

HSPF Watershed Modeling Phase 3 for the Crow Wing, Redeye, and Long Prairie Rivers Watersheds: Calibration and Validation of Hydrology, Sediment, and Water Quality Constituents

Final Report

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EXECUTIVE SUMMARY

The United States Environmental Protection Agency (USEPA) requires the Minnesota Pollution Control Agency (MPCA) to carry out the Total Maximum Daily Load (TMDL) Program in the state of Minnesota. In an effort to expedite the completion of TMDL projects, MPCA has decided to construct watershed models to support the simultaneous development of TMDL studies for multiple listings within a cataloging unit or 8-digit Hydrologic Unit Code (HUC) watershed. As part of the model development process AQUA TERRA Consultants was contracted to develop watershed models for the Crow Wing River (HUC - 07010106), the Redeye River (HUC - 07010107), and the Long Prairie River (HUC - 07010108). Both the Long Prairie and Redeye Rivers flow into the Crow Wing River which flows into the Mississippi River.

This project was divided into multiple phases where the first two phases required the compilation and processing of geographical, meteorological, point source, and observed data for model development; proposal of model calibration approach; and completion of initial hydrologic calibration. In this final phase of the project, AQUA TERRA Consultants was contracted to finalize the hydrologic and water quality calibration and validation.

This report documents the final phase of the modeling project that includes:

- the results of hydrology calibration and validation,
- the review for sediment apportionment, and
- the results of water quality calibration and validation that include water temperature, sediment, nitrogen, phosphorus, organics, and chlorophyll A

Overall, the model performance for hydrology calibration and validation was satisfactory based on the model performance criteria, except at the most upstream gage, Straight River in Crow Wing watershed. This station is affected significantly by groundwater flow from outside the watershed, and the management of an upstream lake. Additional data collection and groundwater study may be required to improve the calibration at this location.

The water quality data was available at multiple locations in the watersheds and the model simulated water quality constituents close to the observed data. The observed data was not sufficient to conduct detailed statistical analysis, and therefore the quality of calibration and validation was based on the visual assessment of various graphs.

The watershed model for these three watersheds was developed at a scale so that all the waterbodies included in the draft 2010 TMDL list were modeled explicitly. Thus, the final model can be successfully used for TMDL development of smaller waterbodies in the watershed, and the model outputs can be used for finer scale assessments, or as input to other waterbody models.

As reported by MPCA, additional water quality data was collected after the calibration period (2003 to 2009) and significant water quality data was collected in 2011. Extending the model calibration period to include the additional years could improve model performance and increase the confidence in model results. Model extension should also provide enough data to analyze the model performance statistically. The Crow Wing watersheds have a significant number of lakes, and the water quality simulation of lakes can be improved with better hydraulic information.

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SECTION 1.0 INTRODUCTION

1.1 BACKGROUND

The United States Environmental Protection Agency (USEPA) requires the Minnesota Pollution Control Agency (MPCA) to carry out the Total Maximum Daily Load (TMDL) Program in the state of Minnesota. Minnesota has an abundance of lakes and rivers, many of which will require a TMDL study. In an effort to expedite the completion of TMDL projects, MPCA has decided to construct watershed models. These models have the potential to support the simultaneous development of TMDL studies for multiple listings within a cataloging unit or 8-digit Hydrologic Unit Code (HUC) watersheds within the State. This report documents the modeling of three 8-digit HUC watersheds: Crow Wing River (HUC - 07010106), Redeye River (HUC - 07010107), and Long Prairie River (HUC - 07010108). Both the Long Prairie and Redeye Rivers flow into the Crow Wing River which flows into the Mississippi River.

The objective of this work order is the successful calibration and validation of hydrologic and water quality model applications for the three watersheds using HSPF. These models can simulate the following constituents:

- Hydrology/flow
- Sediment/TSS
- Water Temperature
- Dissolved Oxygen
- Phytoplankton as Chlorophyll A
- Nitrite-Nitrate as Nitrogen
- Ammonia as Nitrogen
- Orthophosphate as Phosphorus
- BOD/Organics, comprised of
 - Labile BOD
 - Refractory Organic Nitrogen
 - Refractory Organic Phosphorus
 - Refractory Organic Carbon

1.2 WATERSHED DESCRIPTIONS

The Crow Wing river watershed (8 Digit HUC: 07010106) is located in the Northern Lakes and Forest, and North Central Hardwoods Forest ecoregions of Minnesota (Figure 1.1). This watershed is largely forested and is about 313 sq. mi. in size. The Redeye watershed (8 Digit HUC: 07010107) is predominantly located within the North Central hardwood Forest ecoregion of Minnesota with small sections in the Northern Lakes and Forests ecoregion. Forest and agriculture are the major land uses in this watershed, and it is about 141 sq. mi. in size. The Redeye watershed discharges into the Crow Wing river watershed. The Long Prairie watershed (8 Digit HUC: 07010108) is primarily located within the North Central Hardwood Forest ecoregion, with a small section in the Northern Lakes and Forests ecoregion. Forest and agriculture are the predominant land uses in this watershed as well. The Long Prairie watershed is about 140 sq. mi. in size, and flows into the Crow Wing river watershed. Some basic facts about the three watersheds are summarized in Table 1.1.

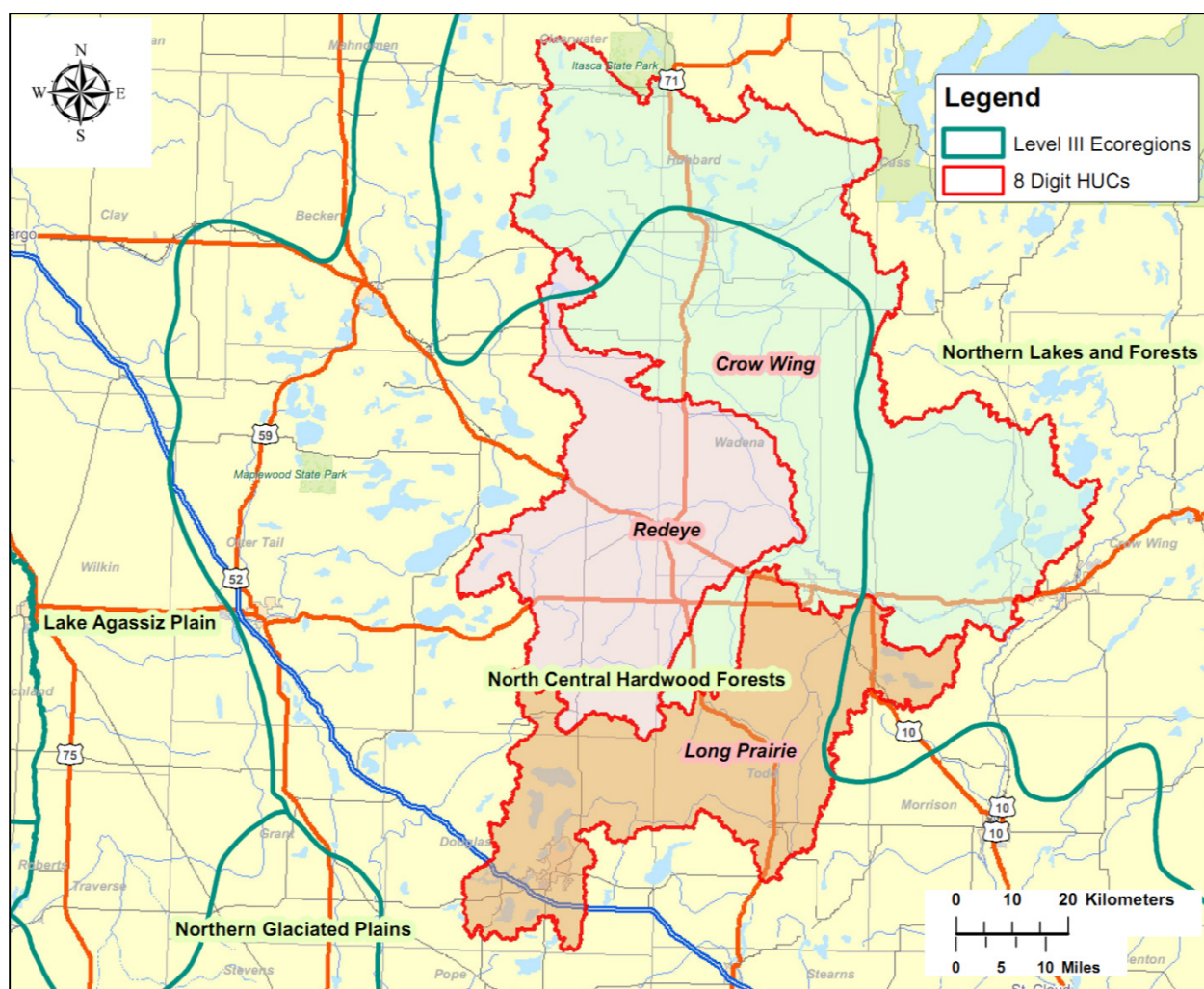


Figure 1.1 Location of Crow Wing, Redeye and Long Prairie watersheds in Minnesota

Table 1.1 Basic facts about Crow Wing, Redeye, and Long Prairie river watersheds

	Crow Wing	Redeye	Long Prairie
Area (sq. mi.)	313.4	141.4	140.0
Average Elevation above mean sea level (ft.)	1,357	1394	1367
Annual Precipitation (in.)	25-27	25-29	25-29
Major Land use(s)	Forest	Forest and Agriculture	Forest and Agriculture
Number of impaired Streams (draft 2010)	15	0	8
Streams needing TMDL (non-mercury)	1	0	3
Number of impaired Lakes (draft 2010)	44	1	19
Lakes needing TMDL (non-mercury)	6	0	3

1.3 OBJECTIVE OF THIS REPORT

This report provides details on final hydrologic and water quality calibration and validation of Redeye, Long Prairie and Crow Wing River watersheds. The earlier portions of this project

were completed in FY 2011 and FY 2012, and included model building, data procurement, and initial calibration. The objectives of individual work orders are presented below.

1. Compile both the geographic and timeseries data required to construct the model framework. (FY 2011)
2. Develop representation of watershed area and drainage network. (FY 2011)
3. Model point source representation. (FY 2012)
4. Formulate timeseries from observed flow and water quality monitoring to be used for watershed model calibration and validation. (FY 2012)
5. Perform the initial hydrologic calibration. (FY 2012)
6. Finalize hydrologic calibration, conduct hydrologic validation, and provide water balance. (FY 2013)
7. Define the sources of sediment within the watershed and conduct sediment calibration and validation tests. (FY 2013)
8. Conduct water quality calibration, validation and model evaluation. (FY 2013)

This report includes details on the three work orders completed in FY 2013.

SECTION 2.0 HYDROLOGY CALIBRATION AND VALIDATION

2.1 MODEL SETUP AND DESCRIPTION

The Redeye, Long Prairie, Crow Wing River watershed models were developed as three separate but linked HSPF models. The output in the form of flow and nutrients from the Redeye and Long Prairie models is input into the Crow Wing model at Crow Wing River upstream of Staples and Crow Wing River near Motley respectively (Figure 2.1). The details on model setup are described in earlier memos (AQUA TERRA Consultants, 2011 and 2012). Table 2.1 summarizes the number of subwatersheds in each HSPF model. The land use distribution of each model is presented in Table 2.2. The drainage networks of the three watersheds are shown in Figure 2.2.

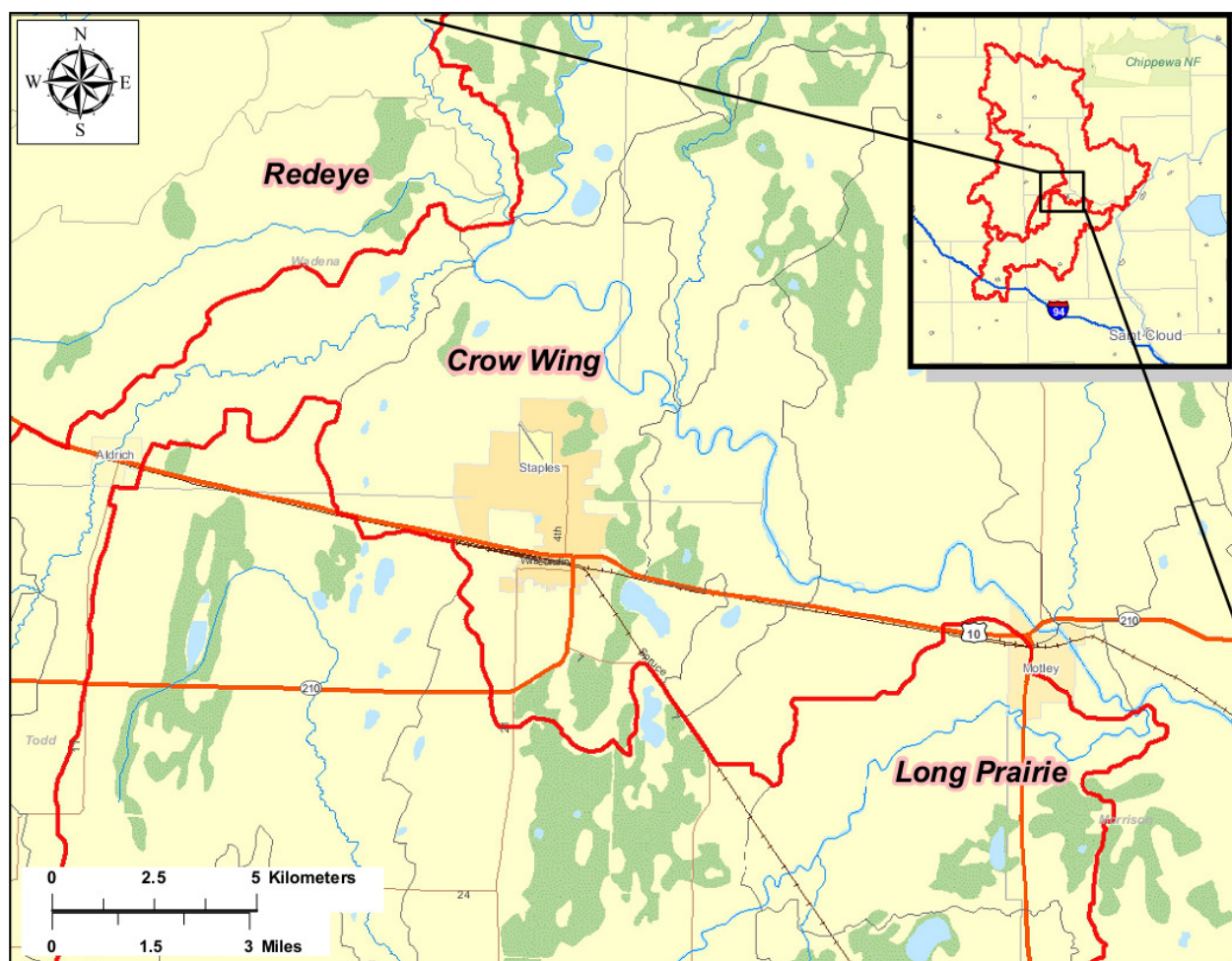


Figure 2.1 Location of Redeye and Long Prairie Rivers flowing into Crow Wing River

Table 2.1 The number and distribution of subwatersheds in the HUC 8 watersheds according to different levels of delineation

HUC 8 Watersheds	Parameters	HUC 12 Watersheds	DNR Level 7 Watersheds	DNR Level 8 Watersheds
Crow Wing	Count	59	136	273
	Mean Area (ac)	21490	9318	4645
	Median Area (ac)	19860	7654	3114
	Minimum Area (ac)	9747	1790	62
	Maximum Area (ac)	43783	30719	28740
Redeye	Count	23	58	83
	Mean Area (ac)	24870	9863	6892
	Median Area (ac)	25730	7558	5341
	Minimum Area (ac)	11468	2258	170
	Maximum Area (ac)	37075	37009	37010
Long Prairie	Count	30	64	129
	Mean Area (ac)	18880	8829	4391
	Median Area (ac)	18210	7400	3191
	Minimum Area (ac)	10320	3051	19
	Maximum Area (ac)	40871	21235	21240

Table 2.2 The number and distribution of subwatersheds in the HUC 8 watersheds after final delineation for model development

HUC 8 Watersheds	Parameters	Subwatershed Segmentation
Crow Wing	Count	103
	Mean Area (ac)	12,311
	Median Area (ac)	11,683
	Minimum Area (ac)	391
	Maximum Area (ac)	43,783
Redeye	Count	33
	Mean Area (ac)	17,335
	Median Area (ac)	15,244
	Minimum Area (ac)	1,115
	Maximum Area (ac)	37,075
Long Prairie	Count	47
	Mean Area (ac)	12,053
	Median Area (ac)	12,241
	Minimum Area (ac)	686
	Maximum Area (ac)	26,368



Figure 2.2 Drainage network of Redeye, Long Prairie, and Crow Wing River watersheds

The meteorological input data was obtained from the EPA's BASINS database and local precipitation records were provided by MPCA. The meteorological input data was assigned to the watersheds based on proximity to the station and quality of the data. The watershed maps in Figure 2.3 show the Meteorological stations that were used in the final watershed models. The detailed procedure of processing meteorological data and model segmentation has been described in AQUA TERRA Consultants, 2011.

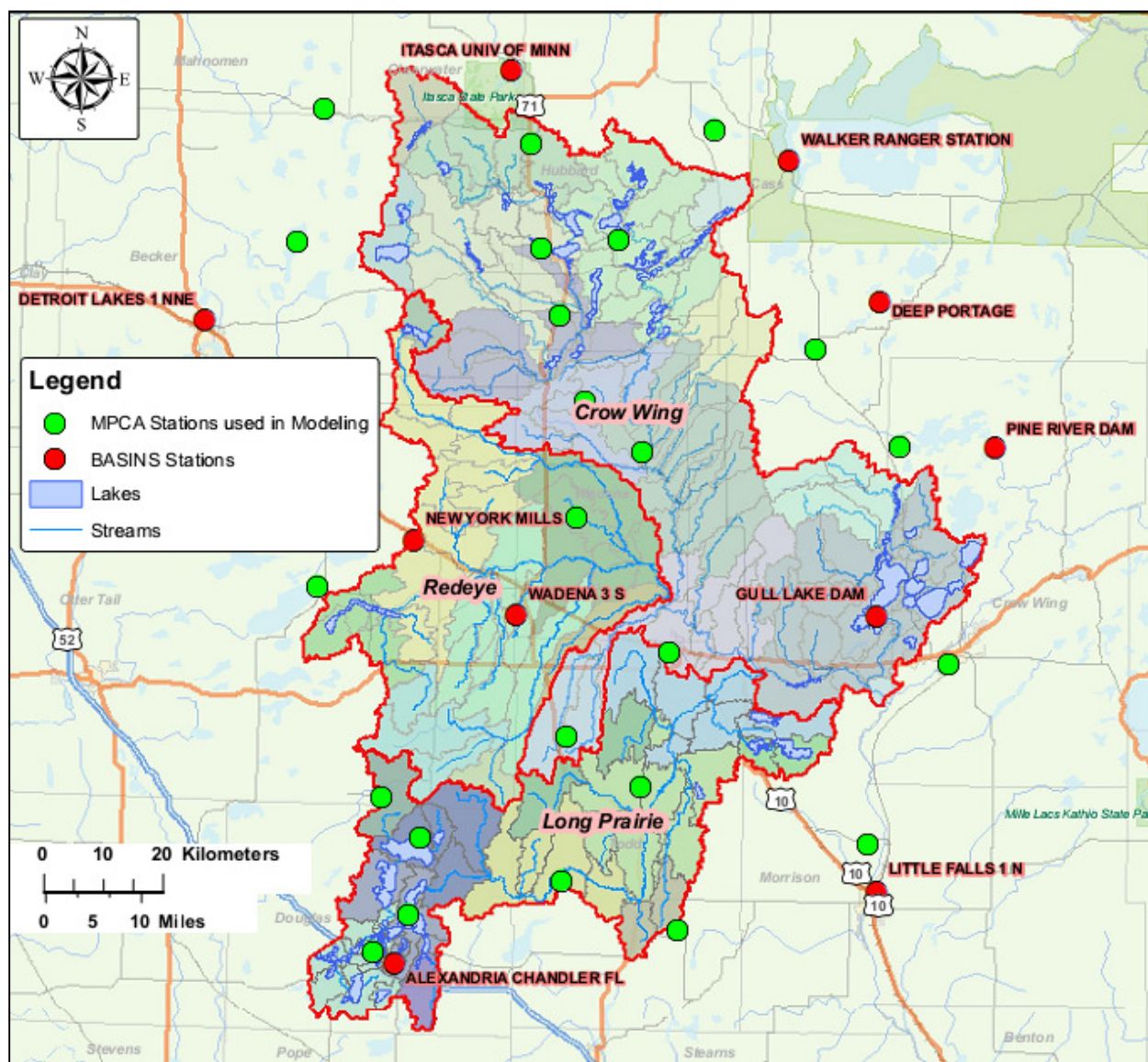


Figure 2.3 Locations of BASINS and MPCA stations with precipitation data

2.2 HYDROLOGY CALIBRATION

As described in the hydrologic calibration approach memo (AQUA TERRA Consultants, 2012), the calibration process started with the Long Prairie watershed where long term flow data was available at the USGS station (#05245100) on the Long Prairie River. The calibration period extended from 2003 to 2009, whereas the validation period was from 1995 to 2002. The initial parameter sets were obtained from an earlier Crow Wing Watershed Model (AQUA TERRA Consultants, 2005). Following the calibration on the Long Prairie river watershed, the

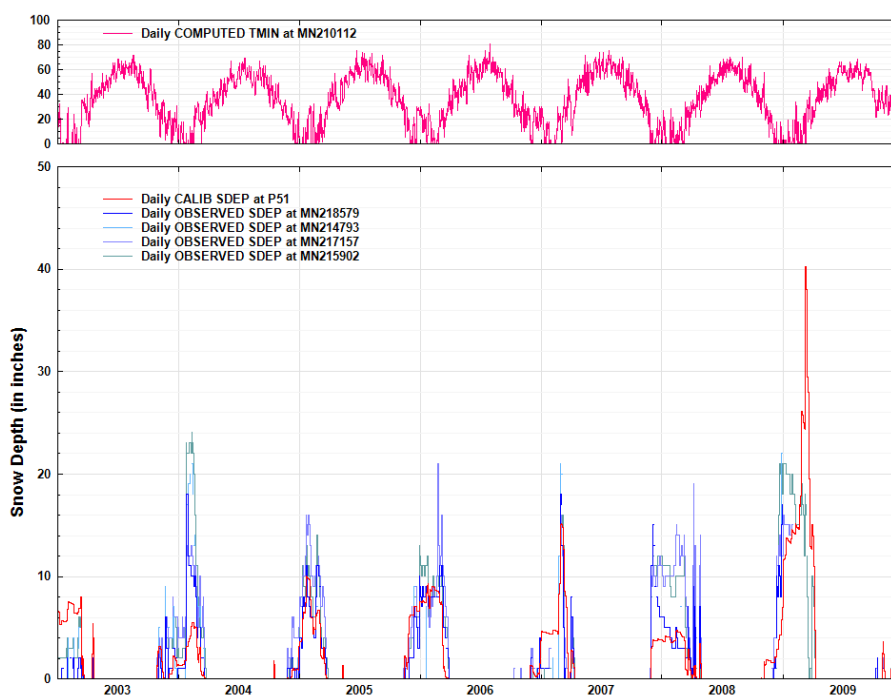
parameters from the Long Prairie model were adapted for the Redeye River watershed. The Redeye River watershed didn't have any long term flow gage data and therefore no extensive calibration was performed for this watershed.

The parameters from the Long Prairie River model were also used as the starting point for the Crow Wing River watershed. The Crow Wing River watershed has long term flow data at three USGS gages. The Straight River gage (#05243725) and the Crow Wing River gage near Nimrod (#05244000) are upstream of the locations where the Redeye and Long Prairie Rivers contribute flow to the Crow Wing River. The Crow Wing River gage near Pillager (#05247500) includes flow from all three watersheds.

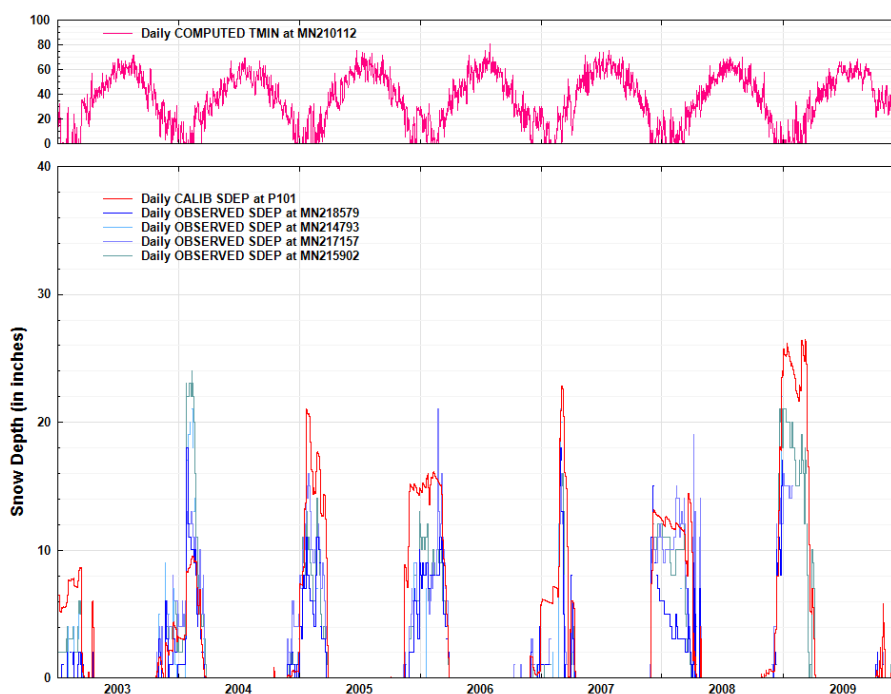
2.2.1 Long Prairie River Watershed

The Long Prairie River gage at Long Prairie, MN has a drainage area of 434 square miles which is about half of the total area of the Long Prairie watershed. As noted above, the initial set of parameters for this watershed was adapted from a prior Crow Wing Study (AQUA TERRA Consultants, 2005). The parameters were adjusted to reflect differences among the landuses of these watersheds (AQUA TERRA Consultants, 2012).

If snow is responsible for a dominant part of hydrology, as is the case for Minnesota watersheds, the first step in watershed calibration is to calibrate the snow depth to available observed data.. Snow depth data were available at a few locations in and around the watershed. Since snow depth data are notoriously variable across the landscape (due to wind drifting, exposure, vegetation, etc.) , simulated snow depths at various land segments in the watershed were compared with observed data at multiple locations, including some that are outside the watershed (Figure 2.4). Along with the time series of snow depth simulation, frequency duration curves of snow depth were plotted for the winter months (Figure 2.5) *i.e.* October-April, as another measure of comparison between observed and simulated values.

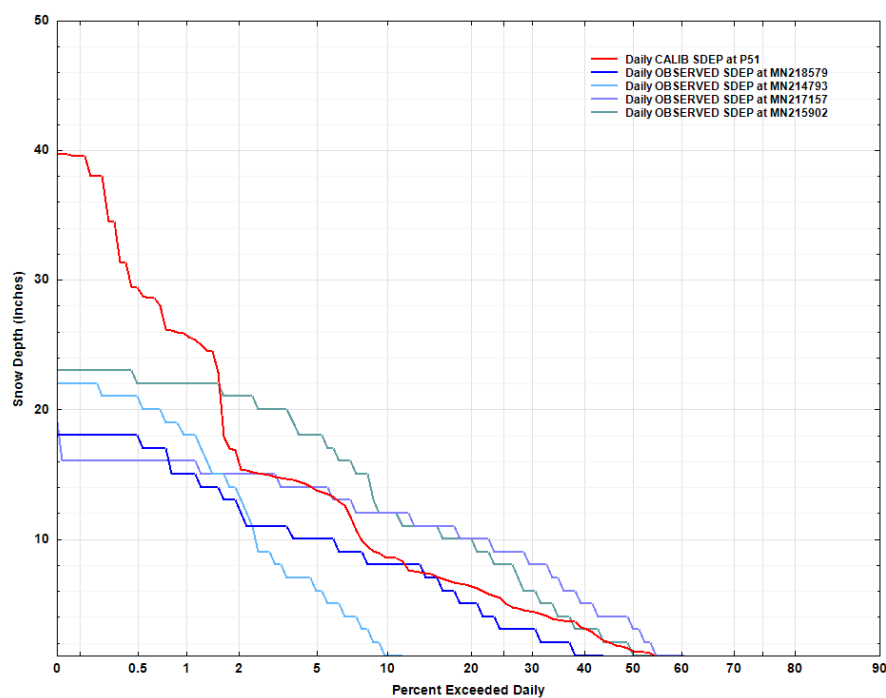


(a)

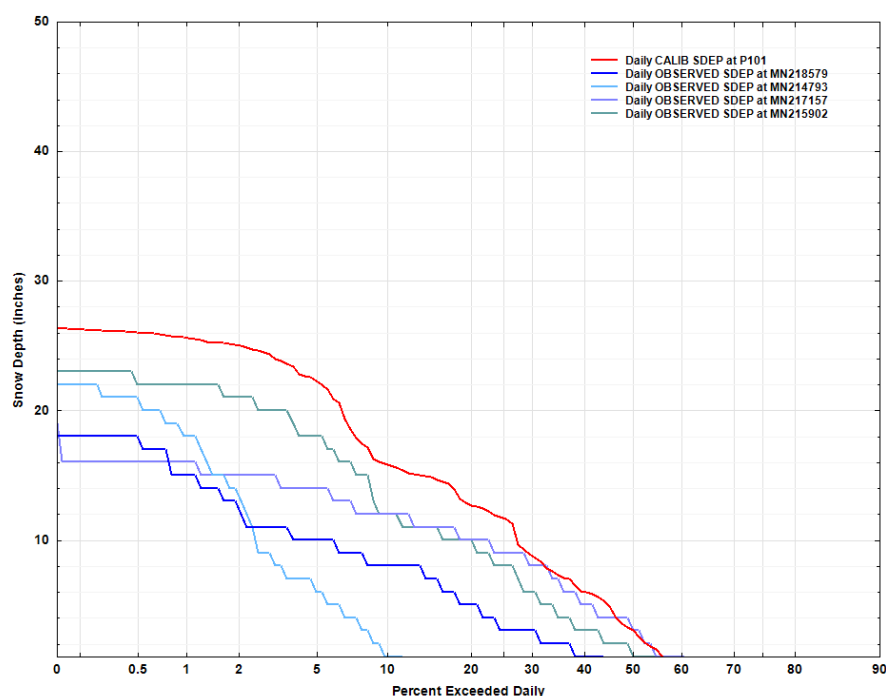


(b)

Figure 2.4 Snow depth simulation at (a) PERLND 51 and (b) PERLND 101 (Forest land areas in two different segment of the Long Prairie watershed) for the calibration period; simulated data is shown in red and observed data is shown in other colors



(a)



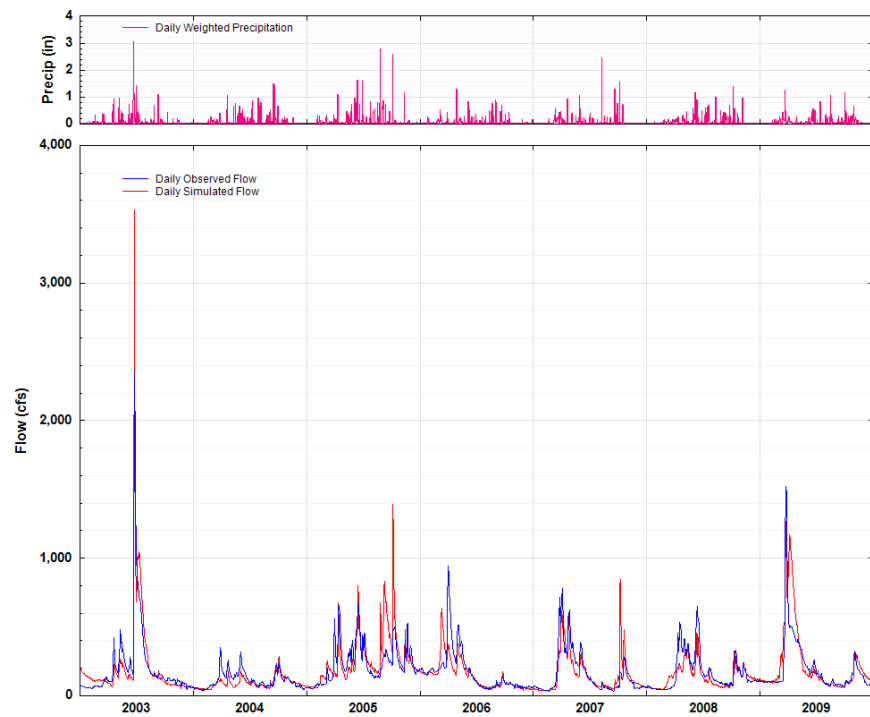
(b)

Figure 2.5 Comparison of snow depth frequency simulation for winter months (October to April) at (a) PERLND 51 and (b) PERLND 101 for the calibration period; simulated results are shown in the red curve and observed data is presented in other colors

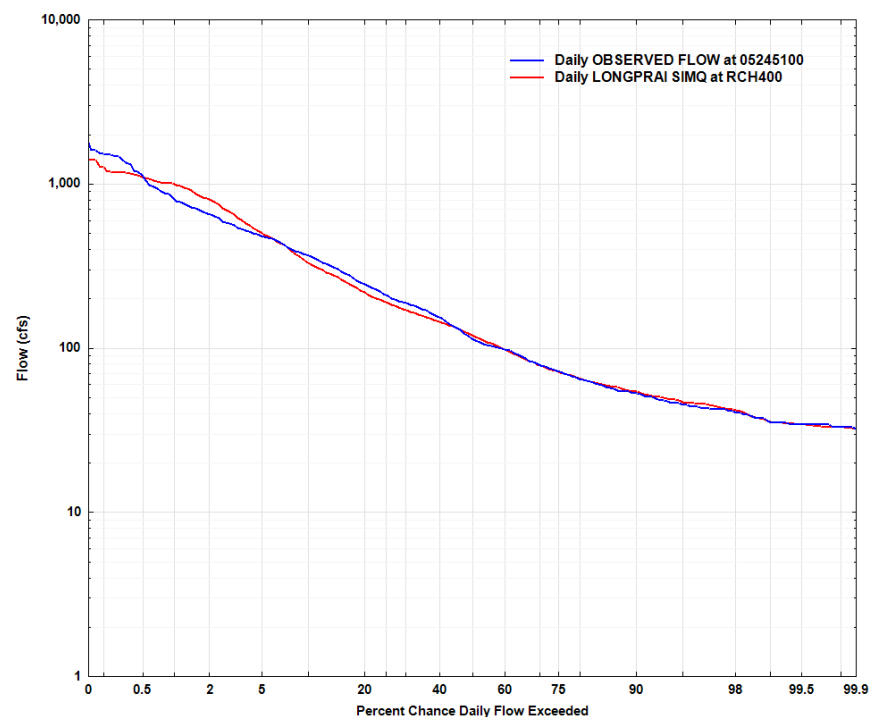
To calibrate the snow depth, snow parameters including SHADE (fraction of PERLND that is shaded from the sun's direct radiation), SNOWCF (factor by which recorded precipitation is multiplied during snow events to account for poor gage catch efficiency), COVIND (maximum snowpack depth at which entire land segment is covered with snow), TSNOW (wet bulb air temperature below which precipitation occurs as snow), SNOEVP (factor to adjust evaporation from the snowpack), CCFACT (factor to adjust the rate of heat transfer from the atmosphere to the snowpack), MWATER (maximum liquid water holding capacity in the snowpack), and MGMELT (Maximum rate of snowmelt by ground heat) were adjusted. Most of these parameters were in the range recommended by BASINS Technical Note #6, except CCFACT. The lowest recommended CCFACT value is 0.5; however, the calibrated values in this watershed were about 0.1. This was done to delay the timing of snow melt and better match the timing of observed snow depth data, its melt period, and flow data.

In general, the snow depth simulation appears adequate. The snow depth values of the simulation were generally in the range of the observed snow depth. The timing of snow depth was also reasonably simulated. However, in PERLND 51, the snow depth simulation was about 20 inches greater than the observed snow depth for some parts of the year 2009. The excess depth could be explained by greater precipitation at this segment compared to other gages in this watershed. Personal communication with staff at MCPA (Chuck Regan and Doug Wetzstein) suggests that this kind of variation is normal in Minnesota watersheds. Furthermore, the nearest snow depth gage to this segment (PERLND 51) was 28 miles away, so substantial differences are to be expected. Similar snow depth comparisons were conducted at multiple segments in the watershed; all of the graphs are provided in APPENDIX A.

Once the initial snow depth calibration was complete, the streamflow calibration was conducted. To conduct streamflow calibration, multiple parameters were adjusted as recommended by BASINS Technical Note #6. Sometimes, the streamflow calibration required us to revisit the snow calibration and adjust the parameters to better match the snow melt event timings and flow volumes. The hydrograph and frequency duration plots (Figure 2.6) of flow at the Long Prairie gage show a reasonable and good simulation.



(a)



(b)

Figure 2.6 Comparison of simulated and observed (a) flow hydrograph and (b) flow duration frequency curves at the Long Prairie River gage in Long Prairie River watershed for the calibration period

Along with graphical comparisons, multiple statistics were calculated to help guide and assess the calibration process. Table 2.3 shows the various flow components (these are also referred to as HSPEXP or expert system statistics, since they are calculated by that program), and Table 2.4 shows the error terms associated with these flows. All of these criteria meet the calibration standards. Also, it should be noted that no storm flows were recorded in the winter months in MN (since precip is snow), so the winter storm volume is often zero. Personal communication with MPCA staff suggests that the gages in these watersheds sometimes freeze and the observed flow volume during winter is estimated, instead of measured. Therefore, the calibration effort should primarily focus on non-winter volumes.

Table 2.3 Annual average statistics of flow at the Long Prairie gage in Long Prairie watershed for the calibration period

	Observed Total Runoff	Simulated Total Runoff	Simulated Surface Runoff	Simulated Interflow
total (inches)	5.33	5.26	0.43	0.91
10% high (inches)	1.74	1.86		
25% high (inches)	2.99	2.98		
50% high (inches)	4.21	4.13		
50% low (inches)	1.12	1.13		
25% low (inches)	0.42	0.42		
10% low (inches)	0.14	0.14		
storm volume (inches)	1.58	1.42	0.25	0.61
average storm peak (cfs)	691.06	700.16	899.5	698.1
baseflow recession rate	0.99	0.99		
summer volume (inches)	1.54	1.48		
winter volume (inches)	0.62	0.69		
summer storms (inches)	0.68	0.65	0.15	0.32

Table 2.4 Error values and criteria for the annual average flow statistics at the Long Prairie gage in Long Prairie Watershed for the calibration period

	Current	Criteria	Meets Criteria
Error in total volume (%)	-1.2	10	OK
Error in 10% highest flows (%)	7.1	15	OK
Error in 25% highest flows (%)	-0.3	10	OK
Error in 50% highest flows (%)	-1.9	10	OK
Error in 50% lowest flows (%)	1.4	10	OK
Error in 25% lowest flows (%)	1.9	15	OK
Error in 10% lowest flows (%)	3.2	20	OK
Error in low-flow recession	0.001	0.03	OK
Error in storm volumes (%)	-9.9	15	OK
Seasonal volume error (%)	-15.3	20	OK
Error in average storm peak (%)	1.3	15	OK
Summer volume error (%)	-4.1	20	OK
Winter volume error (%)	11.2	15	OK
Summer storm volume error (%)	-5.4	15	OK

Annual (Table 2.5) and monthly (Table 2.6) flow volume comparisons were also conducted. Different model statistics were calculated for monthly and daily flow volumes (Table 2.7).

