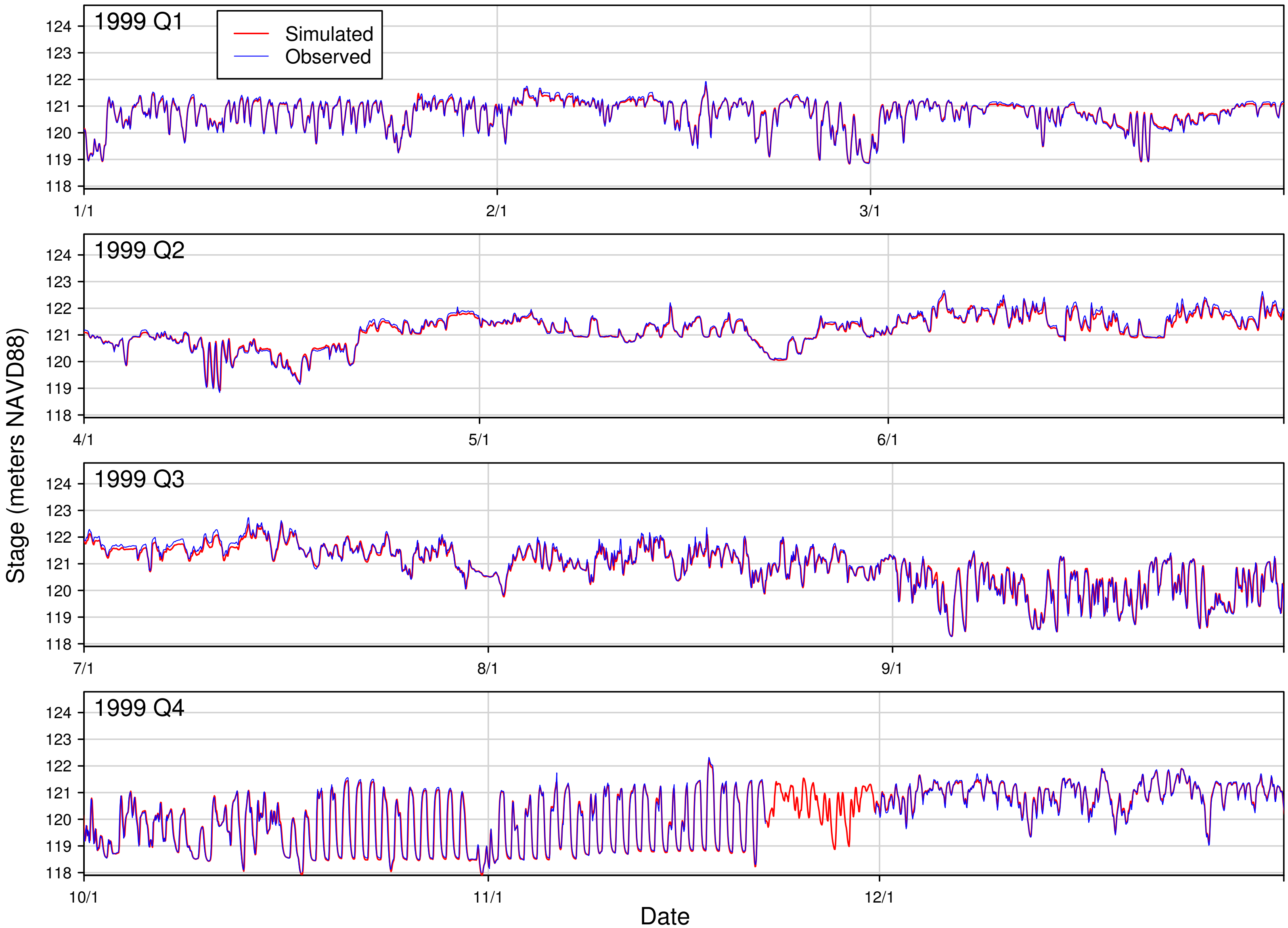

Figure D.1. Columbia River stage at 100-B, 1999.

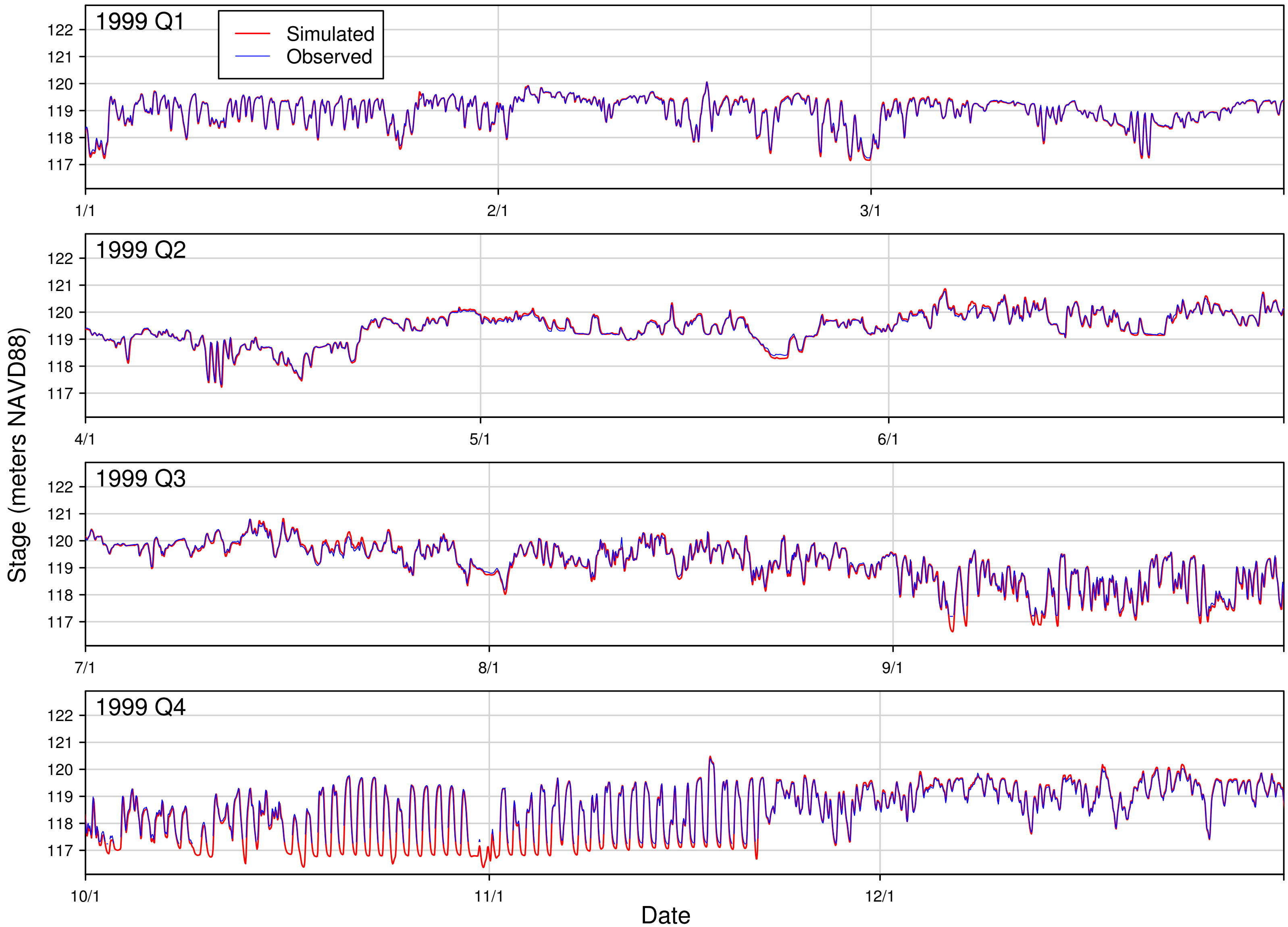

Figure D.2. Columbia River stage at 100-N, 1999.

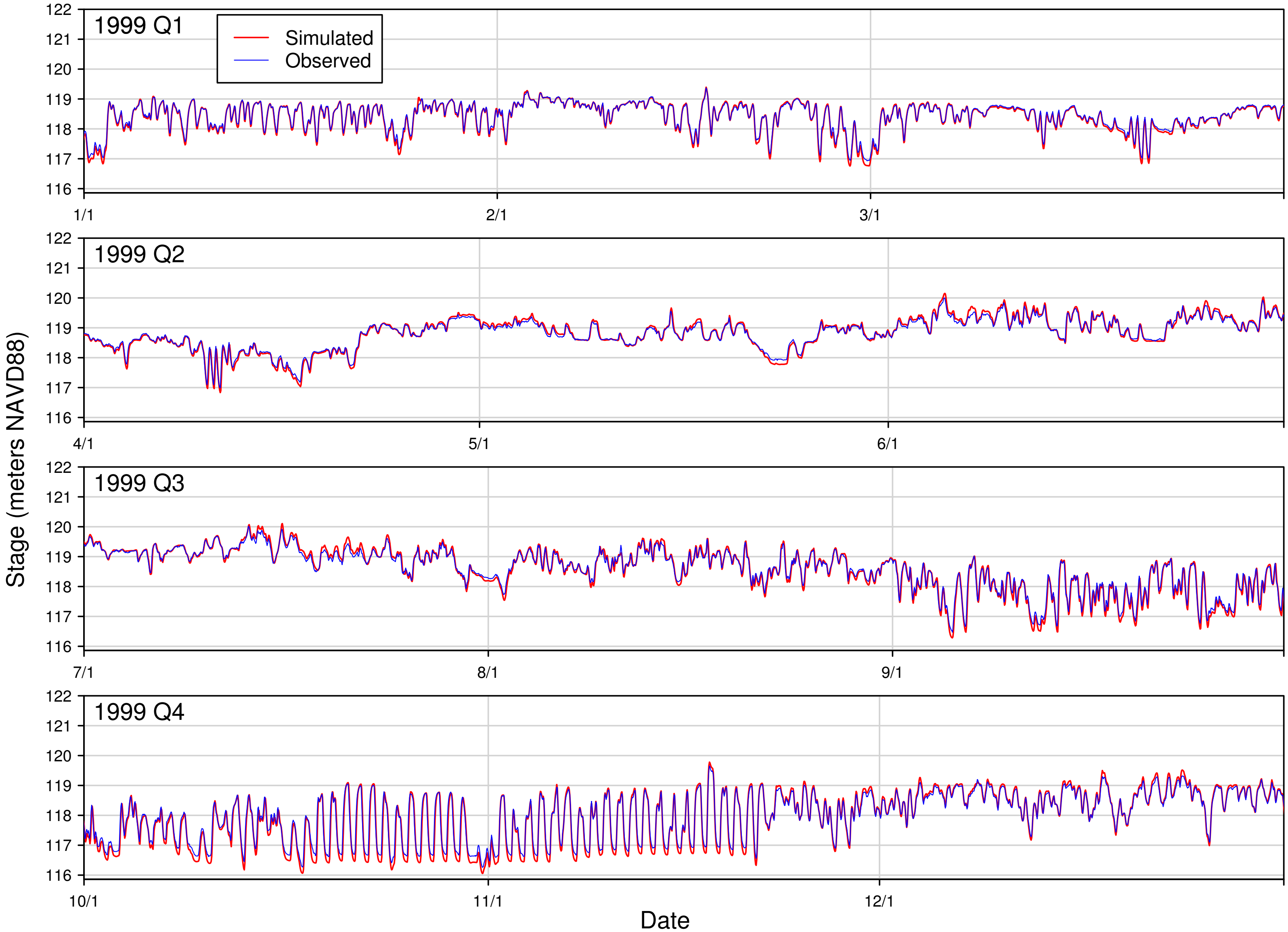

Figure D.3. Columbia River stage at 100-D, 1999.

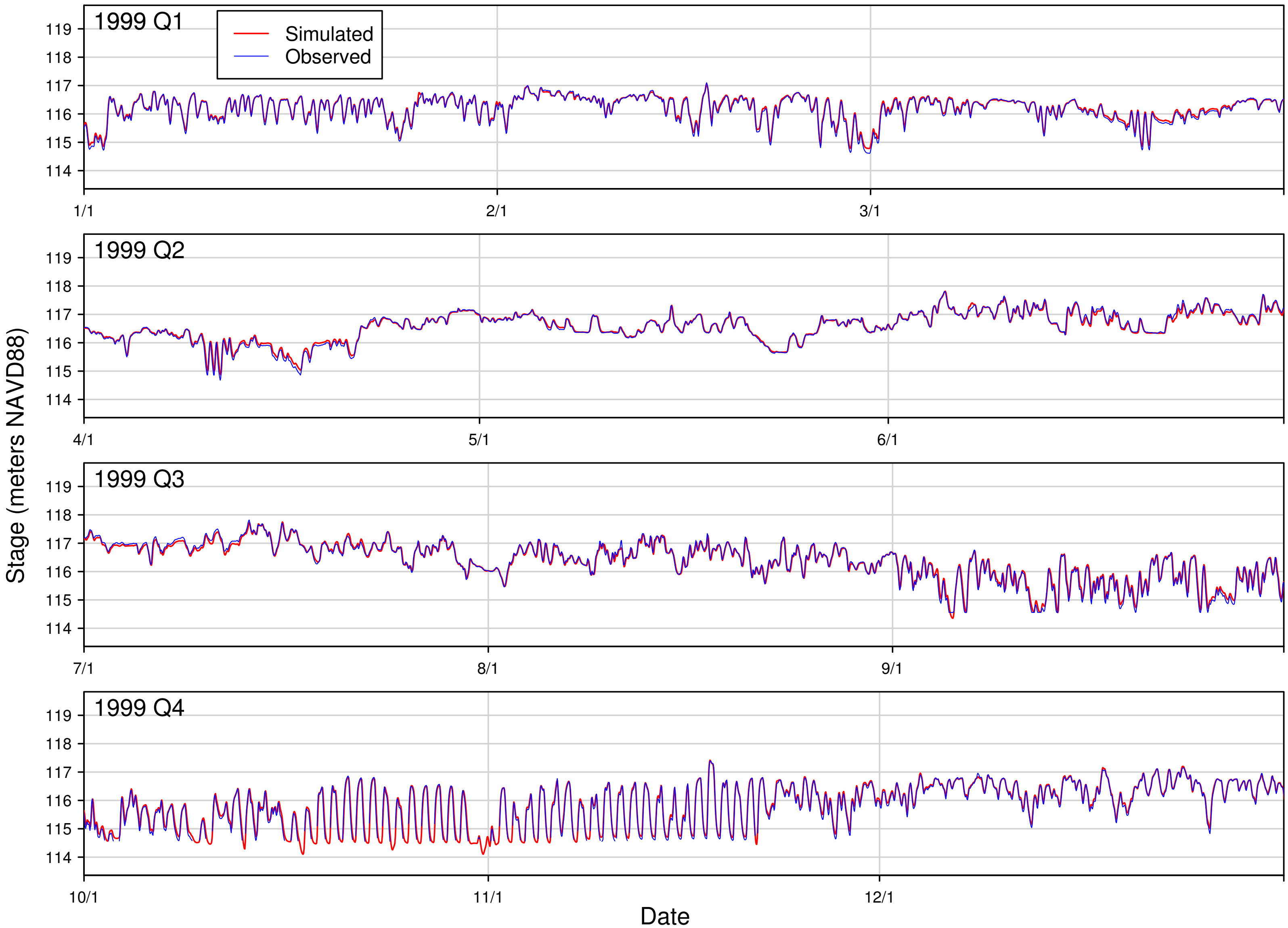

Figure D.4. Columbia River stage at 100-H, 1999.

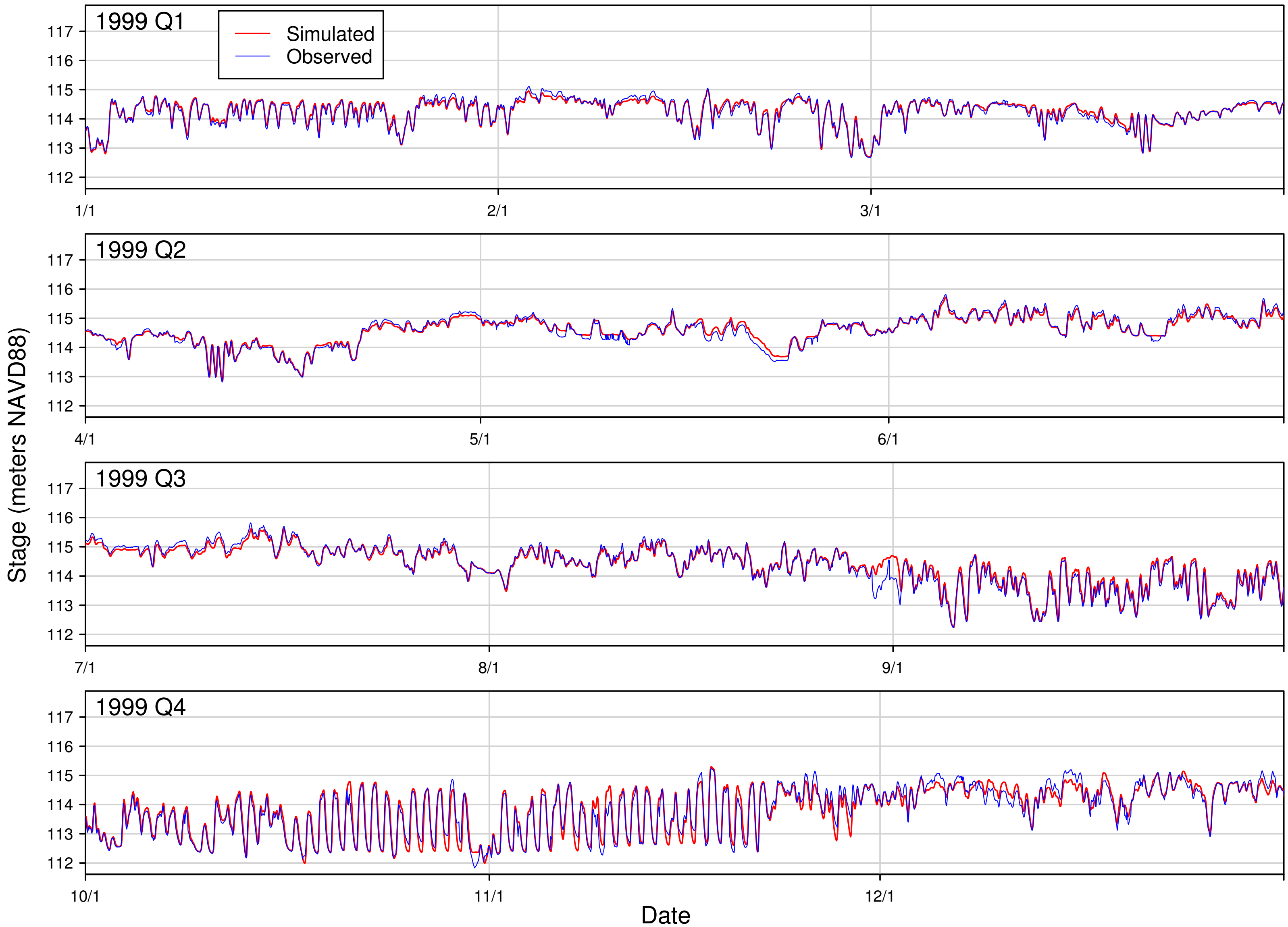

Figure D.5. Columbia River stage at 100-F, 1999.

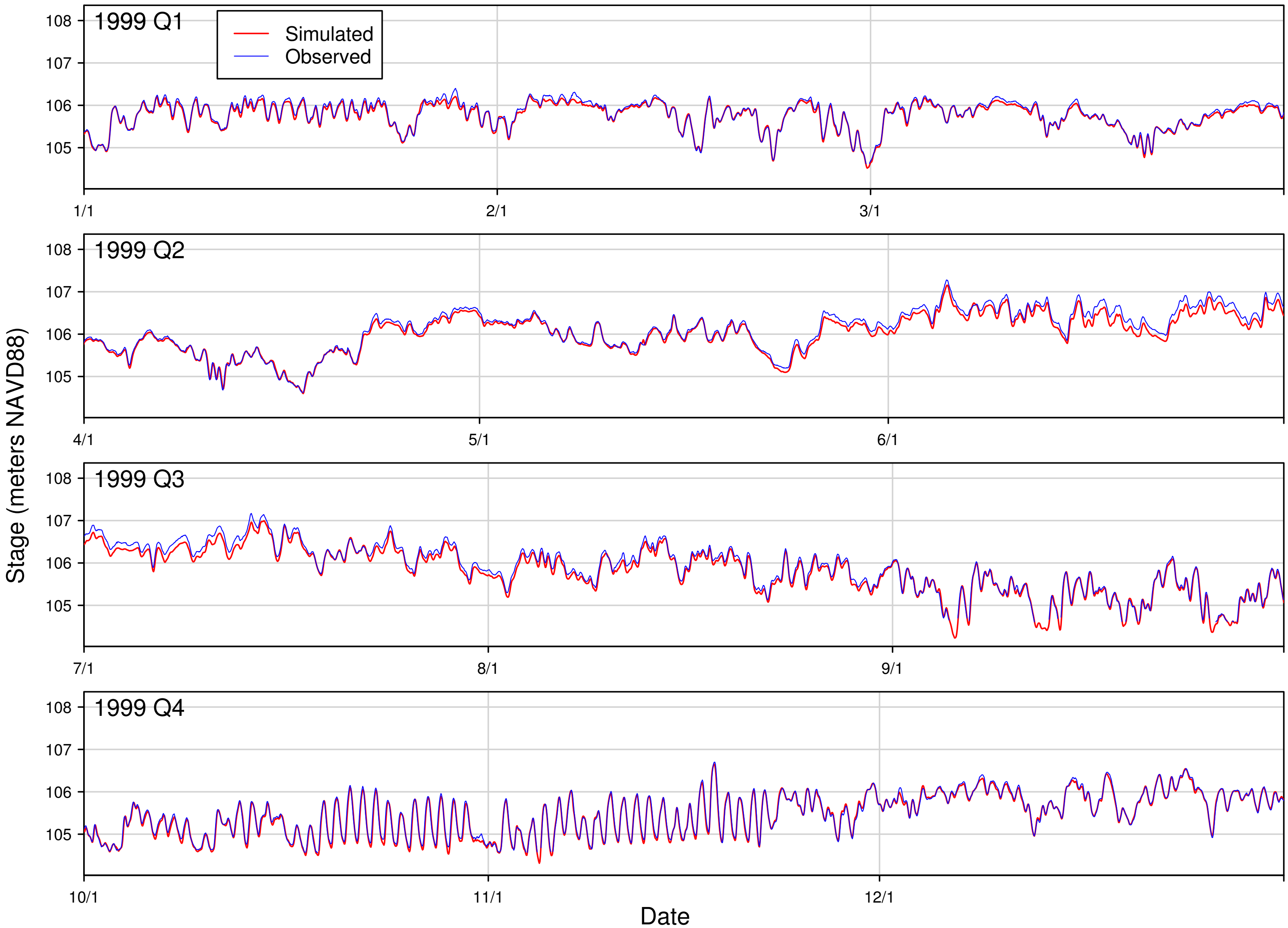

Figure D.6. Columbia River stage at 300 Area, 1999.

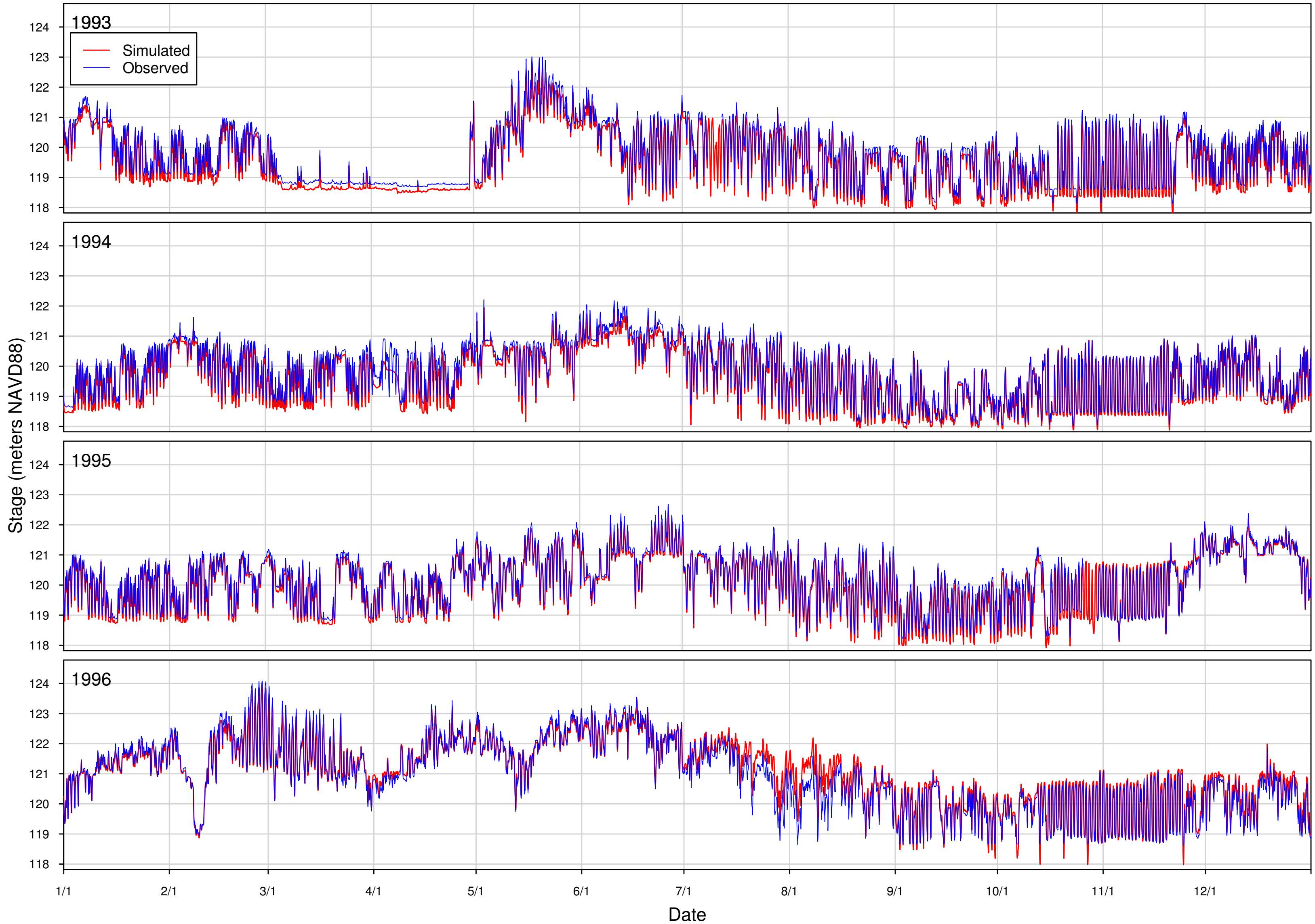

Figure D.7. Columbia River stage at 100-B, 1993–1996.