Generally, it can be observed that volumes are slightly under-simulated in dry years and over-simulated in wet years, with the exception of year 2009, when the gage was apparently stuck at approximately 200 cfs for a long period. The monthly flow comparison table suggests that, in general, the flow was over-predicted in winter months and under-predicted in late spring/early summer months. It must be noted that the winter flows were estimated because of freezing flow gages and therefore poor flow comparisons during winter months is expected. The model statistics improved from daily to monthly comparisons, as expected. Overall the model statistics suggest that model performance is fair to good.

Table 2.5 Simulated and observed annual flow volumes (in) for the calibration period at the Long Prairie gage in Long Prairie watershed

Year	Precipitation	Simulated	Observed	Residual	% Error
2003	27.2	6.39	6.27	0.12	1.9
2004	26.6	2.74	3.32	-0.59	-17.6
2005	34.8	8.03	7.25	0.79	10.8
2006	22.4	4.34	4.98	-0.64	-12.9
2007	26.9	4.42	4.58	-0.16	-3.5
2008	27.4	4.11	4.9	-0.80	-16.3
2009	26.0	6.79	5.97	0.82	13.7
Mean	27.3	5.26	5.33	-0.07	-1.2

Table 2.6 Comparison of simulated and observed average monthly flow volumes (in) at the Long Prairie gage in Long Prairie watershed for the calibration period

Month	Simulated	Observed	Residual	% Error
Jan	0.23	0.20	0.03	13.8
Feb	0.20	0.18	0.02	10.5
Mar	0.55	0.51	0.04	7.5
Apr	0.77	0.88	-0.11	-12.1
May	0.52	0.71	-0.19	-27.0
Jun	0.64	0.76	-0.12	-16.2
Jul	0.55	0.52	0.03	6.4
Aug	0.29	0.26	0.03	10.4
Sep	0.38	0.30	0.08	26.9
Oct	0.52	0.42	0.10	23.1
Nov	0.36	0.35	0.01	2.9
Dec	0.26	0.24	0.02	9.6
Totals	5.26	5.33	-0.07	-1.2

Table 2.7 Monthly and daily statistics of flow volume at the Long Prairie gage in Long Prairie watershed for the calibration period

Statistics	Monthly	Daily
Correlation Coefficient	0.86	0.83
Coefficient of Determination	0.73	0.68
Mean Error (cfs)	-2.2	-2.2
Mean Absolute Error (cfs)	47.0	57.6
RMS Error	77.3	110.2
Model Fit Efficiency	0.66	0.61

The water balance components were also calculated at Long Prairie gage and the watershed outlet to ensure that the distribution of water in different storages is reasonable (Table 2.8).

Water balance of all land uses for the entire watershed was also calculated (Table 2.9) to ensure that the properties of different land uses were well represented. The infiltration capacity of soils in group AB is generally greater than the soils in CD group, therefore it is expected that land uses with the AB soils group would have lower runoff than the same land uses within the CD group. However, that was not observed in Forest-AB and Forest-CD, as the slopes of the PERLNDs representing Forest-AB are greater (up to 5-6 times greater) than those of the PERLNDs representing Forest-CD.

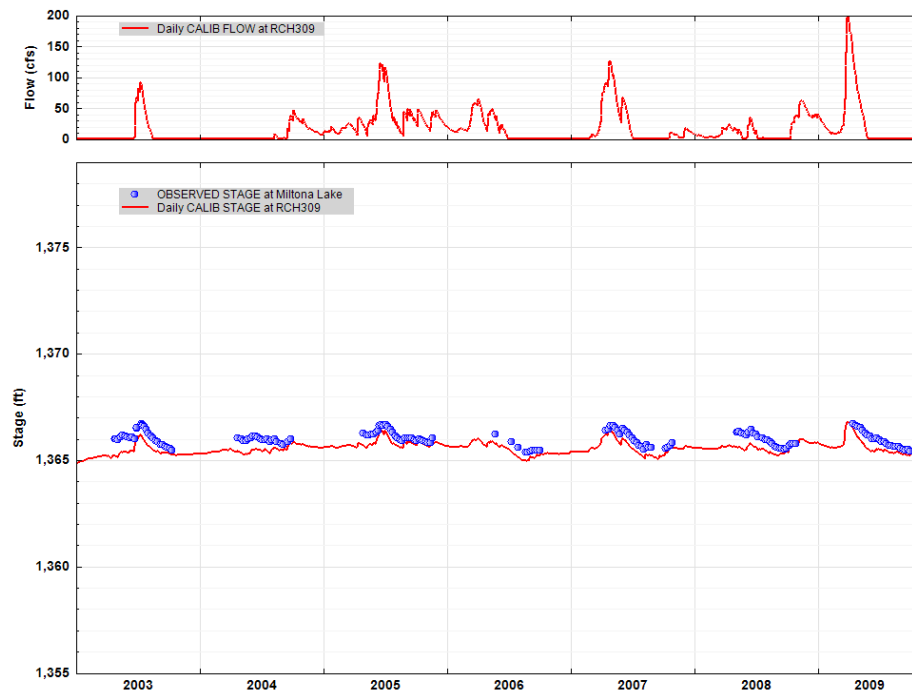
Table 2.8 Water balance components (in) at Long Prairie gage in Long Prairie watershed and the watershed outlet for the calibration period

Influx	R:400 (USGS Gage)	R:347 (Long Prairie River Outlet)
Rainfall	27.32	27.93
Runoff		
Surface-Pervious	0.31	0.24
Surface-Impervious	0.12	0.08
Interflow	0.91	0.94
Base flow	5.24	5.86
Total	6.58	7.12
GW Inflow		
Deep	0.03	0.03
Active	5.81	6.51
Evaporation		
Potential	34.02	31.77
Interception Storage	5.50	5.63
Upper Zone	3.91	4.04
Lower Zone	10.27	9.95
Ground Water	0.32	0.39
Base flow	0.29	0.28
Impervious	0.02	0.01
Total	20.29	20.29

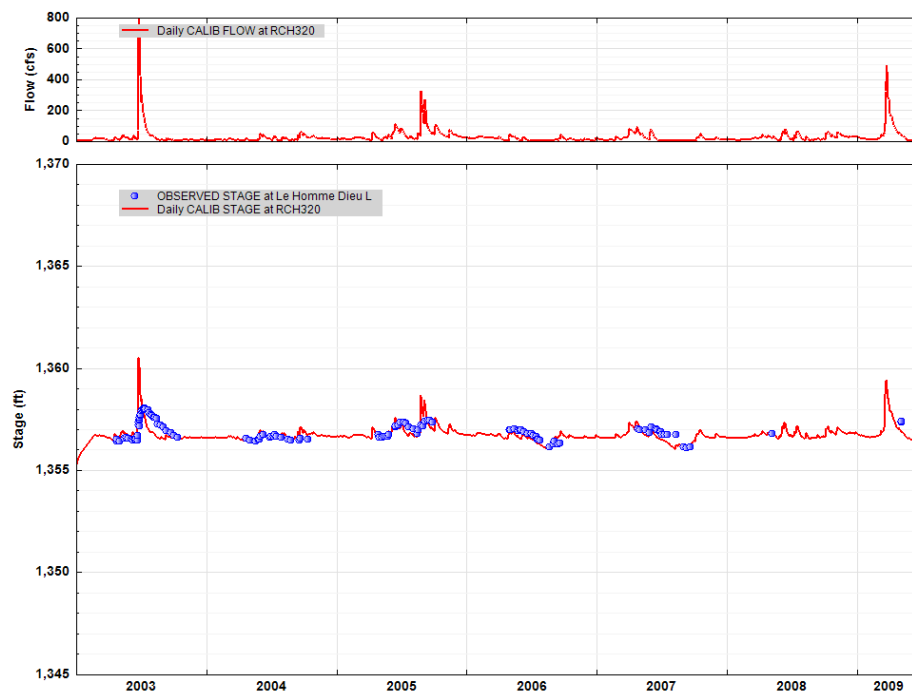
During hydrologic calibration, the observed and simulated lake levels were also compared and the parameters were adjusted to ensure that the model is simulating lake levels adequately. Figure 2.7 shows the simulated and observed lake level at two lakes in the Long Prairie watershed. At this stage the Long Prairie Watershed was considered calibrated.

Table 2.9 Water balance components of different land uses for the Long Prairie Watershed for the calibration period

PERLND		Runoff				GW Inflow		Evaporation						
Land Use	Rainfall	Surface	Interflow	Baseflow	Total	Deep	Active	Potential	Interception Storage	Upper Zone	Lower Zone	Ground Water	Baseflow	Total
Forest - AB	27.78	0.06	0.51	5.36	5.93	0.03	5.99	31.51	6.39	3.48	10.73	0.00	0.41	21.01
Forest - CD	28.12	0.04	0.66	5.63	6.34	0.03	6.25	31.17	6.57	3.55	10.48	0.00	0.40	21.01
Wetlands	27.92	0.00	0.06	4.94	5.00	0.04	8.19	31.18	6.18	2.49	10.46	3.15	0.17	22.44
Grassland - AB	27.72	0.30	1.25	6.34	7.89	0.03	6.52	32.13	5.26	4.31	9.52	0.00	0.26	19.34
Grassland - CD	28.33	0.41	1.76	6.63	8.80	0.03	6.81	30.95	5.41	4.13	9.27	0.00	0.25	19.06
Pasture - AB	27.59	0.29	1.25	6.21	7.75	0.03	6.40	32.62	5.26	4.25	9.58	0.00	0.26	19.35
Pasture - CD	28.35	0.43	1.75	6.63	8.81	0.03	6.81	31.10	5.45	4.08	9.28	0.00	0.25	19.06
Cropland-AB	27.46	0.17	0.73	6.00	6.90	0.03	6.14	33.05	5.11	4.45	10.37	0.00	0.26	20.19
Cropland-CD	28.39	0.24	1.04	6.29	7.57	0.03	6.42	31.01	5.30	5.24	9.64	0.00	0.25	20.42
Cropland-Drained	27.99	0.04	1.30	5.76	7.11	0.03	5.90	32.64	5.27	5.10	9.90	0.00	0.26	20.53
Dev, Open Space	27.87	1.15	1.64	5.46	8.26	0.03	5.59	32.12	5.19	4.50	9.32	0.00	0.25	19.26
Dev, Low Intensity	27.67	1.35	1.57	5.16	8.08	0.03	5.29	33.04	5.14	4.43	9.43	0.00	0.26	19.26
Dev, Medium Intensity	28.03	1.33	1.66	5.28	8.26	0.03	5.41	33.27	5.21	4.49	9.47	0.00	0.26	19.43
Average	27.93	0.25	0.97	5.89	7.10	0.03	6.53	31.77	5.65	4.00	9.99	0.40	0.28	20.31
IMPLND		Runoff		Evaporation										
Land Use	Rainfall	Surface	Potential	Actual										
Dev, Open Space	28.64	24.55	31.91	4.08										
Dev, Low Intensity	28.41	24.35	32.87	4.06										
Dev, Medium Intensity	28.97	24.85	33.11	4.12										
Average	28.69	24.60	32.66	4.09										



(a)

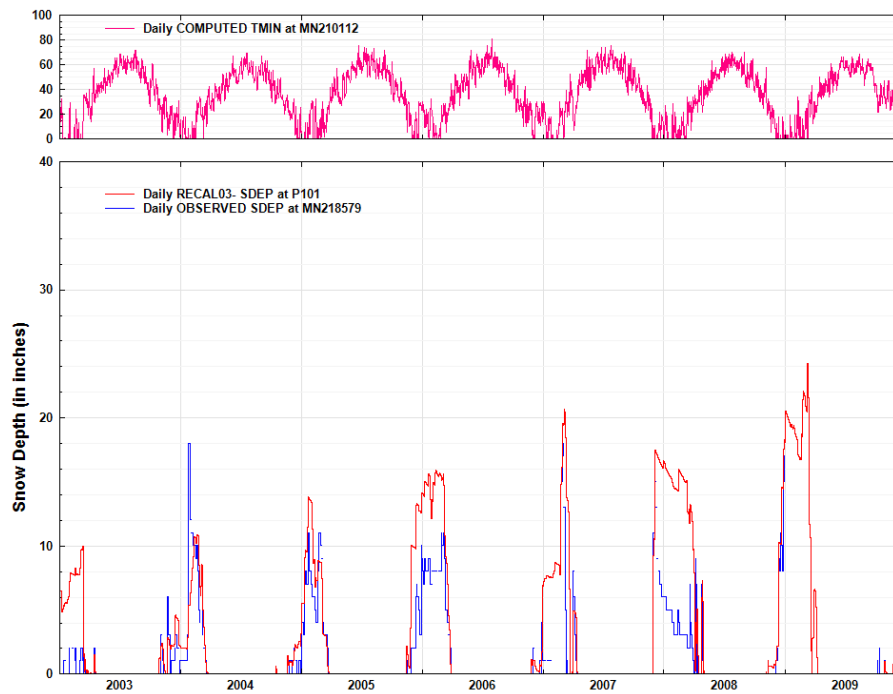


(b)

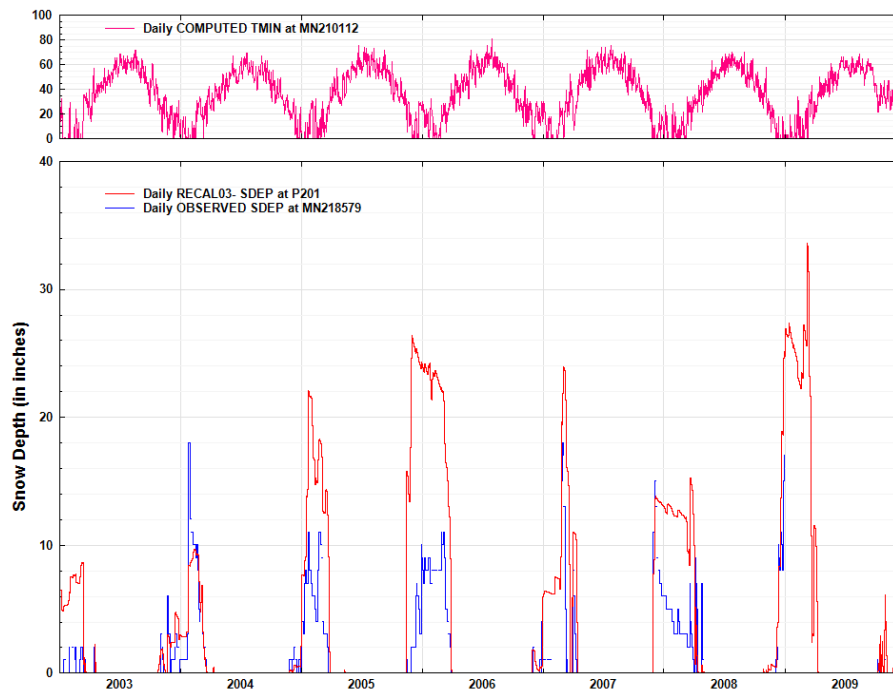
Figure 2.7 Comparison of observed and simulated lake levels at (a) Miltona Lake and (b) Le Homme Dieu Lake in the Long Prairie River Watershed for the calibration period

2.2.2 Redeye River Watershed

The Redeye River Watershed did not have a long term calibration gage available for detailed streamflow calibration, so the parameters from the Long Prairie River watershed model were used to develop the Redeye River model. There are three stations in the Redeye River watershed with some snow depth data; however, only one station (MN218579) had reliable snow depth data for the calibration and validation periods. Snow depth simulations for various PERLNDs were compared with the limited observed data. Because snow depth data was missing for significant periods of time, no extensive long term calibration was conducted for snow depth in the Redeye River watershed. Figure 2.8 and Figure 2.9 show the snow depth simulation in two PERLNDs. Similar comparisons of observed and simulated snow depth were made at various locations in the watershed; these graphs are provided in APPENDIX A. The snow depth frequency curves show that snow depth was over-predicted for the calibration period. Observed data were not available in the Redeye River watershed for a significant period of time, especially in the year 2009, which caused the discrepancy in the depth duration curve between observed and simulated data. Overall, snow depth and timing in the Redeye River watershed were simulated reasonably well, considering the limited data available.

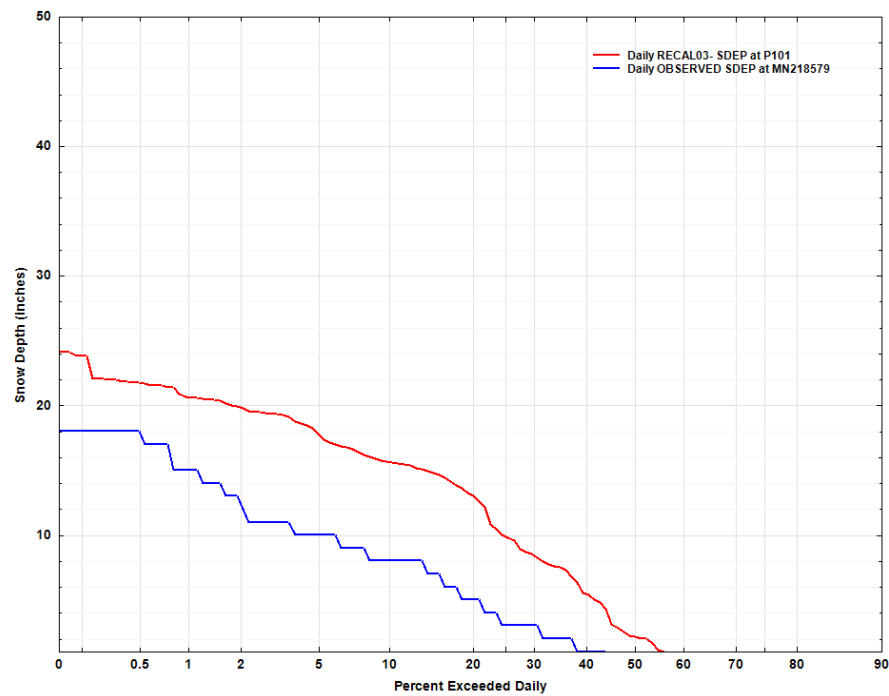


(a)

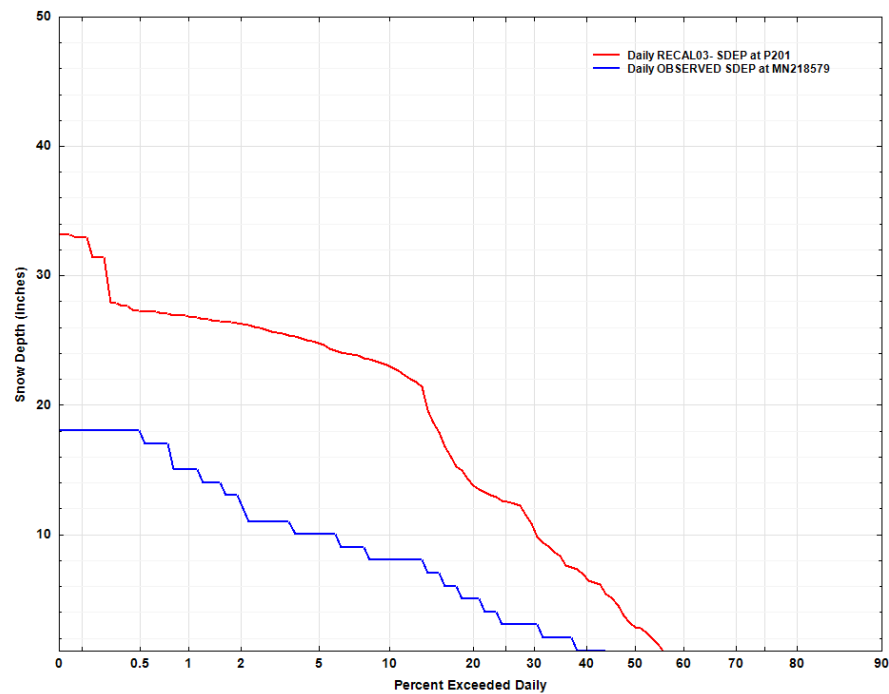


(b)

Figure 2.8 Snow Depth Simulation at (a) PERLND 101 and (b) PERLND 201 (Forest land areas in two different segments of the Redeye River watershed) for the calibration period; simulated data is shown by the red curve; observed data is shown in other colors. The auxiliary graph shows the recorded minimum daily temperature



(a)



(b)

Figure 2.9 Comparison of snow depth frequency simulation for winter months (October to April) at (a) PERLND 101, and (b) PERLND 201 in the Redeye River watershed for the calibration period; simulated results are shown by the red curve and observed data is presented in other colors

Although no extensive calibration was conducted for the Red River Watershed, the water balance for the entire watershed (Table 2.10) and the water balance by land use (Table 2.11) were reviewed for consistency.

Table 2.10 Water Balance Components (in) in the Redeye River watershed for the calibration period

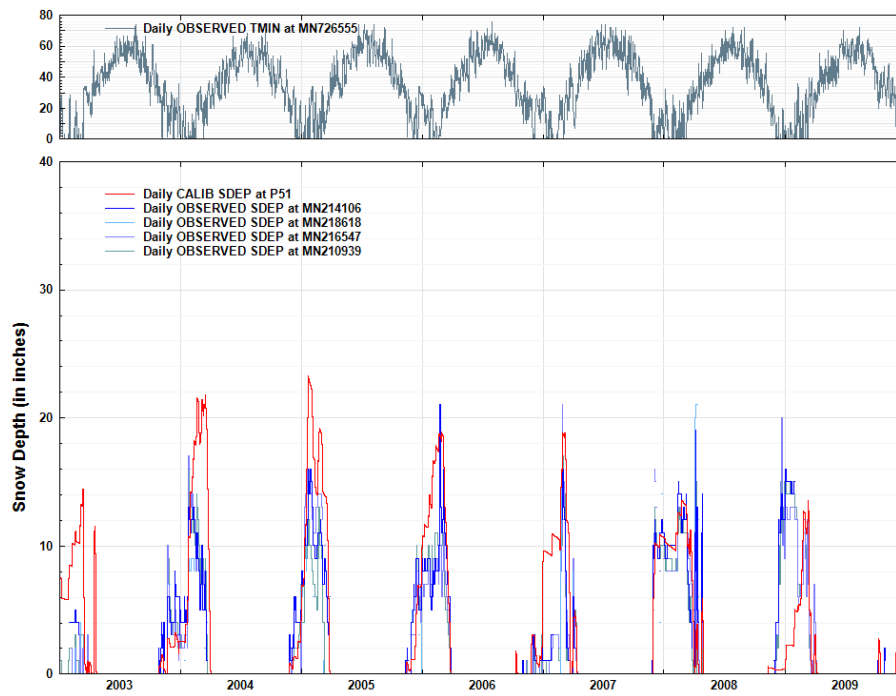
Influx	R:133 (Redeye River Outlet)
Rainfall	27.11
Runoff	
Surface-Pervious	0.11
Surface-Impervious	0.04
Interflow	0.72
Base flow	5.92
Total	6.78
GW Inflow	
Deep	0.03
Active	6.73
Evaporation	
Potential	30.11
Interception Storage	5.20
Upper Zone	3.63
Lower Zone	9.72
Ground Water	0.53
Base flow	0.26
Impervious	0.01
Total	19.34

Table 2.11 Water balance components by land use for the Redeye River Watershed for the calibration period

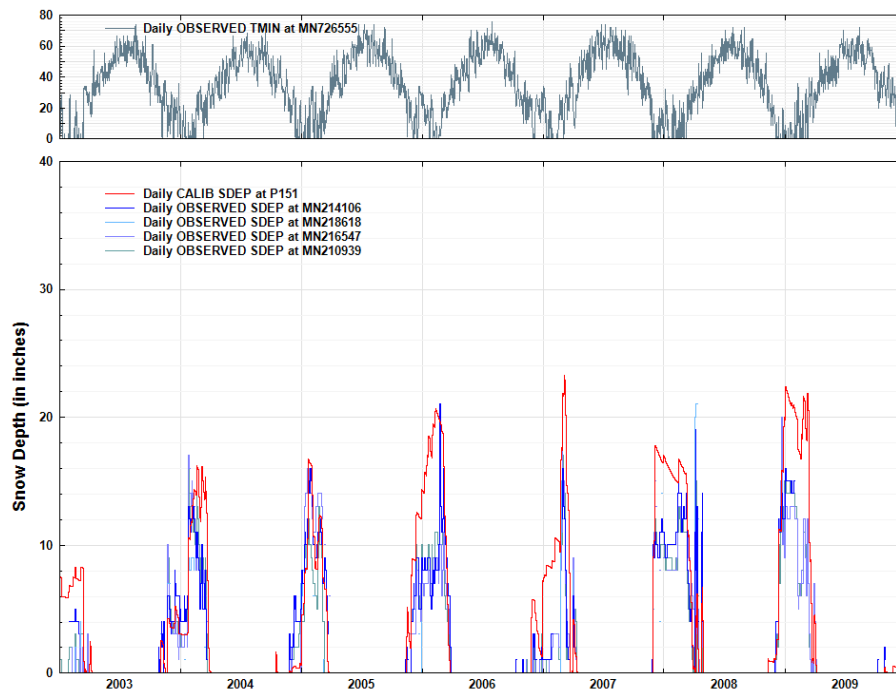
PERLND		Runoff				GW Inflow		Evaporation						
Land Use	Rainfall	Surface	Interflow	Baseflow	Total	Deep	Active	Potential	Interception Storage	Upper Zone	Lower Zone	Ground Water	Baseflow	Total
Forest - AB	26.70	0.03	0.40	5.39	5.82	0.03	5.94	30.17	5.83	3.03	10.42	0.00	0.39	19.67
Forest - CD	27.11	0.02	0.48	5.60	6.10	0.03	6.17	29.82	5.85	3.43	10.17	0.00	0.38	19.83
Wetlands	27.12	0.00	0.05	4.82	4.86	0.04	7.99	30.13	5.83	2.08	10.20	3.00	0.16	21.26
Grassland - AB	26.98	0.15	1.10	6.59	7.84	0.03	6.80	30.28	4.87	3.83	9.24	0.00	0.24	18.18
Grassland - CD	27.19	0.21	1.31	6.43	7.94	0.03	6.65	30.09	4.90	4.20	9.01	0.00	0.24	18.35
Pasture - AB	27.01	0.13	1.11	6.63	7.86	0.03	6.84	30.20	4.87	3.87	9.23	0.00	0.24	18.20
Pasture - CD	27.17	0.22	1.30	6.43	7.94	0.03	6.65	29.97	4.90	4.21	8.98	0.00	0.24	18.33
Cropland-AB	27.20	0.06	0.62	6.57	7.25	0.03	6.75	30.30	4.66	4.27	9.88	0.00	0.24	19.04
Cropland-CD	27.21	0.15	0.85	6.09	7.08	0.03	6.26	29.97	4.65	4.96	9.44	0.00	0.23	19.29
Cropland-Drained	27.41	0.03	1.10	6.07	7.20	0.03	6.24	30.07	4.66	5.01	9.47	0.00	0.23	19.37
Dev, Open Space	27.14	0.67	1.67	5.69	8.02	0.03	5.86	30.17	4.74	4.31	9.02	0.00	0.24	18.30
Dev, Low Intensity	27.32	0.64	1.73	5.83	8.19	0.03	6.00	30.19	4.67	4.35	9.07	0.00	0.23	18.32
Dev, Medium Intensity	27.54	0.55	1.82	5.98	8.36	0.03	6.16	30.12	4.65	4.42	9.09	0.00	0.23	18.39
Average	27.11	0.11	0.72	5.93	6.76	0.03	6.74	30.11	5.21	3.64	9.73	0.53	0.26	19.37
IMPLND		Runoff	Evaporation											
Land Use	Rainfall	Surface Runoff	Potential	Actual										
Dev, Open Space	27.44	23.82	30.13	3.61										
Dev, Low Intensity	27.59	24.04	30.12	3.55										
Dev, Medium Intensity	27.86	24.34	30.00	3.52										
Average	27.58	24.01	30.09	3.57										

2.2.3 Crow Wing River Watershed

The hydrology calibration in the Crow Wing River watershed model also started with snow depth calibration. The snow depth comparison in two different PERLNDs is shown in Figure 2.10 and Figure 2.11. The snow depth simulation shown in these figures appears reasonable and acceptable in terms of depth and timing. The snow parameters that were adjusted were similar to the ones adjusted for the Long Prairie watershed.

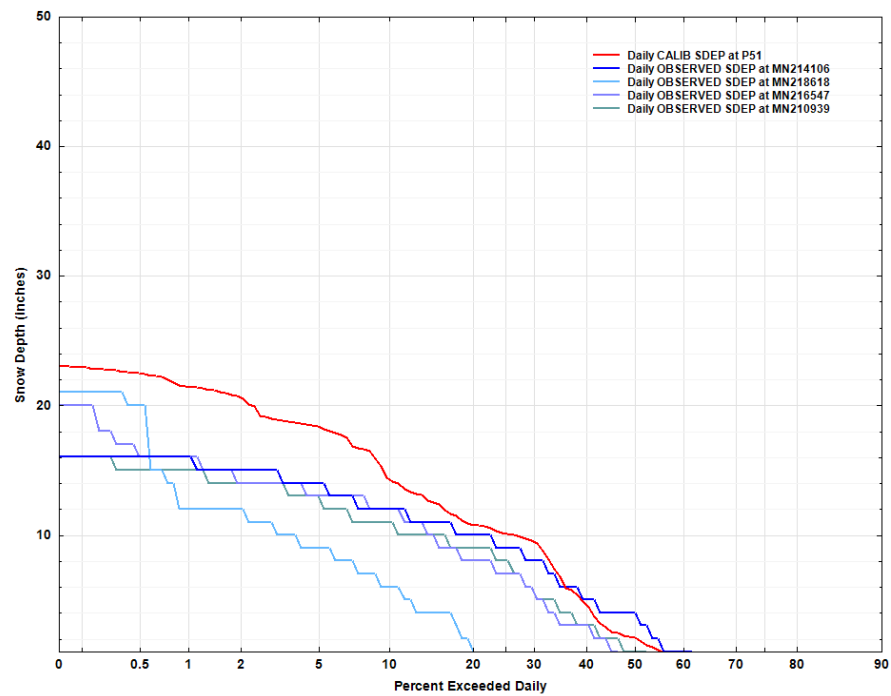


(a)

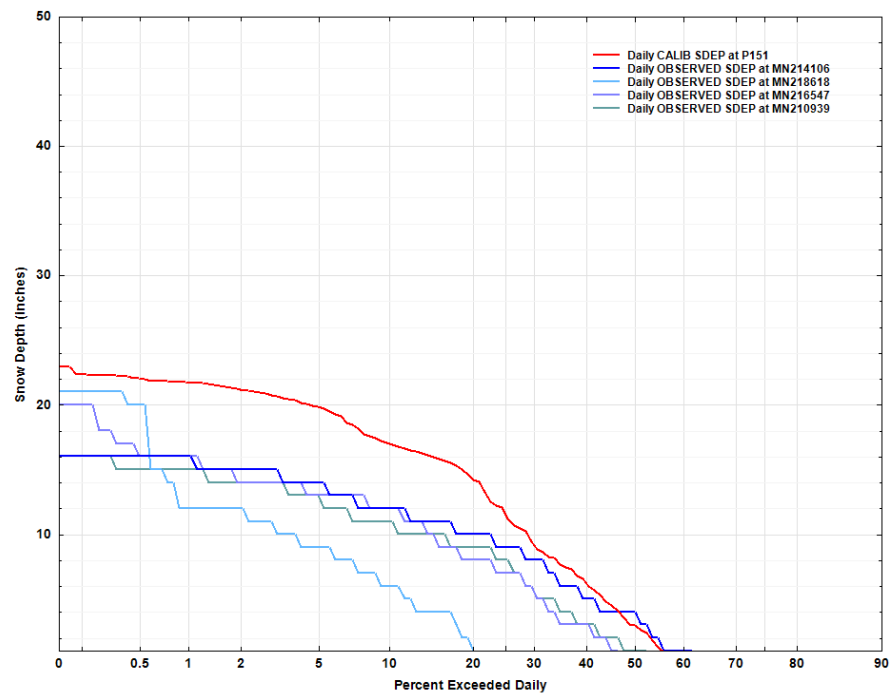


(b)

Figure 2.10 Snow depth simulation at (a) PERLND 51 and (b) PERLND 151 (Forest land areas in two different segments of the Crow Wing River watershed) for the calibration period; simulated data is shown by the red curve and observed data is shown in other colors



(a)

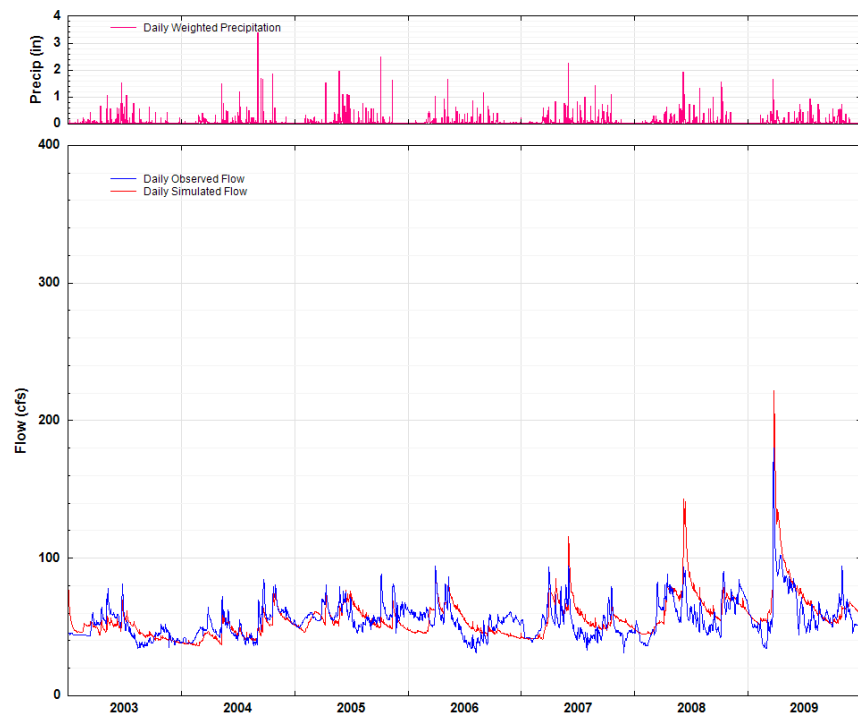


(b)

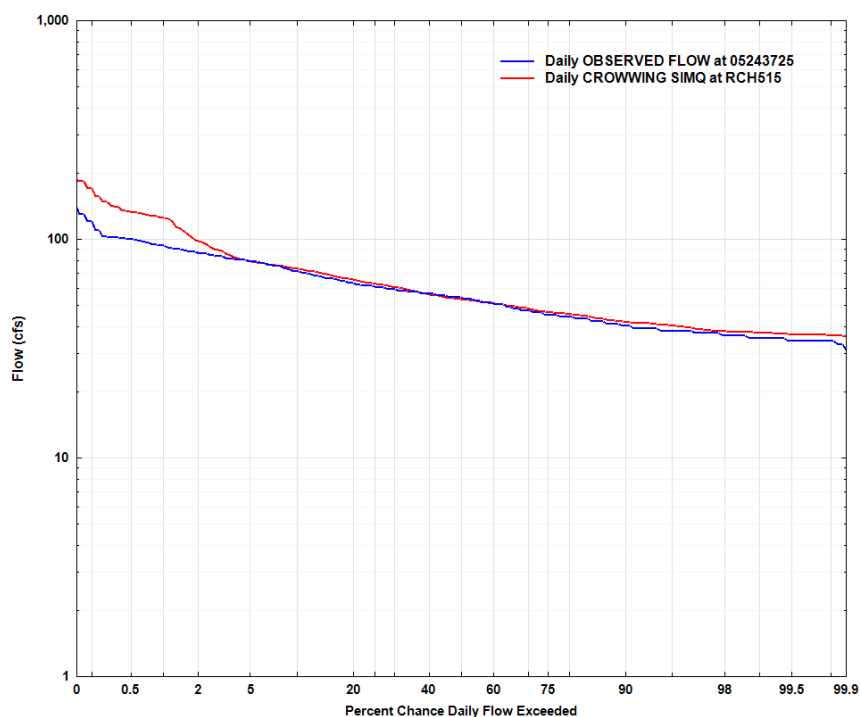
Figure 2.11 Comparison of snow depth frequency simulation for winter months (October to April) at (a) PERLND 51, and (b) PERLND 151 in the Crow Wing River watershed for the calibration period; simulated results are shown by the red curve and observed data is presented in other colors

Streamflow calibration for the Crow Wing watershed model was initiated using the parameters from the calibrated Long Prairie River watershed model. The most upstream gage in the Crow Wing, the Straight River gage near Park Rapids, was the first to be calibrated. The Straight River gage has a drainage area of about 53 sq. miles and drains only one model segment flows to it. The average observed runoff at the Straight River gage over the calibration period was more than 12", which is 2 to 2.5 times greater than the observed runoff at any of the other gages in the Crow Wing and Long Prairie watersheds. The excess streamflow indicated that the Straight River watershed likely receives flow from groundwater from outside the watershed. This conclusion is also supported by Stark et al. (1995). To simulate the groundwater inflow, a constant inflow of 0.75 ac-ft/hr into Straight Lake and 1.75 ac-ft/hr into Straight River downstream of Straight Lake was assumed. This value was obtained by calibration. There was no additional information about the groundwater flow and its seasonal variation, so a constant flow was assumed.

To conduct the streamflow calibration, parameters were adjusted as recommended in BASINS Technical Note #6. Figure 2.12 shows the hydrograph and the flow frequency duration curve. The Straight River watershed is unique as the flow in the stream stays between 30 and 105 cfs for the entire simulation period; the flow duration curve for the Straight River gage is much flatter than the corresponding flow duration curves for any of the other gages in these watersheds. It is generally difficult to calibrate a watershed with such a low variance in output flow, as the effect of external forcing factors such as precipitation is muted. The model fit efficiency for watersheds like this is generally pretty low and can even be negative (Krause et al., 2005).