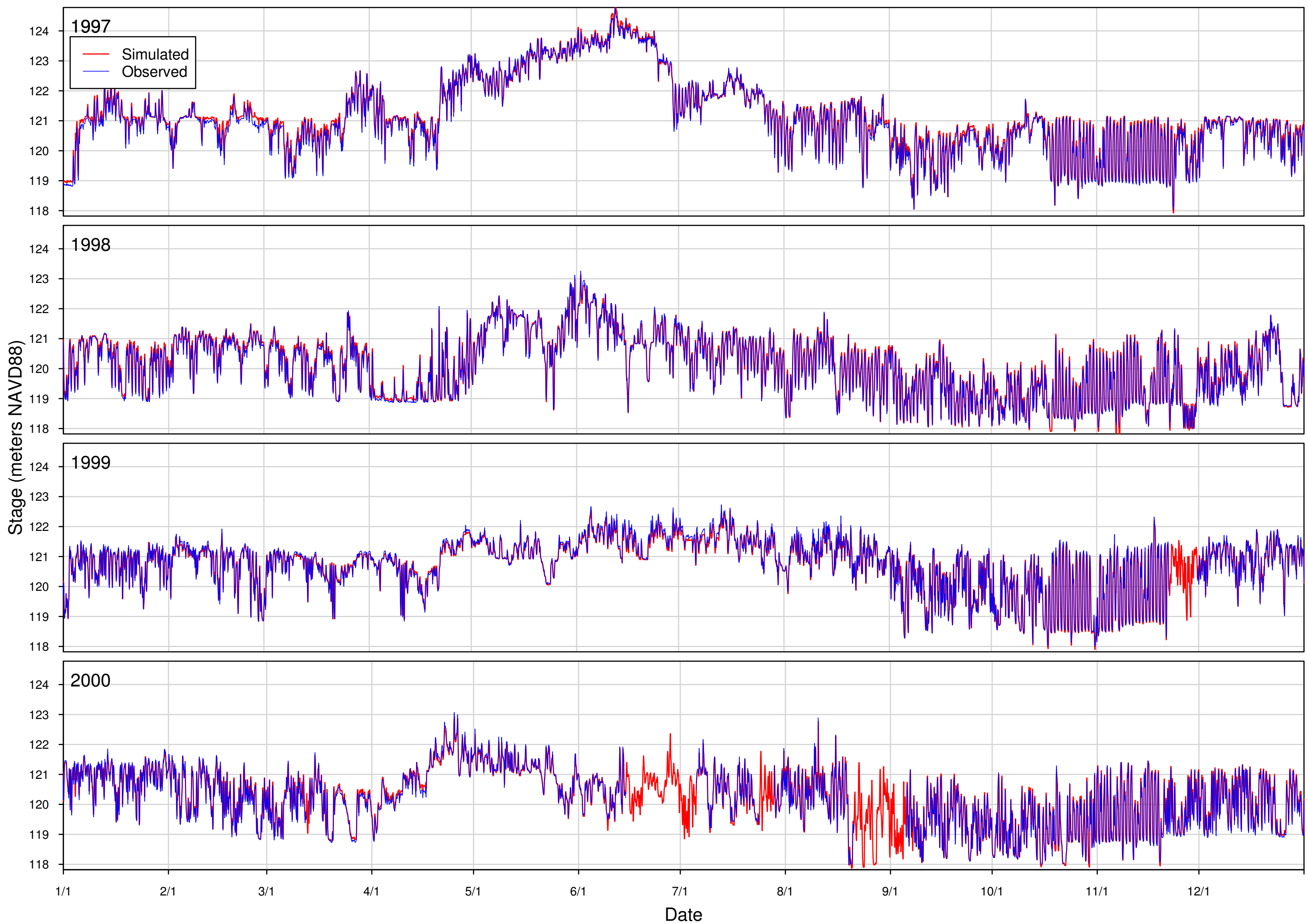

Figure D.8. Columbia River stage at 100-B, 1997–2000.

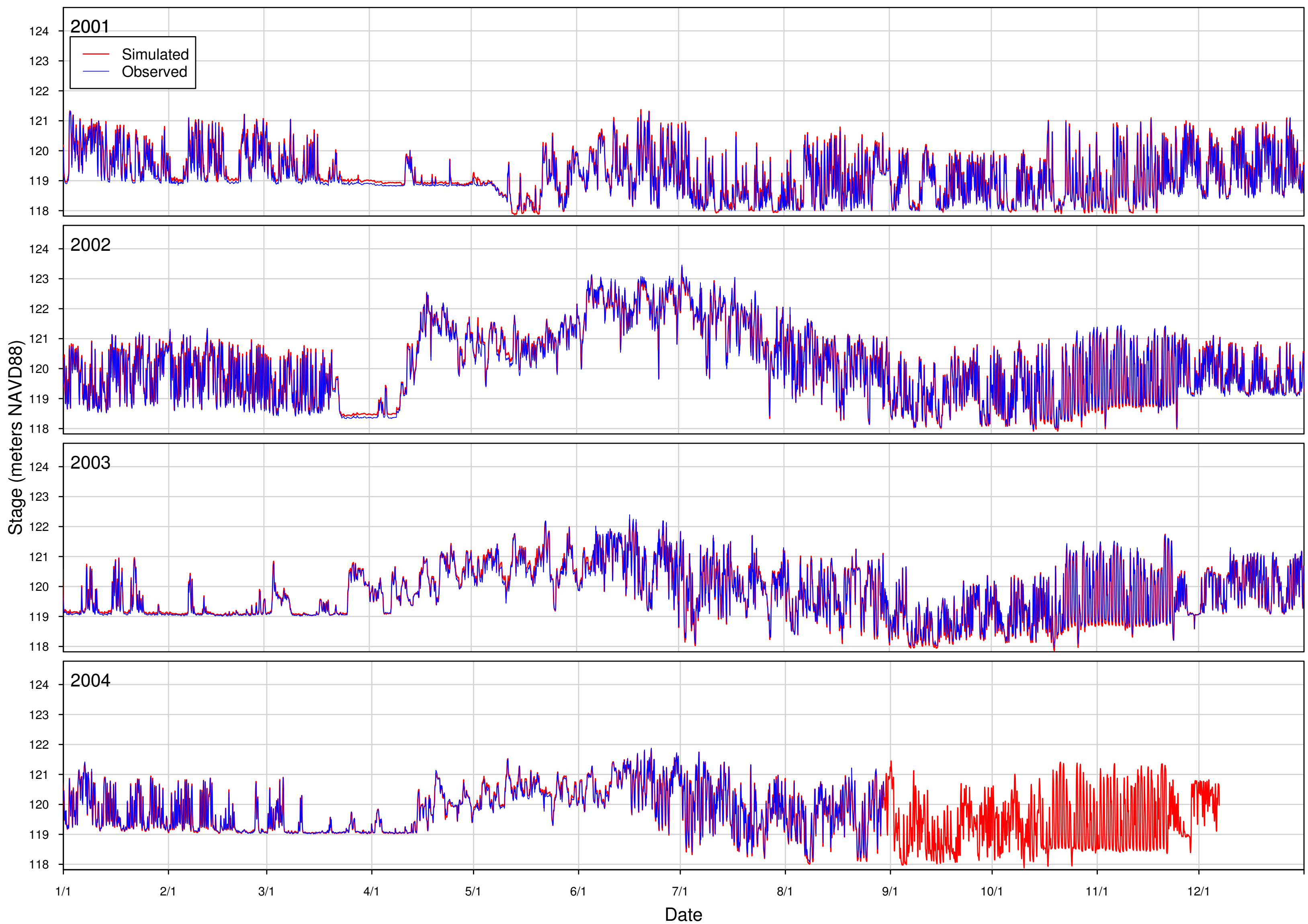

Figure D.9. Columbia River stage at 100-B, 2001–2004.

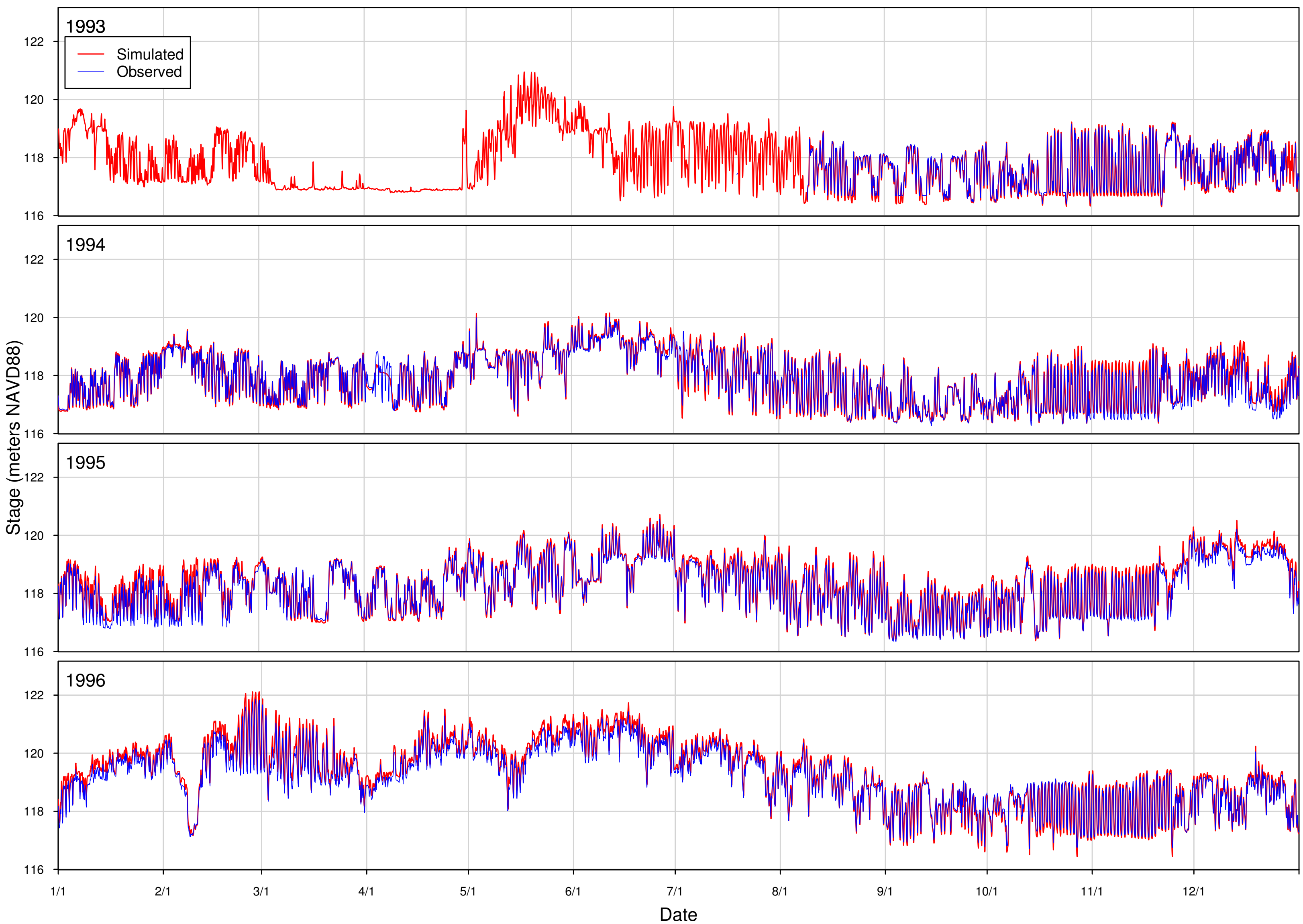

Figure D.10. Columbia River stage at 100-N, 1993–1996.

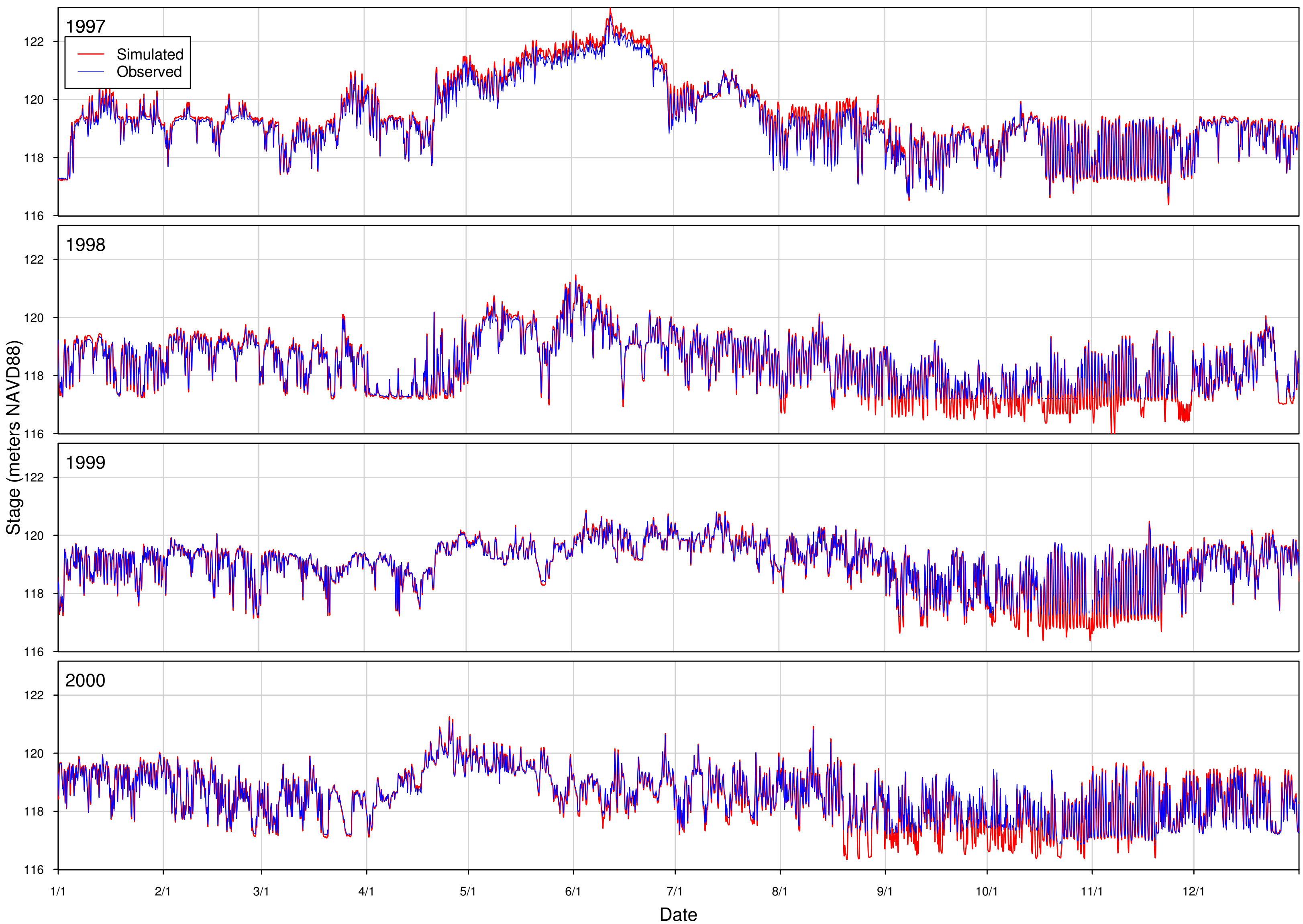

Figure D.11. Columbia River stage at 100-N, 1997–2000.

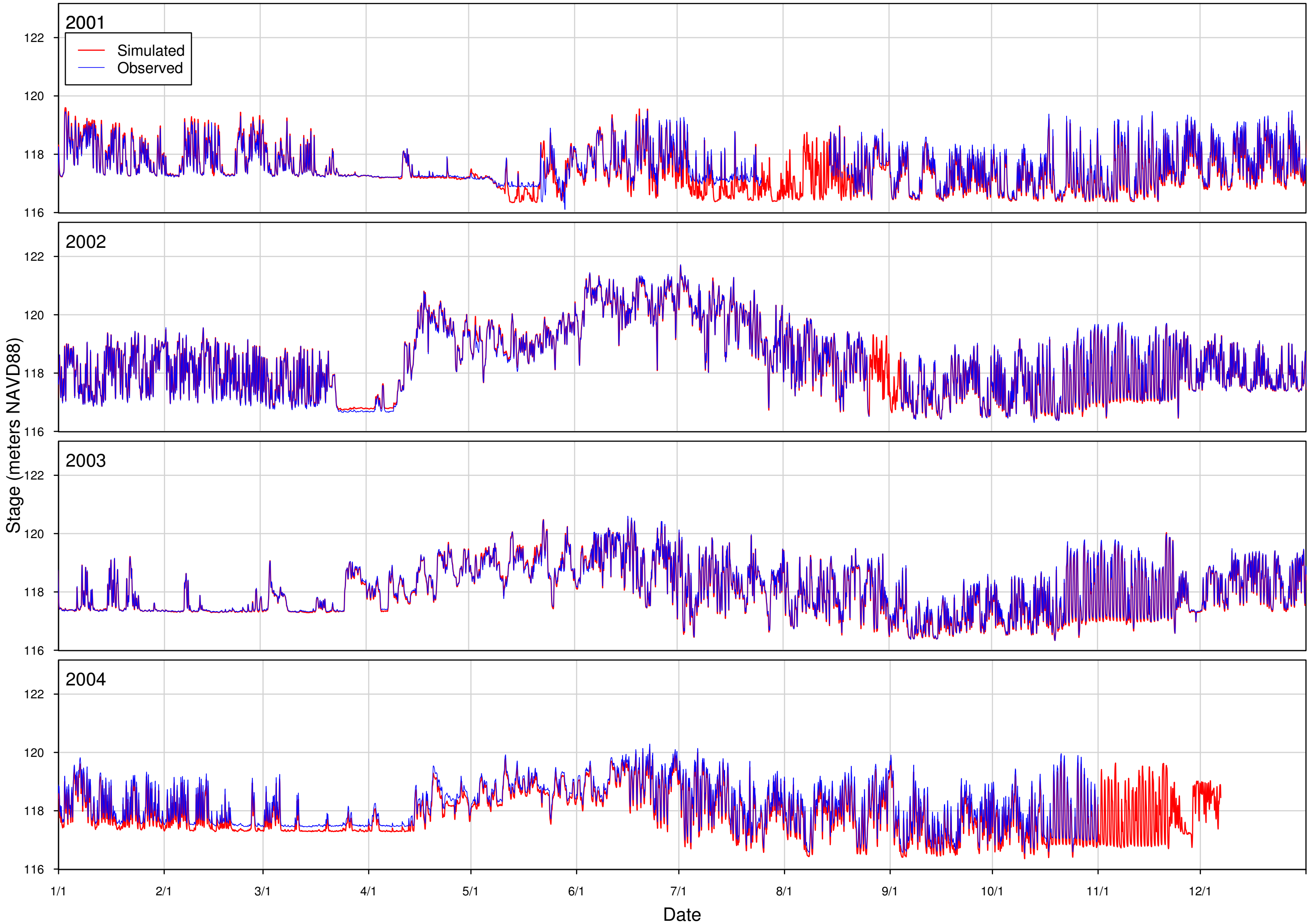

Figure D.12. Columbia River stage at 100-N, 2001–2004.

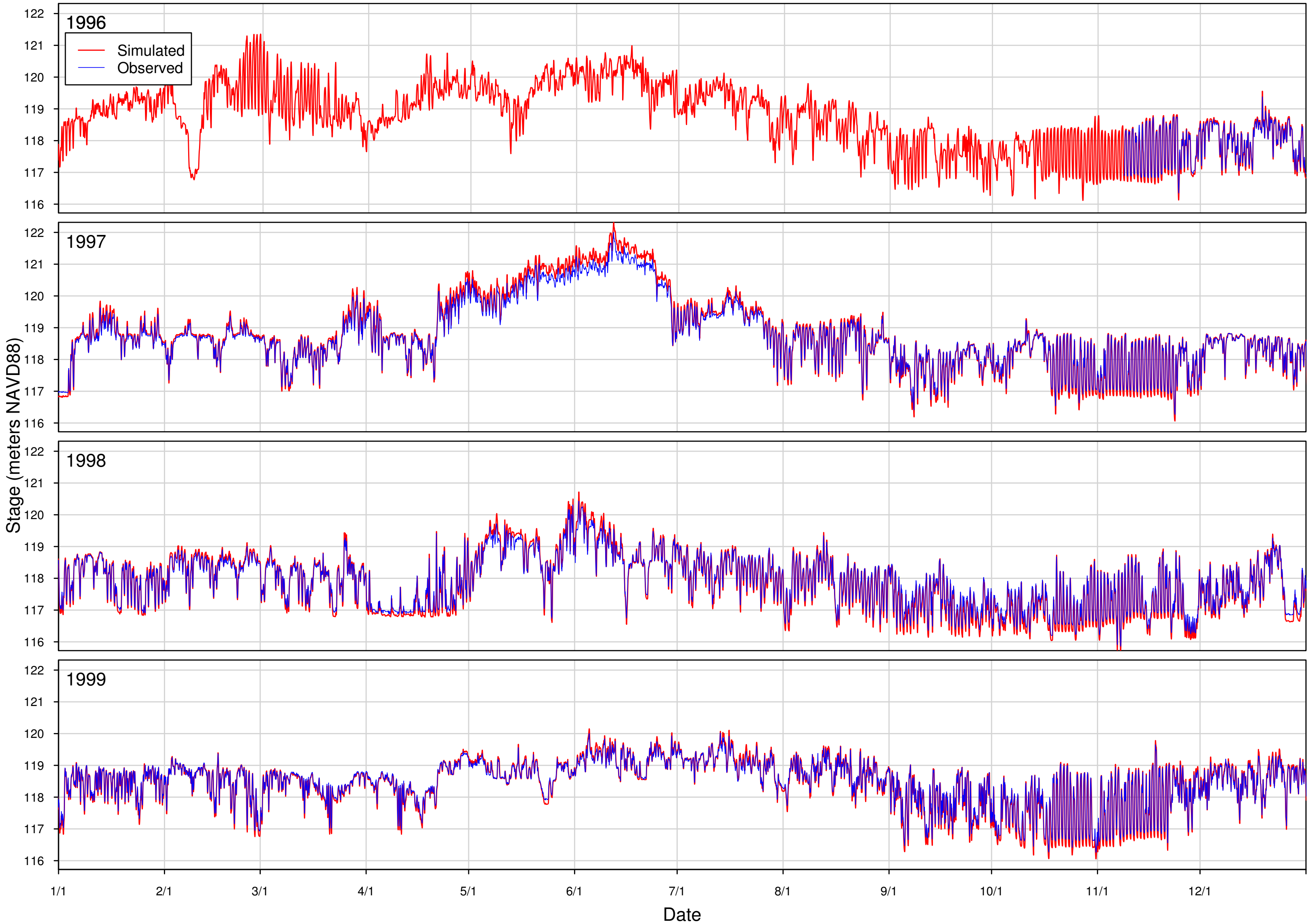

Figure D.13. Columbia River stage at 100-D, 1996–1999.

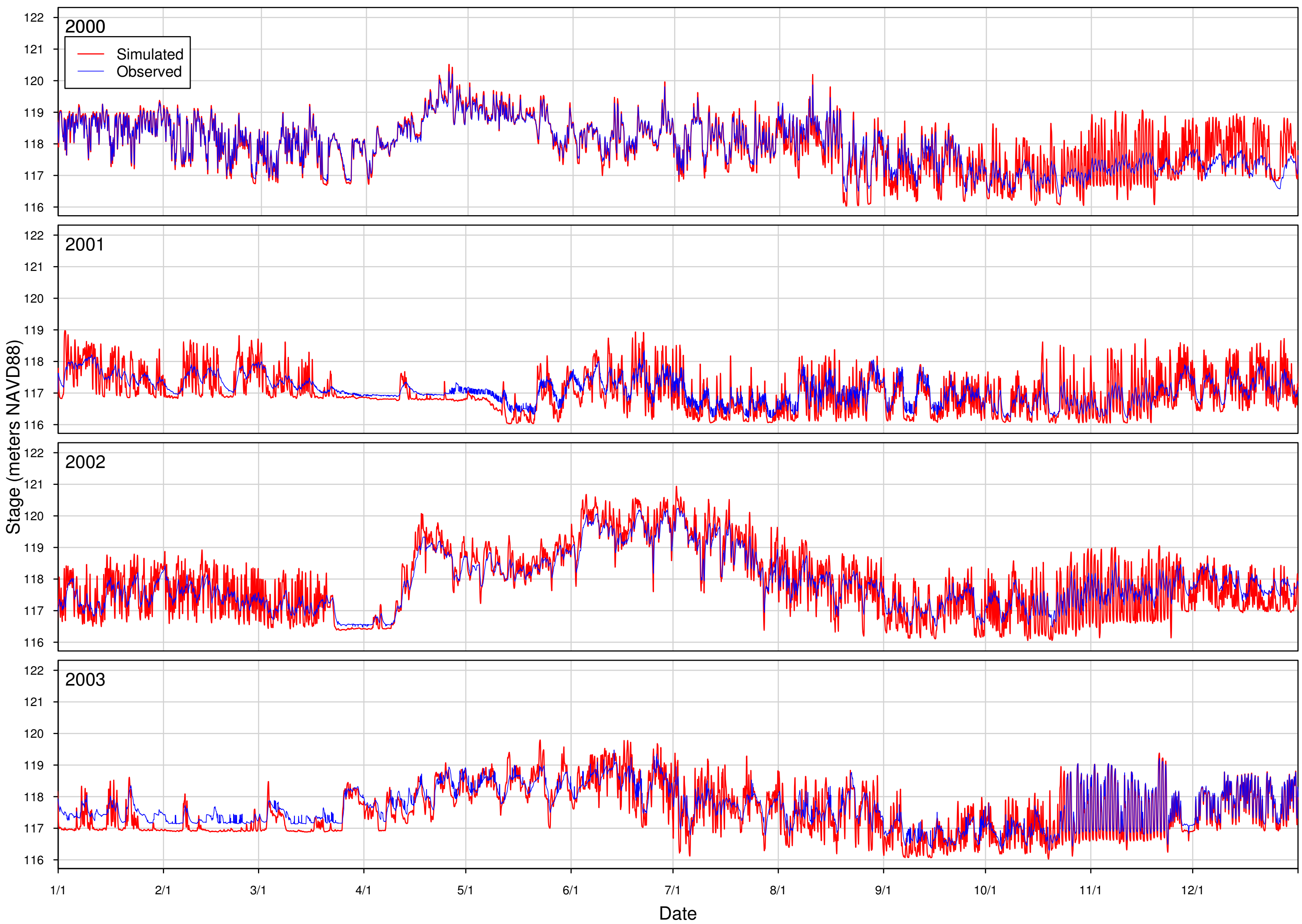

Figure D.14. Columbia River stage at 100-D, 2000–2003.

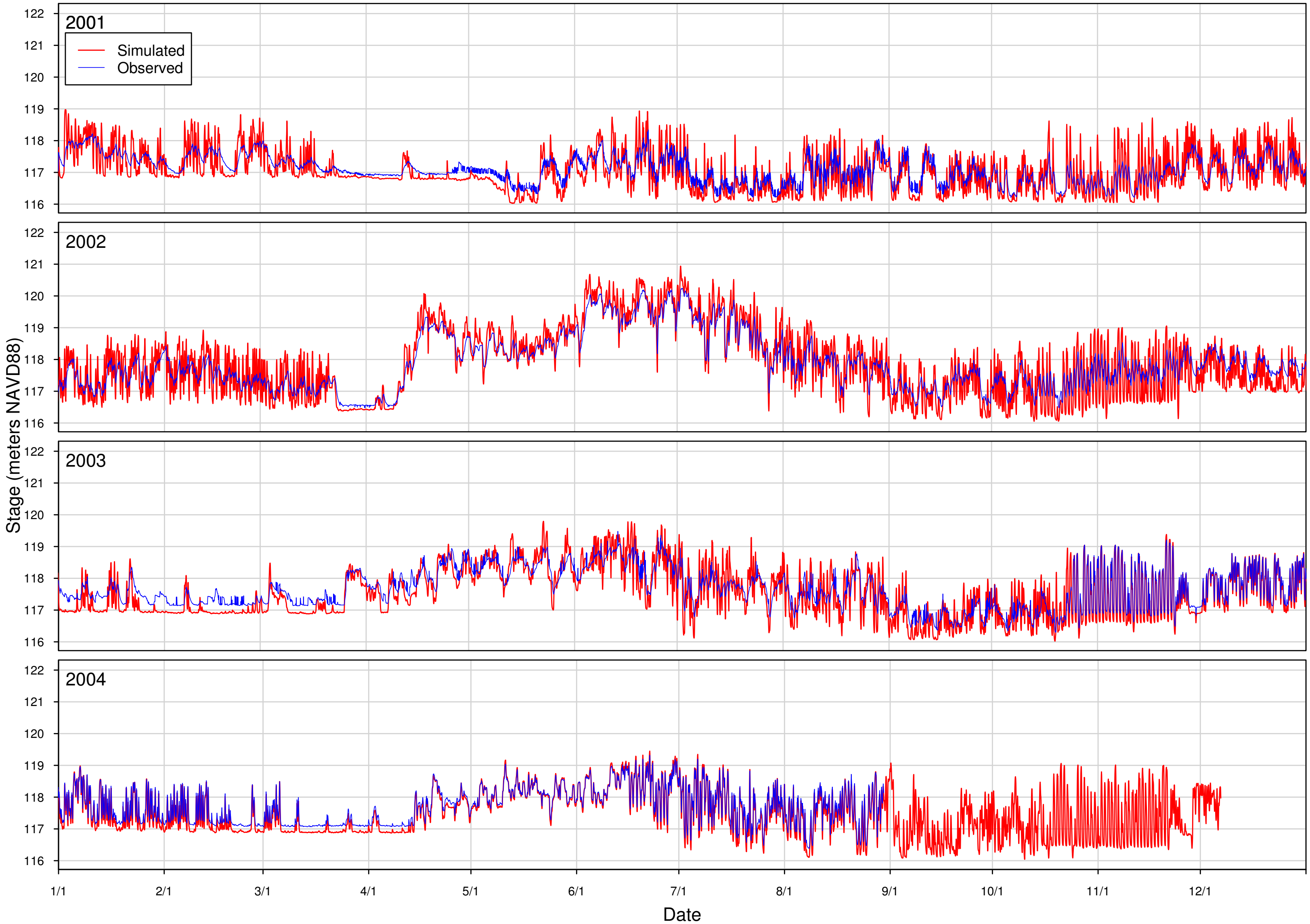

Figure D.15. Columbia River stage at 100-D, 2001–2004.