(a)



(b)

Figure 2.12 Comparison of simulated and observed (a) flow hydrograph and (b) flow duration frequency curves at the Straight River gage in Crow Wing River watershed for the calibration period

The model calibration statistics are presented in Table 2.12 and Table 2.13. The calibration statistics satisfy all the calibration criteria except the seasonal flow error. The primary reason for the seasonal flow error is the overestimation of flow volume in the summer. This overestimation of summer flow volume is likely the result of constant groundwater inflows from external sources.

Table 2.12 Annual Average Statistics of flow at the Straight River gage in the Crow Wing River watershed

	Observed Total Runoff	Simulated Total Runoff	Simulated Surface Runoff	Simulated Interflow
total (inches)	12.78	13.19	0.049	0.454
10% high (inches)	1.93	2.10		
25% high (inches)	4.20	4.45		
50% high (inches)	7.50	7.79		
50% low (inches)	5.27	5.39		
25% low (inches)	2.38	2.48		
10% low (inches)	0.88	0.92		
storm volume (inches)	2.62	2.72	0.032	0.344
average storm peak (cfs)	77.64	74.61	6.905	24.387
baseflow recession rate	1.00	0.996		
summer volume (inches)	2.98	3.55		
winter volume (inches)	2.89	2.80		
summer storms (inches)	0.79	0.92	0.013	0.100

Table 2.13 Error Terms and Criteria for the Annual Average Flow Statistics at the Straight River gage in the Crow Wing River Watershed

	Current	Criteria	Meets Criteria
Error in total volume (%)	3.2	10	OK
Error in 10% highest flows (%)	9.1	15	OK
Error in 25% highest flows (%)	6.1	10	OK
Error in 50% highest flows (%)	3.9	10	OK
Error in 50% lowest flows (%)	2.3	10	OK
Error in 25% lowest flows (%)	4.0	15	OK
Error in 10% lowest flows (%)	5.1	20	OK
Error in low-flow recession	0.004	0.03	OK
Error in storm volumes (%)	3.9	15	OK
Seasonal volume error (%)	22.2	20	Fails
Error in average storm peak (%)	-3.9	15	OK
Summer volume error (%)	19.2	20	OK
Winter volume error (%)	-3.0	15	OK
Summer storm volume error (%)	15.6	15	OK

Annual (Table 2.14) and monthly (Table 2.15) flow comparisons were also conducted. Model performance statistics were calculated for the daily and monthly flow (Table 2.16). Overall, the yearly and monthly percent errors are small. The monthly and daily statistics show that the model prediction is fair. Model fit efficiency is extremely poor due to the low variance of output flow, as discussed above. Overall, the model outputs for the Straight River gage were considered acceptable.

Table 2.14 Simulated and Observed Yearly Flow Volume (in) for the Straight River Gage in the Crow Wing River Watershed for the calibration period

Year	Precipitation	Simulated	Observed	Residual	% Error
2003	19.8	11.13	11.0	0.10	0.9
2004	26.4	11.03	11.8	-0.80	-6.8
2005	26.5	13.15	13.7	-0.56	-4.1
2006	20.8	12.21	12.4	-0.21	-1.7
2007	27.1	12.88	11.8	1.09	9.3
2008	30.4	15.42	14.0	1.38	9.9
2009	25.8	16.47	14.6	1.86	12.8
Mean	25.3	13.2	12.8	0.41	3.2

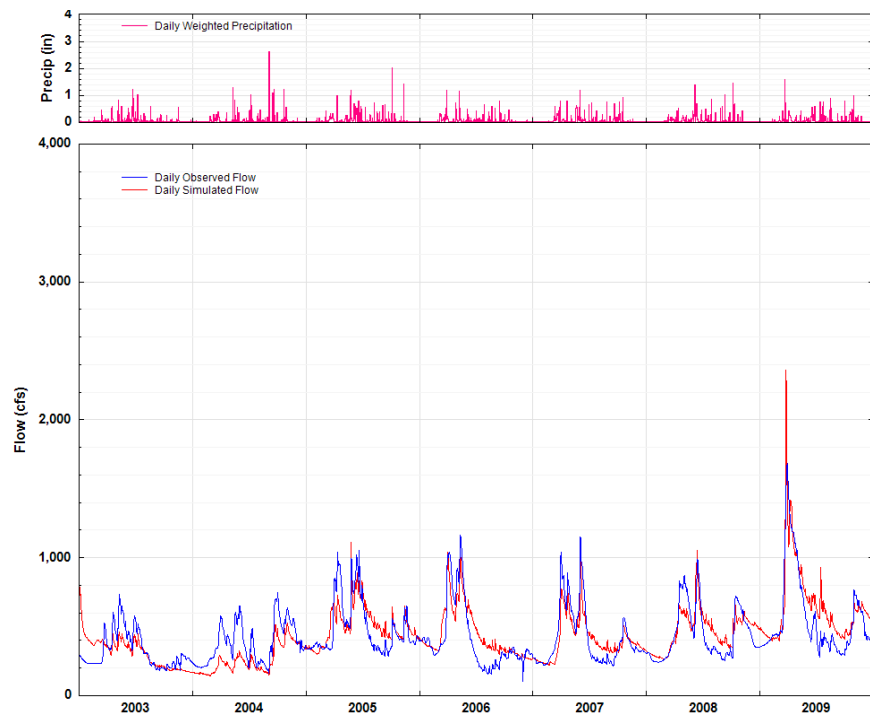
Table 2.15 Comparison of Simulated and Observed Average Monthly Flow Volume (in) for the Straight River Gage in the Crow Wing River Watershed for the calibration period

Month	Simulated	Observed	Residual	% Error
Jan	0.94	0.96	-0.02	-2.0
Feb	0.83	0.84	-0.01	-1.2
Mar	1.15	1.14	0.01	0.5
Apr	1.30	1.26	0.04	3.5
May	1.27	1.26	0.01	0.8
Jun	1.33	1.12	0.21	18.7
Jul	1.18	0.95	0.22	23.2
Aug	1.04	0.90	0.14	15.6
Sep	0.97	0.97	0.00	-0.1
Oct	1.06	1.16	-0.10	-8.5
Nov	1.07	1.11	-0.04	-3.2
Dec	1.03	1.09	-0.06	-5.3
Totals	13.19	12.8	0.41	3.2

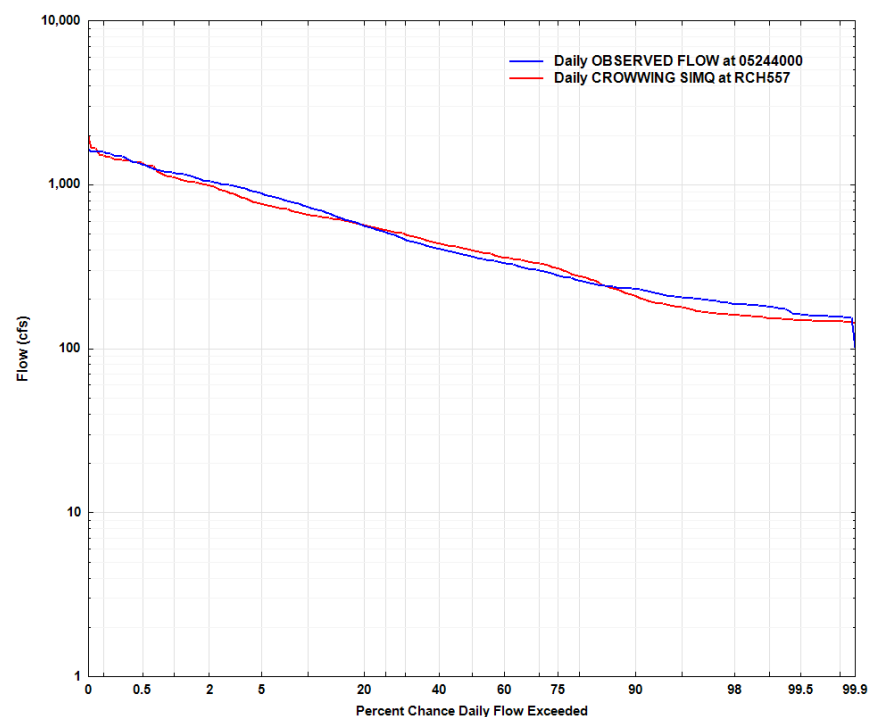
Table 2.16 Monthly and daily Statistics of flow volume for the Straight River gage in the Crow Wing River Watershed for the calibration period

Statistics	Monthly	Daily
Correlation Coefficient	0.75	0.73
Coefficient of Determination	0.56	0.53
Mean Error (cfs)	1.8	1.8
Mean Absolute Error (cfs)	7.4	8.4
RMS Error	9.4	11.1
Model Fit Efficiency	0.20	0.27

The Crow Wing River gage near Nimrod is downstream of the Straight River gage and has a drainage area of about 1,030 sq. miles. The streamflow calibration at the Nimrod gage followed the streamflow calibration at the Straight River gage. The flow hydrograph and the flow frequency duration curves are presented in the Figure 2.13. The graphs show that the model simulates observed flow well. It must be noted that the hydrology in these watersheds is heavily affected by lakes, of which some are managed and some are not. In addition, there are no detailed records available on the flow management for these lakes. Therefore it is a challenge to calibrate these watersheds to match the regulated observed flow without knowledge of the regulatory operations.



(a)



(b)

Figure 2.13 Comparison of simulated and observed (a) flow hydrograph and (b) flow duration frequency curves at the Nimrod Gage on Crow Wing River in Crow Wing River watershed

The expert system statistics are presented in the Table 2.17, and the errors and error criteria are presented in the Table 2.18. The model performs very well on all the error criteria. Simulated and observed flow were also compared yearly (Table 2.19) and monthly (Table 2.20). The model performs very well for all the years; however it under-predicts the flow for the year 2004 and over predicts the flow for the year 2009, significantly. The model also under-predicts the spring flow and over-predicts the summer flow. The monthly and daily statistics (Table 2.21) suggest that model performance is fair to good.

Table 2.17 Annual Average Statistics of flow at the Nimrod gage on the Crow Wing River in the Crow Wing River watershed

	Observed Total Runoff	Simulated Total Runoff	Simulated Surface Runoff	Simulated Interflow
total (inches)	5.4	5.5	0.062	0.369
10% high (inches)	1.2	1.1		
25% high (inches)	2.3	2.2		
50% high (inches)	3.7	3.6		
50% low (inches)	1.8	1.8		
25% low (inches)	0.7	0.7		
10% low (inches)	0.3	0.2		
storm volume (inches)	1.4	1.3	0.041	0.263
average storm peak (cfs)	745.9	667.3	149.99	343.81
baseflow recession rate	0.994	0.994		
summer volume (inches)	1.3	1.5		
winter volume (inches)	1.0	1.1		
summer storms (inches)	0.4	0.4	0.01	0.06

Table 2.18 Error Terms and Criteria for the Annual Average Flow Statistics at the Nimrod gage on the Crow Wing River in the Crow Wing River watershed

	Current	Criteria	Meets Criteria
Error in total volume (%)	1.0	10	OK
Error in 10% highest flows (%)	-8.7	15	OK
Error in 25% highest flows (%)	-5.5	10	OK
Error in 50% highest flows (%)	-0.7	10	OK
Error in 50% lowest flows (%)	4.5	10	OK
Error in 25% lowest flows (%)	-2.4	15	OK
Error in 10% lowest flows (%)	-12.9	20	OK
Error in low-flow recession	0.001	0.03	OK
Error in storm volumes (%)	-13.2	15	OK
Seasonal volume error (%)	6.0	20	OK
Error in average storm peak (%)	-10.5	15	OK
Summer volume error (%)	15.2	20	OK
Winter volume error (%)	9.2	15	OK
Summer storm volume error (%)	-8.0	15	OK

Table 2.19 Simulated and Observed Yearly Flow Volume (in) for the Calibration Period for the Nimrod gage on the Crow Wing River in the Crow Wing River Watershed

Year	Precipitation	Simulated	Observed	Residual	% Error
2003	20.5	3.98	4.1	-0.08	-1.9
2004	28.0	3.30	4.8	-1.50	-31.2
2005	29.3	6.37	6.2	0.17	2.8
2006	22.5	5.60	5.1	0.50	9.9
2007	27.3	5.04	5.2	-0.14	-2.6
2008	27.9	5.93	5.6	0.30	5.3
2009	27.2	8.18	7.1	1.11	15.7
Mean	26.1	5.5	5.4	0.05	1.0

Table 2.20 Comparison of Simulated and Observed Average Monthly Flow Volume (in) for the for the Nimrod gage on the Crow Wing River in the Crow Wing River Watershed

Month	Simulated	Observed	Residual	% Error
Jan	0.37	0.32	0.04	13.8
Feb	0.30	0.29	0.01	3.1
Mar	0.47	0.46	0.00	0.9
Apr	0.64	0.78	-0.14	-18.2
May	0.59	0.70	-0.11	-15.2
Jun	0.59	0.60	-0.01	-1.9
Jul	0.49	0.39	0.11	28.0
Aug	0.40	0.30	0.10	32.8
Sep	0.36	0.31	0.06	18.2
Oct	0.43	0.45	-0.03	-5.8
Nov	0.44	0.46	-0.02	-4.2
Dec	0.41	0.38	0.04	9.9
Totals	5.49	5.43	0.05	1.0

Table 2.21 Monthly and daily Statistics of flow volume for the for the Nimrod gage on the Crow Wing River in the Crow Wing River Watershed

Statistics	Monthly	Daily
Correlation Coefficient	0.83	0.82
Coefficient of Determination	0.69	0.67
Mean Error (cfs)	3.92	4.21
Mean Absolute Error (cfs)	90.2	98.9
RMS Error	111.4	128.4
Model Fit Efficiency	0.68	0.66

Following the calibration of the Straight River and the Crow Wing River gage near Nimrod, calibration of the Crow Wing River gage near Pillager was undertaken. This gage includes the inflows from the Redeye and Long Prairie rivers. During the calibration process, it was noted that at least three lakes (Hubert Lake, Edward Lake, and North Long Lake) had greater evaporation loss than the sum of rainfall and total inflow of water from the local drainage area. In other words, the lakes were losing water during the simulation period. It was therefore assumed that they receive some contribution from groundwater, so a constant groundwater inflow, obtained by calibration, was added to these lakes. Figure 2.14 shows the comparison of observed and simulated flows and the flow frequency duration curves at the Pillager gage. The visual comparison suggests that the model simulates flow very well.

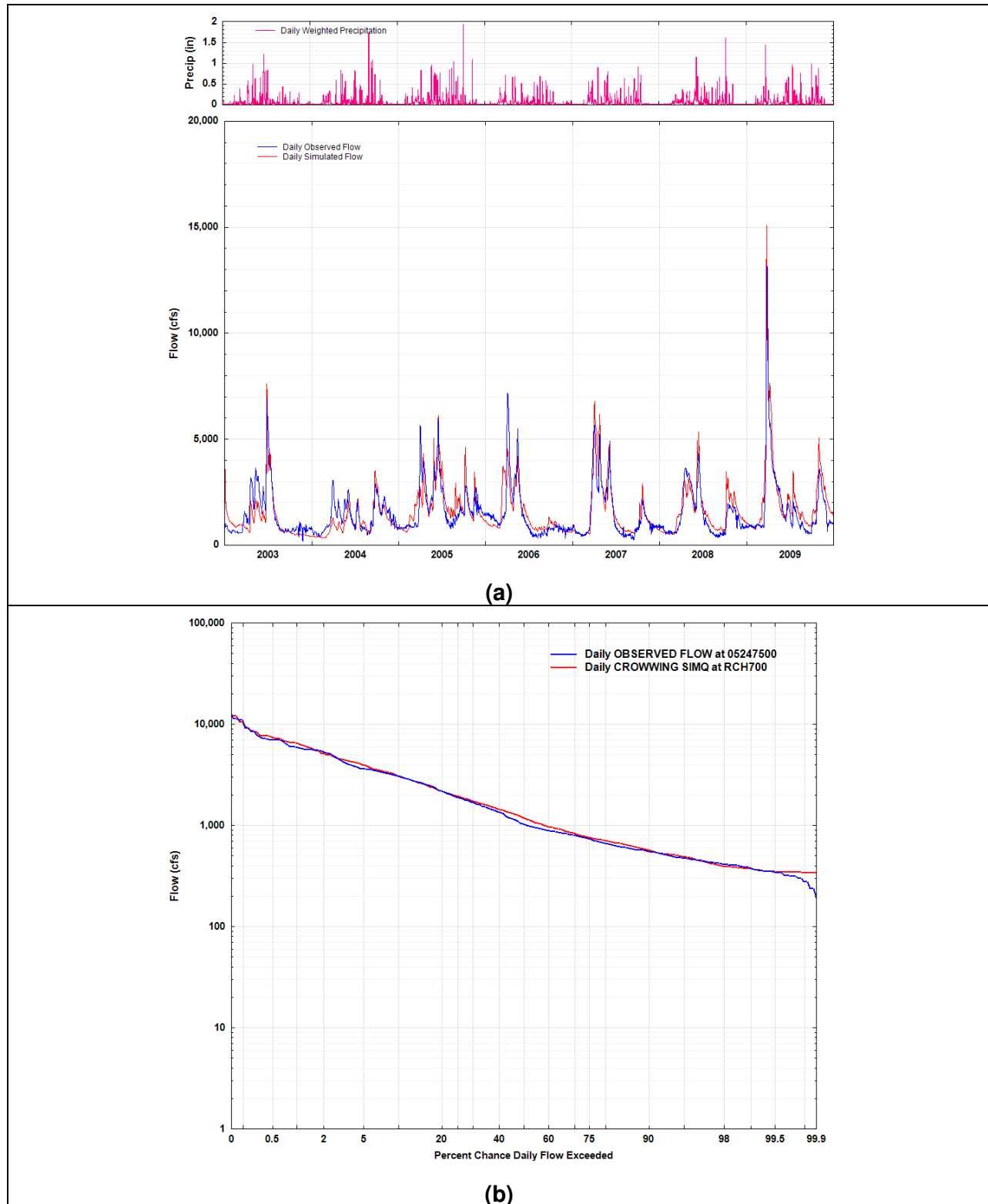


Figure 2.14 Comparison of simulated and observed (a) flow hydrograph, and (b) flow duration frequency curves at the Pillager Gage on the Crow Wing River in the Crow Wing River watershed for the calibration period

Expert system statistics were also calculated for this gage (Table 2.22 and Table 2.23). The model performs well on all the error criteria for the expert system. The yearly (Table 2.24) and monthly (Table 2.25) comparisons show that the model simulates different hydrologic conditions well. The model generally over-predicts summer flows. It is important to note that the difference in flow regime during different months could be a result of flow management at lakes for which no detailed data is available. Table 2.26 shows that the model performance is good for monthly and daily simulations.

Table 2.22 Annual average statistics of flow at the Crow Wing Gage near Pillager, MN for the calibration period

	Observed Total Runoff	Simulated Total Runoff	Simulated Surface Runoff	Simulated Interflow
total (inches)	5.44	5.70	0.15	0.59
10% high (inches)	1.56	1.63		
25% high (inches)	2.86	2.93		
50% high (inches)	4.15	4.31		
50% low (inches)	1.29	1.39		
25% low (inches)	0.51	0.53		
10% low (inches)	0.17	0.17		
storm volume (inches)	1.88	1.81	0.10	0.43
average storm peak (cfs)	3,690	3,729	1,217.0	1,865.2
baseflow recession rate	1.00	0.99		
summer volume (inches)	1.32	1.55		
winter volume (inches)	0.76	0.77		
summer storms (inches)	0.56	0.57	0.043	0.137

Table 2.23 Error terms and criteria for the annual average flow statistics at the Crow Wing Gage near Pillager, MN for the calibration period

	Current	Criteria	Meets Criteria
Error in total volume (%)	4.7	10	OK
Error in 10% highest flows (%)	4.2	15	OK
Error in 25% highest flows (%)	2.3	10	OK
Error in 50% highest flows (%)	3.9	10	OK
Error in 50% lowest flows (%)	7.3	10	OK
Error in 25% lowest flows (%)	4.6	15	OK
Error in 10% lowest flows (%)	1.6	20	OK
Error in low-flow recession	0.007	0.03	OK
Error in storm volumes (%)	-3.9	15	OK
Seasonal volume error (%)	16.7	20	OK
Error in average storm peak (%)	1.0	15	OK
Summer volume error (%)	17.1	20	OK
Winter volume error (%)	0.4	15	OK
Summer storm volume error (%)	1.2	15	OK

Table 2.24 Simulated and observed yearly flow volume (in) at the Crow Wing River Gage near Pillager, MN for the calibration period

Year	Precipitation	Simulated	Observed	Residual	% Error
2003	23.55	4.41	5.02	-0.60	-12.2
2004	28.17	3.83	4.64	-0.80	-17.5
2005	31.64	7.10	6.65	0.45	6.8
2006	23.42	5.01	4.92	0.10	2.0
2007	26.99	5.60	5.10	0.49	9.7
2008	26.91	5.52	4.90	0.62	12.7
2009	28.36	8.41	6.86	1.55	22.7
Mean	27.00	5.70	5.44	0.26	4.7

Table 2.25 Comparison of simulated and observed average monthly flow volume (in) at the Crow Wing River Gage near Pillager, MN for the calibration period

Month	Simulated	Observed	Residual	% Error
Jan	0.25	0.25	0.00	-1.4
Feb	0.20	0.21	0.00	-1.3
Mar	0.60	0.50	0.09	18.7
Apr	0.86	0.97	-0.12	-12.0
May	0.65	0.77	-0.13	-16.7
Jun	0.71	0.67	0.03	5.2
Jul	0.52	0.43	0.09	22.2
Aug	0.32	0.22	0.10	43.5
Sep	0.32	0.25	0.07	26.8
Oct	0.51	0.42	0.08	19.9
Nov	0.46	0.43	0.03	5.9
Dec	0.31	0.30	0.01	3.1
Totals	5.70	5.44	0.26	4.7

Table 2.26 Monthly and daily statistics of flow volume at the Crow Wing River Gage near Pillager, MN for the calibration period

Statistics	Monthly	Daily
Correlation Coefficient	0.90	0.89
Coefficient of Determination	0.81	0.79
Mean Error (cfs)	69.64	70.8
Mean Absolute Error (cfs)	365.1	420.2
RMS Error	468.6	604.7
Model Fit Efficiency	0.78	.77

The water balance at all the gages in the Crow Wing River watershed was calculated to ensure that the distribution of water in different storages was reasonable (Table 2.27). The water balance for the entire Crow Wing watershed for each land use was also calculated to ensure that the land uses are represented reasonably (Table 2.28).

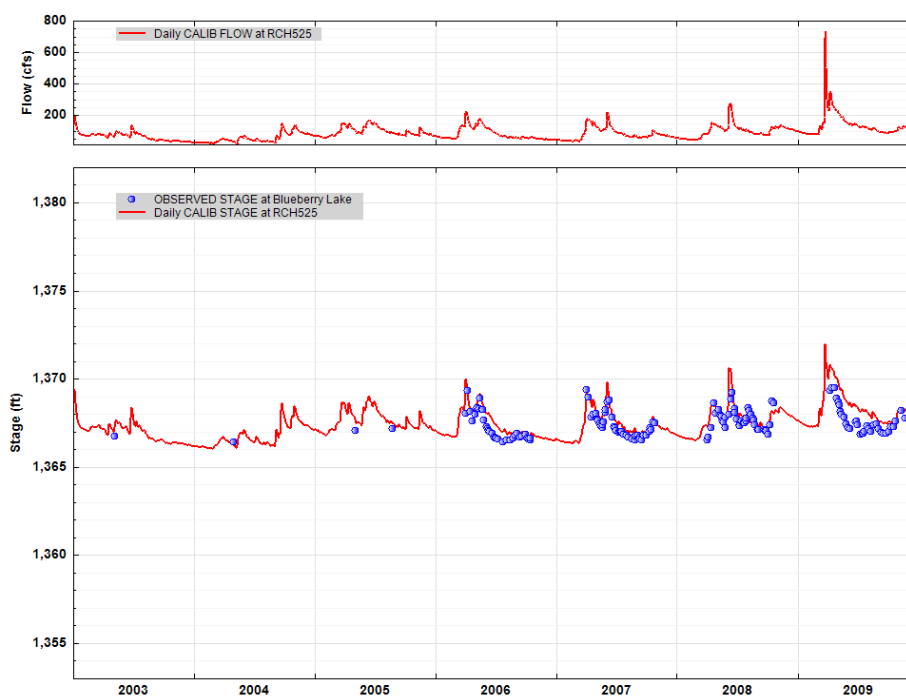
Table 2.27 Water balance components (in) at USGS gages in the Crow Wing watershed for the calibration period

Influx	R:515 (Straight River Gage at Straight River)	R:557 (Crow Wing River Gage Near Nimrod)	R:700 (Crow Wing near gage near Pillager)
Rainfall	25.26	26.09	26.55
Runoff			
Surface-Pervious	0.03	0.03	0.04
Surface-Impervious	0.02	0.03	0.03
Interflow	0.45	0.37	0.38
Base flow	5.76	5.20	5.10
Total	6.26	5.63	5.55
GW Inflow			
Deep	0.02	0.04	0.04
Active	6.44	5.92	6.01
Evaporation			
Potential	32.40	32.26	33.24
Interception Storage	5.51	5.85	5.85
Upper Zone	3.04	3.14	3.23
Lower Zone	9.84	10.56	10.79
Ground Water	0.16	0.27	0.45
Base flow	0.33	0.32	0.34
Impervious	0.01	0.01	0.01
Total	18.88	20.15	20.66

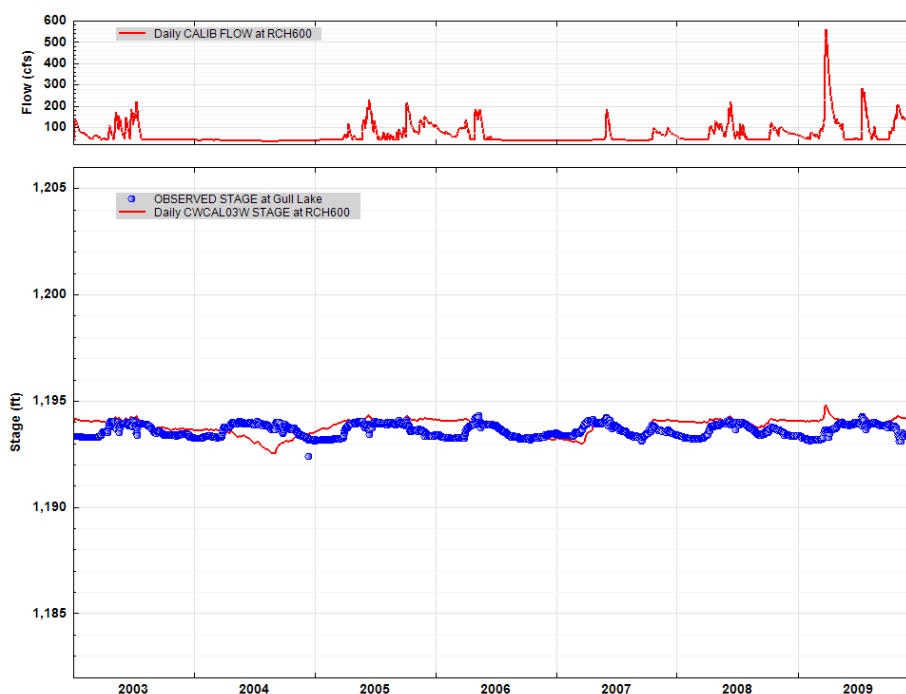
Table 2.28 Water balance components of different land uses in the Crow Wing River Watershed for the calibration period

PERLND		Runoff				GW Inflow		Evaporation						
Land Use	Rainfall	Surface	Interflow	Baseflow	Total	Deep	Active	Potential	Interception Storage	Upper Zone	Lower Zone	Ground Water	Baseflow	Total
Forest - AB	25.84	0.01	1.02	5.94	6.97	0.02	6.03	32.39	4.81	4.02	9.93	0.00	0.20	18.96
Forest - CD	26.20	0.01	0.21	4.66	4.88	0.03	5.29	32.88	6.21	2.91	11.31	0.00	0.44	20.87
Wetlands	26.69	0.01	0.26	4.81	5.08	0.04	5.47	33.08	6.20	3.25	11.23	0.00	0.46	21.15
Grassland - AB	26.69	0.00	0.04	4.01	4.06	0.05	7.00	33.83	6.15	1.74	11.58	2.49	0.25	22.22
Grassland - CD	26.54	0.12	0.94	7.10	8.16	0.04	7.35	33.19	5.25	4.83	7.77	0.00	0.23	18.08
Pasture - AB	27.15	0.21	1.10	6.97	8.28	0.06	7.24	33.72	5.28	5.33	7.71	0.00	0.27	18.59
Pasture - CD	26.56	0.05	0.62	5.97	6.64	0.04	6.20	33.52	5.26	3.98	10.23	0.00	0.24	19.72
Cropland-AB	27.40	0.11	0.81	6.00	6.92	0.05	6.23	33.44	5.30	4.50	10.20	0.00	0.26	20.26
Cropland-CD	26.35	0.03	0.60	6.50	7.13	0.03	6.62	32.98	5.00	3.73	10.29	0.00	0.22	19.24
Cropland-Drained	27.55	0.07	0.83	6.09	6.99	0.05	6.20	34.19	5.07	4.64	10.53	0.00	0.26	20.50
Dev, Open Space	26.57	0.37	1.01	5.33	6.71	0.03	5.48	33.53	5.11	4.77	9.68	0.00	0.25	19.80
Dev, Low Intensity	26.55	0.34	1.03	5.33	6.69	0.03	5.48	33.67	5.07	4.77	9.71	0.00	0.25	19.80
Dev, Medium Intensity	26.51	0.25	1.09	5.47	6.80	0.03	5.61	33.40	5.02	4.76	9.66	0.00	0.24	19.68
Average	26.56	0.04	0.38	5.10	5.52	0.04	6.02	33.26	5.86	3.24	10.80	0.45	0.34	20.69
IMPLND		Runoff		Evaporation										
Land Use	Rainfall	Surface	Potential	Actual										
Dev, Open Space	25.44	20.13	33.30	5.31										
Dev, Low Intensity	25.45	20.18	33.42	5.26										
Dev, Medium Intensity	25.60	20.41	33.14	5.18										
Average	25.48	20.21	33.30	5.26										

During the hydrologic calibration, the simulated and observed lake levels were also compared and the parameters were adjusted to ensure that the model is simulating acceptable lake levels. Figure 2.15 shows the observed and simulated lake levels for two lakes in the Crow Wing River Watershed. The lake level simulation appears to be adequate. The Crow Wing watersheds were considered calibrated at this stage. The validation of all the watershed models was conducted following the calibration.



(a)



(b)

Figure 2.15 Comparison of observed and simulated lake levels at (a) Blueberry Lake and (b) Gull Lake in the Crow Wing River watershed

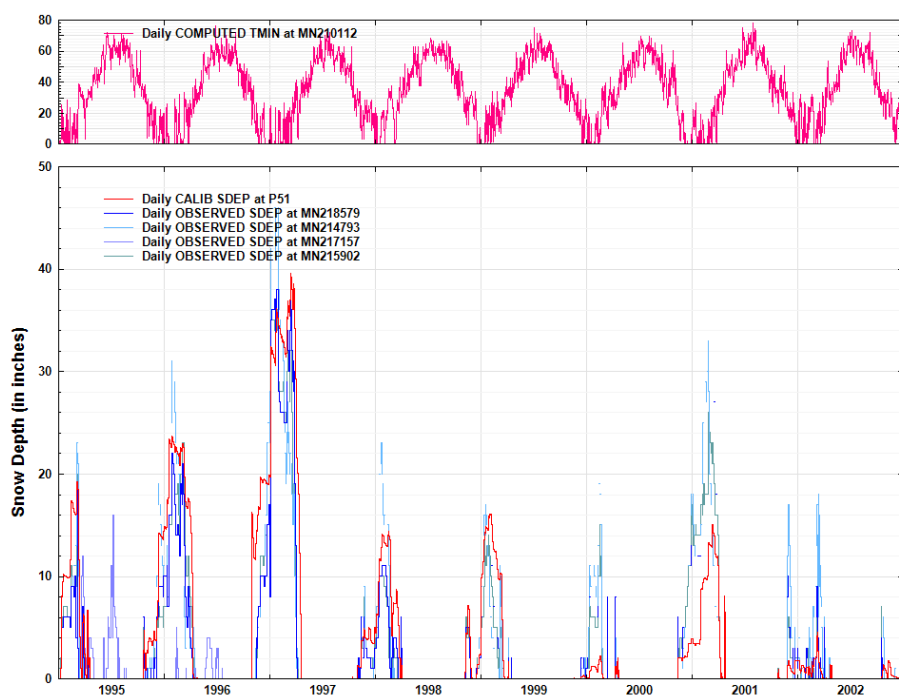
2.3 HYDROLOGY VALIDATION

The hydrology validation followed the hydrology calibration. Based on the data available, the validation period was established as 1995-2002, using the land use data from the year 2001 (AQUA TERRA Consultants, 2012). To conduct hydrology validation, the parameters obtained from hydrology calibration were used and similar statistics calculated. If the validation statistics did not satisfy the criteria, the calibration was revisited. As with the hydrologic calibration, the validation process started with Long Prairie watershed.

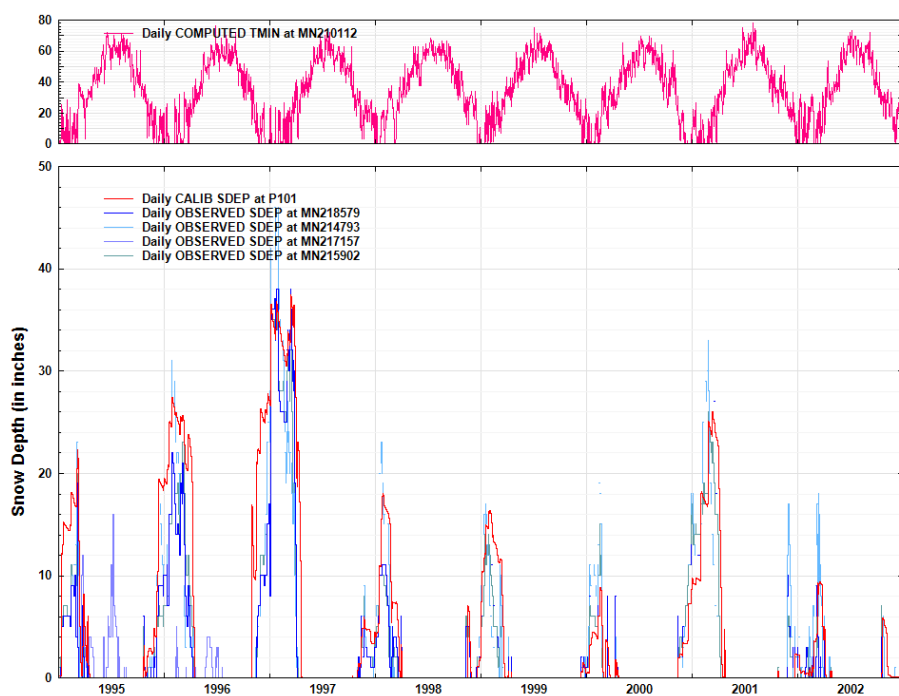
2.3.1 Long Prairie River Watershed

The first step in hydrologic validation was to compare snow depth and snow frequency. The sample graphs in Figure 2.16 and Figure 2.17. show that snow simulation was adequate.

The flow hydrograph and flow frequency curve (Figure 2.18) illustrate a reasonable streamflow simulation. Expert system statistics and errors (Table 2.29) were also calculated for the validation period. The simulation results satisfy all the criteria except the lowest 10% flows. It has been noted before that the observed winter flow was likely estimated rather than measured, which probably accounts for the high error in simulation of low flows and in winter volume. The daily and monthly statistics show that model performance is good to very good. At this stage the model was considered validated.

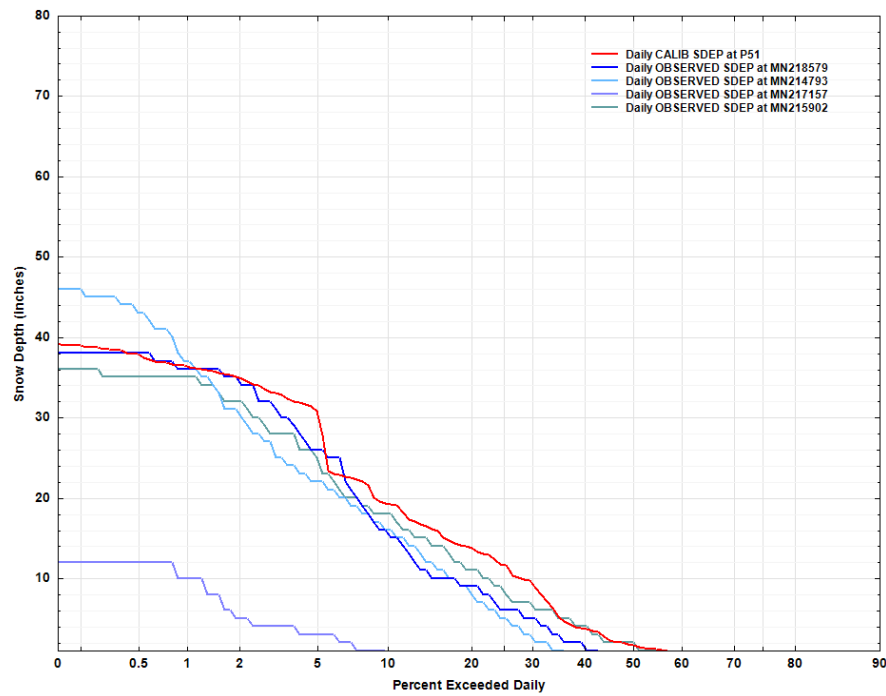


(a)

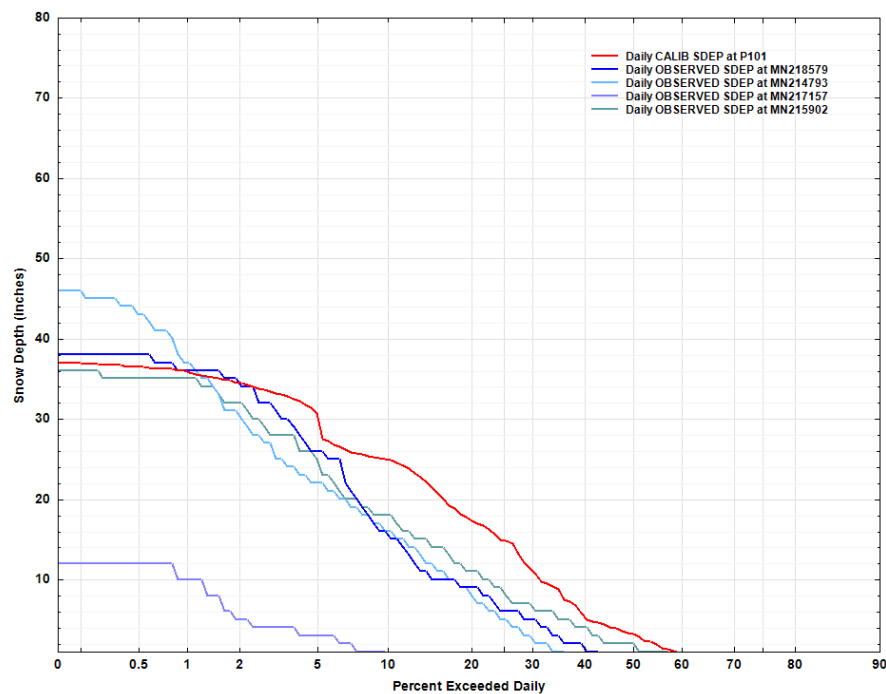


(b)

Figure 2.16 Snow Depth Simulation at (a) PERLND51, and (b) PERLND 101 (Forest land areas in two different segment of the Long Prairie watershed) for the validation period. Red curve shows the simulated data and observed data is shown in other colors.