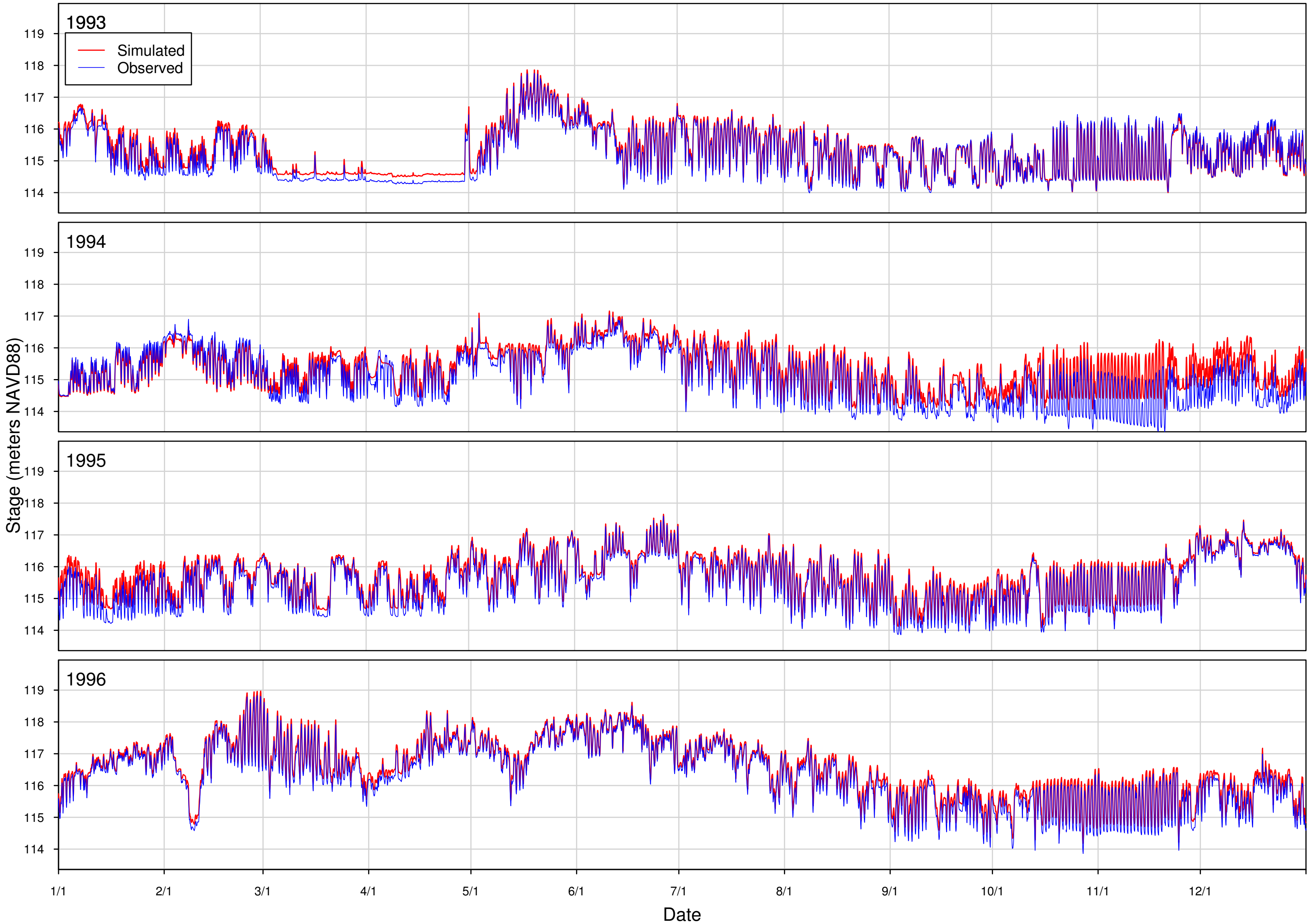

Figure D.16. Columbia River stage at 100-H, 1993–1996.

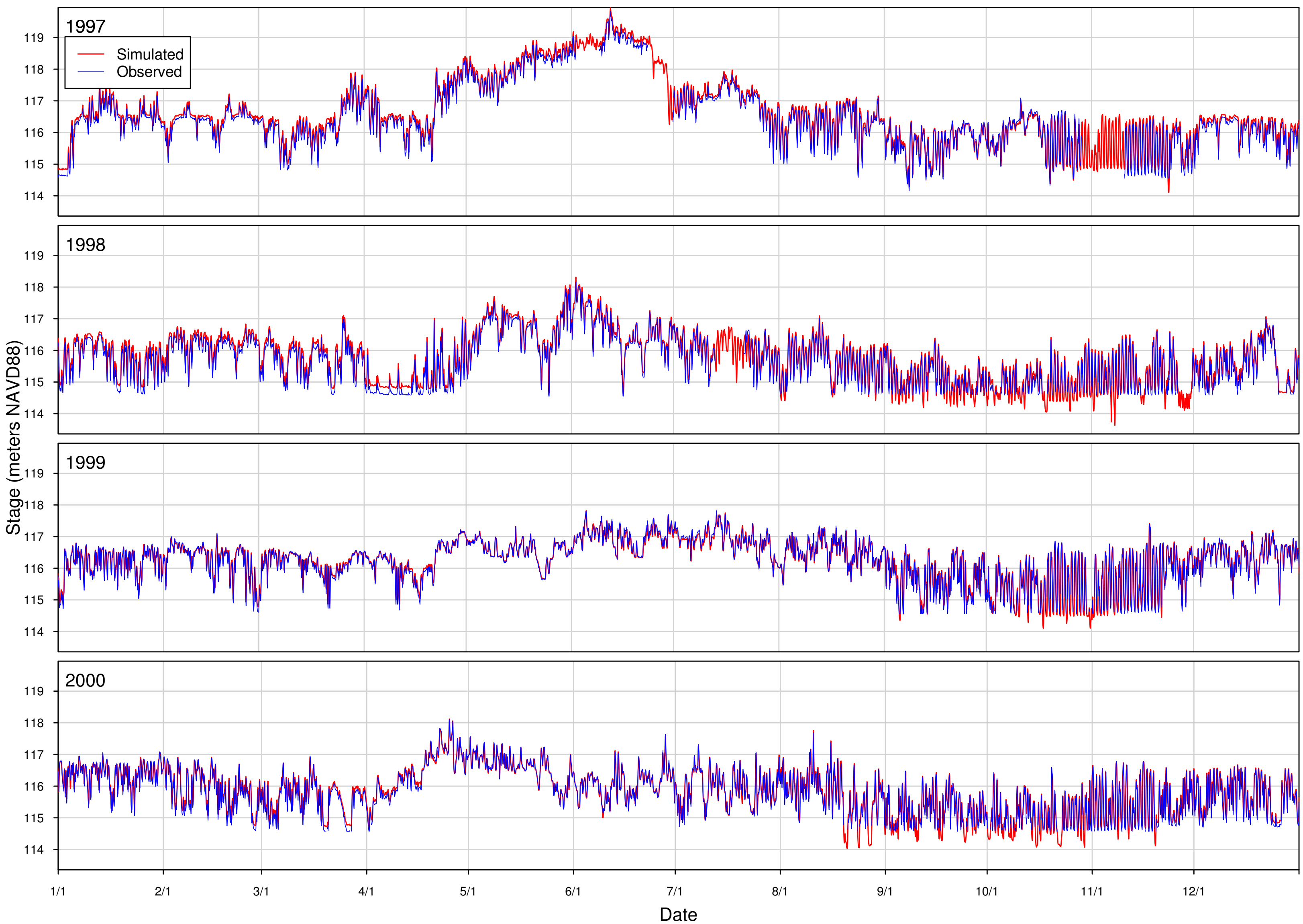

Figure D.17. Columbia River stage at 100-H, 1997–2000.

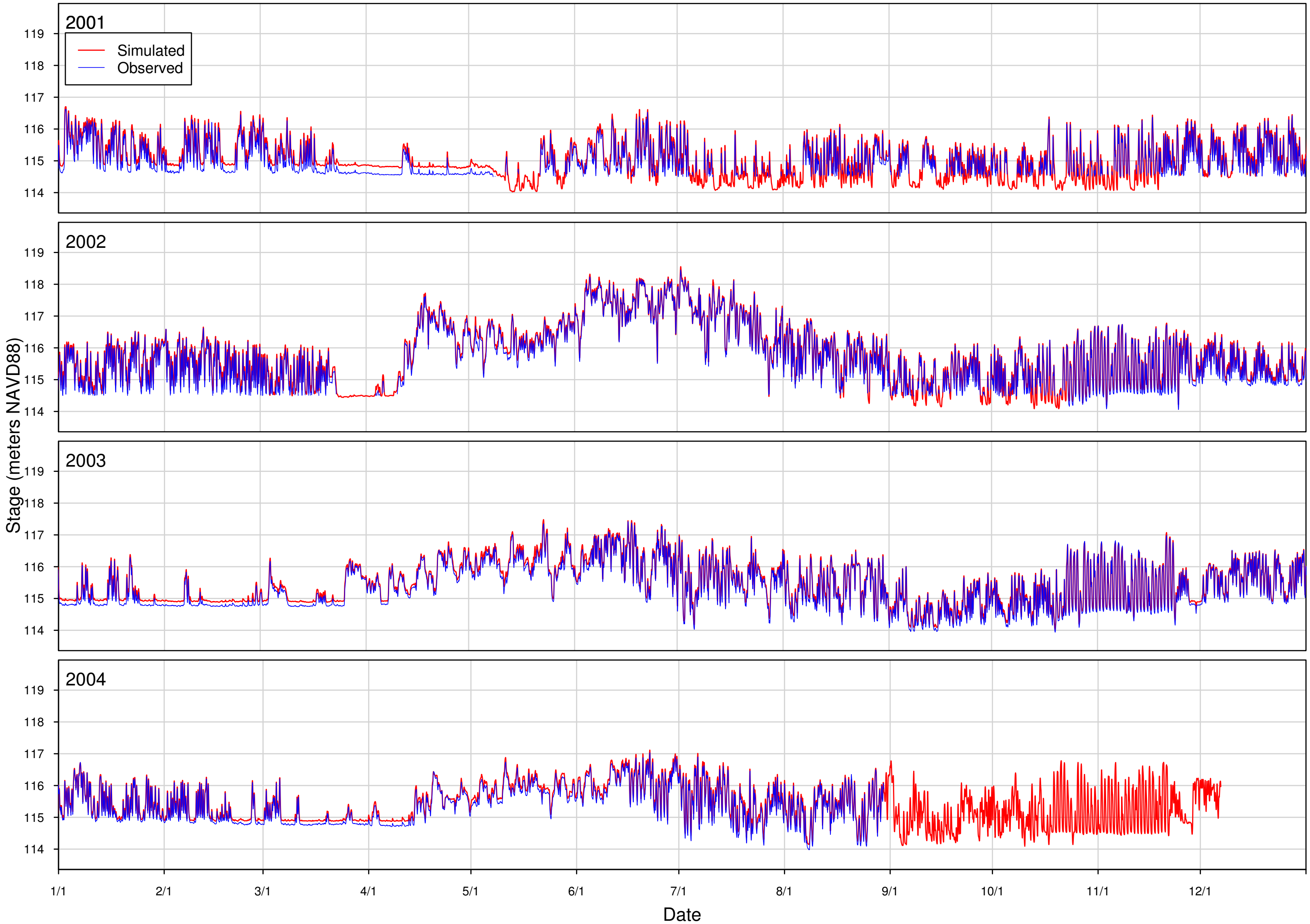

Figure D.18. Columbia River stage at 100-H, 2001–2004.

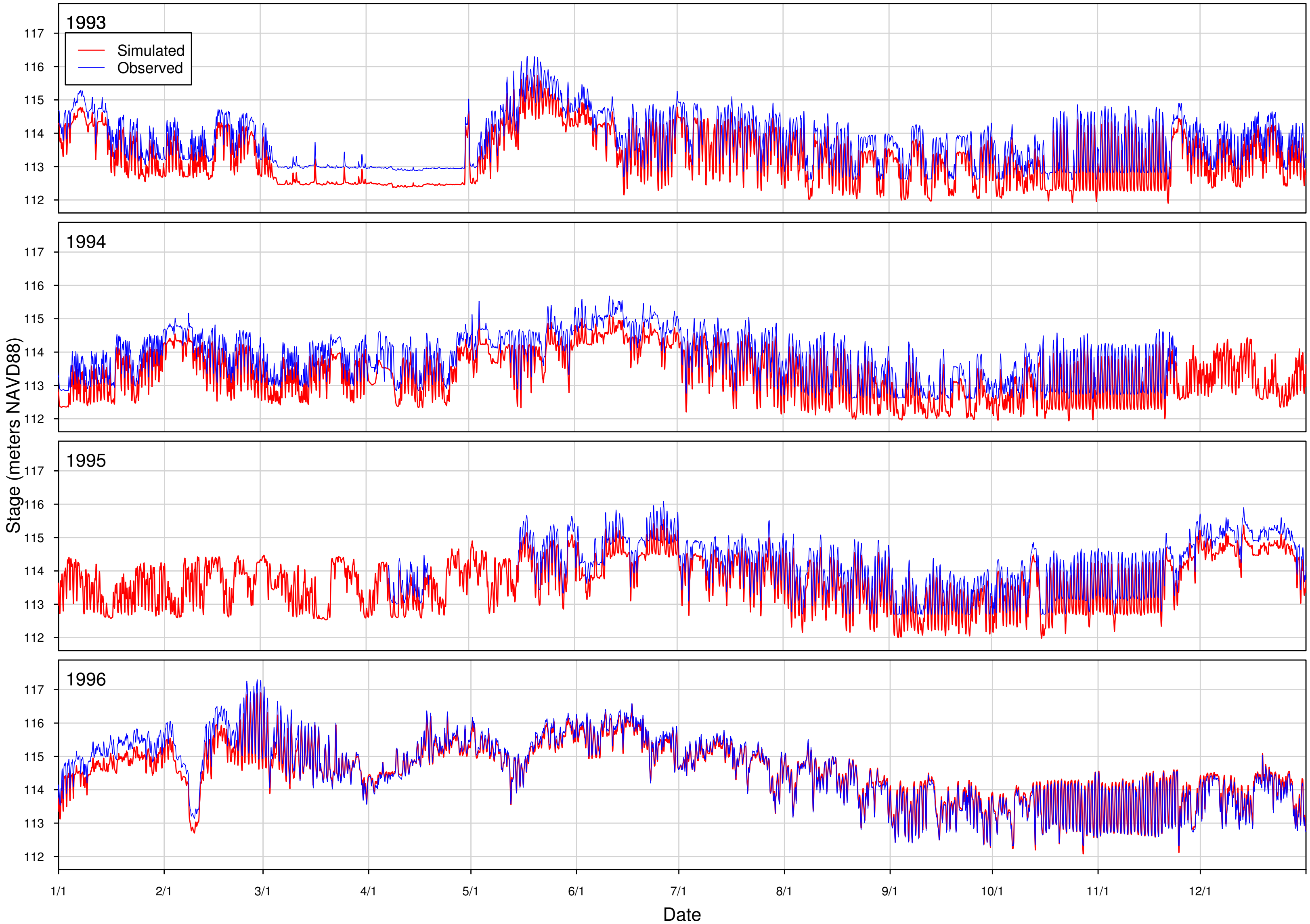

Figure D.19. Columbia River stage at 100-F, 1993–1996.

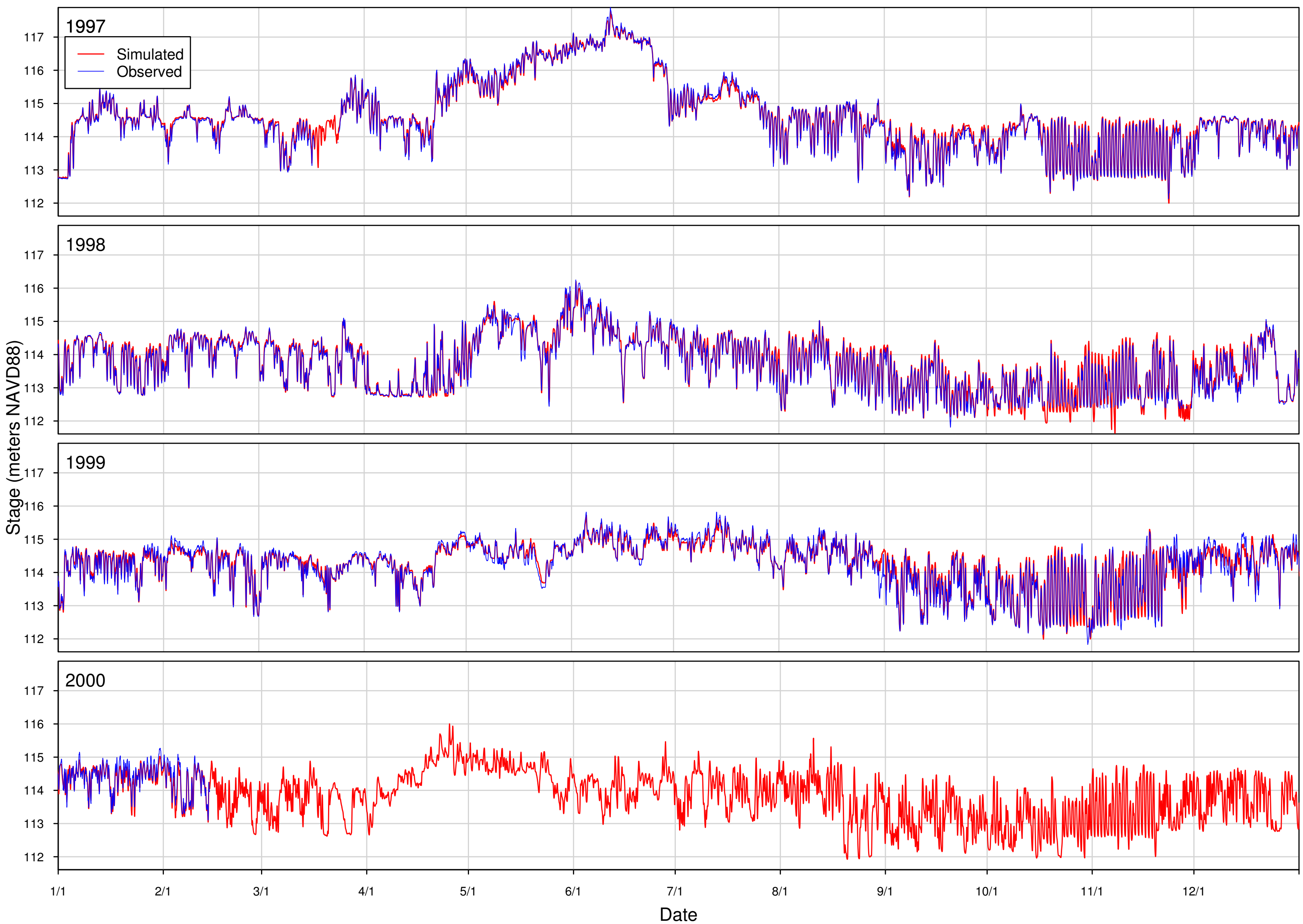

Figure D.20. Columbia River stage at 100-F, 1997–2000.

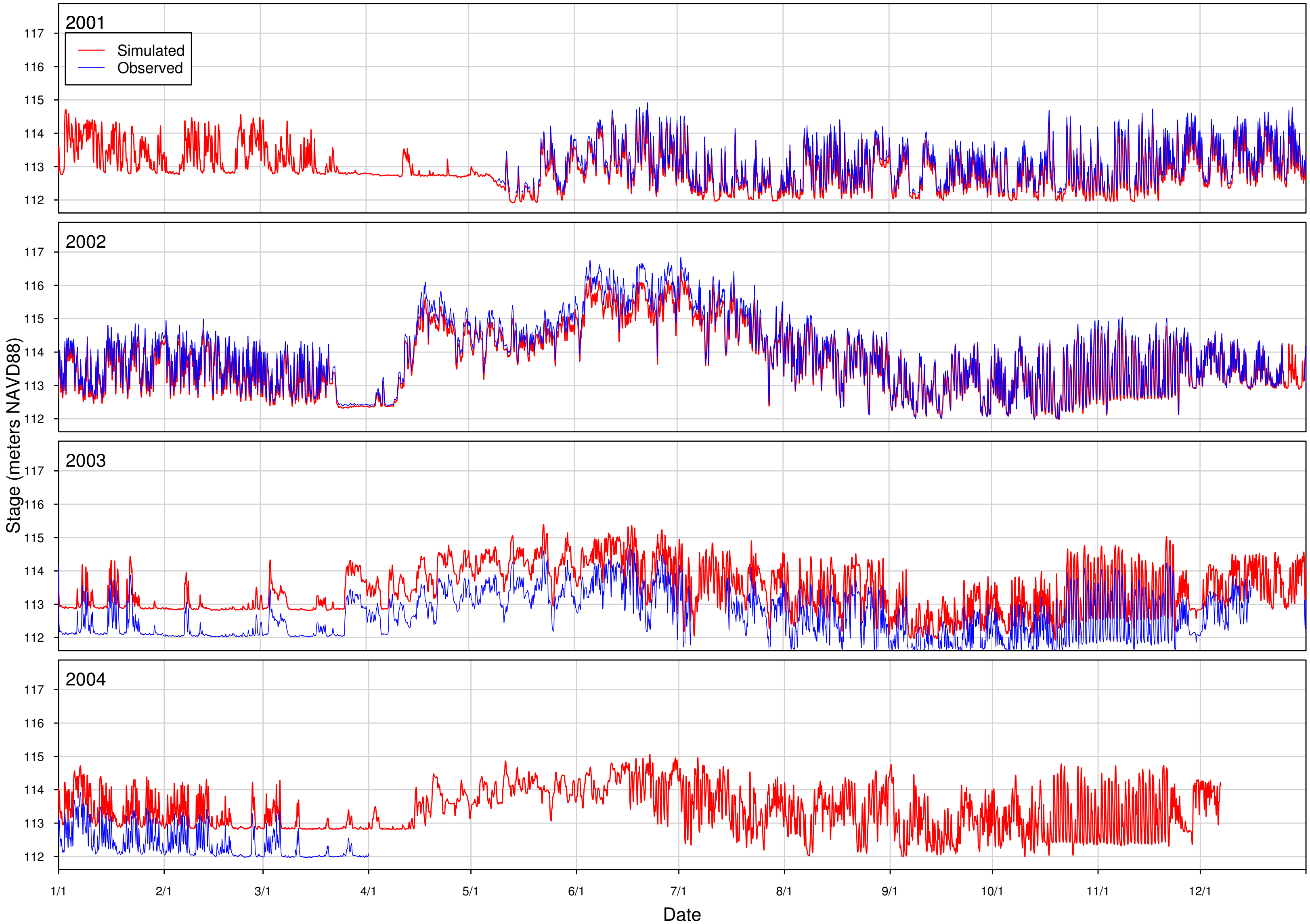

Figure D.21. Columbia River stage at 100-F, 2001–2004.

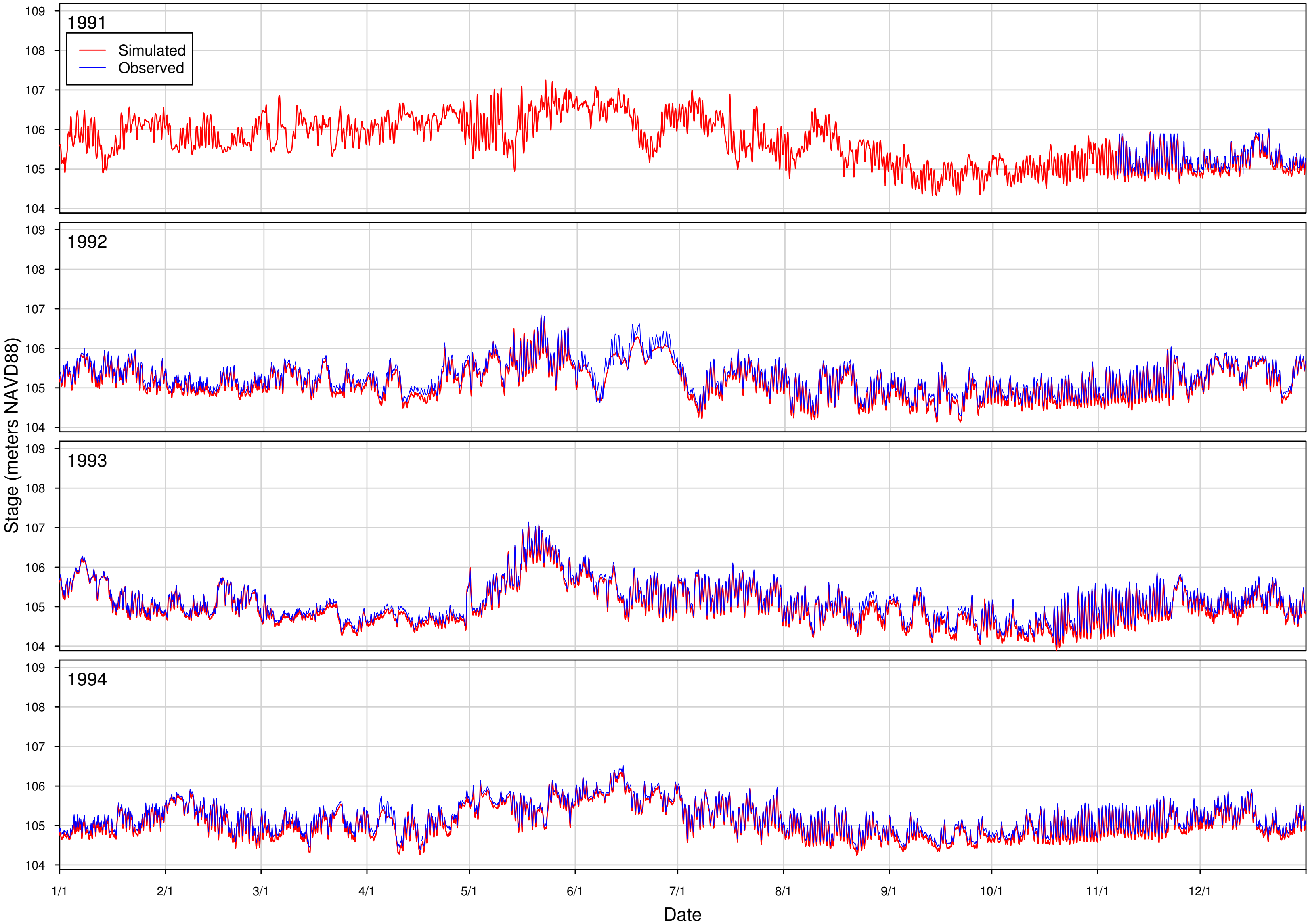

Figure D.22. Columbia River stage at 300 Area, 1991–1994.