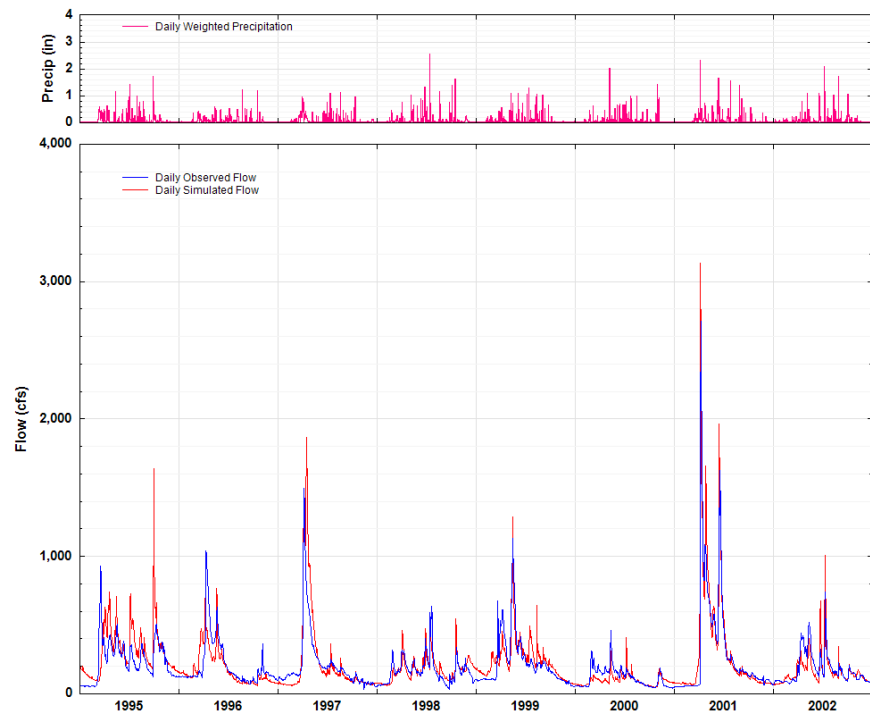


(a)

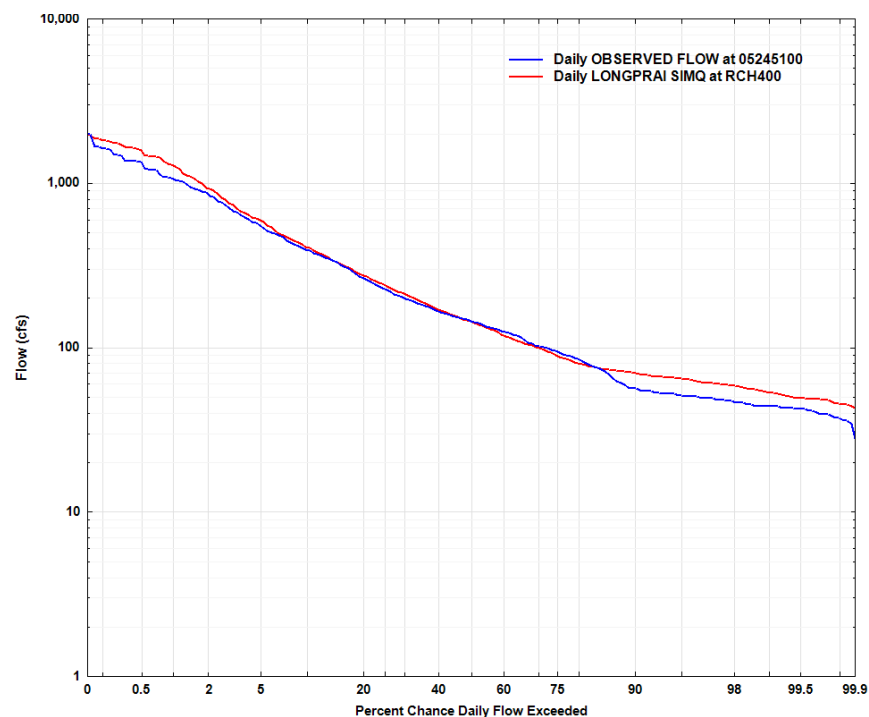


(b)

Figure 2.17 Comparison of snow depth frequency simulation for winter months (October to April) at (a) PERLND 51 and (b) PERLND 101 for the validation period. The red curve shows the simulated results and observed data is presented in other colors.



(a)



(b)

Figure 2.18 Comparison of simulated and observed (a) flow hydrograph, and (b) flow duration frequency curves at the Long Prairie River gage in Long Prairie River watershed for the validation period.

Table 2.29 Error Terms and Criteria for the Annual Average Flow Statistics at the Long Prairie gage in the Long Prairie watershed for the validation period

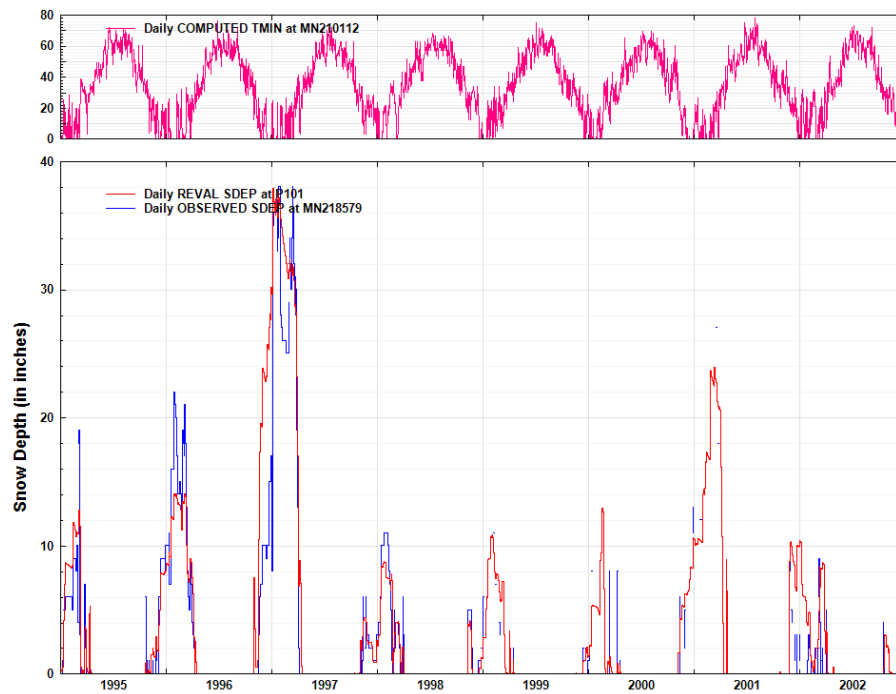
	Current	Criteria	Meets Criteria
Error in total volume (%)	4.6	10	OK
Error in 10% highest flows (%)	9.3	15	OK
Error in 25% highest flows (%)	6.8	10	OK
Error in 50% highest flows (%)	5.8	10	OK
Error in 50% lowest flows (%)	0.8	10	OK
Error in 25% lowest flows (%)	8.5	15	OK
Error in 10% lowest flows (%)	25.1	20	Fails
Error in low-flow recession	0.005	0.03	OK
Error in storm volumes (%)	-0.7	15	OK
Seasonal volume error (%)	-13.0	20	OK
Error in average storm peak (%)	9.4	15	OK
Summer volume error (%)	5.4	20	OK
Winter volume error (%)	18.4	15	Fails
Summer storm volume error (%)	2.6	15	OK

Table 2.30. Monthly and Daily Statistics of Flow Volume

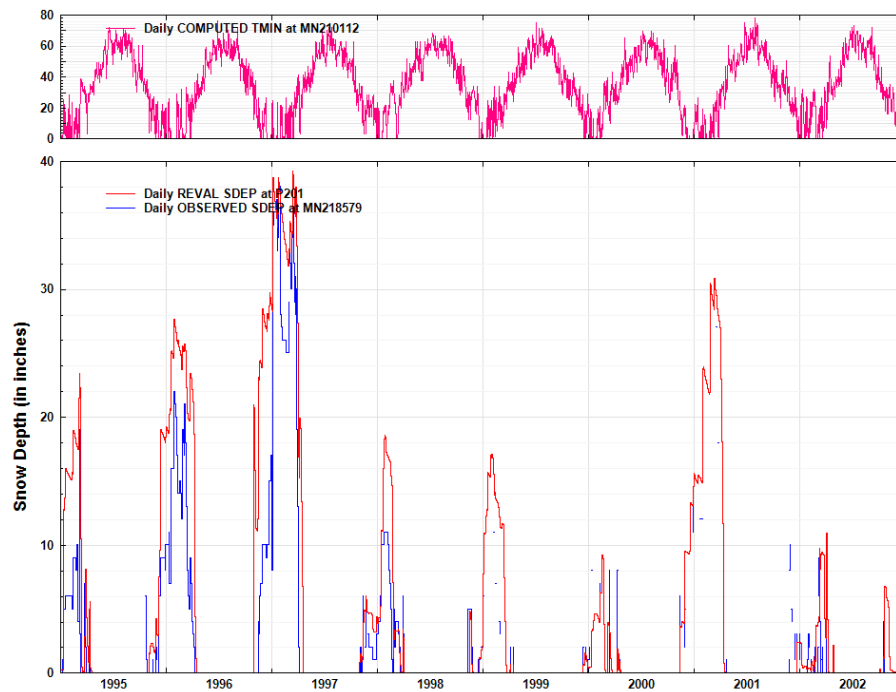
Statistics	Monthly	Daily
Correlation Coefficient	0.93	0.86
Coefficient of Determination	0.87	0.73
Mean Error (cfs)	9.3	9.4
Mean Absolute Error (cfs)	48.7	62.6
RMS Error	73.2	119.4
Model Fit Efficiency	0.82	0.66

2.3.2 Redeye River Watershed

The Redeye River watershed did not have any long term gage; therefore hydrology validation for was not conducted for this watershed. For the Redeye model, the simulated snow depth (e.g. Figure 2.19) and depth frequency (e.g. Figure 2.20) were compared for multiple land segments in the watershed. These graphical comparisons suggest that the model simulates reasonable snow depth.

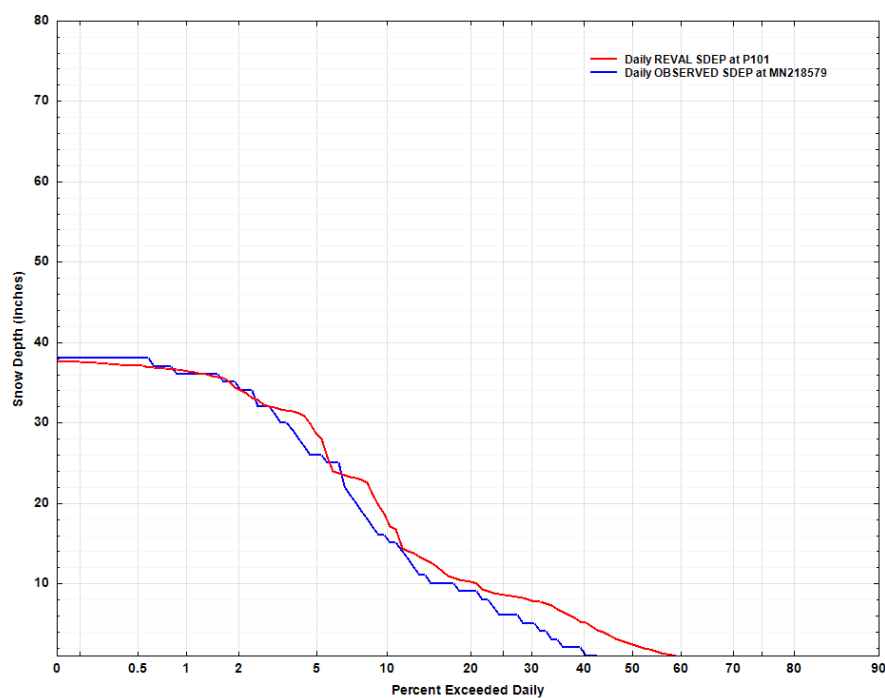


(a)

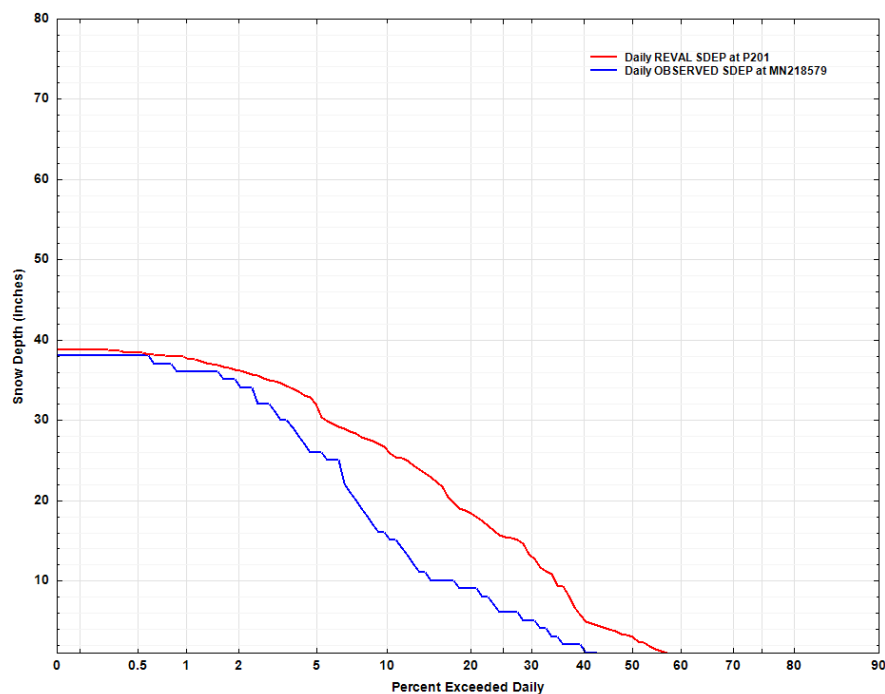


(b)

Figure 2.19 Snow Depth Simulation at (a) PERLND101, and (b) PERLND 201 (Forest land areas in two different segment of the Redeye River watershed) for the validation period. Red curve shows the simulated data and observed data is shown in other colors. The auxiliary graph shows the recorded minimum daily temperature.



(a)

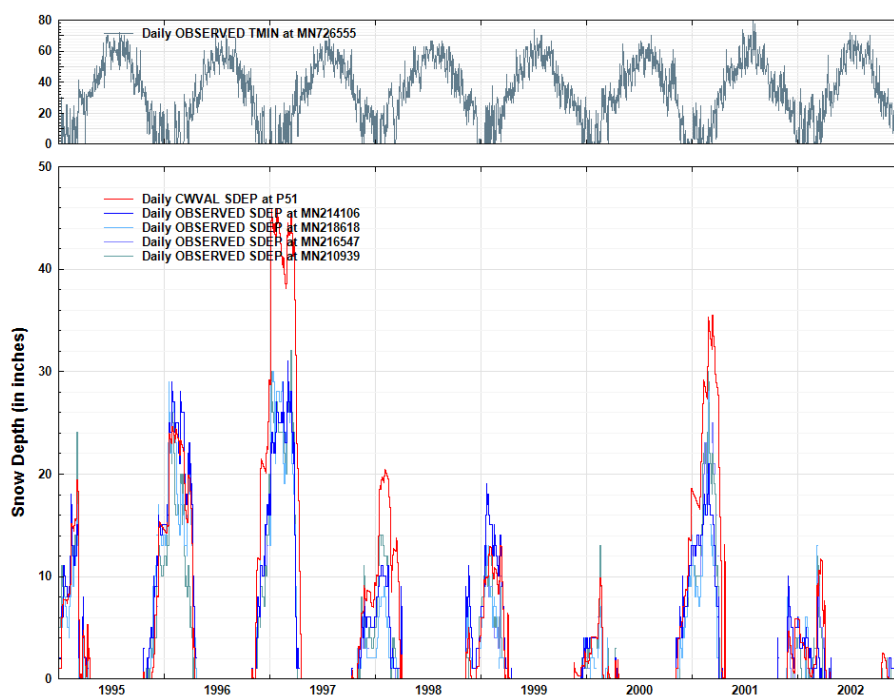


(b)

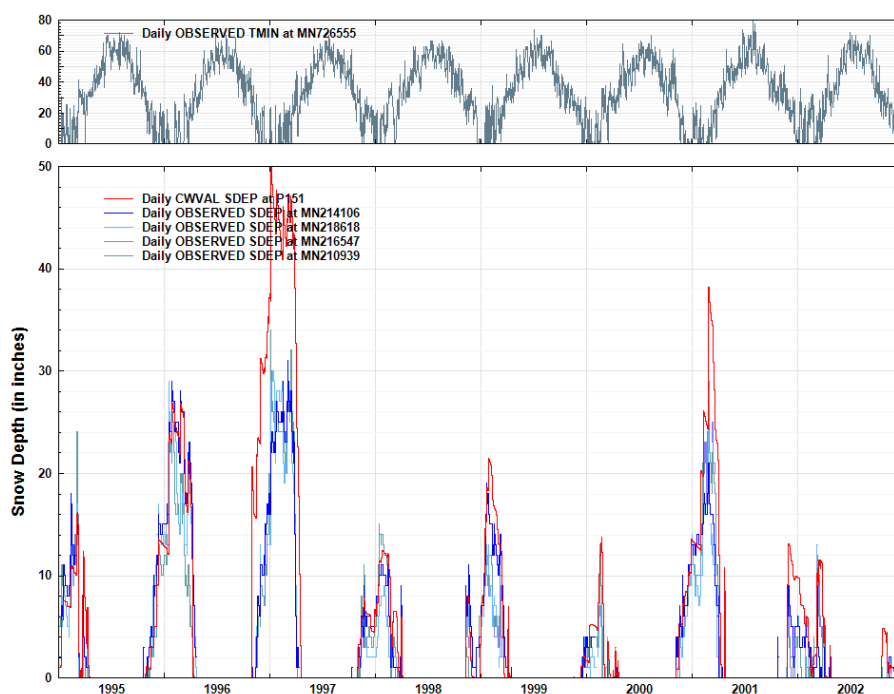
Figure 2.20 Comparison of snow depth frequency simulation for winter months (October to April) at (a) PERLND 101 and (b) PERLND 201 in the Redeye River watershed for the validation period; simulated results are shown by the red curve and observed data is presented in other colors

2.3.3 Crow Wing River Watershed

Following the validation at the Long Prairie and Redeye River watersheds, the Crow Wing River watershed model was validated. As with the other models, validation started with snow depth simulation (e.g. Figure 2.21 and Figure 2.22). The simulated snow depth in the winters of 1996 and 1997 was greater than the observed snow depth. Higher simulated snow depth during this period also impacts the snow depth frequency curves, as shown in Figure 2.2. Clearly, a large difference in the simulation for one or two years can dramatically impact the agreement shown by the frequency curves. The snow depth simulation for all other years, however was satisfactory, therefore the model was accepted as satisfactory for snow depth simulation.

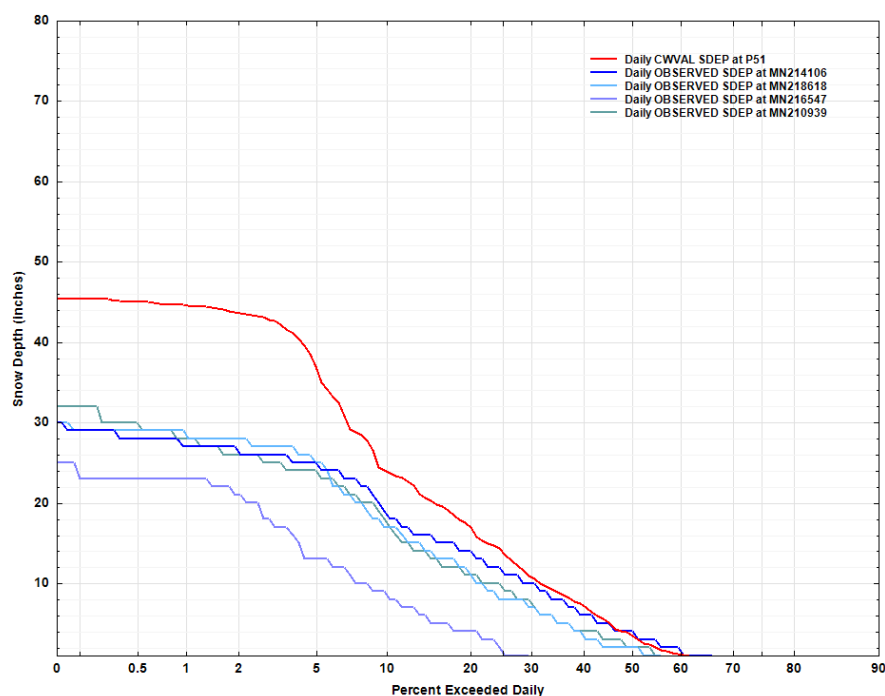


(a)

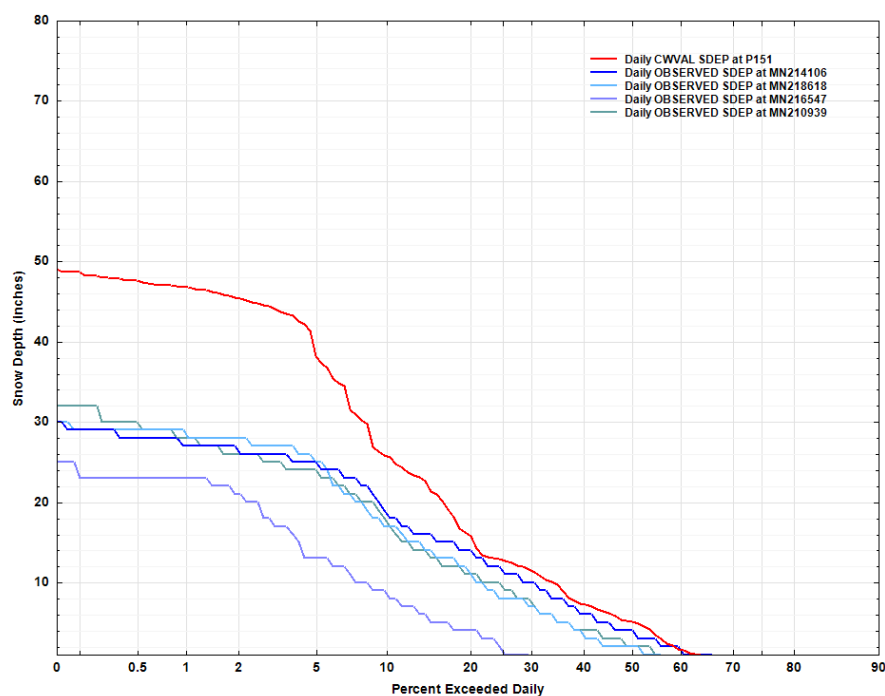


(b)

Figure 2.21 Snow Depth Simulation at (a) PERLND 51 and (b) PERLND 151 (Forest land areas in two different segments of the Crow Wing River watershed); simulated data is shown by the red curve and observed data is shown in other colors



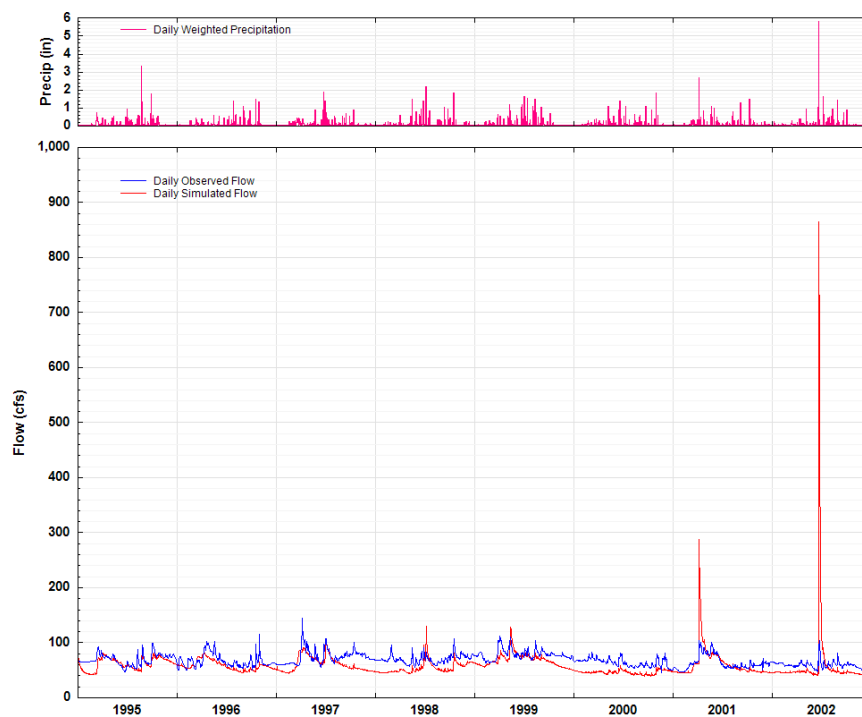
(a)



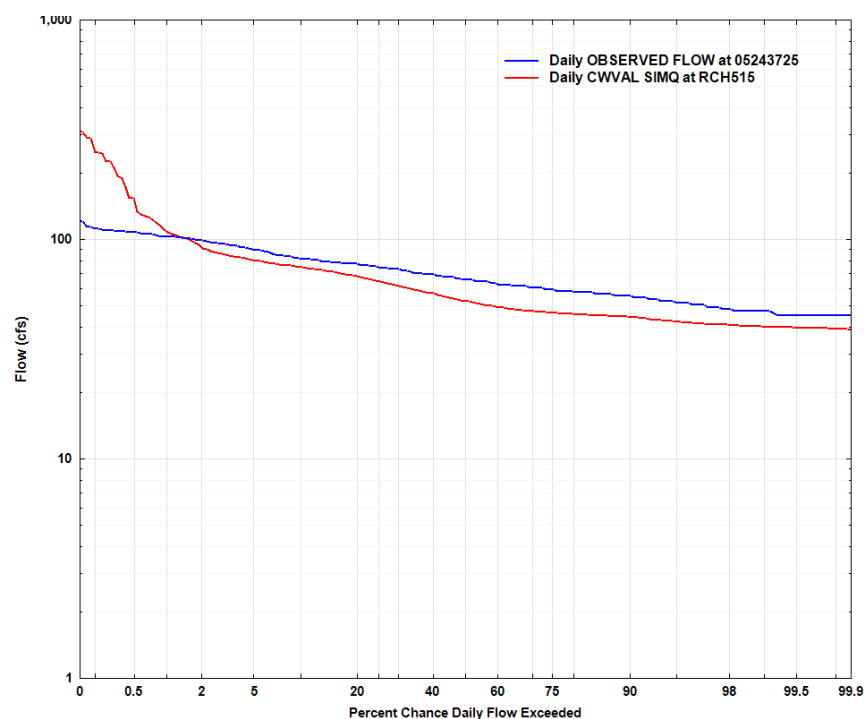
(b)

Figure 2.22 Comparison of snow depth frequency simulation for winter months (October to April) at (a) PERLND 51 and (b) PERLND 151 in the Crow Wing River watershed; simulated results are shown by the red curve and observed data is presented in other colors

Following the validation of snow depth simulation, streamflow validation was conducted. As in calibration, streamflow validation started with the Straight River Gage (Figure 2.23). The graphs suggest that the validation results at the Straight River gage were poor. In the year 2002, the simulated flow was 4-5 times greater than the flow observed at any time during the validation period. This was a result of about 6 inches of rainfall occurring in one day in the watershed contributing flow to the Straight River. It is difficult to determine if the rainfall during that time was incorrectly recorded or if there is an error in the observed flow. Also, there is about -14% error in the simulation of average flow volume (Table 2.31) for the validation period. The watershed draining to the Straight River gage received about the same rainfall (25.7 in during the validation period and 25.3 in during the calibration period), but the observed flow volume was about 25% greater (15.7 in during the validation period, and 12.7 in during the calibration period). These results indicate that there are significant errors in the observed rainfall and runoff data for the Straight River gage. As described later, these kinds of errors were not observed for the downstream gages; therefore this was considered to be a local error which led to the inability to validate the model at the Straight River gage.



(a)



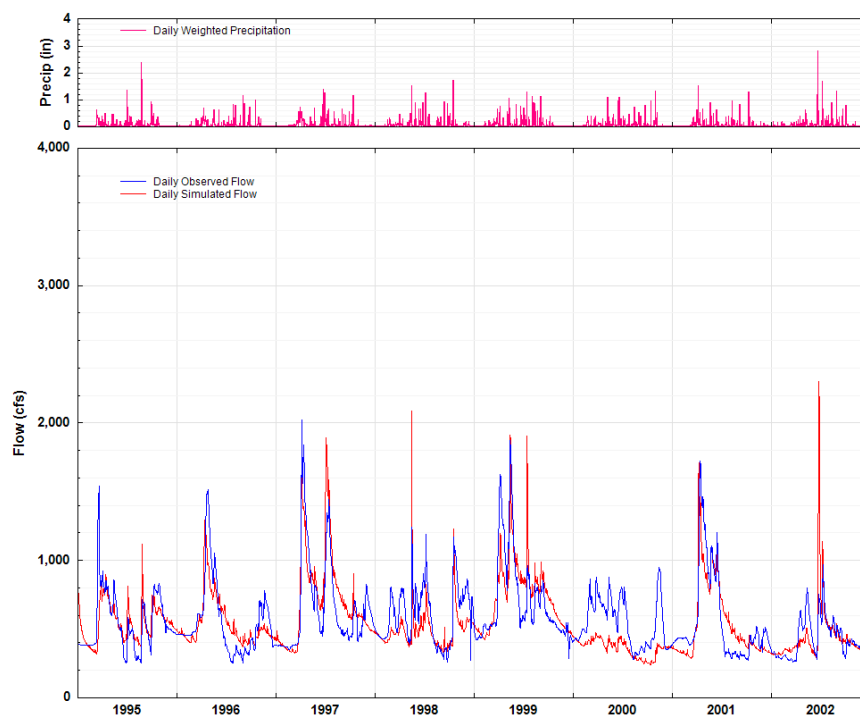
(b)

Figure 2.23 Comparison of simulated and observed (a) flow hydrograph and (b) flow duration frequency curves at the Straight River gage in Crow Wing River watershed for the validation period

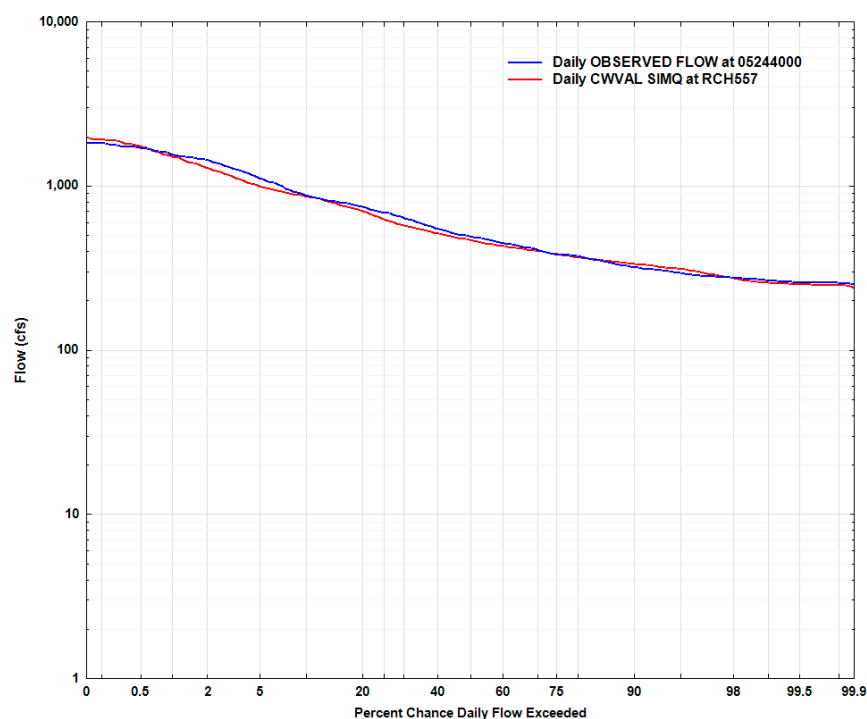
Table 2.31 Error Terms and Criteria for the Annual Average Flow Statistics at the Straight River gage in Crow Wing River Watershed for the validation period

	Current	Criteria	Meets Criteria
Error in total volume (%)	-14.5	10	Fails
Error in 10% highest flows (%)	4.5	15	OK
Error in 25% highest flows (%)	-4.0	10	OK
Error in 50% highest flows (%)	-9.9	10	OK
Error in 50% lowest flows (%)	-20.5	10	Fails
Error in 25% lowest flows (%)	-19.4	15	Fails
Error in 10% lowest flows (%)	-17.5	20	OK
Error in low-flow recession	0.004	0.03	OK
Error in storm volumes (%)	-1.7	15	OK
Seasonal volume error (%)	18.83	20	Fails
Error in average storm peak (%)	35.2	15	Fails
Summer volume error (%)	-2.9	20	OK
Winter volume error (%)	-21.7	15	Fails
Summer storm volume error (%)	20.4	15	Fails

The validation results at the Crow Wing River gage near Nimrod were promising and showed a good match between observed and simulated values (Figure 2.24). When observed closely, the simulated flow during the storm in June 2002 shows greater volume (by about 3 times) than the observed flow. The daily precipitation during this time was the greatest value recorded for the entire validation period. It is possible that the excess precipitation recorded at upstream rain gages caused this unusual increase in simulated flow volume. The error terms calculated for the Expert System Statistics (Table 2.32) show that all the errors are within acceptable limits. The model statistics (Table 2.33) also show that the validation results are fair. The overall model validation results for the Crow Wing River gage near Nimrod were considered acceptable, especially considering the very good agreement of the flow duration curves shown in Figure 2.23. The next step was validation at the Crow Wing River gage near Pillager.



(a)



(b)

Figure 2.24 Comparison of simulated and observed (a) flow hydrograph and (b) flow duration frequency curves at the Nimrod Gage on Crow Wing River in Crow Wing River watershed for the validation period

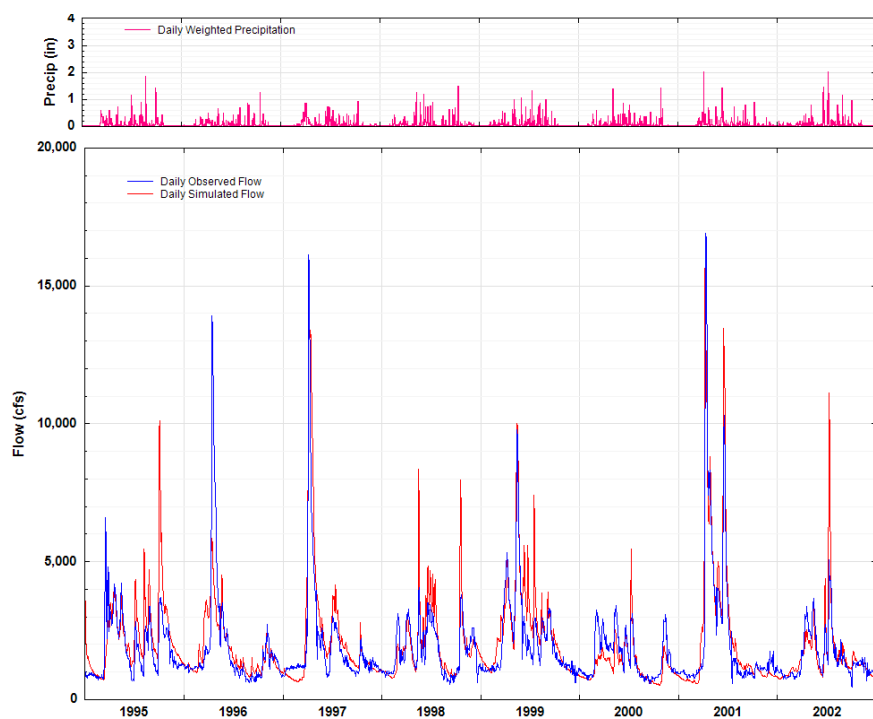
Table 2.32 Error Terms and Criteria for the Annual Average Flow Statistics at the Nimrod gage on Crow Wing River in Crow Wing River watershed for the validation period

	Current	Criteria	Meets Criteria
Error in total volume (%)	-4.6	10	OK
Error in 10% highest flows (%)	-6.4	15	OK
Error in 25% highest flows (%)	-5.3	10	OK
Error in 50% highest flows (%)	-6.2	10	OK
Error in 50% lowest flows (%)	-1.5	10	OK
Error in 25% lowest flows (%)	1.4	15	OK
Error in 10% lowest flows (%)	3.4	20	OK
Error in low-flow recession	0.003	0.03	OK
Error in storm volumes (%)	-13.8	15	OK
Seasonal volume error (%)	18.8	20	OK
Error in average storm peak (%)	0.8	15	OK
Summer volume error (%)	12.9	20	OK
Winter volume error (%)	-5.9	15	OK
Summer storm volume error (%)	7.8	15	OK

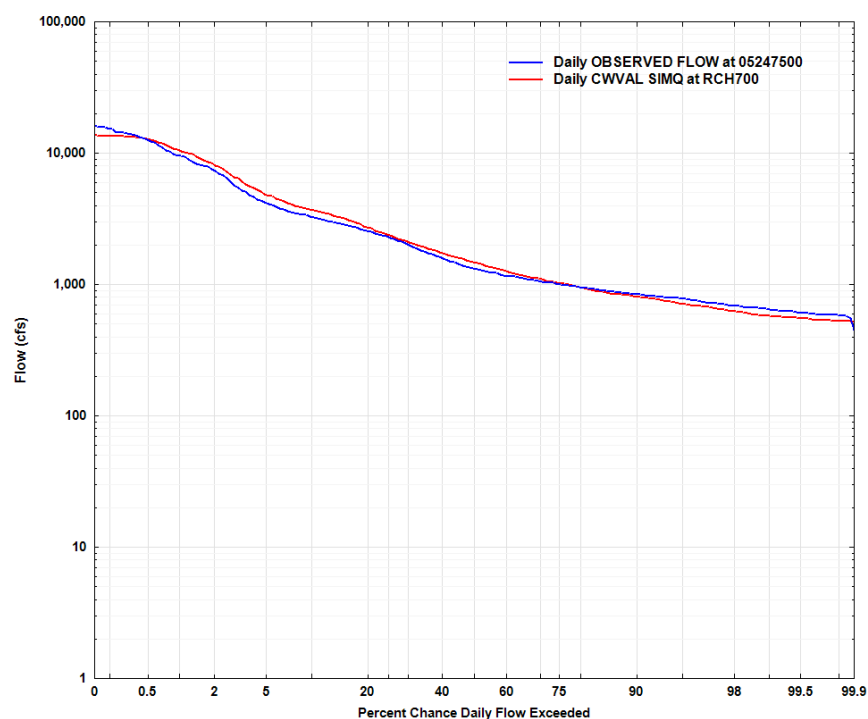
Table 2.33 Monthly, and daily Statistics of flow volume for the for the Nimrod gage on Crow Wing River in the Crow Wing River Watershed for the validation period

Statistics	Monthly	Daily
Correlation Coefficient	0.81	0.77
Coefficient of Determination	0.66	0.59
Mean Error (cfs)	-26.8	-26.4
Mean Absolute Error (cfs)	110.5	125.2
RMS Error	142.8	178.2
Model Fit Efficiency	0.63	0.55

The validation results at the Crow Wing River gage near Pillager show that the model simulated the streamflow well based on the flow duration comparison (Figure 2.25). The error criteria for the expert system are all within acceptable bounds (Table 2.34) except for flow volume in summers and storm volume in summers. The model performance statistics suggest that model performance was fair to good for the validation period. Although further rigorous calibration effort and cleanup of observed meteorological and flow data can be continued to improve the validation results, the model is quite acceptable at this stage and can be used as a sound basis for water quality simulation.



(a)



(b)

Figure 2.25 Comparison of simulated and observed (a) flow hydrograph and (b) flow duration frequency curves at the Pillager Gage on Crow Wing River in Crow Wing River watershed for the validation period

Table 2.34 Error Terms and Criteria for the Annual Average Flow Statistics at Crow Wing Gage near Pillager, MN for the validation period

	Current	Criteria	Meets Criteria
Error in total volume (%)	7.6	10	OK
Error in 10% highest flows (%)	10.5	15	OK
Error in 25% highest flows (%)	10.0	10	OK
Error in 50% highest flows (%)	9.4	10	OK
Error in 50% lowest flows (%)	2.62	10	OK
Error in 25% lowest flows (%)	-3.1	15	OK
Error in 10% lowest flows (%)	-6.8	20	OK
Error in low-flow recession	0.009	0.03	OK
Error in storm volumes (%)	1.4	15	OK
Seasonal volume error (%)	33.4	20	Fails
Error in average storm peak (%)	6.4	15	OK
Summer volume error (%)	29.4	20	Fails
Winter volume error (%)	-4.0	15	OK
Summer storm volume error (%)	30.3	15	Fails

Table 2.35 Monthly and Daily Statistics of flow volume at Crow Wing River gage near Pillager, MN for the validation period

Statistics	Monthly	Daily
Correlation Coefficient	0.92	0.85
Coefficient of Determination	0.84	0.73
Mean Error (cfs)	140.6	143.1
Mean Absolute Error (cfs)	414.3	515.9
RMS Error	615.3	948.1
Model Fit Efficiency	0.80	.67

SECTION 3.0 SEDIMENT CALIBRATION AND VALIDATION

3.1 SEDIMENT TARGETS

One of the objectives for the Crow Wing, Redeye, and Long Prairie Rivers watershed modeling project required defining the sources of sediment loads within the watersheds and conducting sediment calibration and validation tests. In order to define and quantify sediment targets, a literature review was performed.

A study of historical sediment fluxes conducted by Kelley and Nater, 2000, suggests that the sediment contribution in Minnesota River Basin increased by about 12 times in last 160 years which can mostly be attributed to modern cultivation of row crops and animals. A recent effort by Schottler et al. (2010) to apportion the sediment contributions using sediment fingerprinting suggests that non-field sources contribute the majority of the sediment load. They determined that non-field sources contribute 60-85% of the sediment erosion entering the Minnesota River. Non-field loads were greatest in the large and steeply incised Blue Earth-LeSueur watershed. Schottler et al. (2013) also concluded that the rate of sediment erosion from non-field sources has accelerated in the last 100 years, and they attributed this increase in sediment loading to increase in erosive nature of rivers, which can be attributed to the change in landuse over last couple of centuries. The Minnesota River Turbidity TMDL study estimated that 35% of the sediment load originates from fields, 30% from gullies/ravines, and 35% from bank and bluff erosion (Tetra Tech, 2009).

While the Minnesota River Basin is located in the Western Corn Belt Plains Ecoregion, the Crow Wing Watersheds (focus of the present study) are mostly in the North Central Hardwood Forests Ecoregion, with their northern and eastern sections located in the Northern Lakes and Forests Ecoregion (Figure 3.1). These ecoregions are mostly forested and are less arable than the Western Corn Belt Plains where as much as 80% of the area is used for agriculture. The area under agriculture increases in the southern portion of North Central hardwood Forests. According to the Ecological Classification System of Minnesota, the Crow Wing, Long Prairie, and Redeye River watersheds are primarily in the Pine Moraines & Outwash Plains and Hardwood Hills subsections (Figure 3.2). The Sauk River, Crow River and South Fork Crow River are primarily in Minnesota River Prairie, Hardwood Hills and Big Woods.

In the Sauk River Watershed, 55% of sediment loading was attributed to stream bed, bank, and gully erosion (Reisinger and Love, 2012). In the South Fork River watershed, 45% of sediment loading was attributed to stream bed, bank, and gully sources, and in the North Crow River watershed, 55% of sediment loading was attributed to stream bed, bank, and gully sources.

The rapid watershed assessment report for Long Prairie (USDA, 2010a) suggests that gully erosion along with sheet and rill erosion are responsible for sediment loading in this watershed. However, in the watershed tour conducted in 2011, we did not see any areas that showed significant gully erosion. The MPCA staff also confirmed that gully erosion in the Long Prairie watershed may not be a significant issue requiring explicit modeling. The rapid watershed assessment report for Crow Wing (USDA, 2010b) and Redeye River (USDA, 2010) watersheds suggests that soil erosion due to wind, water, and woodland management are of major concern. For the Crow Wing, Long Prairie, and Redeye River watersheds, the contribution of sediment load from non-field sources should be less than the Southern watersheds, as these watersheds are mostly forested, and the river valleys are not incised.

During a phone conversation with Mr. Chuck Regan from MPCA (April 19, 2013) regarding the sediment source contribution in the Crow Wing watersheds, it was concluded that about 80% of

sediment load in these watersheds could be attributed to field sources and the remaining 20% could be attributed to scour processes in the stream. These watersheds are not expected to have any gullies and bluffs; therefore these sources were not included in the model as contributors to total sediment load.

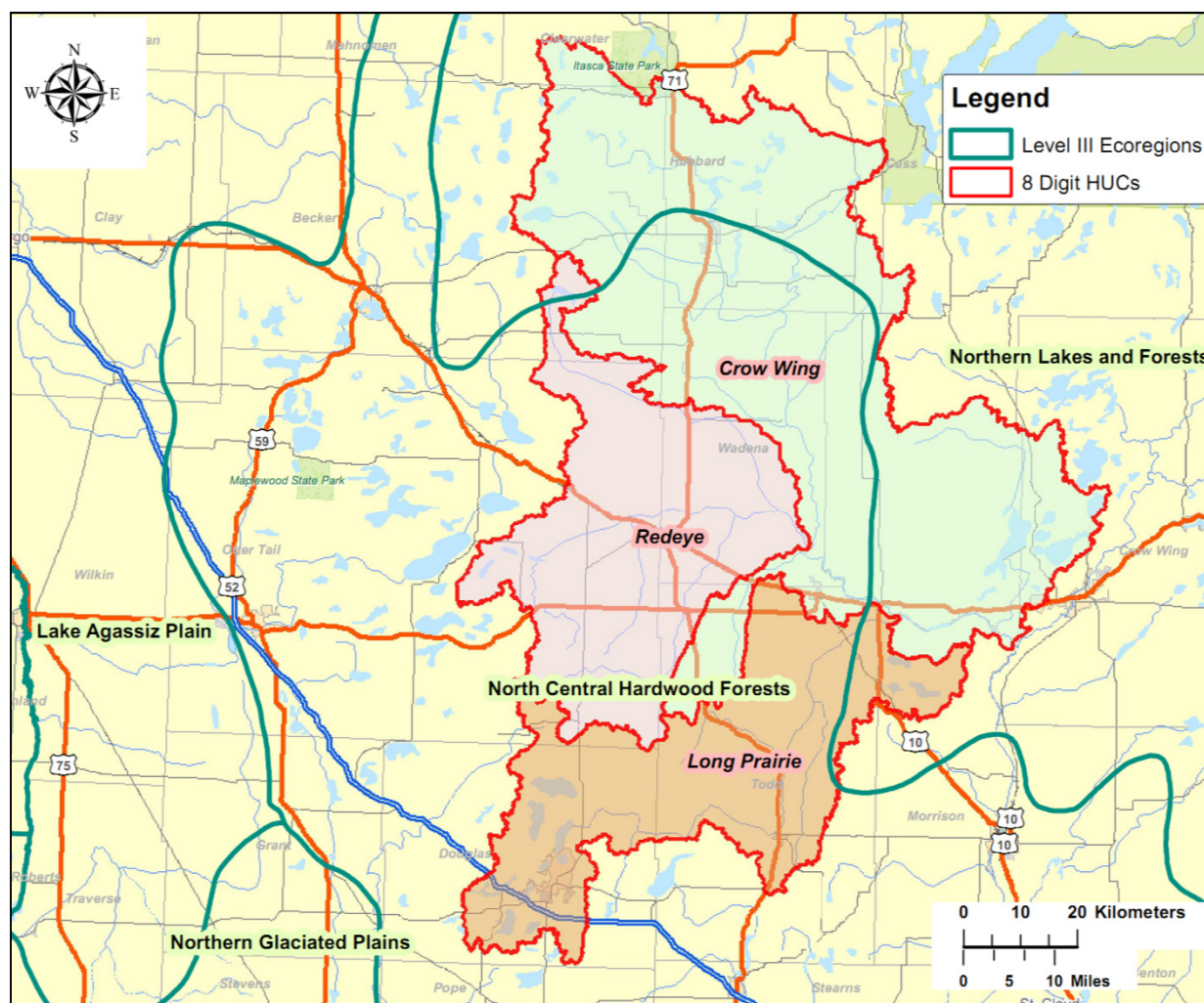


Figure 3.1 Location of Crow Wing, Redeye, and Long Prairie Watersheds and Level III Ecoregions

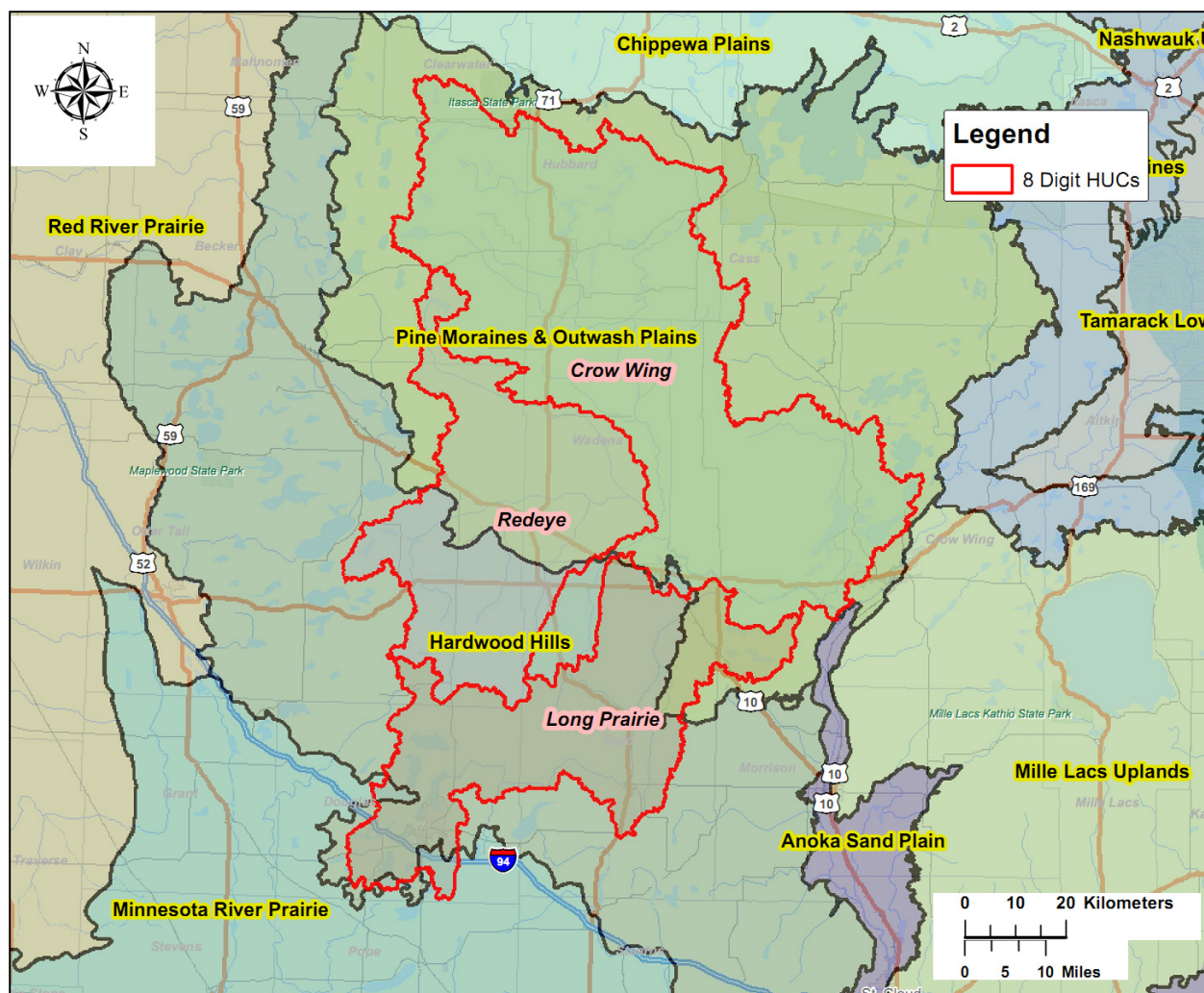


Figure 3.2 Location of Crow Wing, Redeye, and Long Prairie Watersheds and Ecological Subsections of Minnesota

With regards to sediment loading from field sources, the calibrated sediment loading rates from previous studies in the Crow Wing and the Minnesota River watersheds were reviewed and tabulated (Table 3.1). The loading rates from the Crow Wing watershed study were primarily used as the target loading rates for corresponding land uses in the Crow Wing, Redeye and Long Prairie watersheds. In the 1977 Basic Statistics National Resources inventory (USDA 1982), the annual rate of sheet and rill erosion for cropland was 2.5 tons per acre for cropland, 0.5 tons per acre for pasture and 0.5 tons per acre for forest.

Sediment transport through the tile drainage system is expected to be very small in these watersheds as about 2.5% and 2% of the Long Prairie and Redeye River watersheds respectively are under the Cultivated Crops -Drained category (AQUA TERRA Consultants, 2011).

Table 3.1 Calibrated sediment loading from different Watersheds in t/ac-yr (USEPA, 2005 and Tetra Tech, 2009)

	Conservation Tillage	Conventional Tillage	Manured Cropland	Forest	High Till Cropland	Low Till Cropland	Grass / Pasture	Urban	Impervious Area
Crow Wing Watershed				0.012	0.042	0.019	0.007	0.013	0.148
Blue Earth River	0.330	0.396	0.166	0.076			0.137	0.235	
Chippewa	0.055	0.077	0.010	0.007			0.006	0.177	
Cottonwood	0.125	0.192	0.027	0.027			0.032	0.198	
Hawk	0.055	0.083	0.008	0.025			0.033	0.061	
Le Sueur	0.347	0.389	0.204	0.156			0.165	0.357	
Lower MN	0.067	0.146	0.052	0.032			0.034	0.201	
Middle MN	0.041	0.121	0.019	0.025			0.022	0.266	
Redwood	0.086	0.092	0.031	0.039			0.059	0.161	
Watsonwan	0.066	0.126	0.009	0.032			0.034	0.215	
Yellow Medicine	0.093	0.101	0.027	0.040			0.068	0.094	

3.2 SEDIMENT CALIBRATION

The sediment calibration and validation periods were same as those for hydrologic calibration (1/1/2003 - 12/31/2009), and validation (1/1/1995 - 12/31/2002). The sediment calibration process started with calculating the K_{RE} (detachment coefficient dependent on soil properties) parameter for all of the PERLNDs. The K_{RE} is similar to the K Factor in the Universal Soil Loss Equation, which is available in the Soils Data Map provided by NRCS. As recommended in the Minnesota River Turbidity TMDL report (Tetra Tech, 2009), the J_{RE} (detachment exponent dependent on soil properties) was set to 1.81. The remaining sediment parameters were adapted from the previous Crow Wing Parameter study (AQUA TERRA Consultants, 2005).

The sediment parameters K_{SER} (coefficient for transport of detached sediment), AFFIX (the fraction by which detached sediment storage decreases each day as a result of soil compaction), and NVSI (the rate at which sediment enters detached storage from the atmosphere) were adjusted to match the overall sediment loading rates from different land uses to the target loading rates compiled from studies of nearby areas. The sediment loading rates for the three watersheds are shown in Table 3.2 along with the target rates. The overall sediment loading rates from all land uses are within the ranges that were obtained by previous studies in the region. The sediment loading rates in the Crow Wing River watershed were lower than the rates in the Long Prairie and Redeye River watersheds. The primary reason for this difference was the lower surface runoff volume in Crow Wing River watershed (Section 2.2.3).

Table 3.2 Sediment loading rates in t/ac from different land uses and the target loading rates for the calibration period

	Forest - AB	Forest - CD	Wetlands	Grassland - AB	Grassland - CD	Pasture - AB	Pasture - CD	Cropland- AB	Cropland- CD	Cropland- Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity
Target Rate (min)	0.007			0.006				0.042			0.013		
Target Rate (max)	0.156			0.165				0.396			0.357		
Met Segment	Long Prairie Watershed												
50	0.031	0.021	0	0.132	0.073	0.131	0.092	0.195	0.210	0.037	0.221	0.210	0.205
100	0.001	0.001	0	0.031	0.037	0.026	0.038	0.004	0.020	0.001	0.091	0.090	0.079
150	0.008	0.013	0	0.096	0.123	0.084	0.117	0.068	0.167	0.012	0.177	0.183	0.187
200	0.002	0.002	0	0.056	0.092	0.046	0.092	0.008	0.055	0.002	0.120	0.119	0.113
250	0.006	0.010	0	0.093	0.125	0.092	0.128	0.095	0.203	0.021	0.142	0.133	0.114
300	0.001	0.003	0	0.072	0.123	0.053	0.126	0.008	0.056	0.002	0.180	0.196	0.152
350	0.056	0.046	0	0.135	0.101	0.131	0.112	0.240	0.221	0.096	0.253	0.239	0.227
400	0.027	0.016	0	0.117	0.092	0.116	0.112	0.177	0.256	0.039	0.201	0.207	0.207
450	0.012	0.010	0	0.036	0.049	0.032	0.044	0.047	0.044	0.019	0.083	0.083	0.083
500	0.001	0.001	0	0.072	0.085	0.050	0.113	0.006	0.049	0.002	0.177	0.174	0.129
550	0.030	0.020	0	0.085	0.078	0.080	0.071	0.218	0.128	0.080	0.161	0.150	0.195
Weighted Average	0.014	0.006	0	0.080	0.093	0.075	0.105	0.083	0.097	0.016	0.170	0.194	0.196
Minimum	0.001	0.001	0	0.031	0.037	0.026	0.038	0.004	0.020	0.001	0.083	0.083	0.079
Maximum	0.056	0.046	0	0.135	0.125	0.131	0.128	0.240	0.256	0.096	0.253	0.239	0.227
Met Segment	Redeye Watershed												
100	0.001	0.002	0	0.039	0.069	0.052	0.077	0.01	0.04	0.004	0.223	0.201	
200	0.013	0.011	0	0.052	0.043	0.045	0.054	0.056	0.046	0.029	0.137	0.118	0.086
300	0.013	0.011	0	0.111	0.086	0.11	0.097	0.04	0.063	0.017	0.21	0.205	0.196
400	0.003	0.005	0	0.049	0.074	0.042	0.076	0.009	0.037	0.005	0.164	0.15	0.173
500	0.002	0.003	0	0.051	0.049	0.035	0.053	0.017	0.087	0.01	0.149	0.147	0.147
600	0.004	0.007	0	0.022	0.036	0.022	0.038	0.036	0.047	0.024	0.1	0.095	0.086
700	0.001	0.004	0	0.042	0.066	0.042	0.085	0.028	0.236	0.025	0.151	0.155	0.143
800	0.002	0.003	0	0.066	0.093	0.044	0.098	0.007	0.084	0.004	0.22	0.194	0.19
Weighted Average	0.006	0.005	0	0.05	0.052	0.043	0.060	0.034	0.090	0.018	0.145	0.126	0.102
Minimum	0.001	0.002	0	0.022	0.036	0.022	0.038	0.007	0.037	0.004	0.100	0.095	0.086
Maximum	0.013	0.011	0	0.111	0.093	0.110	0.098	0.056	0.236	0.029	0.223	0.205	0.196

	Forest - AB	Forest - CD	Wetlands	Grassland - AB	Grassland - CD	Pasture - AB	Pasture - CD	Cropland- AB	Cropland- CD	Cropland- Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity
Target Rate (min)	0.007			0.006				0.042			0.013		
Target Rate (max)	0.156			0.165				0.396			0.357		
Met Segment	Crow Wing Watershed												
50	0.000	0.000	0	0.041	0.037	0.018	0.038	0.002	0.007	0.001	0.056	0.054	0.058
100	0.000	0.000	0	0.048	0.074	0.013	0.057	0.005	0.028	0.004	0.086	0.088	0.093
150	0.000	0.001	0	0.047	0.077	0.016	0.049	0.005	0.029	0.004	0.115	0.099	0.075
200	0.001	0.002	0	0.047	0.082	0.012	0.049	0.007	0.040	0.005	0.110	0.107	0.092
250	0.000	0.001	0	0.049	0.067	0.033	0.042	0.026	0.066	0.012	0.088	0.094	0.060
300	0.001	0.003	0	0.096	0.113	0.057	0.095	0.057	0.099	0.007	0.142	0.142	0.137
350	0.002	0.003	0	0.099	0.162	0.029	0.092	0.012	0.073	0.011	0.163	0.137	0.082
400	0.001	0.002	0	0.022	0.077	0.010	0.025	0.005	0.025	0.002	0.069	0.060	0.047
450	0.000	0.000	0	0.030	0.060	0.010	0.029	0.004	0.020	0.001	0.062	0.062	0.045
500	0.000	0.000	0	0.017	0.098	0.005	0.039	0.003	0.026	0.004	0.066	0.023	
550	0.001	0.002	0	0.096	0.138	0.025	0.082	0.008	0.038	0.006	0.164	0.165	0.169
600	0.000	0.000	0	0.044	0.068	0.021	0.047	0.019	0.056	0.007	0.115	0.092	0.080
650	0.000	0.000	0	0.022	0.049	0.002	0.011	0.001	0.003	0.000	0.049	0.045	0.013
700	0.000	0.001	0	0.051	0.081	0.027	0.054	0.024	0.054	0.007	0.116	0.108	0.100
750	0.000	0.001	0	0.077	0.156	0.046	0.069	0.027	0.068	0.008	0.154	0.155	0.109
Weighted Average	0.001	0.001	0	0.049	0.086	0.020	0.058	0.009	0.037	0.003	0.095	0.086	0.065
Minimum	0.000	0.000	0	0.017	0.037	0.002	0.011	0.001	0.003	0.000	0.049	0.023	0.013
Maximum	0.002	0.003	0	0.099	0.162	0.057	0.095	0.057	0.099	0.012	0.164	0.165	0.169

Once the sediment loading rates were calibrated, the instream transport of sediment, which is affected by stream hydraulics, was calibrated. The eroded sediment from land surface is assumed to be made of 55% silt, 40% clay, and 5% sand. This fractionation is the same as that used in the previous Crow Wing Study (AQUA TERRA Consultants, 2005). In HSPF, the transport of sand is commonly calculated as a power function of average velocity, whereas the transport of silt and clay depends upon the shear stress values calculated in the HYDR module, and the input critical shear stress parameter values for deposition and scour. At every time step, the scour or deposition of sand is calculated based on transport capacity of flow, and the scour and deposition of silt and clay is calculated based on the relative magnitudes of the calculated shear stress compared to the input critical (threshold) shear stress parameters and erodibility rate.

The critical shear stresses of each reach are different for scour and deposition, as each reach has its own FTABLE that affects the hydraulics and therefore shear stress. To calculate critical shear stress for sediment and deposition for each reach for silt and clay, hourly shear stress values for each reach were output and different percentiles were calculated (99, 95, 90, 80, 70, 30, 20, 10, 5, and 1). Reasonable starting values for critical shear stress were chosen based on graphical analysis (Donigian and Love, 2007) of a few reaches. For each reach, 20th and 10th percentiles of hourly shear stress values were used as critical shear stress values for deposition of silt and clay respectively, and 95th and 90th percentiles were used as critical shear stress values for scour of silt and clay respectively.

The shear stress on a lake bed is calculated differently than the shear stress in streams; these values generally are very low and closer to zero. We do not expect any scouring to happen in the lake beds, so we assigned a critical shear stress value of 0.001 lb/ft² for all the lakes for silt and clay for deposition and scour.

Following the initial parameter assignment, the annual sediment scour and deposition as well as bed depth for each reach was output and analyzed. The bed depths are generally expected to stay stable for the period of simulation with no dramatic changes unless supported by a physical observation of aggrading or degrading stream reaches. The critical shear stresses for scour and deposition were adjusted until all of the reaches exhibited relatively stable behavior. Bed depth outputs of lakes increased slightly as expected due to deposition.

Based on the research described in Section 3.1, it was postulated that in the three Crow Wing watersheds, about 80% of sediment erosion is contributed by land surfaces and 20% is contributed by streams. We calculated the total sediment erosion for each stream and calculated the percent contribution from land surfaces, point sources, and scour from the streams (Table 3.3). In these calculations, the watersheds draining to the lakes were ignored, as lakes are mostly sediment traps where no scour of bed sediment occurs.

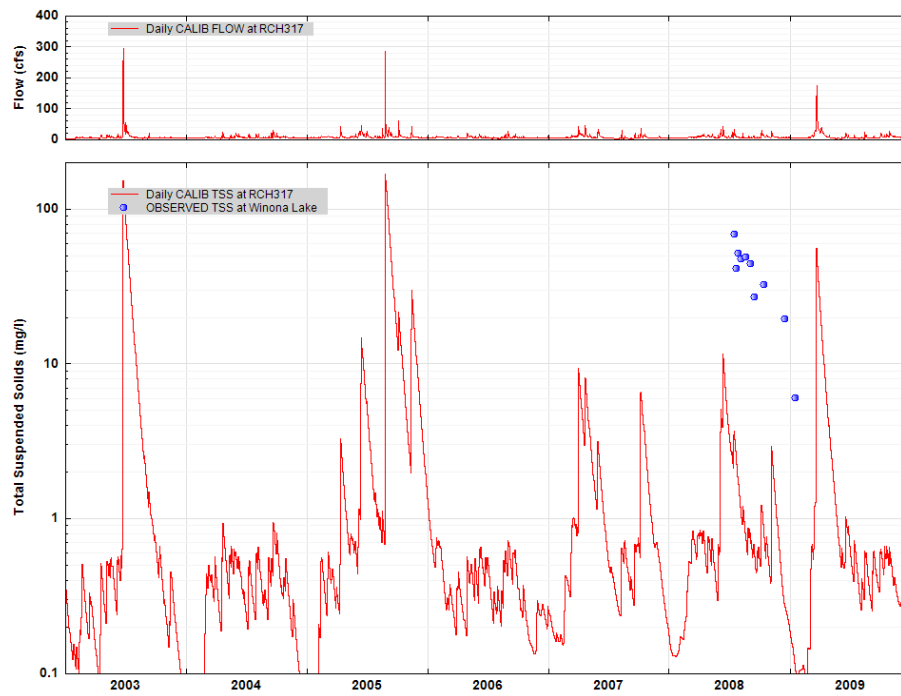
Table 3.3 Sediment erosion from land surface and streams in the watersheds for the calibration period

	Long Prairie River Watershed	Redeye River Watershed	Crow Wing River Watershed
Total sediment erosion in the watershed from the land surface (t/yr)	34,682.6	19,027.6	17,675.7
Total sediment erosion from land surfaces in watersheds with no lakes (t/yr)	20,834.4	17,363.7	13,376.0
Total Point Source Contribution of sediments (t/yr)	43.7	-	25.2
Total Point source contribution of sediments in watersheds with no lakes (t/yr)	24.3	-	25.2

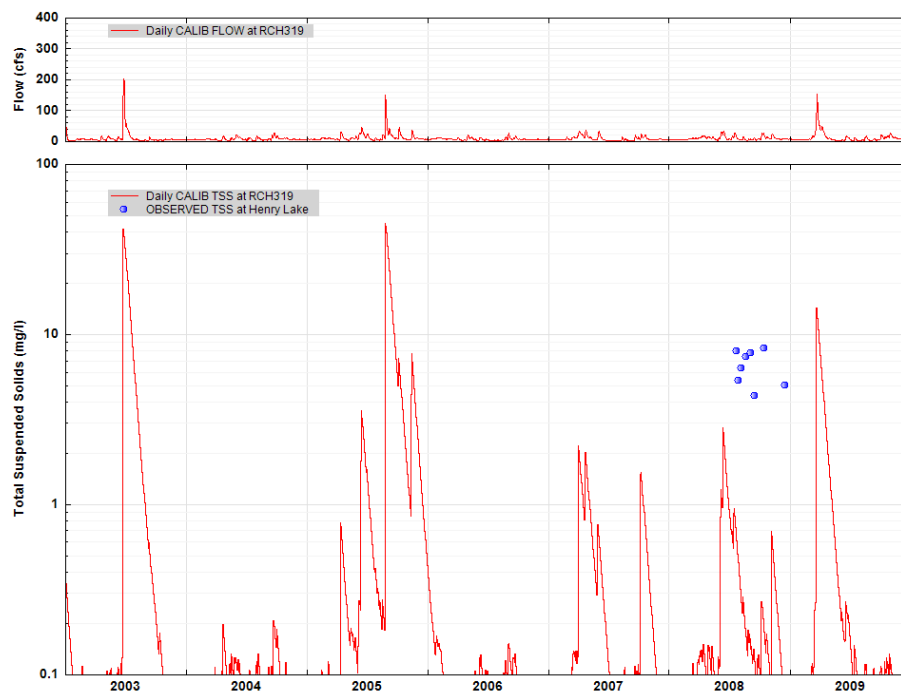
	Long Prairie River Watershed	Redeye River Watershed	Crow Wing River Watershed
Total Deposition (+) / Scour (-) of sediment in all the lakes and streams (t/yr)	10,568.8	-3,011.80	4,000.0
Total Deposition (+) / Scour (-) in streams only (t/yr)	-3,971.53	-5,638.90	-3,652.30
Fraction of sediment from land surfaces in watersheds with no lakes	84%	75%	78%
Fraction of sediment erosion from streams in watersheds with no lakes.	16%	25%	22%

The fraction of sediment loading from land surfaces and streams is close to the fractions that were postulated. Following this step, the simulated total suspended sediment (TSS) concentrations and observed TSS data were plotted for 46 locations in the three watersheds. Parameters affecting sediment loading from land surface and sediment transport were adjusted to obtain a good fit between observed and simulated data. The calibration process required going back to previous steps and readjusting parameters to match the outputs with the target sediment loading and sediment apportionment rates.

A selection of graphs is presented here for illustration (Figure 3.3 to Figure 3.6); the complete set of is provided in APPENDIX E. Because the observed and simulated TSS concentrations are in the same general range, the graphs illustrate that sediment simulation by the model is acceptable. It must be noted that the simulated and observed TSS concentrations are not expected to match exactly, as the observed data is collected at different depths and at different parts of the lake (generally near the outlet), whereas HSPF assumes the whole lake to be a well-mixed reservoir.

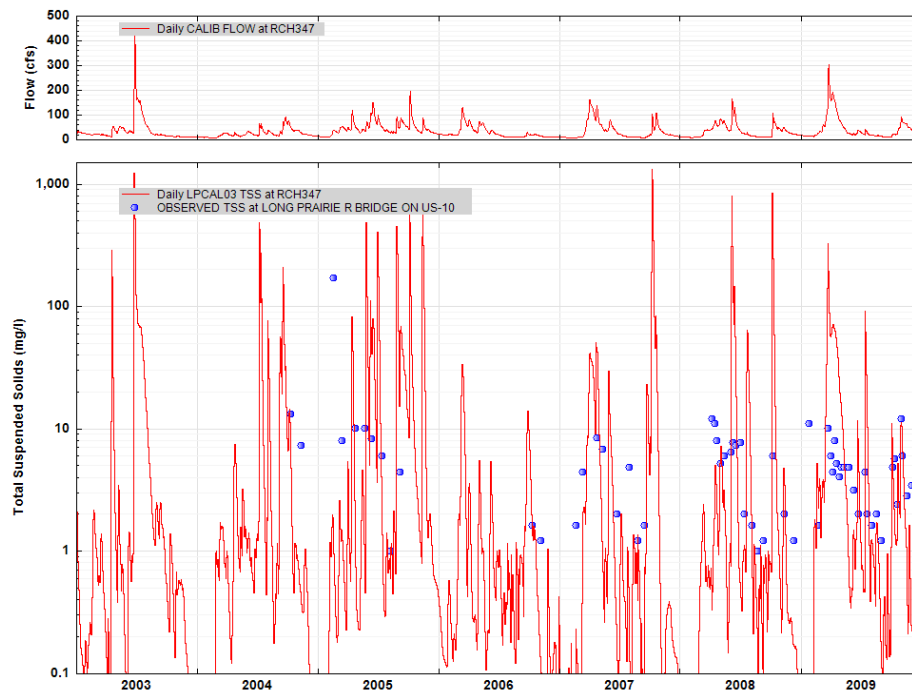


(a)

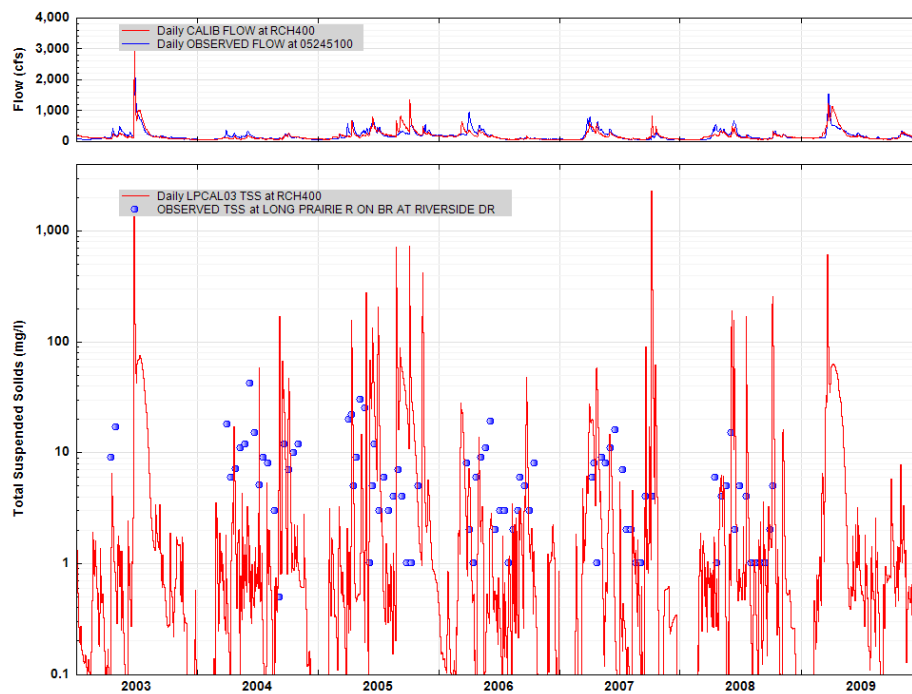


(b)

Figure 3.3 Observed and simulated TSS concentrations in (a) Winona Lake and (b) Henry Lake in Long Prairie River Watershed for the calibration period

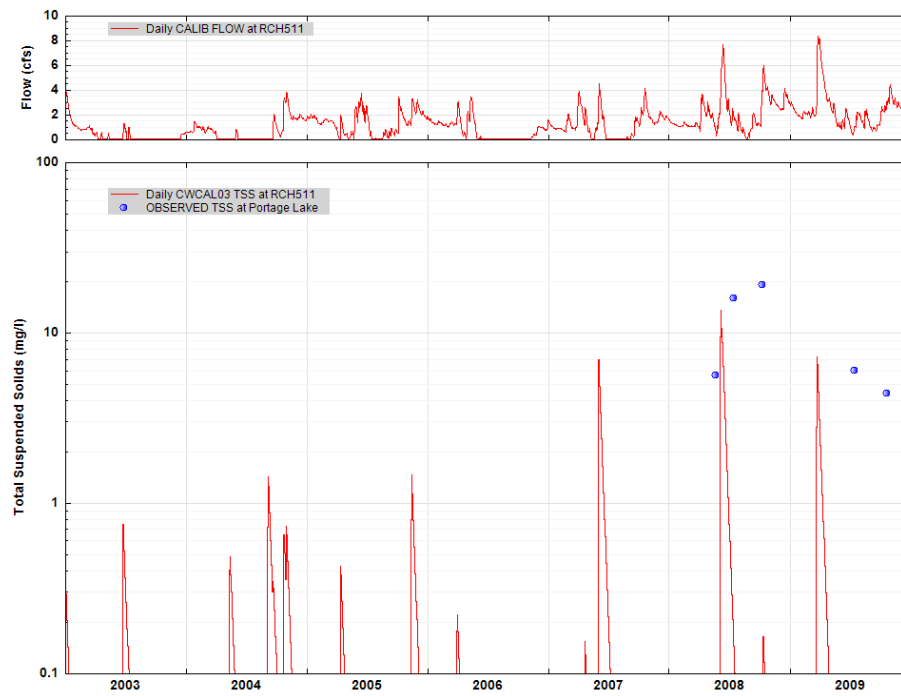


(a)