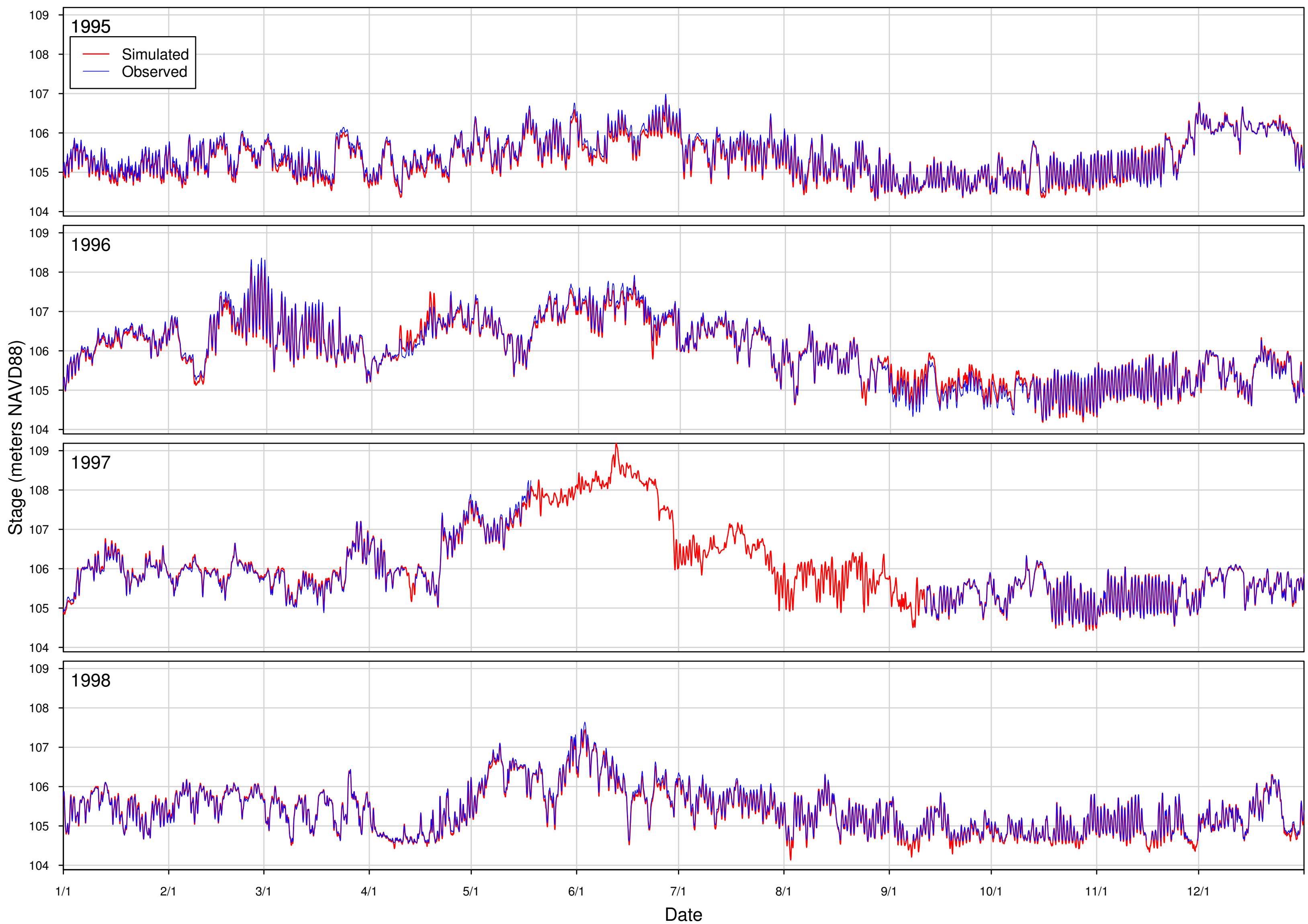

Figure D.23. Columbia River stage at 300 Area, 1995–1998.

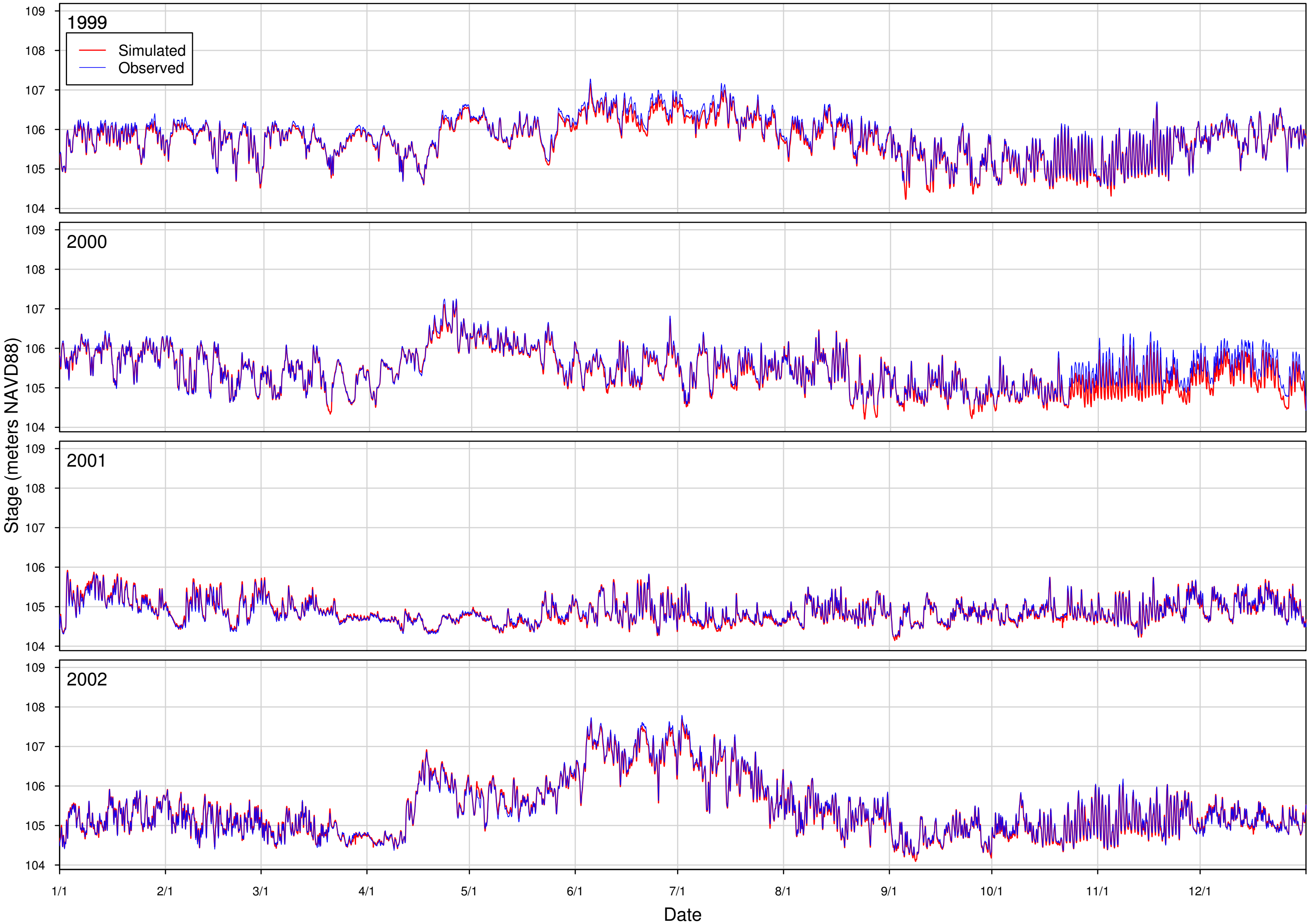

Figure D.24. Columbia River stage at 300 Area, 1999–2002.

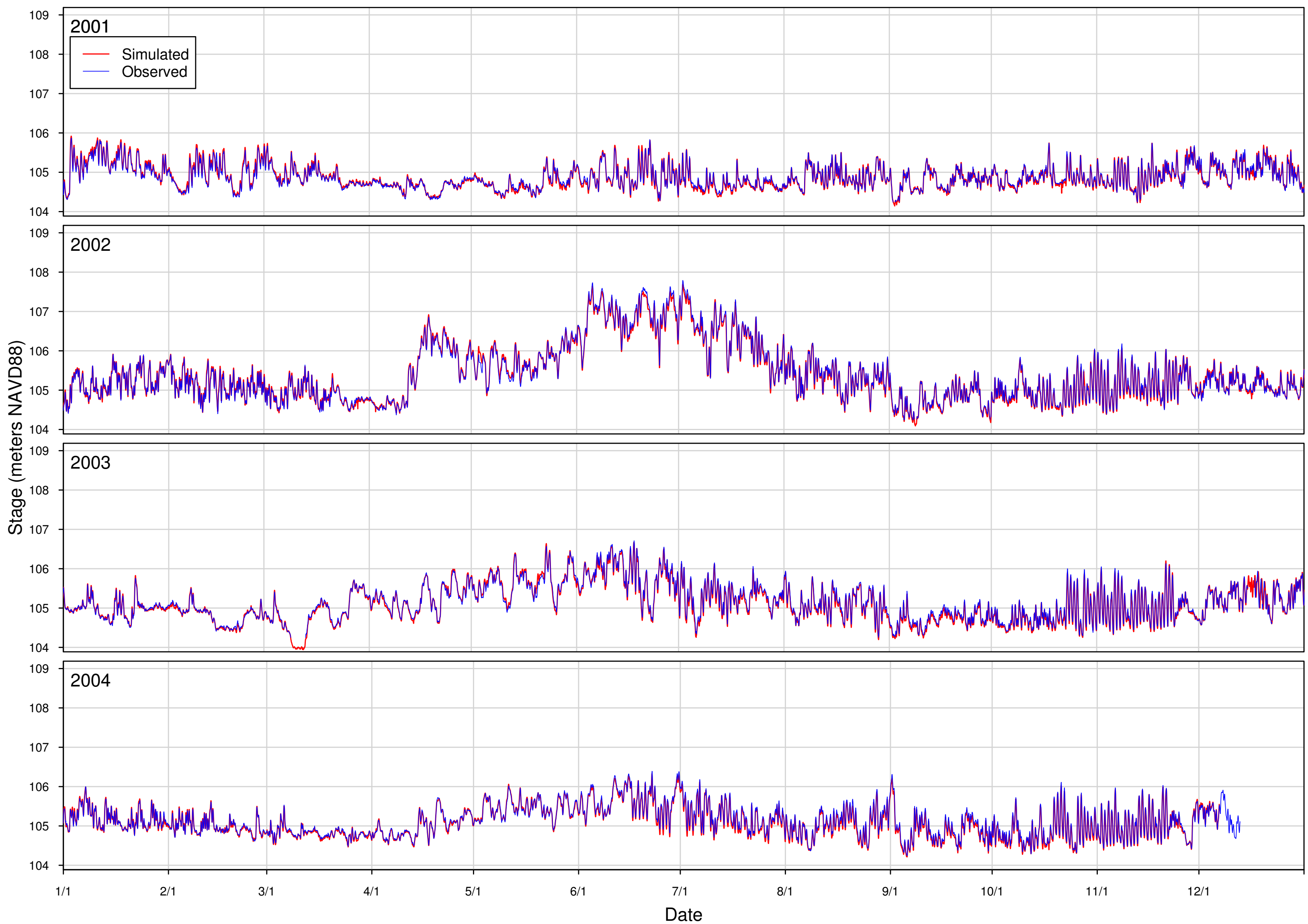

Figure D.25. Columbia River stage at 300 Area, 2001–2004.

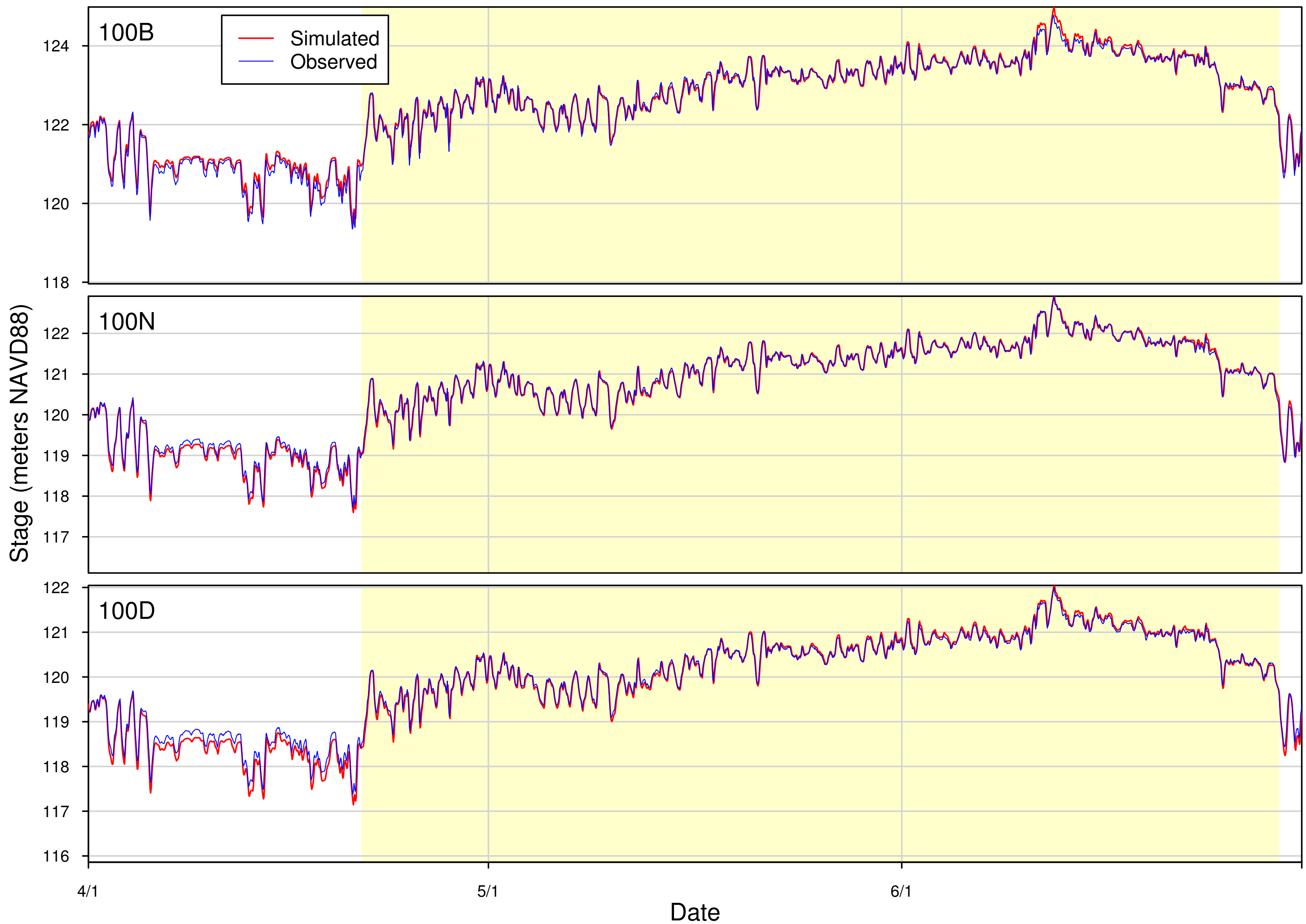

Figure D.26. Columbia River stage and high-flow calibration, 100B, 100N, 100D Areas. Period is April–June 1997. Yellow region is calibration period.