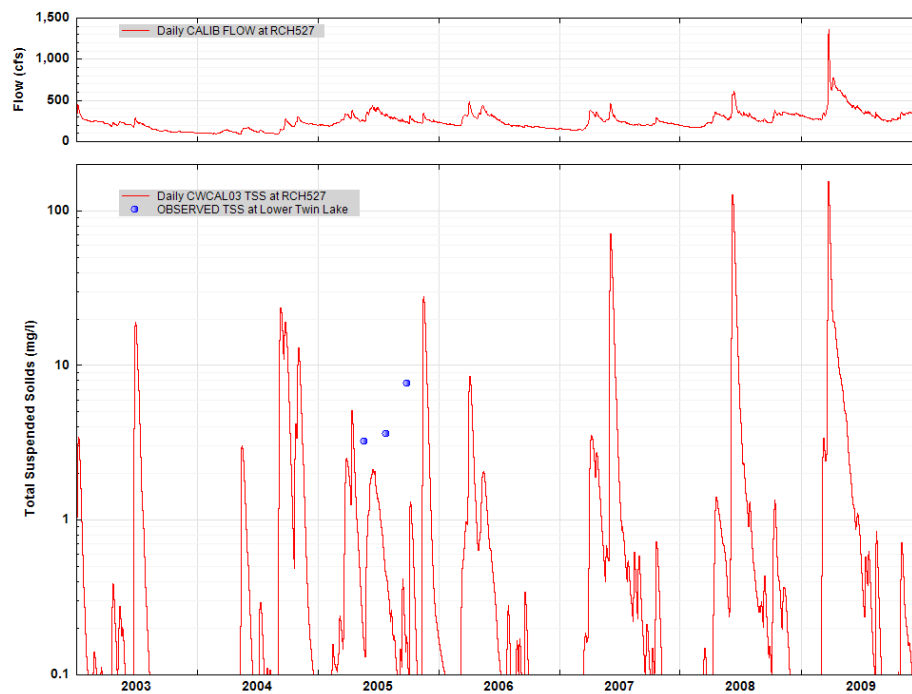


(b)

Figure 3.4 Observed and Simulated TSS Concentrations in Long Prairie River at (a) the outlet of Long Prairie River, and (b) at the USGS gage on Long Prairie River for the calibration period

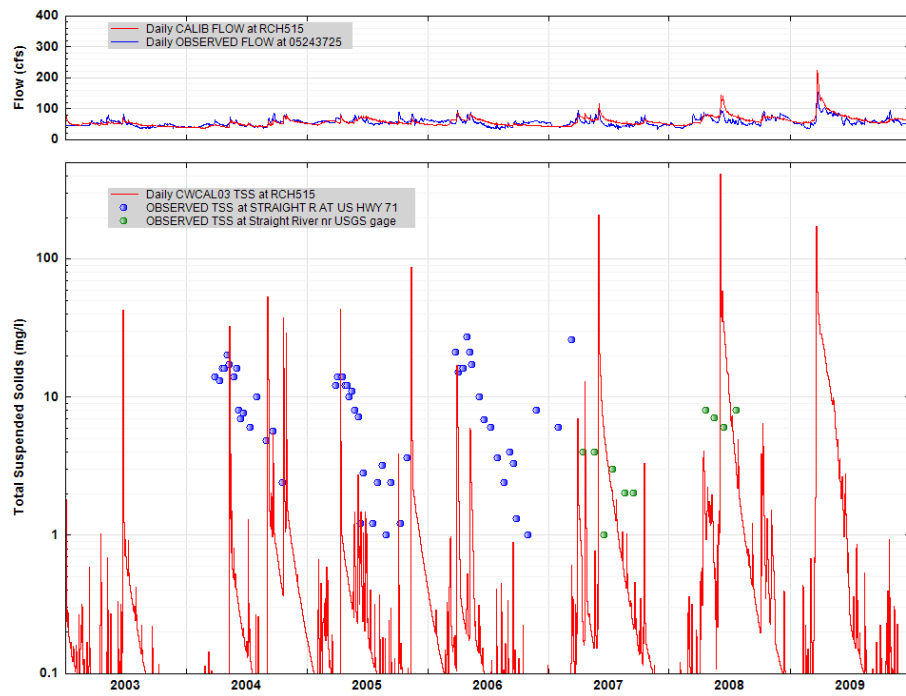


(a)

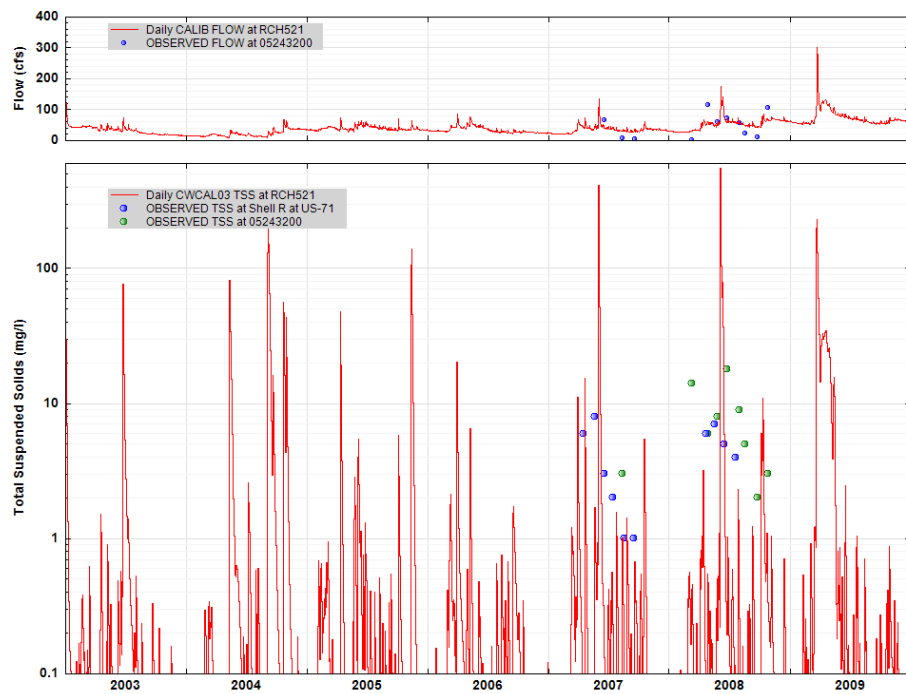


(b)

Figure 3.5 Observed and simulated TSS concentrations at (a) Portage Lake and (b) Lower Twin Lake in Crow Wing Watershed



(a)



(b)

Figure 3.6 Observed and simulated TSS concentrations at (a) Straight River and (b) Shell River in Crow Wing River watersheds

3.3 SEDIMENT VALIDATION

Sediment validation followed sediment calibration. As with hydrology, the sediment parameters from the calibrated model were used in the validation model. Reports similar to the calibrated model were generated (Table 3.4 and Table 3.5). The sediment loading rates of different land uses are generally close to the target sediment loading rate. When the sediment contributions by land surfaces and reaches were compared, the apportionment for the validation period was found to be close to the assumed sediment apportionment. The overall contribution of sediment loading from land surfaces ranged from 79% (Crow Wing River Watershed) to 89% (Redeye River) with the remaining sediment loading coming from the reaches.

Simulated and observed TSS concentrations were plotted at several locations for the validation period (Figure 3.7 and Figure 3.8). The simulated TSS concentrations matched the observed values well. At this stage, the sediment simulation was considered acceptable and the calibration and validation process of the remaining water quality constituents was started.

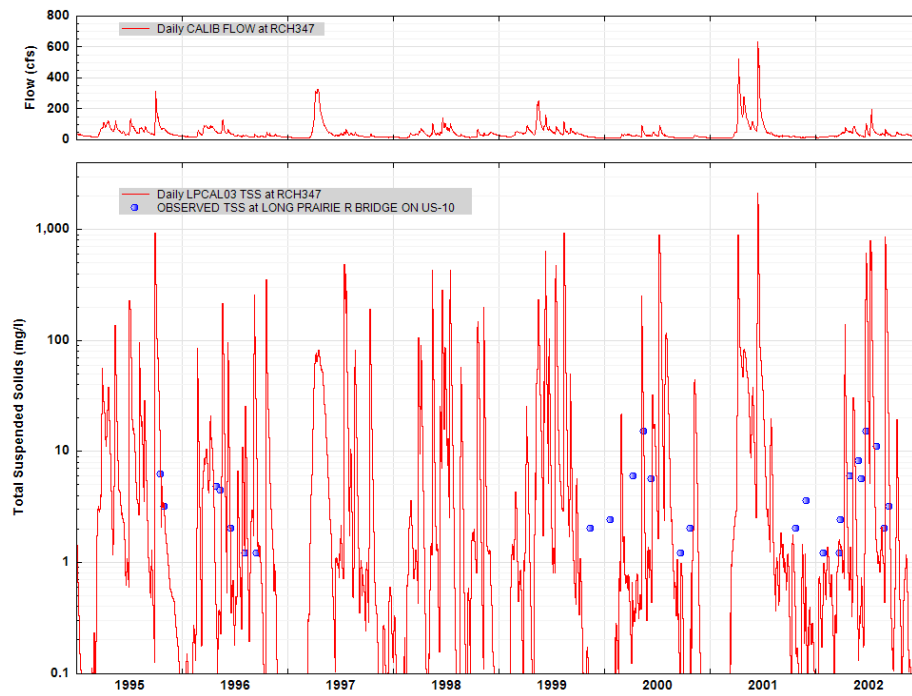
Table 3.4 Sediment erosion from land surface and streams in the watersheds for the validation period

	Long Prairie River Watershed	Redeye River Watershed	Crow Wing River Watershed
Total sediment erosion in the watershed from the land surface (t/yr)	46,132.0	54,997.7	58,497.9
Total sediment erosion from land surfaces in watersheds with no lakes (t/yr)	39,344.9	53,261.1	39,679.6
Total Point Source Contribution of sediments (t/yr)	157.7	-	22.8
Total Point source contribution of sediments in watersheds with no lakes (t/yr)	135.0	-	22.8
Total Deposition (+) / Scour (-) of sediment in all the lakes and streams (t/yr)	3,335.9	-2,767.00	3,904.8
Total Deposition (+) / Scour (-) in streams only (t/yr)	-6,196.60	-6,873.20	-10,662.50
Fraction of sediment from land surfaces in watersheds with no lakes	86%	89%	79%
Fraction of sediment erosion from streams in watersheds with no lakes.	14%	11%	21%

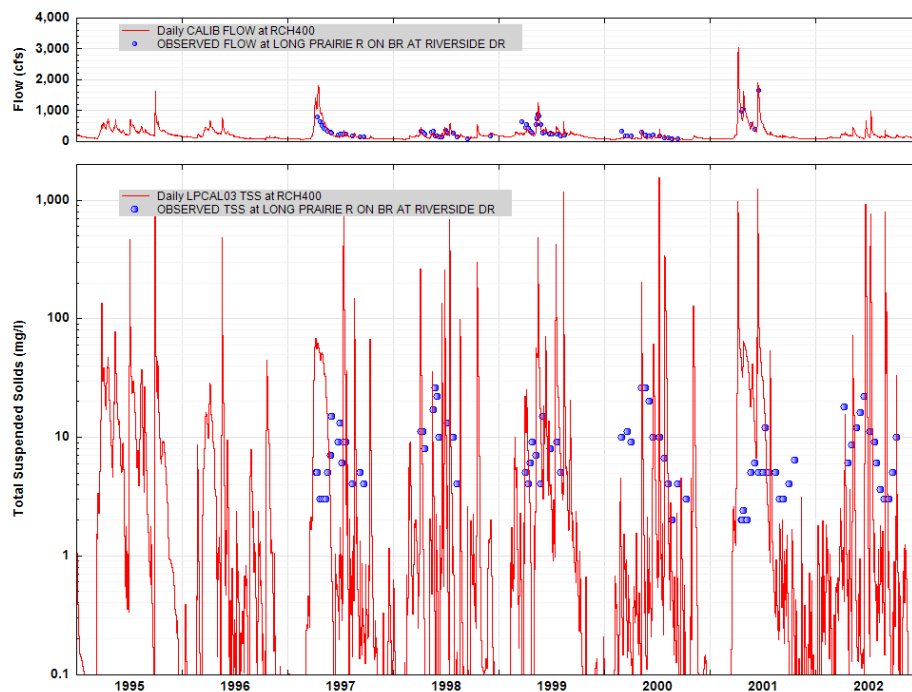
Table 3.5 Sediment loading rates in t/ac from different land uses and the target loading rates for the validation period

	Forest - AB	Forest - CD	Wetlands	Grassland - AB	Grassland - CD	Pasture - AB	Pasture - CD	Cropland - AB	Cropland - CD	Cropland - Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity
Target Rate (min)	0.007			0.006				0.042			0.013		
Target Rate (max)	0.156			0.165				0.396			0.357		
Met Segment	Long Prairie Watershed												
50	0.010	0.008	0	0.102	0.108	0.096	0.118	0.036	0.079	0.007	0.181	0.180	0.172
100	0.003	0.003	0	0.085	0.080	0.074	0.088	0.025	0.075	0.006	0.185	0.183	0.173
150	0.002	0.003	0	0.053	0.085	0.049	0.084	0.060	0.092	0.027	0.113	0.126	0.130
200	0.035	0.027	0	0.110	0.139	0.101	0.147	0.210	0.376	0.143	0.241	0.238	0.232
250	0.054	0.054	0	0.244	0.256	0.238	0.263	0.314	0.563	0.105	0.409	0.384	0.353
300	0.001	0.002	0	0.093	0.139	0.075	0.144	0.026	0.099	0.006	0.205	0.216	0.195
350	0.004	0.006	0	0.072	0.064	0.068	0.067	0.028	0.061	0.004	0.142	0.134	0.114
400	0.012	0.007	0	0.092	0.110	0.072	0.120	0.033	0.087	0.008	0.168	0.178	0.164
450	0.041	0.029	0	0.120	0.123	0.117	0.124	0.215	0.323	0.080	0.228	0.229	0.228
500	0.007	0.009	0	0.138	0.151	0.113	0.168	0.033	0.141	0.010	0.256	0.254	0.223
550	0.043	0.030	0	0.134	0.081	0.126	0.072	0.168	0.185	0.030	0.225	0.206	0.268
Weighted Average	0.017	0.015	0	0.104	0.134	0.092	0.140	0.074	0.277	0.047	0.205	0.186	0.162
Minimum	0.001	0.002	0	0.053	0.064	0.049	0.067	0.025	0.061	0.004	0.113	0.126	0.114
Maximum	0.054	0.054	0	0.244	0.256	0.238	0.263	0.314	0.563	0.143	0.409	0.384	0.353
Met Segment	Redeye Watershed												
100	0.001	0.002	0	0.060	0.076	0.074	0.09	0.037	0.076	0.012	0.269	0.211	
200	0.048	0.035	0	0.128	0.102	0.121	0.127	0.359	0.187	0.189	0.306	0.289	0.243
300	0.008	0.006	0	0.098	0.071	0.082	0.078	0.047	0.067	0.019	0.23	0.221	0.188
400	0.003	0.003	0	0.101	0.108	0.089	0.113	0.03	0.1	0.015	0.261	0.243	0.288
500	0.016	0.012	0	0.136	0.112	0.122	0.121	0.183	0.279	0.082	0.268	0.266	0.261
600	0.012	0.017	0	0.173	0.169	0.167	0.186	0.11	0.381	0.045	0.355	0.336	0.322
700	0.011	0.019	0	0.100	0.153	0.101	0.175	0.098	0.351	0.042	0.295	0.314	0.304
800	0.009	0.015	0	0.135	0.158	0.113	0.166	0.051	0.285	0.027	0.348	0.312	0.300
Weighted Average	0.018	0.016	0	0.131	0.136	0.123	0.151	0.147	0.315	0.059	0.300	0.305	0.305
Minimum	0.001	0.002	0	0.060	0.071	0.074	0.078	0.030	0.067	0.012	0.230	0.211	0.188
Maximum	0.048	0.035	0	0.173	0.169	0.167	0.186	0.359	0.381	0.189	0.355	0.336	0.322

	Forest - AB	Forest - CD	Wetlands	Grassland - AB	Grassland - CD	Pasture - AB	Pasture - CD	Cropland - AB	Cropland - CD	Cropland - Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity
Target Rate (min)	0.007			0.006				0.042			0.013		
Target Rate (max)	0.156			0.165				0.396			0.357		
Met Segment	Crow Wing Watershed												
50	0.007	0.011	0	0.202	0.19	0.18	0.195	0.073	0.247	0.049	0.279	0.27	0.272
100	0.001	0.003	0	0.059	0.092	0.043	0.06	0.011	0.049	0.007	0.103	0.106	0.108
150	0.002	0.003	0	0.145	0.165	0.069	0.138	0.024	0.089	0.015	0.226	0.213	0.185
200	0.016	0.022	0	0.143	0.100	0.137	0.091	0.156	0.106	0.075	0.211	0.208	0.208
250	0.024	0.02	0	0.182	0.187	0.122	0.173	0.179	0.211	0.123	0.279	0.299	0.214
300	0.026	0.02	0	0.145	0.164	0.095	0.123	0.158	0.123	0.048	0.24	0.236	0.229
350	0.005	0.01	0	0.196	0.25	0.102	0.183	0.069	0.174	0.045	0.291	0.221	0.136
400	0.000	0.001	0	0.062	0.121	0.026	0.062	0.006	0.030	0.002	0.134	0.119	0.099
450	0.029	0.022	0	0.124	0.119	0.087	0.096	0.201	0.149	0.111	0.184	0.183	0.167
500	0.010	0.024	0	0.164	0.198	0.113	0.186	0.096	0.245	0.076	0.257	0.246	
550	0.001	0.001	0	0.094	0.142	0.047	0.08	0.034	0.104	0.018	0.152	0.153	0.155
600	0.002	0.002	0	0.140	0.128	0.082	0.118	0.032	0.08	0.011	0.213	0.201	0.193
650	0.001	0.001	0	0.090	0.146	0.031	0.087	0.008	0.032	0.004	0.17	0.161	0.088
700	0.033	0.03	0	0.209	0.227	0.146	0.179	0.292	0.427	0.279	0.326	0.309	0.31
750	0.000	0.000	0	0.068	0.131	0.027	0.06	0.004	0.024	0.001	0.138	0.139	0.118
Weighted Average	0.015	0.011	0	0.149	0.173	0.105	0.125	0.101	0.11	0.037	0.214	0.201	0.158
Minimum	0.000	0.000	0	0.059	0.092	0.026	0.060	0.004	0.024	0.001	0.103	0.106	0.088
Maximum	0.033	0.030	0	0.209	0.250	0.180	0.195	0.292	0.427	0.279	0.326	0.309	0.310

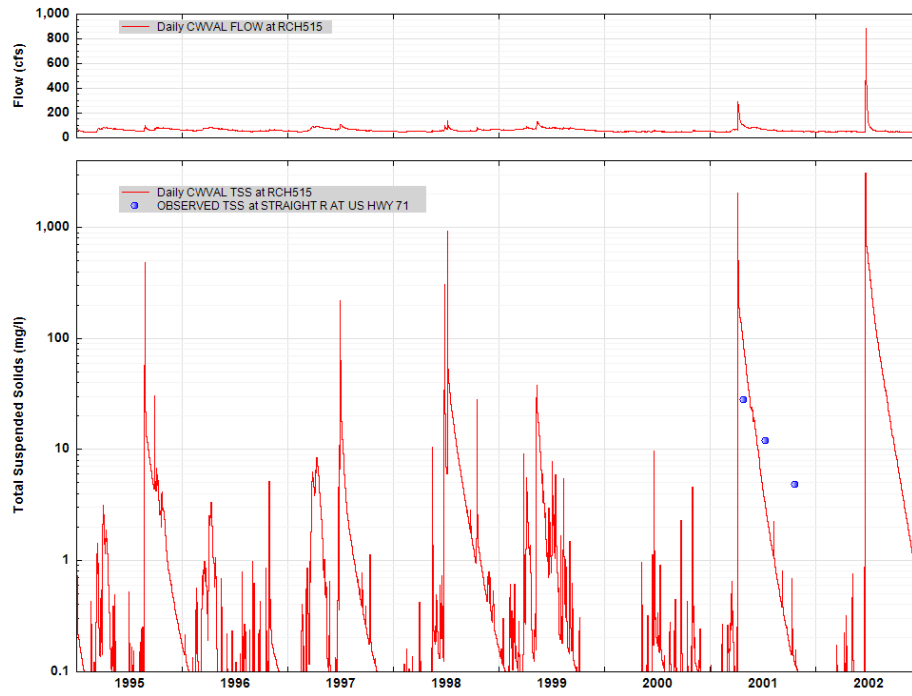


(a)

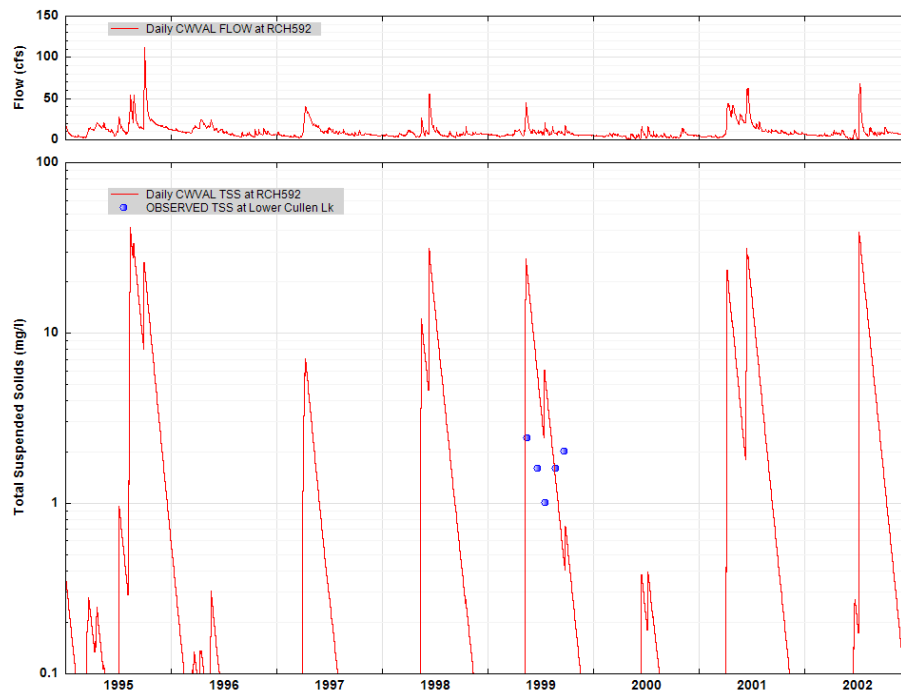


(b)

Figure 3.7 Observed and Simulated TSS Concentrations in Long Prairie River at (a) the outlet of Long Prairie River to the Crow Wing River and (b) at the USGS gage for the validation period



(a)



(b)

Figure 3.8 Observed and Simulated TSS Concentrations at (a) Straight River and (b) Lower Cullen Creek

SECTION 4.0

WATER QUALITY CALIBRATION AND VALIDATION

In the Crow Wing River watersheds, various forms of Nitrogen (N) and Phosphorus (P), their interactions and transformations, and other associated constituents (water temperature, Dissolved Oxygen, Biological Oxygen Demand, and Phytoplankton) were modeled. The sources of these nutrients include point sources, nonpoint sources, and atmospheric deposition. Nonpoint sources are calculated considering accumulation, depletion/removal, and a first-order washoff rate of the available constituent removed by the overland flow. Quantities of these constituents in the subsurface flow are simulated using monthly varying concentrations. Resulting nonpoint loadings, calculated separately for each land use in each met segment, are input to the reaches and lakes along with the point sources in order to simulate fate, transport, and delivery of the nutrients. Atmospheric deposition on all land surfaces provides a contribution to the nonpoint source load through the runoff/washoff process; deposition onto water surfaces represented in the model is also considered a direct input to the river systems.

Following the estimation of nutrient contributions from all land uses, the modeled hydrological and hydraulic processes are superimposed to provide transport mechanisms, and then water quality modeling is performed to allow adjustments in parameters and evaluation of sources as part of the calibration process. Nonpoint contributions from the watershed include following constituents.

- Sediment
- Heat
- Nitrite-Nitrate as Nitrogen ($\text{NO}_3\text{-N}$)
- Ammonia as Nitrogen ($\text{NH}_4\text{-N}$)
- Orthophosphate as Phosphorus ($\text{PO}_4\text{-P}$)
- Biological Oxygen Demand (BOD)/Organics, comprised of
 - Labile BOD
 - Refractory Organic Nitrogen
 - Refractory Organic Phosphorus
 - Refractory Organic Carbon

Sediment was discussed in previous chapter. All of the remaining constituents are modeled within the stream module, along with algal components of phytoplankton and benthic algae. Water quality calibration is an iterative process; the model predictions are the integrated result of all the assumptions used in developing the model input and representing the model processes. Differences in model predictions and observations require the model user to re-evaluate these assumptions, in terms of both the estimated model input and parameters, and to consider the accuracy and uncertainty in the observations. It must be noted that at the current time, water quality calibration is more an art than a science, especially for comprehensive simulations of nonpoint, point, and atmospheric sources and their impacts on water quality.

The time periods used for water quality calibration/validation were the same as those used for hydrologic calibration and validation. The following steps were performed for water quality calibration.

1. Estimate all model parameters, including land use specific accumulation and depletion/removal rates, washoff rates, and subsurface concentrations.
2. Tabulate, analyze, and compare simulated nonpoint loadings with expected range of nonpoint loadings from each land use and adjust loading parameters as necessary.
3. Calibrate instream water temperature.

4. Compare simulated and observed instream concentrations at all the locations where data is available.
5. Analyze the comparisons in steps 3 and 4 to determine appropriate instream and/or nonpoint parameter adjustments.

The primary instream water quality parameters adjusted were advection and settling rates for phytoplankton and refractory organics, settling rates for BOD, benthic release of BOD, $\text{NH}_4\text{-N}$, or $\text{PO}_4\text{-P}$ with secondary changes to nitrification rates, phytoplankton and benthic algae rates, and algal nutrient update parameters. Initial parameter values were obtained from the Crow Wing Watershed Study (AQUA TERRA Consultants, 2007).

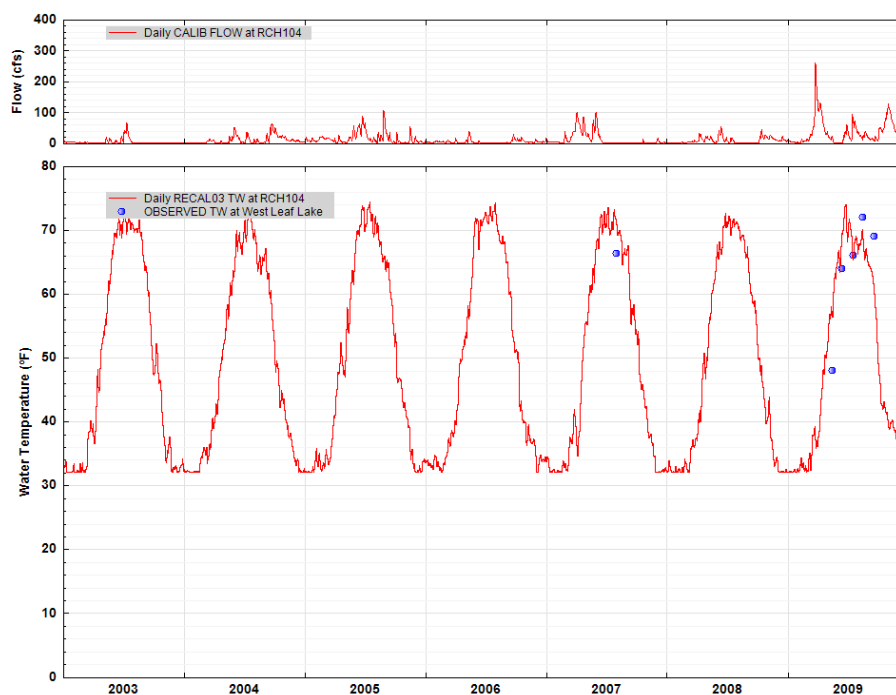
This section discusses each of the water quality constituents individually and presents the calibration and validation results.

4.1 WATER TEMPERATURE

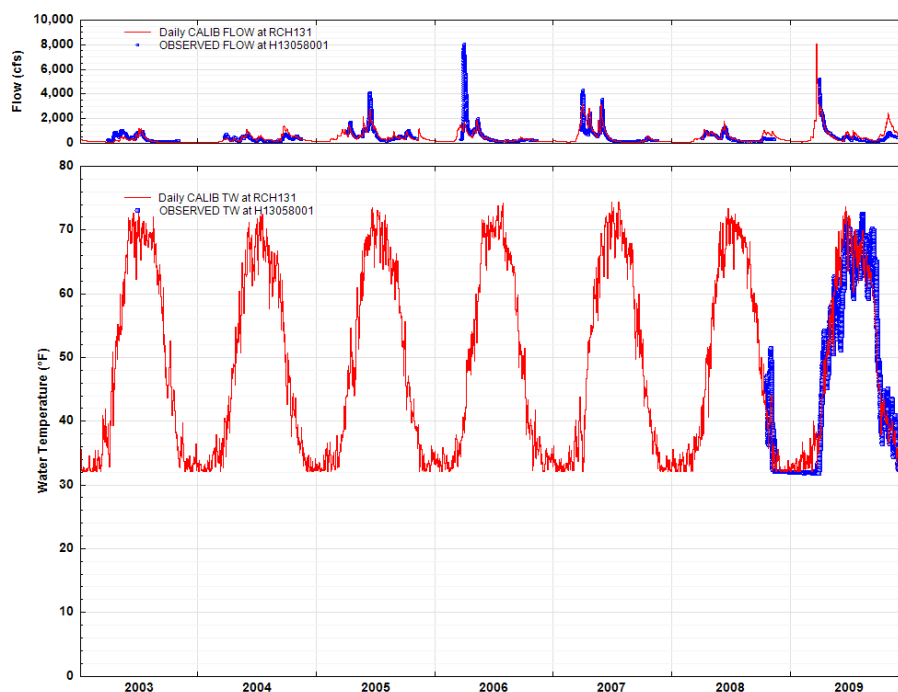
Water temperature controls the instream reaction rates and also determines the saturation concentration of dissolved oxygen; therefore temperature calibration is conducted before calibration of other water quality constituents. To model the instream water temperature, HSPF calculates the heat loadings to a stream reach from all sources and then performs a balance of the heat fluxes across the reach boundaries to arrive at the reach water temperature in each model step. Heat sources/sinks to a reach include upstream or tributary reaches, nonpoint runoff, point sources, heat exchange with the atmosphere, and conduction from streambed. Heat outputs from a reach include downstream advection, losses to the atmosphere, and conduction to the streambed.

The details on heat loading and water temperature simulation are available in the HSPF Manual (Bicknell et al. 2005). To conduct temperature calibration, first the soil temperature parameters are adjusted as the heat content of the runoff is a function of the modeled soil temperatures in each soil layer. The monthly ASLT (Y intercept for surface layer temperature regression equation), BLST (slope for surface layer temperature regression equation), ULTP1 (intercept for upper layer temperature regression equation), ULTP2 (slope for upper layer temperature regression equation), LGTP1 (intercept for lower layer and active groundwater temperature regression equation), and LGTP2 (slope for lower layer and active groundwater temperature regression equation) were adjusted for each PERLND, to improve the soil temperature simulation. After reasonable soil temperatures are attained, the instream parameters of monthly TGRND (ground temperature), CFSAX (fraction of RCHRES exposed to sun's radiation), KATRAD (longwave radiation coefficient), and KCOND (conduction-convection heat transport coefficient) were adjusted for each RCHRES, in comparison with available stream water temperature data.

Although water temperature data was available at a few locations in the watershed the data was not dense enough to conduct a detailed statistical analysis. However, plotting the data at several locations provided a good indication of how well the model was performing in terms of water temperature simulation. Plots of observed and simulated water temperature, such as those presented in Figure 4.1 to Figure 4.5, show that simulated water temperatures match the observed data very well. It must be recognized that the observed data represents a snapshot of time and a location, whereas simulated data is averaged for the whole day with the assumption that the entire water body (lake or a reach) is a well-mixed reservoir. Therefore, the simulated data demonstrates the water temperature trends and is not expected to match the observed data exactly. All of the graphs prepared for the calibration and validation periods are presented in APPENDIX G and APPENDIX H.

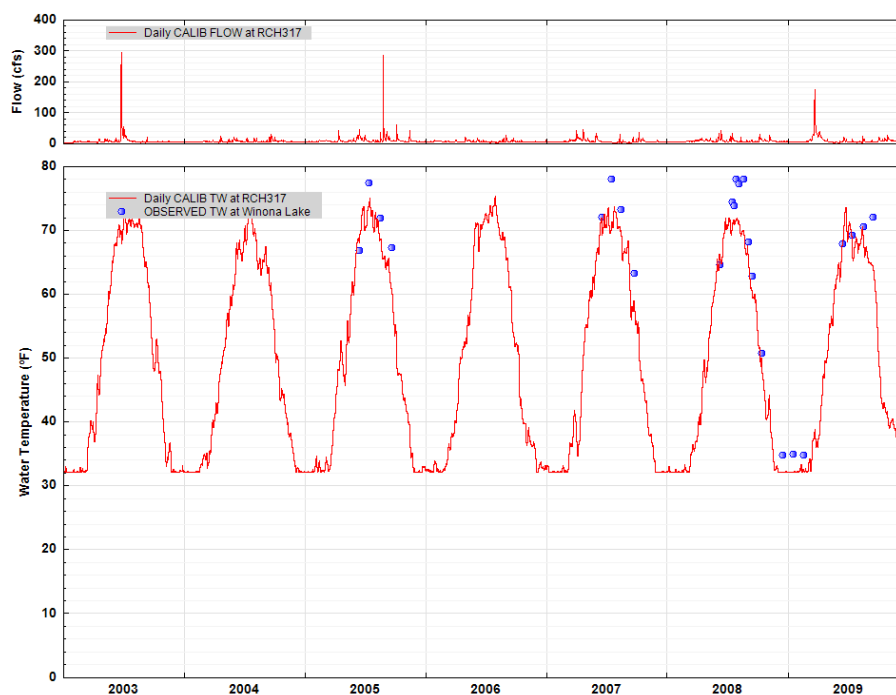


(a)

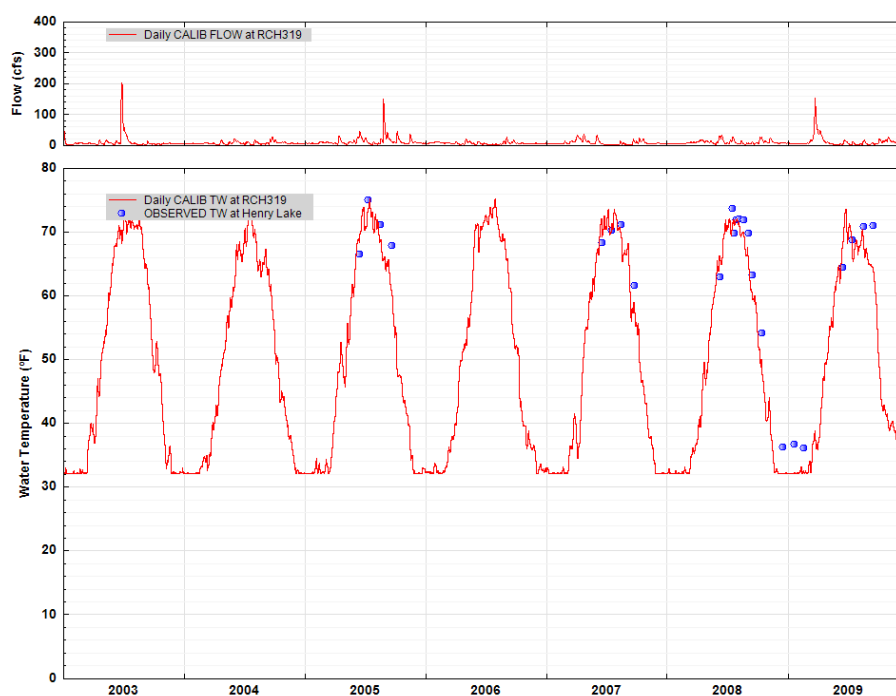


(b)

Figure 4.1 Observed and simulated water temperature at two locations in Redeye River watershed for the calibration period

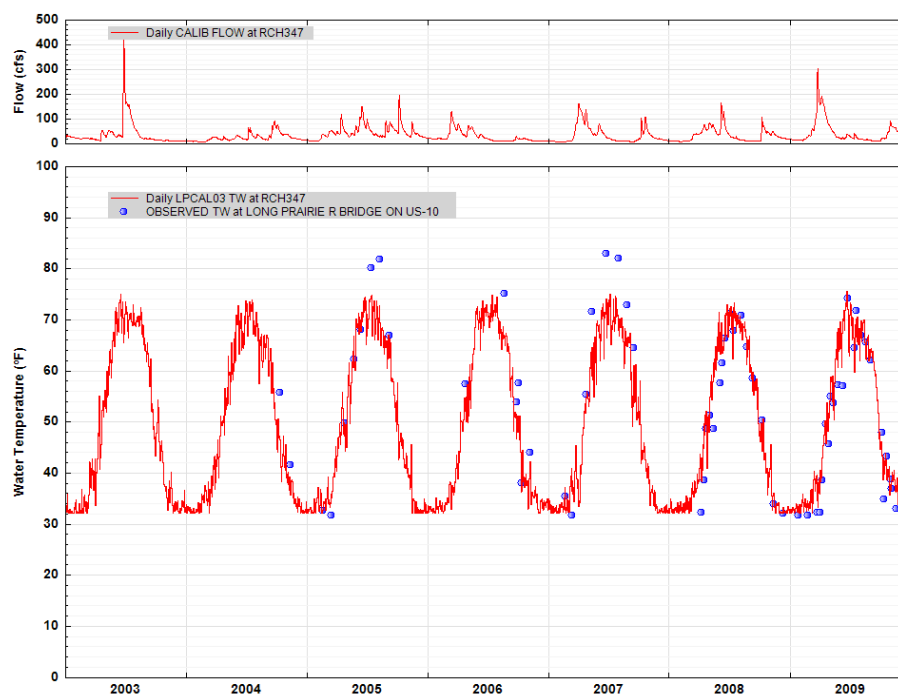


(a)