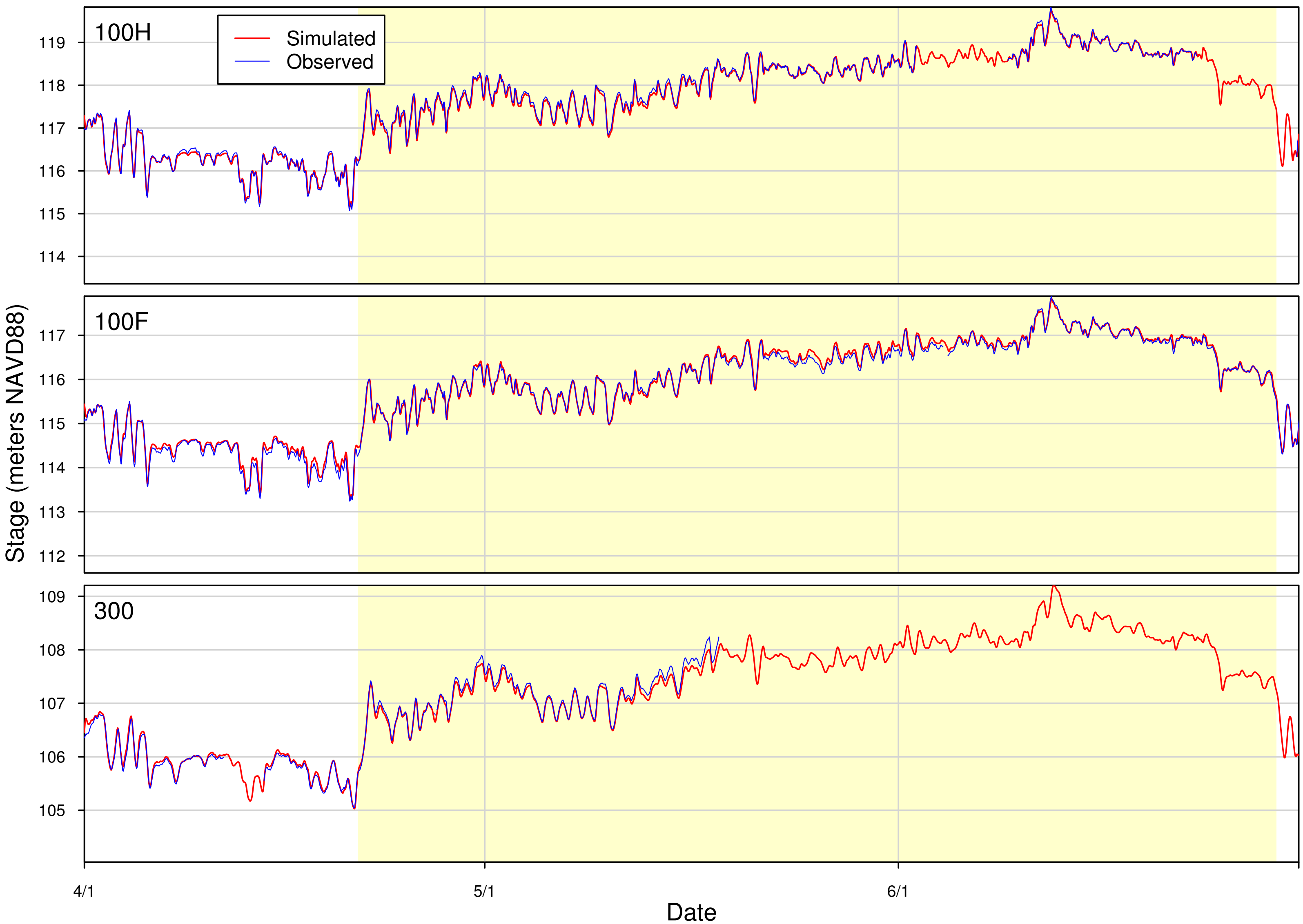

Figure D.27. Columbia River stage and high-flow calibration, 100H, 100F, 300 Areas. Period is April–June 1997. Yellow region is calibration period.

Table D.1. Goodness-of-fit statistics, 300 Area-only calibration (N_1 = number of hourly timesteps for Bias, MAE, R^2, E_2; MAE= mean absolute error, N_2 = number of hourly timesteps for E_1'; E_1'= baseline-adjusted first-degree efficiency [see Appendix C]).

Year	N_1	Bias (m)	MAE (m)	R^2	E_2	N_2	E_1'
			100-B				
1993	8658	-0.061	0.093	0.985	0.981	8640	0.907
1994	8759	-0.030	0.109	0.970	0.969	8736	0.884
1995	8661	0.028	0.103	0.977	0.975	8616	0.890
1996	8783	0.200	0.230	0.963	0.929	8760	0.817
1997	8756	0.181	0.188	0.993	0.971	8736	0.861
1998	8706	0.182	0.197	0.983	0.950	8520	0.810
1999	8554	0.102	0.129	0.979	0.964	8496	0.857
2000	7752	0.162	0.181	0.980	0.949	7536	0.806
2001	8344	0.217	0.230	0.970	0.873	7392	0.652
2002	8760	0.161	0.163	0.995	0.977	8760	0.874
2003	8759	0.148	0.150	0.993	0.962	8736	0.826
2004	5812	0.146	0.146	0.994	0.952	5808	0.805
All years	100304	0.118	0.160	0.979	0.968	98736	0.861
			100-N				
1993	3425	-0.299	0.302	0.973	0.770	3384	0.546
1994	8760	-0.268	0.277	0.969	0.856	8760	0.680
1995	8760	-0.248	0.252	0.977	0.890	8760	0.723
1996	8784	-0.296	0.296	0.991	0.902	8784	0.727
1997	8760	-0.310	0.311	0.992	0.922	8760	0.755
1998	8104	-0.365	0.365	0.982	0.791	6672	0.580
1999	8454	-0.417	0.417	0.982	0.622	7824	0.400
2000	8438	-0.383	0.383	0.972	0.729	7728	0.516
2001	8206	-0.339	0.346	0.925	0.641	8088	0.453
2002	8540	-0.340	0.341	0.994	0.906	8520	0.730
2003	8760	-0.349	0.349	0.993	0.814	8760	0.594
2004	7320	-0.505	0.505	0.991	0.536	7320	0.366
All years	96311	-0.343	0.345	0.983	0.874	93360	0.704
			100-D				
1996	1281	-0.427	0.427	0.993	0.443	1272	0.226
1997	8760	-0.438	0.438	0.996	0.814	8760	0.604
1998	8760	-0.431	0.431	0.987	0.693	8760	0.500
1999	8760	-0.485	0.485	0.987	0.485	8760	0.319
2000	8784	-0.384	0.471	0.810	0.529	8784	0.436
2001	8760	-0.346	0.425	0.607	-0.299	8760	0.123
2002	8758	-0.384	0.459	0.832	0.579	8736	0.501
2003	8754	-0.470	0.512	0.781	0.158	8736	0.226

Table D.1. (continued)

Year	N_1	Bias (m)	MAE (m)	R^2	E_2	N_2	E'_1
2004	5812	-0.488	0.488	0.995	0.245	5808	0.186
All years	68429	-0.426	0.462	0.919	0.682	68376	0.525
			100-H				
1993	8760	-0.234	0.234	0.973	0.869	8760	0.697
1994	8759	-0.066	0.223	0.898	0.873	8736	0.734
1995	8758	-0.173	0.186	0.981	0.916	8736	0.765
1996	8783	-0.222	0.225	0.994	0.933	8760	0.786
1997	8080	-0.273	0.273	0.992	0.915	7944	0.738
1998	7677	-0.218	0.220	0.982	0.888	6312	0.701
1999	8503	-0.355	0.355	0.986	0.666	7992	0.434
2000	8313	-0.310	0.310	0.986	0.768	7440	0.531
2001	6377	-0.143	0.145	0.970	0.867	4536	0.728
2002	7853	-0.256	0.257	0.992	0.909	6552	0.723
2003	8760	-0.244	0.244	0.994	0.862	8760	0.653
2004	5812	-0.234	0.234	0.994	0.823	5808	0.616
All years	96435	-0.228	0.244	0.979	0.909	90336	0.748
			100-F				
1993	8669	-0.347	0.348	0.989	0.765	8640	0.567
1994	7855	-0.339	0.341	0.981	0.747	7848	0.564
1995	5824	-0.268	0.268	0.984	0.869	5784	0.688
1996	8784	0.115	0.205	0.964	0.949	8784	0.809
1997	8584	0.215	0.216	0.995	0.954	8544	0.810
1998	8415	0.198	0.201	0.978	0.914	7800	0.761
1999	8760	0.170	0.190	0.953	0.893	8760	0.745
2000	1073	0.090	0.127	0.920	0.877	1056	0.695
2001	5094	-0.055	0.085	0.977	0.967	4176	0.858
2002	8618	-0.010	0.089	0.991	0.988	8568	0.923
2003	7908	0.926	0.926	0.989	-1.008	7272	-0.338
2004	2184	0.977	0.977	0.995	-4.268	2184	-1.369
All years	81768	0.097	0.306	0.855	0.844	79416	0.730
			300 Area				
1991	1332	-0.072	0.077	0.976	0.903	1320	0.717
1992	8784	-0.072	0.082	0.974	0.940	8784	0.813
1993	8759	-0.060	0.070	0.988	0.968	8736	0.859
1994	8760	-0.056	0.063	0.987	0.961	8760	0.851
1995	8760	-0.024	0.059	0.983	0.980	8760	0.894
1996	8722	0.040	0.080	0.985	0.981	8664	0.912
1997	5901	0.052	0.065	0.993	0.987	5832	0.905
1998	8434	0.016	0.050	0.989	0.989	7776	0.916
1999	8659	-0.006	0.046	0.988	0.987	8352	0.914

Table D.1. (continued)

Year	N_1	Bias (m)	MAE (m)	R^2	E_2	N_2	E_1'
2000	8601	-0.034	0.085	0.945	0.937	8232	0.826
2001	8735	0.024	0.048	0.973	0.957	8688	0.837
2002	8731	0.028	0.046	0.995	0.994	8616	0.938
2003	8603	0.011	0.041	0.987	0.984	8448	0.920
2004	8185	0.005	0.034	0.989	0.988	8184	0.916
All years	110966	-0.008	0.059	0.984	0.983	109152	0.911

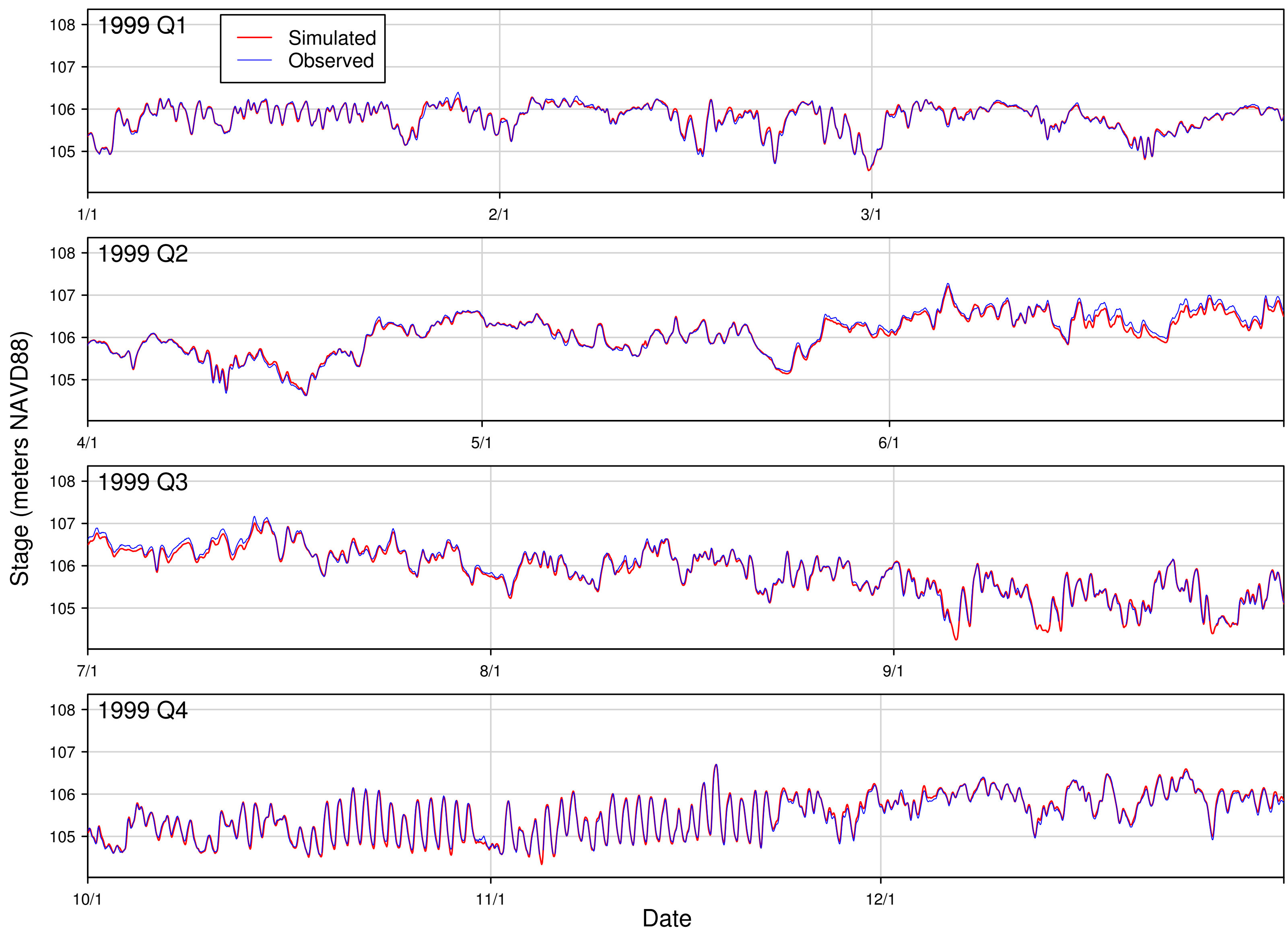

Figure D.28. Columbia River stage, 300 Area-only calibration, 1999 at 300 Area.

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