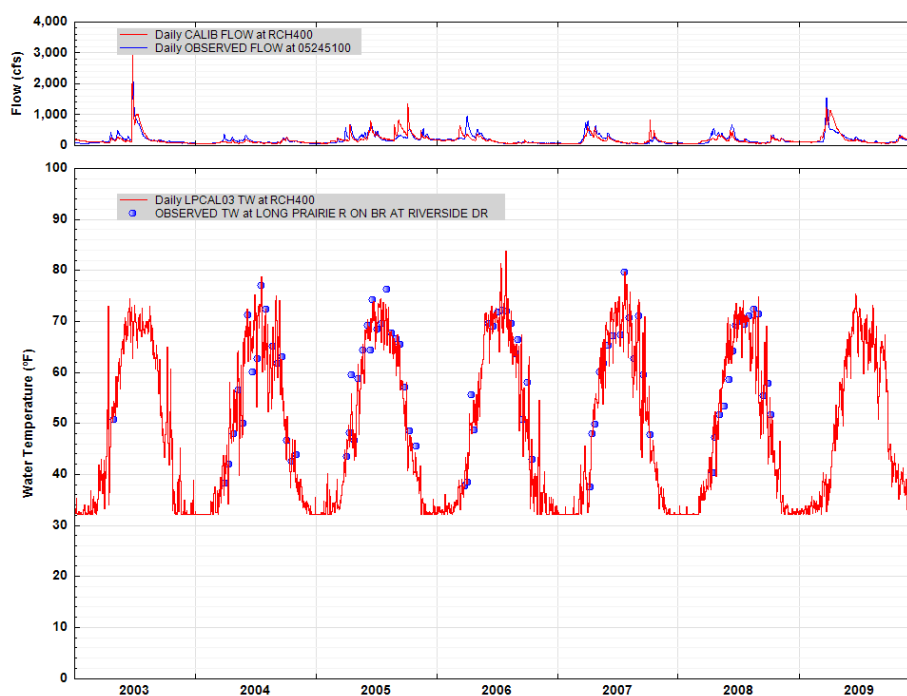


(b)

Figure 4.2 Observed and simulated water temperature at two lakes in the Long Prairie River watershed for the calibration period

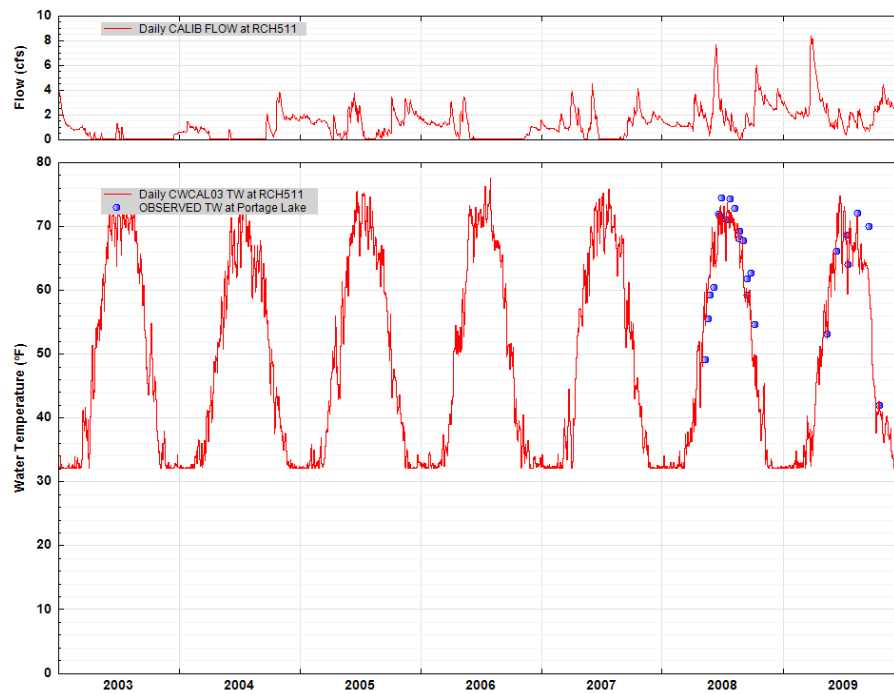


(a)

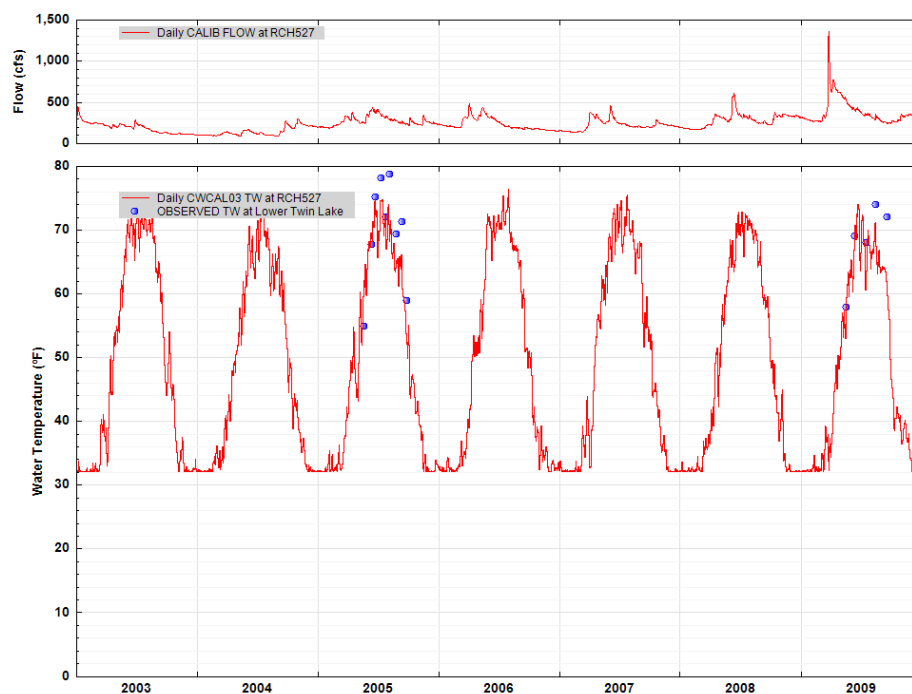


(b)

Figure 4.3 Observed and simulated water temperature at (a) Long Prairie River outlet and (b) USGS gage on Long Prairie River for the calibration period

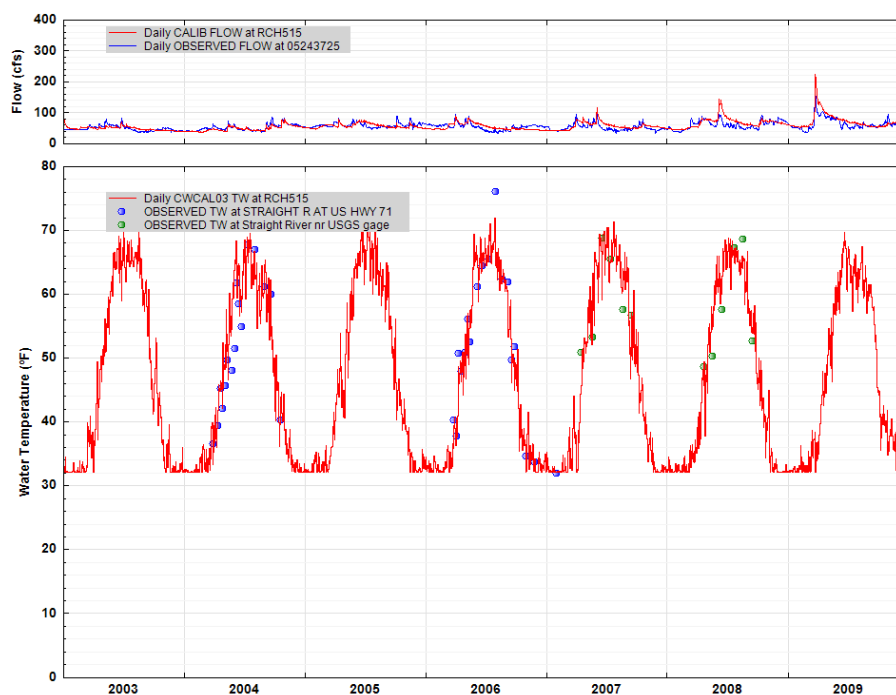


(a)

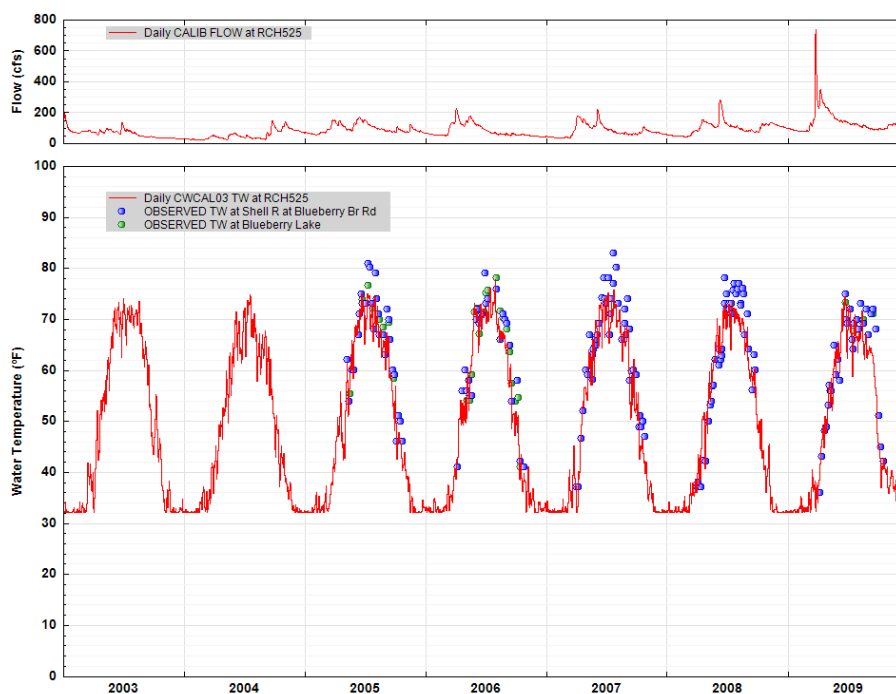


(b)

Figure 4.4 Observed and simulated water temperature at (a) Portage Lake and (b) Lower Twin Lake in the Crow Wing River Watershed for the calibration period



(a)



(b)

Figure 4.5 Observed and simulated water temperature at (a) Straight River and (b) Shell River in the Crow Wing River watershed for the calibration period

4.2 DISSOLVED OXYGEN

Dissolved Oxygen (DO) concentration generally indicates the overall ecological well-being of streams and lakes. In relatively unpolluted waters, the sources and sinks of oxygen are in proper balance and the DO concentration remains close to saturation. However, when the water receives pollutants from different sources, this balance may get upset, populations of oxygen-consuming bacteria may increase, and DO concentration may decrease. DO concentration is affected by a combination of water temperature, reaeration, loading of oxygen-demanding wastes, sediment oxygen demand, production of algae, and respiration by algae. The calibration of DO therefore was an iterative process that included the calibration of other water quality parameters (Chlorophyll A, N, P, etc.) in tandem. During calibration, parameters affecting the loading rates of BOD, N, and P (accumulation rate, monthly concentration of interflow and groundwater) were adjusted. Parameters affecting the release of nutrients from reach beds, nutrient transformation, growth and respiration of phytoplankton, and algae were also adjusted. The loading rates of BOD organics from all the land uses are presented in Table 4.1.

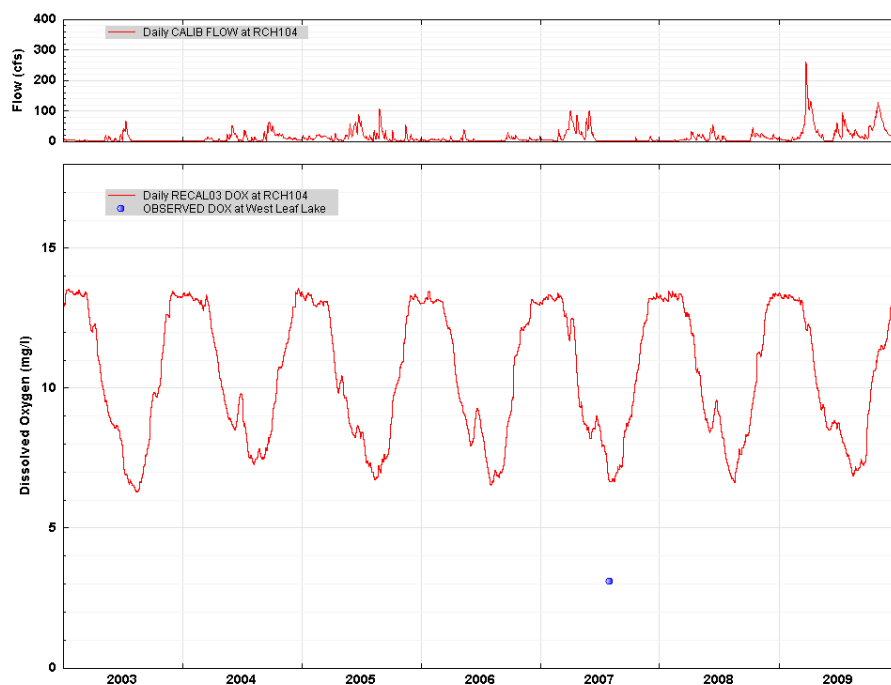
Some of these parameters were reach or lake specific and were adjusted accordingly. For example, the lakes downstream of point sources had a greater release of nutrients from their beds. The size and shape of these lakes also affect the total nutrient release from the bed. Better information about the hydraulics of these lakes, bed depth, and sediment distribution would help in improving the calibration of these waterbodies and possible extension of the model for a longer period would also help.

Overall, the DO simulation appeared reasonable and acceptable in the three watersheds (Figure 4.6 to Figure 4.10), with a good representation of seasonal patterns. It must be noted that the observed DO values are a snapshot in time and space, whereas the simulated DO assumes that the whole lake/reach is a completely mixed reservoir where the values are averaged for the day. Further, observed data is not sufficient to conduct a detailed statistical analysis; therefore visual comparison is the best tool available to judge the goodness of fit. Remaining DO plots for calibration and validation are provided in APPENDIX I and APPENDIX J.

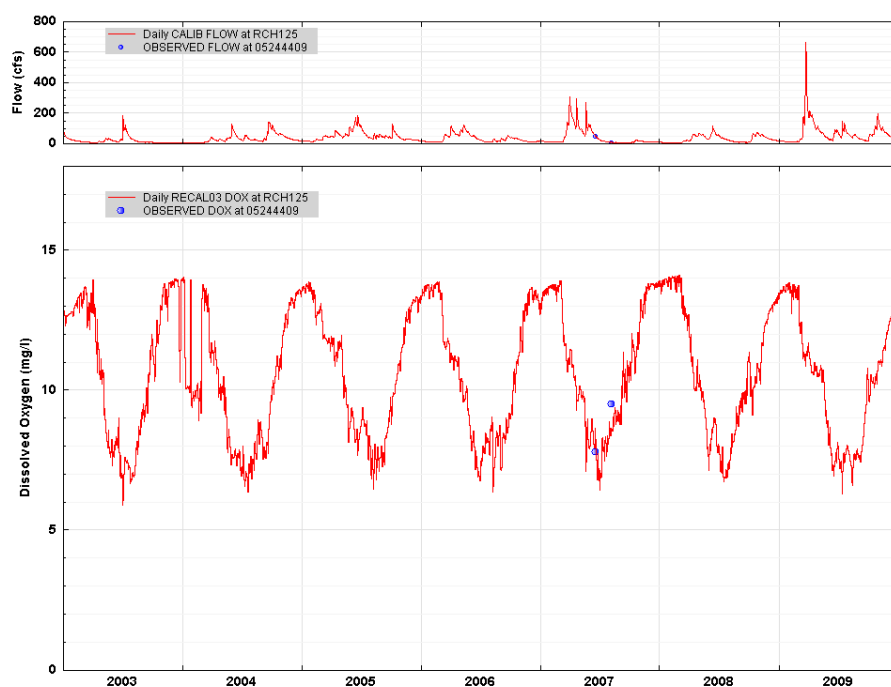
Table 4.1 Average loading of BOD Organics from different land uses in the Long Prairie, Redeye, and Crow Wing River Watersheds

Long Prairie Watershed														
Land Use	Forest - AB	Forest - CD	Wetlands	Grassland - AB	Grassland - CD	Pasture - AB	Pasture - CD	Cropland- AB	Cropland- CD	Cropland- Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Watershed Avg.
Area (ac)	61,920	55,045	66,715	21,689	25,795	46,932	71,722	88,702	47,003	14,007	26,787	5,210	1,211	532,736
SOQUAL	0.358	0.167	0	2.06	2.405	1.935	2.694	2.136	2.507	0.412	4.366	4.989	5.043	1.66
IOQUAL	0.234	0.261	0.025	1.729	1.941	1.728	1.924	2.044	2.827	3.705	4.882	4.745	5.015	1.623
AOQUAL	2.129	2.215	1.905	6.195	6.416	6.073	6.414	33.948	35.038	32.004	11.132	10.524	10.762	12.949
POQUAL	2.722	2.644	1.93	9.984	10.761	9.737	11.032	38.127	40.372	36.12	20.38	20.258	20.82	16.232
IMPLND														
Landuse	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Watershed Avg.										
Area (ac)	547	579	658	1,784										
SOQUAL	30.62	30.50	30.64	30.59										
Redeye River Watershed														
Land Use	Forest - AB	Forest - CD	Wetlands	Grassland - AB	Grassland - CD	Pasture - AB	Pasture - CD	Cropland- AB	Cropland- CD	Cropland- Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Watershed Avg.
Area (ac)	46,871	83,838	100,799	18,787	29,542	51,299	65,232	110,788	23,285	11,703	22,285	2,266	415	567,110
SOQUAL	0.147	0.121	0	1.298	1.337	1.115	1.539	0.865	2.319	0.463	3.733	3.25	2.638	0.856
IOQUAL	0.156	0.19	0.018	1.389	1.642	1.405	1.628	1.383	1.871	2.543	4.905	5.187	5.526	1.107
AOQUAL	2.082	2.155	1.807	6.307	6.146	6.335	6.12	36.657	33.387	33.401	11.229	11.671	12.058	12.336
POQUAL	2.385	2.465	1.824	8.994	9.126	8.855	9.287	38.904	37.577	36.407	19.868	20.108	20.222	14.298
IMPLND														
Landuse	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Watershed Avg.										
Area (ac)	455	252	224	930										
SOQUAL	30.92	31.17	31.28	31.07										
Crow Wing River Watershed														
Land Use	Forest - AB	Forest - CD	Wetlands	Grassland - AB	Grassland - CD	Pasture - AB	Pasture - CD	Cropland- AB	Cropland- CD	Cropland- Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Watershed Avg.
Area (ac)	393,204	201,743	218,953	53,581	34,151	72,855	70,611	99,169	196	27,067	37,387	4,315	739	1,213,970
SOQUAL	0.017	0.029	0	1.251	2.211	0.509	1.504	0.23	0.955	0.068	2.437	2.215	1.671	0.37

IOQUAL	0.082	0.103	0.014	1.18	1.378	0.783	1.013	1.301	1.968	2.299	2.994	3.031	3.22	0.498
AOQUAL	1.829	1.886	1.564	6.864	6.728	5.809	5.823	35.672	33.27	32.114	10.857	10.86	11.142	6.408
POQUAL	1.927	2.017	1.577	9.294	10.316	7.1	8.34	37.203	36.193	34.481	16.289	16.106	16.033	7.276
IMPLND														
Landuse	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Watershed Avg.										
Area (ac)	762	478	398	1,638										
SOQUAL	29.40	29.35	29.48	29.41										

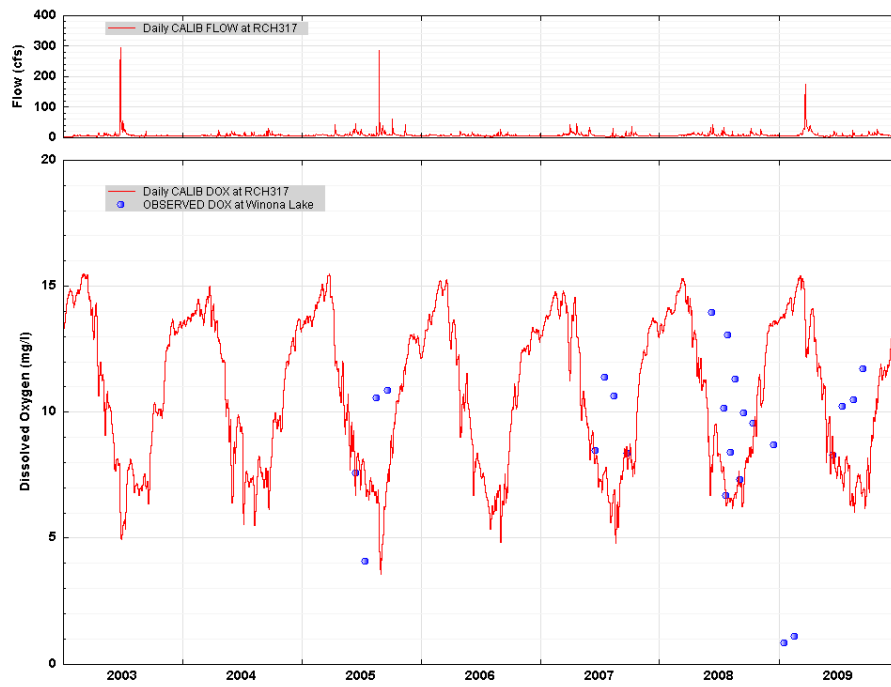


(a)

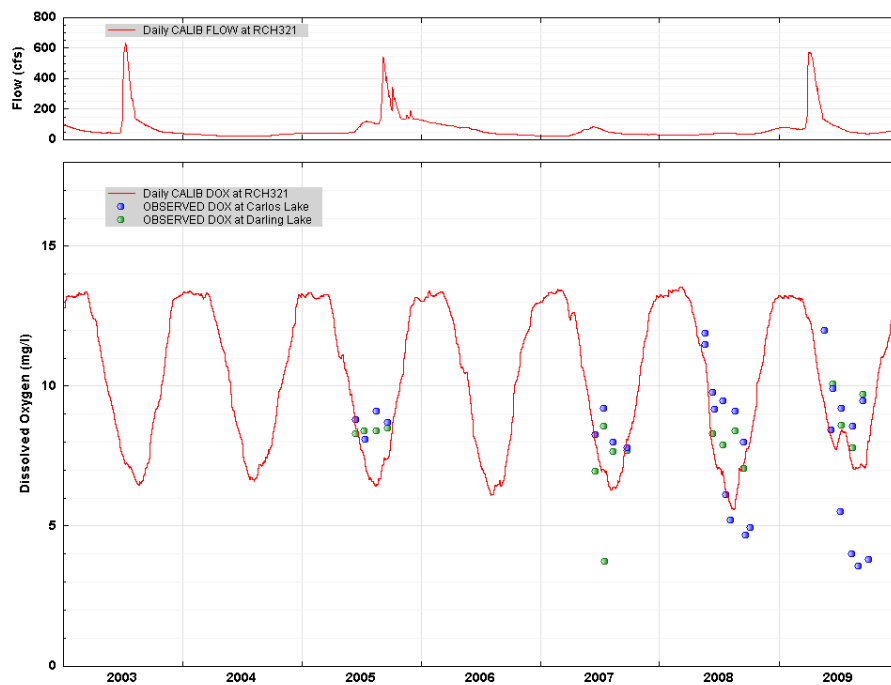


(b)

Figure 4.6 Observed and simulated DO concentrations at two locations in the Redeye River watershed

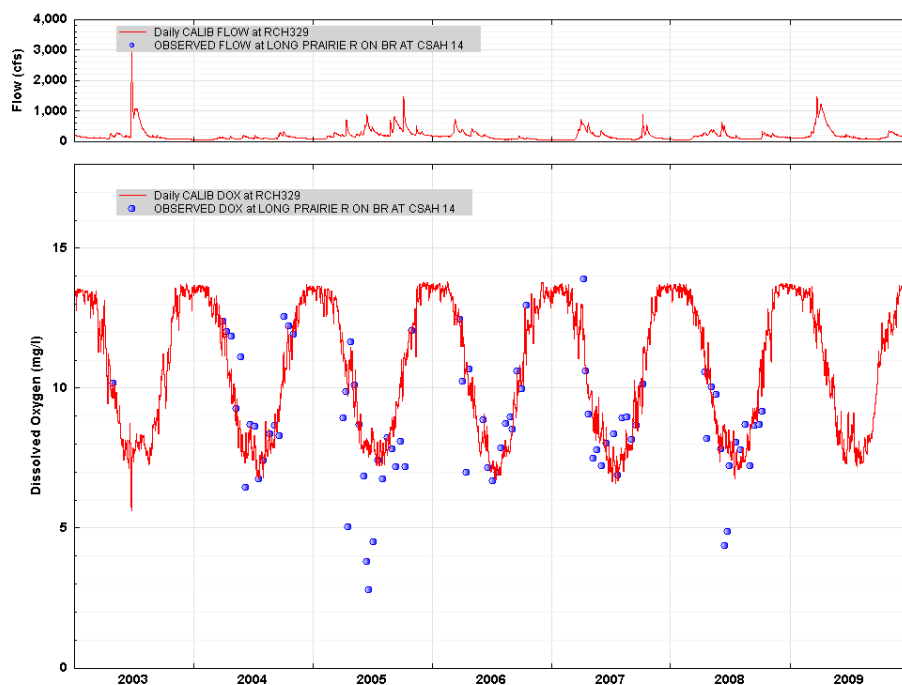


(a)

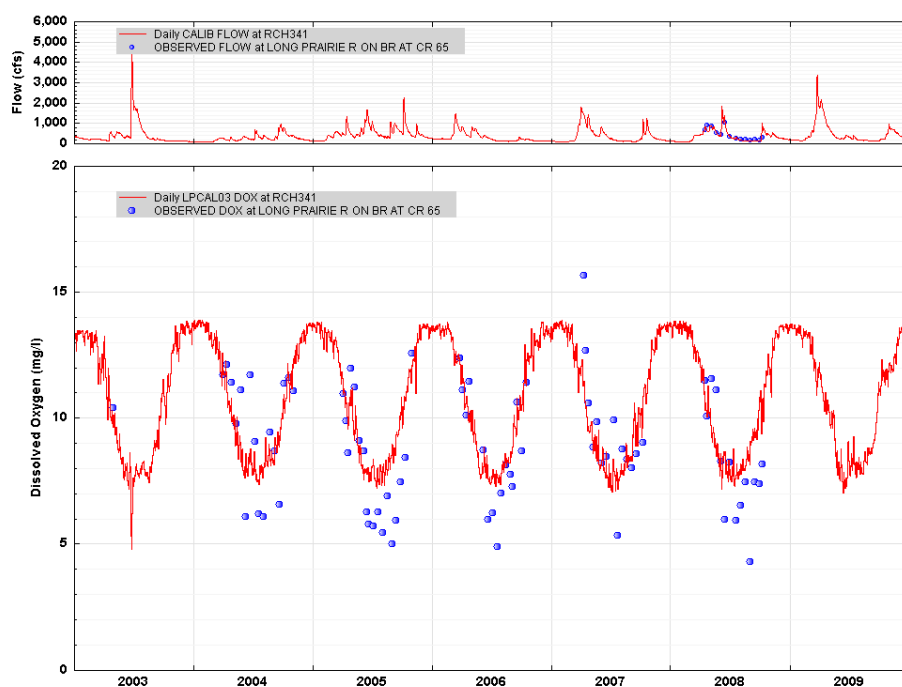


(b)

Figure 4.7 Observed and simulated DO concentrations at (a) Winona Lake and (b) Carlos lake in the Long Prairie River watershed

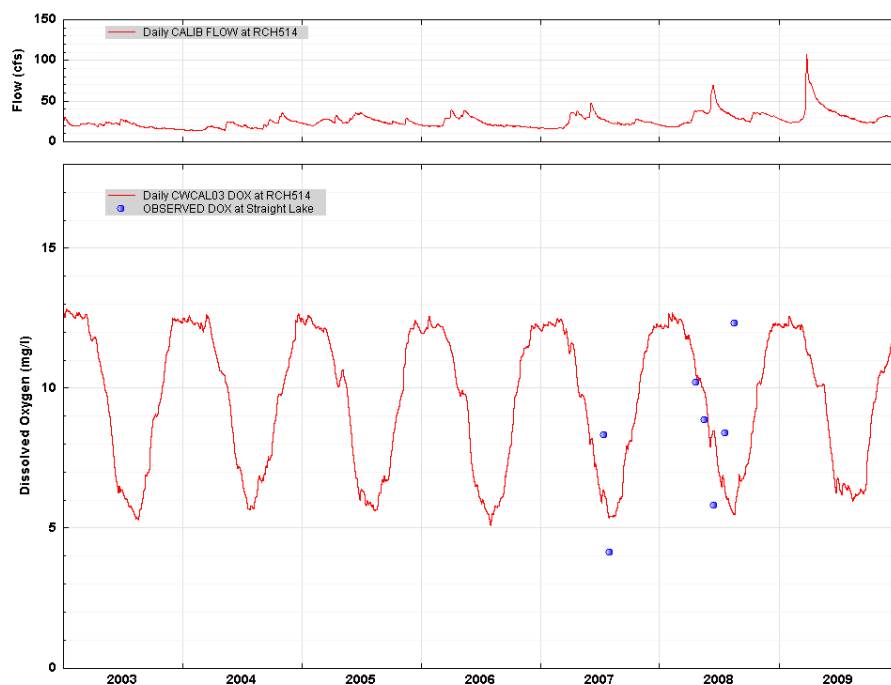


(a)

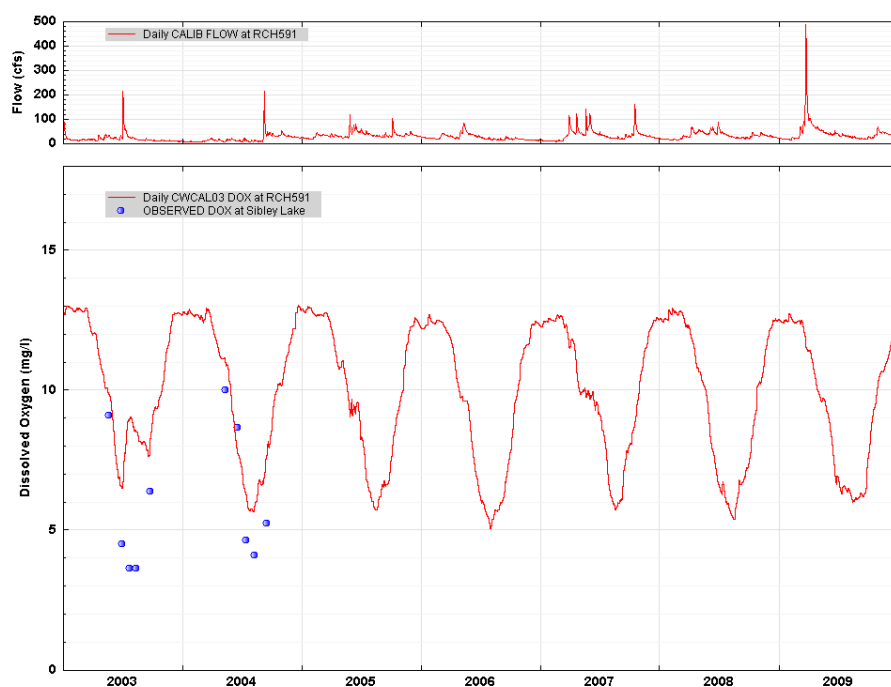


(b)

Figure 4.8 Observed and simulated DO concentrations at two locations on the Long Prairie River in the Long Prairie River watershed

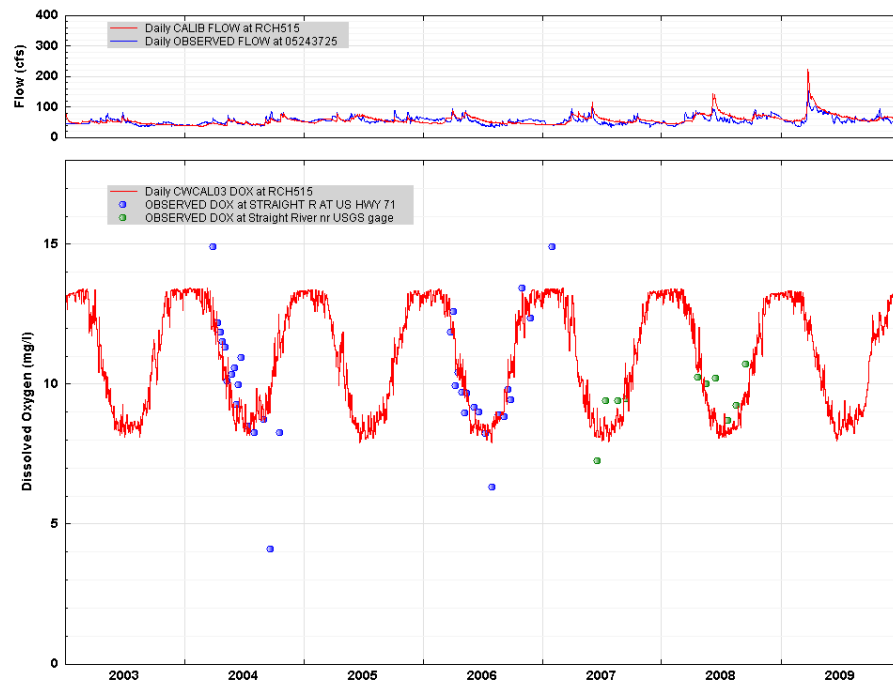


(a)

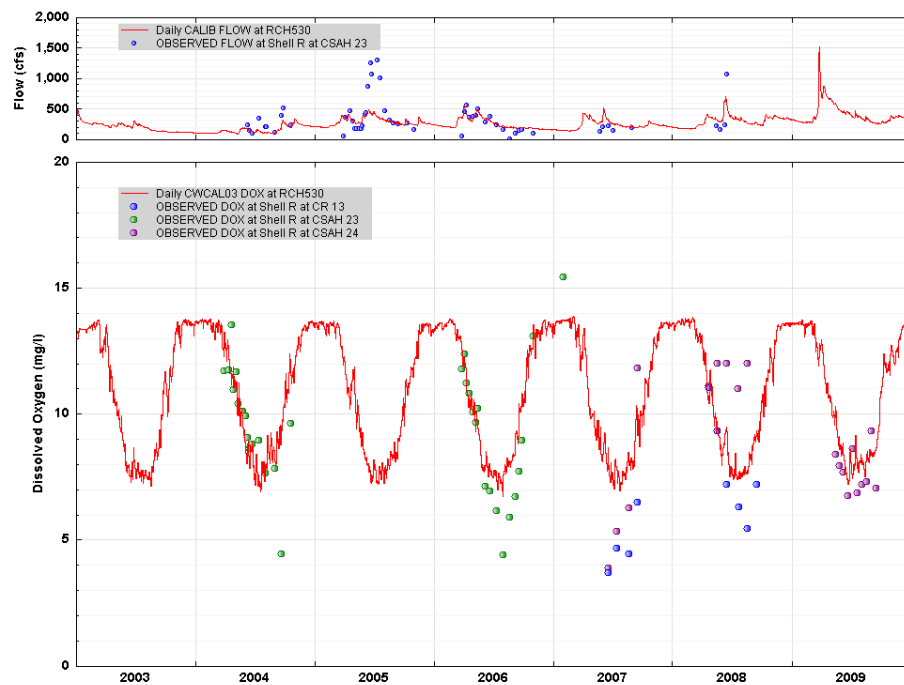


(b)

Figure 4.9 Observed and simulated DO concentrations at (a) Straight Lake and (b) Sibley Lake in the Crow Wing River watershed



(a)



(b)

Figure 4.10 Observed and simulated DO concentrations at (a) Straight River and (b) Shell River in the Crow Wing River Watershed

4.3 NITROGEN

Nitrogen (N) is simulated as Nitrate-Nitrogen ($\text{NO}_3\text{-N}$) and Ammonia-Nitrogen ($\text{NH}_4\text{-N}$) on the land surfaces. Organic N is calculated as a fraction (0.048) of total BOD-Organics entering into streams. $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and BOD are represented as buildup-washoff parameters on the land surface. The buildup and washoff of these constituents, as represented by the parameters ACCUM and SQOLIM, was adopted from the Minnesota River Turbidity TMDL report (Tetra Tech, 2002) for all the land uses except agriculture as explained below, as there was no reason to believe that the loading of these nutrients in Crow Wing River watersheds would differ from Minnesota River watersheds.

The ACCUM and SQOLIM parameters for agricultural areas were calculated in the Minnesota River TMDL based on the type of tillage (conventional and conservation) and manure application. In the Crow Wing watersheds, there was no evidence of conservation tillage (personal communication, Chuck Regan); therefore all the agriculture area was considered under conventional tillage, and under manure application if enough manure was available in the area.

Manure availability was estimated based on the number of animal units in each model segment of the three watersheds. A GIS file obtained from MPCA provided the locations of feedlots, type of animals, and number of animal units in each watershed (Figure 4.11). About 511 out of 1549 feedlots had less than 50 animal units and totaled about 6% of total animal units in the three Crow Wing Watersheds. These feedlots were ignored in the estimation of manure application to cropland and pasture land areas to simplify the calculation. Adapting from the previous studies, an average animal manure application area per animal unit was assumed at 1.29623 acres/animal unit (memo dated June 27, 2002 by Nick Gervino from MPCA to the watershed support unit). The number of acres on which animal manure was applied was calculated by simply multiplying the number of animal units in each model segment by the 1.29623 acres/animal unit factor. The resulting acreage was then compared with the total cropland area in each model segment. A weighted average of ACCUM and SQOLIM based on ACCUM and SQOLIM rates for conventional tillage and manured land as estimated by Tetra Tech (2002) was calculated (e.g., Table 4.2). If the total cropland area was less than the area on which manure could be applied to (5 out of 34 Met segments), the ACCUM rate for manured land was used, and the ACCUM rate for Pasture areas was doubled assuming that the remaining manure will be applied to pasture areas.

The concentration of $\text{NO}_3\text{-N}$, and $\text{NH}_4\text{-N}$ in interflow and groundwater was adopted from Tetra Tech, 2002 and USEPA, 2005. The concentrations of interflow and groundwater for some model segments were adjusted (mostly decreased) during the calibration process to match well with the observed data. In some model segments, the accumulation rate of nutrients was also reduced to better match the observed data.

Overall loading of $\text{NO}_3\text{-N}$, and $\text{NH}_4\text{-N}$, Refractory and Organic N are presented in Table 4.3 to Table 4.5 for all the three watersheds. In general, the $\text{NO}_3\text{-N}$, and $\text{NH}_4\text{-N}$ loadings are greatest from croplands. The lowest loadings are from forested areas. Table 4.6 shows nitrogen loads and percentages from various sources in each watershed.

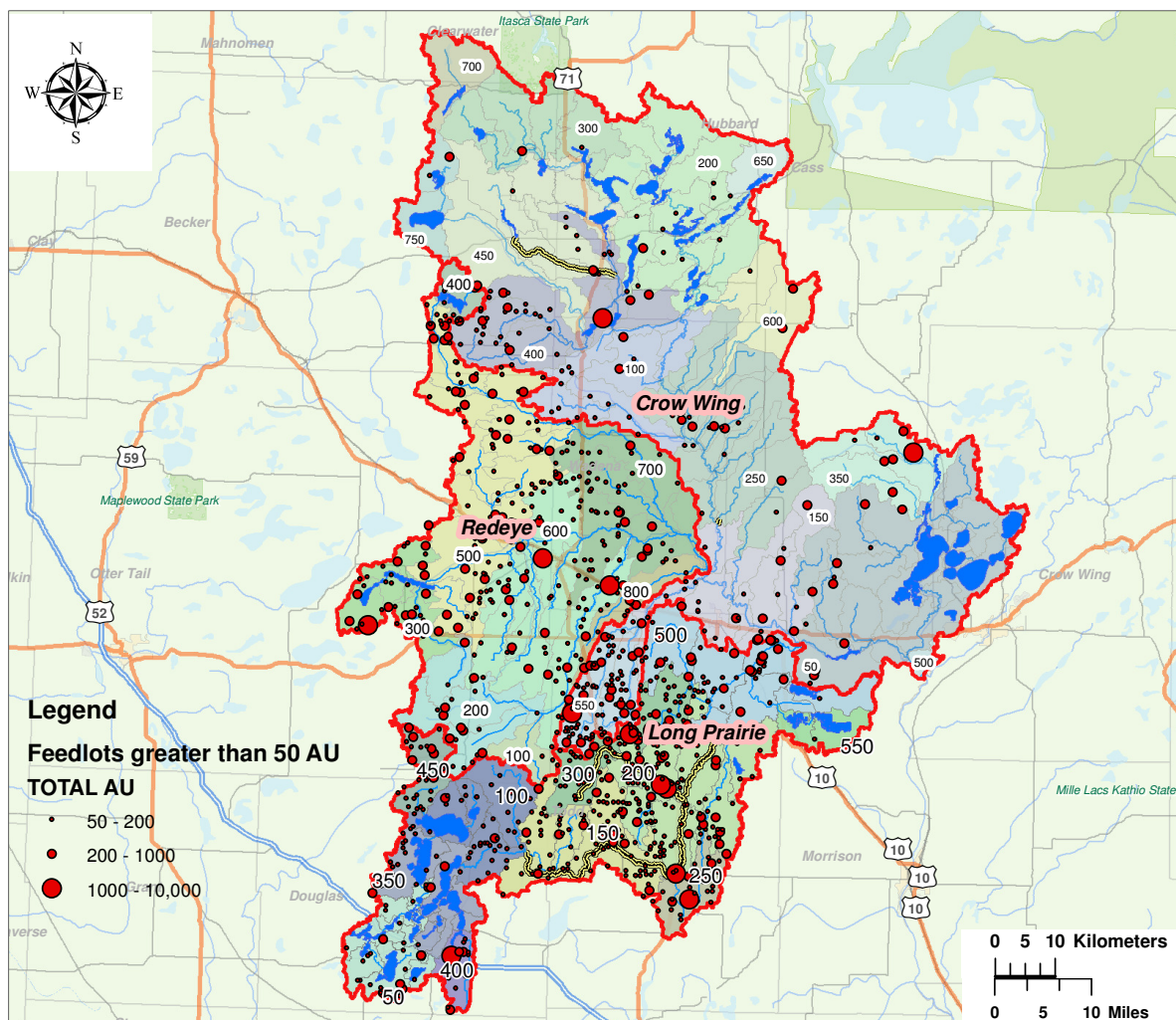


Figure 4.11 Locations of feedlots with more than 50 animal units in the Redeye, Long Prairie, and Crow Wing Watersheds

Table 4.2 Example calculation for ACCUM rate of NO₃-N at one of the Met Segments in Crow Wing River Watershed

Total Cropland (ac)	Area on which the manure can be applied (ac)	Ratio
6987.5	5929.7	0.849
NO ₃ -N ACCUM Rate for Conventional Cropland for January (lbs/ac)		0.297
NO ₃ -N ACCUM Rate for Manured Land in January (lbs/ac)		0.461
Weighted NO ₃ -N ACCUM Rate in January (lbs/ac)		$0.461 * 0.849 + 0.297 * (1 - 0.849)$
		0.436

Table 4.3 Loadings of various forms of nitrogen from different landuses in lbs/ac in the Long Prairie River Watershed for the calibration period

Land Use	Forest AB	Forest CD	Wetland	Grass-land AB	Grass-land CD	Pasture AB	Pasture CD	Crop-land AB	Crop-land CD	Crop-land - Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Watershed Average
PERLND														
Area (ac)	61,920	55,045	66,715	21,689	25,795	46,932	71,722	88,702	47,003	14,007	26,787	5,210	1,211	532,736
NO₃-N														
Surface Flow	0.024	0.014	0.003	0.117	0.133	0.113	0.141	0.468	0.765	0.154	0.857	0.847	0.772	0.247
Interflow	0.026	0.027	0.002	0.252	0.264	0.262	0.267	0.899	1.219	1.581	0.644	0.652	0.698	0.427
Groundwater Flow	0.180	0.167	0.144	1.015	0.979	1.033	0.991	1.927	1.898	1.806	1.654	1.723	1.814	1.009
Total	0.230	0.208	0.150	1.384	1.376	1.407	1.398	3.295	3.882	3.541	3.154	3.223	3.284	1.684
NH₃ + NH₄ as N														
Surface Flow	0.024	0.011	0.003	0.085	0.090	0.085	0.106	0.074	0.128	0.025	0.503	0.511	0.477	0.090
Interflow	0.008	0.009	0.001	0.032	0.038	0.032	0.038	0.042	0.063	0.079	0.090	0.085	0.089	0.033
Groundwater Flow	0.062	0.064	0.056	0.103	0.106	0.101	0.106	0.126	0.132	0.122	0.191	0.181	0.185	0.101
Total	0.094	0.085	0.060	0.220	0.234	0.218	0.250	0.242	0.324	0.226	0.783	0.776	0.750	0.224
Labile Organic N														
Surface Flow	0.008	0.004	0.000	0.044	0.051	0.041	0.057	0.045	0.053	0.009	0.092	0.106	0.107	0.035
Interflow	0.005	0.006	0.001	0.037	0.041	0.037	0.041	0.043	0.060	0.078	0.103	0.100	0.106	0.034
Groundwater Flow	0.045	0.047	0.040	0.131	0.136	0.129	0.136	0.719	0.742	0.678	0.236	0.223	0.228	0.274
Total	0.058	0.056	0.041	0.211	0.228	0.206	0.234	0.807	0.855	0.765	0.432	0.429	0.441	0.344
Refractory Organic N														
Surface Flow	0.017	0.008	0.000	0.099	0.115	0.093	0.129	0.103	0.120	0.020	0.210	0.239	0.242	0.080
Interflow	0.011	0.013	0.001	0.083	0.093	0.083	0.092	0.098	0.136	0.178	0.234	0.228	0.241	0.078
Groundwater Flow	0.102	0.106	0.091	0.297	0.308	0.292	0.308	1.630	1.682	1.536	0.534	0.505	0.517	0.622
Total	0.131	0.127	0.093	0.479	0.517	0.467	0.530	1.830	1.938	1.734	0.978	0.972	0.999	0.779
Total Nitrogen	0.513	0.476	0.344	2.294	2.355	2.298	2.412	6.174	6.999	6.266	5.347	5.400	5.474	3.031
IMPLND														
Area (ac)											547	579	658	1,784
NO ₃ -N (Surface Flow)											5.319	5.307	5.351	5.327
NH ₃ + NH ₄ as N (Surface Flow)											3.496	3.493	3.540	3.511
Labile Organic N (Surface Flow)											0.648	0.646	0.649	0.648
Refractory Organic N (Surface Flow)											1.470	1.464	1.471	1.468
Total N											10.933	10.910	11.011	10.954

Table 4.4 Loading of various forms of nitrogen from different landuses in lbs/ac in the Redeye River Watershed for the calibration period

Land Use	Forest AB	Forest CD	Wetland	Grass-land AB	Grass-land CD	Pasture AB	Pasture CD	Crop-land AB	Crop-land CD	Crop-land - Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Water-shed Average
Pervious Landuses														
Area (ac)	46,871	83,838	100,799	18,787	29,542	51,299	65,232	110,788	23,285	11,703	22,285	2,266	415	567,110
NO₃-N														
Surface Flow	0.006	0.005	0.002	0.055	0.071	0.047	0.076	0.230	0.625	0.145	0.611	0.580	0.512	0.121
Interflow	0.017	0.019	0.002	0.187	0.207	0.183	0.201	0.773	0.998	1.329	0.620	0.650	0.671	0.308
Groundwater Flow	0.157	0.139	0.133	0.999	0.923	0.985	0.910	1.950	1.717	1.744	1.455	1.509	1.432	0.884
Total	0.180	0.163	0.136	1.240	1.202	1.216	1.186	2.954	3.340	3.218	2.685	2.739	2.615	1.312
NH₃ + NH₄ as N														
Surface Flow	0.003	0.002	0.002	0.029	0.039	0.026	0.041	0.025	0.067	0.015	0.313	0.294	0.258	0.032
Interflow	0.006	0.007	0.001	0.026	0.031	0.025	0.031	0.036	0.049	0.065	0.090	0.093	0.097	0.024
Groundwater Flow	0.059	0.063	0.055	0.104	0.102	0.104	0.102	0.134	0.125	0.125	0.196	0.201	0.207	0.096
Total	0.068	0.072	0.057	0.159	0.171	0.155	0.173	0.194	0.241	0.206	0.599	0.588	0.562	0.153
Labile Organic N														
Surface Flow	0.003	0.003	0.000	0.027	0.028	0.024	0.033	0.018	0.049	0.010	0.079	0.069	0.056	0.018
Interflow	0.003	0.004	0.000	0.029	0.035	0.030	0.034	0.029	0.040	0.054	0.104	0.110	0.117	0.023
Groundwater Flow	0.044	0.046	0.038	0.134	0.130	0.134	0.130	0.776	0.707	0.707	0.238	0.247	0.255	0.261
Total	0.051	0.052	0.039	0.190	0.193	0.188	0.197	0.824	0.796	0.771	0.421	0.426	0.428	0.303
Refractory Organic N														
Surface Flow	0.007	0.006	0.000	0.062	0.064	0.054	0.074	0.042	0.111	0.022	0.179	0.156	0.127	0.041
Interflow	0.007	0.009	0.001	0.067	0.079	0.067	0.078	0.066	0.090	0.122	0.235	0.249	0.265	0.053
Groundwater Flow	0.100	0.103	0.087	0.303	0.295	0.304	0.294	1.760	1.603	1.603	0.539	0.560	0.579	0.592
Total	0.114	0.118	0.088	0.432	0.438	0.425	0.446	1.867	1.804	1.748	0.954	0.965	0.971	0.686
Total N (Pervious)	0.413	0.405	0.320	2.021	2.004	1.984	2.002	5.839	6.181	5.943	4.659	4.718	4.576	2.454
Impervious Landuses														
Area (ac)											455	252	224	930
NO ₃ -N (Surface Flow)											6.893	6.954	7.000	6.935
NH ₃ + NH ₄ as N (Surface Flow)											3.432	3.456	3.483	3.451
Labile Organic N (Surface Flow)											0.655	0.660	0.662	0.658
Refractory Organic N (Surface Flow)											1.484	1.496	1.501	1.492
Total N (Impervious)											12.464	12.566	12.646	12.536

Table 4.5 Loading of various forms of Nitrogen from different landuses in lbs/ac in the Crow Wing River Watershed for the calibration period

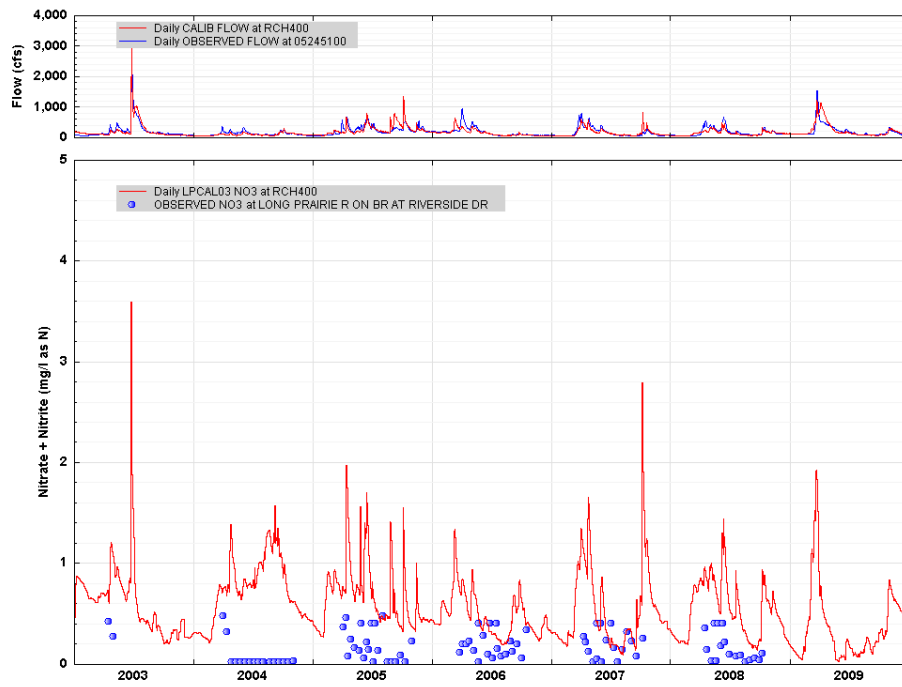
Land Use	Forest AB	Forest CD	Wetland	Grass-land AB	Grass-land CD	Pasture AB	Pasture CD	Crop-land AB	Crop-land CD	Crop-land - Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Water-shed Average
PERLND														
Area (ac)	196	393,204	201,743	218,953	53,581	34,151	72,855	70,611	99,169	27,067	37,387	4,315	739	1,213,970
NO₃-N														
Surface Flow	0.060	0.002	0.002	0.001	0.045	0.077	0.022	0.067	0.111	0.411	0.407	0.382	0.320	0.043
Interflow	1.272	0.013	0.015	0.003	0.200	0.238	0.132	0.171	0.807	1.188	0.447	0.446	0.448	0.149
Groundwater Flow	1.919	0.191	0.191	0.172	1.320	1.326	1.118	1.118	2.397	2.422	2.168	2.077	1.852	0.678
Total	3.250	0.206	0.208	0.175	1.564	1.641	1.272	1.356	3.316	4.021	3.022	2.905	2.620	0.869
NH₃ + NH₄ as N														
Surface Flow	0.006	0.001	0.001	0.001	0.024	0.046	0.010	0.029	0.009	0.044	0.208	0.200	0.171	0.014
Interflow	0.068	0.004	0.004	0.001	0.025	0.029	0.016	0.021	0.039	0.055	0.059	0.060	0.064	0.013
Groundwater Flow	0.138	0.065	0.067	0.055	0.130	0.128	0.108	0.108	0.150	0.140	0.208	0.208	0.213	0.087
Total	0.212	0.069	0.072	0.057	0.179	0.203	0.135	0.158	0.198	0.238	0.475	0.468	0.448	0.114
Labile Organic N														
Surface Flow	0.001	0.000	0.001	0.000	0.026	0.047	0.011	0.032	0.005	0.020	0.052	0.047	0.035	0.008
Interflow	0.049	0.002	0.002	0.000	0.025	0.029	0.017	0.021	0.028	0.042	0.063	0.064	0.068	0.011
Groundwater Flow	0.680	0.039	0.040	0.033	0.145	0.142	0.123	0.123	0.755	0.705	0.230	0.230	0.236	0.136
Total	0.730	0.041	0.043	0.033	0.197	0.218	0.150	0.177	0.788	0.766	0.345	0.341	0.340	0.154
Refractory Organic N														
Surface Flow	0.003	0.001	0.001	0.000	0.060	0.106	0.024	0.072	0.011	0.046	0.117	0.106	0.080	0.018
Interflow	0.110	0.004	0.005	0.001	0.057	0.066	0.038	0.049	0.062	0.094	0.144	0.146	0.155	0.024
Groundwater Flow	1.542	0.088	0.091	0.075	0.329	0.323	0.279	0.280	1.712	1.597	0.521	0.521	0.535	0.308
Total	1.655	0.092	0.097	0.076	0.446	0.495	0.341	0.400	1.786	1.737	0.782	0.773	0.770	0.349
Total Nitrogen	5.847	0.408	0.420	0.341	2.386	2.557	1.898	2.091	6.088	6.762	4.624	4.487	4.178	1.486
IMPLND														
Area (ac)											762	478	398	1,638
NO ₃ -N (Surface Flow)											6.441	6.432	6.463	6.444
NH ₃ + NH ₄ as N (Surface Flow)											3.258	3.259	3.263	3.259
Labile Organic N (Surface Flow)											0.623	0.621	0.624	0.623
Refractory Organic N (Surface Flow)											1.411	1.409	1.415	1.411
Total N											11.733	11.721	11.765	11.737

Table 4.6 Nitrogen loads (lbs) and percentages from various sources in each watershed

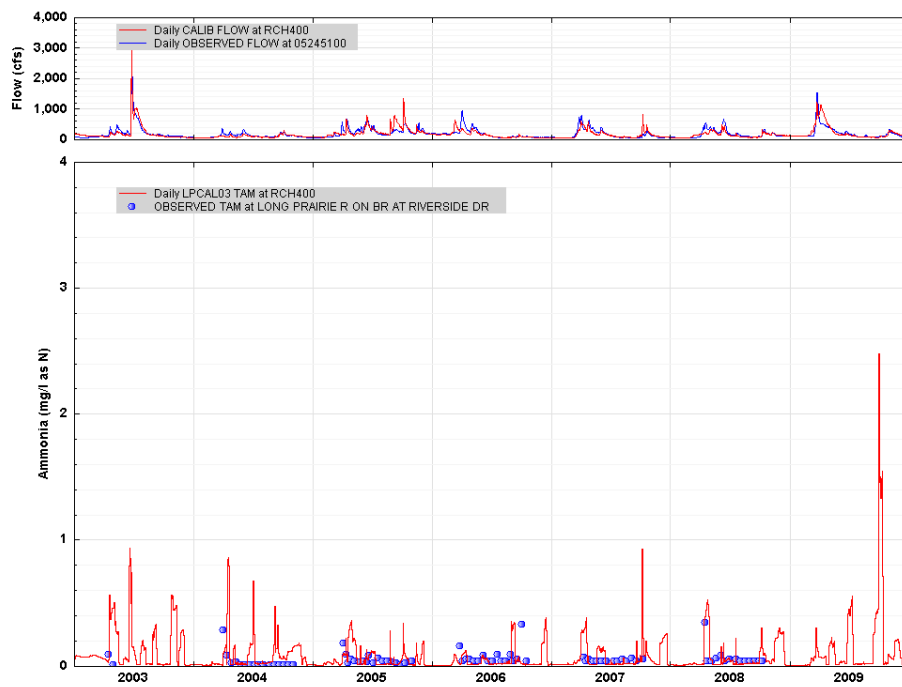
	Long Prairie		Redeye		Crow Wing	
	Load	Percent	Load	Percent	Load	Percent
Pervious	1,614,723	93.3%	1,391,688	98.3%	1,803,959	47.6%
Impervious	19,541	1.1%	11,658	0.8%	19,225	0.5%
Point Sources	95,752	5.5%	12,024	0.8%	130,785	3.5%
Upstream Watersheds	0	0.0%	0	0.0%	1,835,150	48.4%
Total	1,730,015		1,415,370		3,789,119	

The calibration of N components (NO₃-N, NH₄-N, Org-N, and Total N) was conducted in tandem with other water quality constituents. For example, if enough P is not available, then not enough phytoplankton and algae can grow and N concentration keeps increasing during the period of simulation, and vice versa. In some cases, the input of N from point sources was also reduced to better match with the observed data. The Figure 4.12 and Figure 4.13 show example plots of N constituents in the Long Prairie and Crow Wing River watersheds. Remaining plots for all the constituents are available in APPENDIX K. As evident in the graphs, the simulated constituent values are very close to the observed values and are within the margin of expected errors in measurements and recording. Some outliers could not be explained well by the model.

It must be noted here that the quality of water quality simulation depends largely on the quality of hydrology simulation. The hydrology simulation was conducted on the four different USGS gages, but the water quality data is available at several additional locations without detailed hydrology data. Also, these watersheds were dominated by lakes, and the hydrology of lakes depends heavily on the outlet structure about which we had very little information. The water quality calibration can be further improved when extending the model, by collecting more information about the hydraulic structures in the watershed.

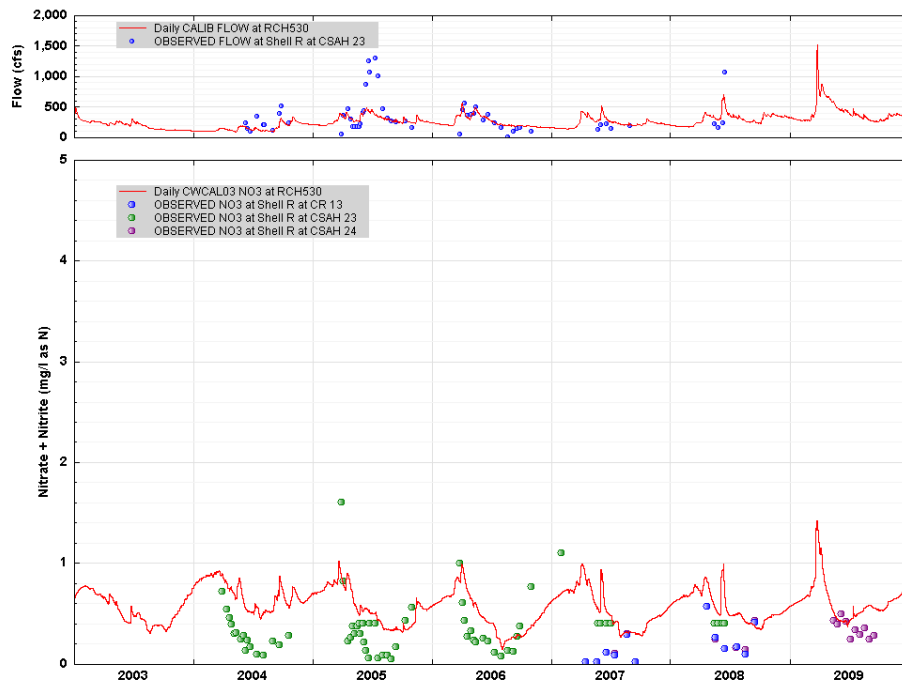


(a)

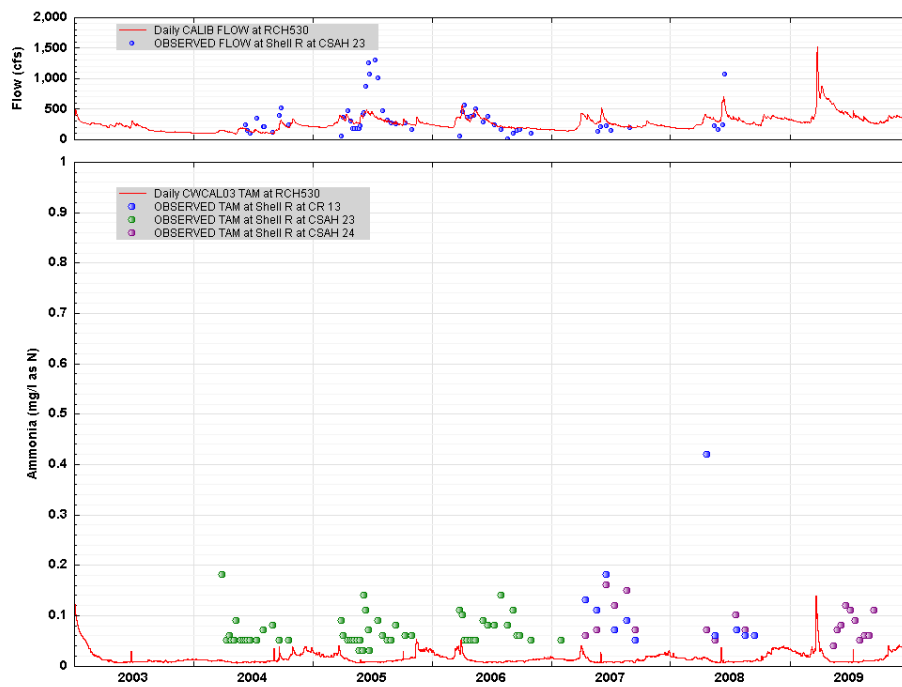


(b)

Figure 4.12 Observed and Simulated (a) Nitrate-Nitrogen, and (b) Total Ammonia concentration at USGS gage 05245100 on the Long Prairie River



(a)



(b)

Figure 4.13 Observed and Simulated (a) Nitrate-Nitrogen, and (b) Total Ammonia concentration at Shell River in the Crow Wing River Watershed

4.4 PHOSPHORUS

HSPF simulates surface washoff of inorganic P using a potency factor approach, where the inorganic P load is estimated as a fraction of sediment yield. Organic P is calculated as a fraction (0.0023) of total BOD-Organics entering into streams.. The potency factors for all the land uses were adopted from the previous models (Tetra Tech, 2009 and AQUA TERRA Consultants, 2005). To calculate the potency factor of inorganic phosphorus and organic matter for agricultural areas, methodology similar to the calculation of ACCUM and SQOLIM for $\text{NO}_3\text{-N}$, and $\text{NH}_4\text{-N}$ was used.

The loading of different P components from land surfaces is presented in Table 4.7 to Table 4.9. As noted above, simulation of P depends upon other water quality constituents as well; therefore calibration of all water quality constituents was conducted in tandem. Table 4.10 shows phosphorus loads from various sources in each watershed. Figure 4.14 and Figure 4.15 show the simulation of Ortho P and Total P at two locations in the Long Prairie and Crow Wing River watersheds. All the remaining graphs for calibration and validation periods are available in APPENDIX M and APPENDIX N. Overall, the model simulates the P concentration reasonably well.

Table 4.7 Loading of various forms of phosphorus from different landuses in lbs/ac in the Long Prairie River Watershed for the calibration period

Land Use	Forest AB	Forest CD	Wetland	Grass-land AB	Grass-land CD	Pasture AB	Pasture CD	Crop-land AB	Crop-land CD	Crop-land - Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Water-shed Average
PERLND														
Area (ac)	61,920	55,045	66,715	21,689	25,795	46,932	71,722	88,702	47,003	14,007	26,787	5,210	1,211	532,736
Ortho P														
Surface Flow	0.012	0.005	0.000	0.067	0.078	0.063	0.088	0.083	0.094	0.016	0.142	0.162	0.164	0.057
Interflow	0.001	0.001	0.000	0.004	0.005	0.004	0.005	0.013	0.016	0.021	0.010	0.010	0.011	0.006
Groundwater Flow	0.004	0.004	0.003	0.018	0.018	0.017	0.018	0.055	0.057	0.052	0.022	0.021	0.021	0.024
Total	0.016	0.010	0.003	0.089	0.102	0.085	0.111	0.151	0.168	0.089	0.174	0.193	0.196	0.088
Refractory Organic P														
Surface Flow	0.001	0.000	0.000	0.005	0.006	0.004	0.006	0.005	0.006	0.001	0.010	0.011	0.012	0.004
Interflow	0.001	0.001	0.000	0.004	0.004	0.004	0.004	0.005	0.007	0.009	0.011	0.011	0.012	0.004
Groundwater Flow	0.005	0.005	0.004	0.014	0.015	0.014	0.015	0.078	0.081	0.074	0.026	0.024	0.025	0.030
Total	0.006	0.006	0.004	0.023	0.025	0.022	0.025	0.088	0.093	0.083	0.047	0.047	0.048	0.037
Labile Organic P														
Surface Flow	0.001	0.000	0.000	0.006	0.007	0.006	0.008	0.006	0.007	0.001	0.013	0.015	0.015	0.005
Interflow	0.001	0.001	0.000	0.005	0.006	0.005	0.006	0.006	0.008	0.011	0.014	0.014	0.015	0.005
Groundwater Flow	0.006	0.006	0.006	0.018	0.019	0.018	0.019	0.099	0.103	0.094	0.033	0.031	0.032	0.038
Total	0.008	0.008	0.006	0.029	0.032	0.029	0.032	0.112	0.118	0.106	0.060	0.059	0.061	0.048
Total Phosphorus	0.030	0.024	0.013	0.141	0.159	0.136	0.168	0.351	0.379	0.278	0.281	0.299	0.305	0.173
IMPLND														
Area (ac)											547	579	658	1,784
Ortho P (Surface Flow)											0.401	0.396	0.399	0.399
Refractory Organic P (Surface Flow)											0.070	0.070	0.070	0.070
Labile Organic P (Surface Flow)											0.090	0.899	0.090	0.090
Total P											0.561	0.555	0.559	0.559

Table 4.8 Loading of various forms of phosphorus from different landuses in lbs/ac in the Redeye River Watershed for the calibration period

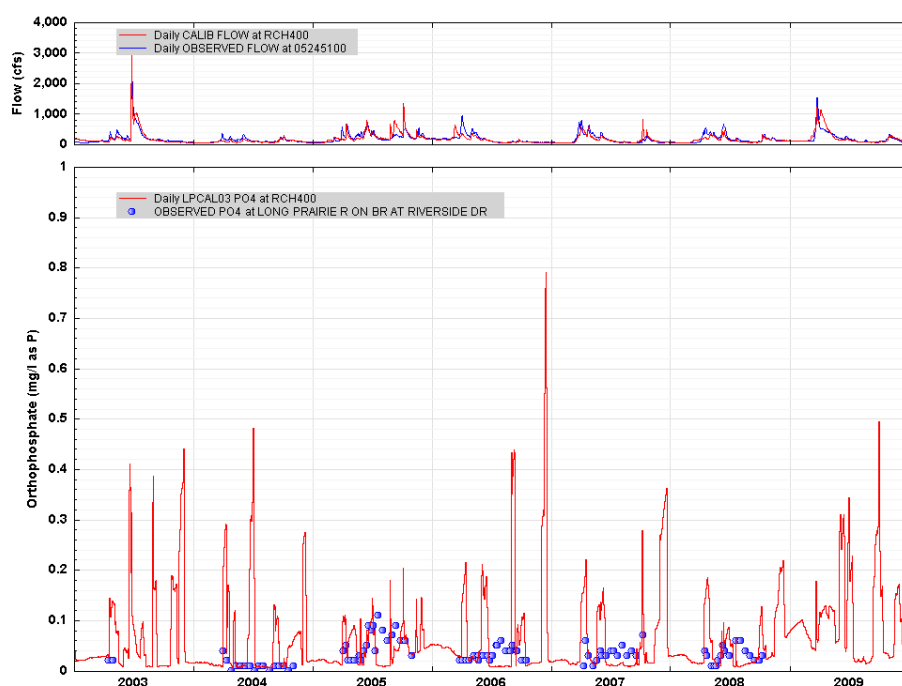
Land Use	Forest AB	Forest CD	Wetland	Grass- land AB	Grass- land CD	Pasture AB	Pasture CD	Crop- land AB	Crop- land CD	Crop- land - Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Water- shed Average
PERLND														
Area (ac)	46,871	83,838	100,799	18,787	29,542	51,299	65,232	110,788	23,285	11,703	22,285	2,266	415	567,110
Ortho P														
Surface Flow	0.005	0.004	0.000	0.042	0.043	0.037	0.050	0.094	0.323	0.053	0.121	0.106	0.086	0.052
Interflow	0.001	0.001	0.000	0.003	0.004	0.003	0.004	0.010	0.013	0.017	0.011	0.011	0.012	0.005
Groundwater Flow	0.004	0.004	0.003	0.018	0.018	0.019	0.018	0.061	0.056	0.056	0.023	0.024	0.024	0.023
Total	0.009	0.009	0.003	0.064	0.066	0.059	0.072	0.164	0.393	0.126	0.155	0.140	0.122	0.079
Refractory Organic P														
Surface Flow	0.000	0.000	0.000	0.003	0.003	0.003	0.004	0.002	0.005	0.001	0.009	0.007	0.006	0.002
Interflow	0.000	0.000	0.000	0.003	0.004	0.003	0.004	0.003	0.004	0.006	0.011	0.012	0.013	0.003
Groundwater Flow	0.005	0.005	0.004	0.015	0.014	0.015	0.014	0.084	0.077	0.077	0.026	0.027	0.028	0.028
Total	0.005	0.006	0.004	0.021	0.021	0.020	0.021	0.089	0.086	0.084	0.046	0.046	0.047	0.033
Labile Organic P														
Surface Flow	0.000	0.000	0.000	0.004	0.004	0.003	0.005	0.003	0.007	0.001	0.011	0.010	0.008	0.003
Interflow	0.000	0.001	0.000	0.004	0.005	0.004	0.005	0.004	0.005	0.007	0.014	0.015	0.016	0.003
Groundwater Flow	0.006	0.006	0.005	0.018	0.018	0.019	0.018	0.107	0.098	0.098	0.033	0.034	0.035	0.036
Total	0.007	0.007	0.005	0.026	0.027	0.026	0.027	0.114	0.110	0.107	0.058	0.059	0.059	0.042
Total Phosphorus	0.021	0.022	0.012	0.111	0.114	0.105	0.120	0.367	0.589	0.317	0.259	0.245	0.228	0.154
IMPLND														
Area (ac)											455	252	224	930
Ortho P (Surface Flow)											0.397	0.401	0.403	0.400
Refractory Organic P (Surface Flow)											0.071	0.072	0.072	0.071
Labile Organic P (Surface Flow)											0.091	0.091	0.092	0.091
Total P											0.559	0.564	0.567	0.562

Table 4.9 Loading of various forms of phosphorus from different landuses in lbs/ac in the Crow Wing River Watershed for the calibration period

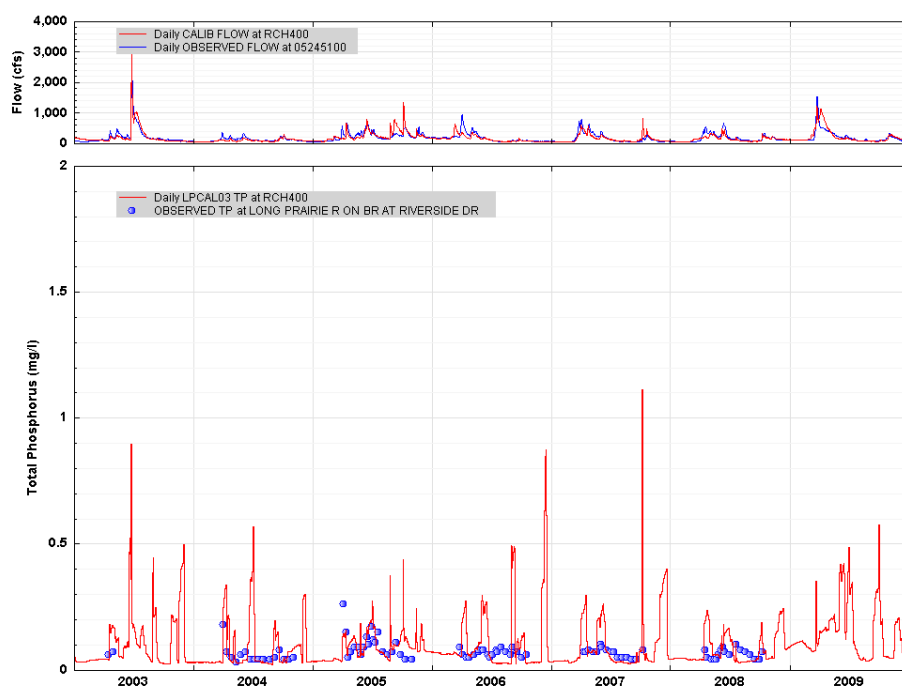
Land Use	Forest AB	Forest CD	Wetland	Grass- land AB	Grass- land CD	Pasture AB	Pasture CD	Crop- land AB	Crop- land CD	Crop- land - Drained	Dev, Open Space	Dev, Low Intensity	Dev, Medium Intensity	Water- shed Average
PERLND														
Area (ac)	196	393,204	201,743	218,953	53,581	34,151	72,855	70,611	99,169	27,067	37,387	4,315	739	1,213,970
Ortho P														
Surface Flow	0.007	0.001	0.001	0.000	0.041	0.072	0.018	0.064	0.021	0.156	0.079	0.072	0.054	0.017
Interflow	0.014	0.000	0.000	0.000	0.003	0.003	0.002	0.002	0.009	0.012	0.006	0.006	0.007	0.002
Groundwater Flow	0.054	0.003	0.003	0.003	0.020	0.019	0.017	0.017	0.060	0.056	0.022	0.022	0.023	0.012
Total	0.075	0.004	0.004	0.003	0.063	0.095	0.036	0.084	0.089	0.224	0.107	0.100	0.083	0.031
Refractory Organic P														
Surface Flow	0.000	0.000	0.000	0.000	0.003	0.005	0.001	0.003	0.001	0.002	0.006	0.005	0.004	0.001
Interflow	0.005	0.000	0.000	0.000	0.003	0.003	0.002	0.002	0.003	0.005	0.007	0.007	0.007	0.001
Groundwater Flow	0.074	0.004	0.004	0.004	0.016	0.015	0.013	0.013	0.082	0.077	0.025	0.025	0.026	0.015
Total	0.079	0.004	0.005	0.004	0.021	0.024	0.016	0.019	0.086	0.083	0.037	0.037	0.037	0.017
Labile Organic P														
Surface Flow	0.000	0.000	0.000	0.000	0.004	0.006	0.001	0.004	0.001	0.003	0.007	0.006	0.005	0.001
Interflow	0.007	0.000	0.000	0.000	0.003	0.004	0.002	0.003	0.004	0.006	0.009	0.009	0.009	0.001
Groundwater Flow	0.094	0.005	0.006	0.005	0.020	0.020	0.017	0.017	0.105	0.097	0.032	0.032	0.033	0.019
Total	0.101	0.006	0.006	0.005	0.027	0.030	0.021	0.024	0.109	0.106	0.048	0.047	0.047	0.021
Total Phosphorus	0.255	0.014	0.015	0.012	0.111	0.149	0.073	0.127	0.284	0.413	0.192	0.184	0.167	0.069
IMPLND														
Area (ac)											762	478	398	1,638
Ortho P (Surface Flow)											0.368	0.367	0.369	0.368
Refractory Organic P (Surface Flow)											0.068	0.068	0.068	0.068
Labile Organic P (Surface Flow)											0.086	0.086	0.086	0.086
Total P											0.522	0.521	0.523	0.522

Table 4.10 Phosphorus loads (lbs) and percentages from various sources in each watershed

	Long Prairie		Redeye		Crow Wing	
	Load	Percent	Load	Percent	Load	Percent
Pervious	92,163	81.9%	87,335	92.2%	83,764	35.4%
Impervious	997	0.9%	523	0.6%	855	0.4%
Point Sources	19,359	17.2%	6,869	7.3%	11,027	4.7%
Upstream Watersheds	0	0.0%	0	0.0%	140,931	59.6%
Total	112,520		94,727		236,577	



(a)



(b)

Figure 4.14 Observed and simulated (a) Orthophosphorus as P, and (b) Total P concentration at USGS gage 05245100 in Long Prairie River

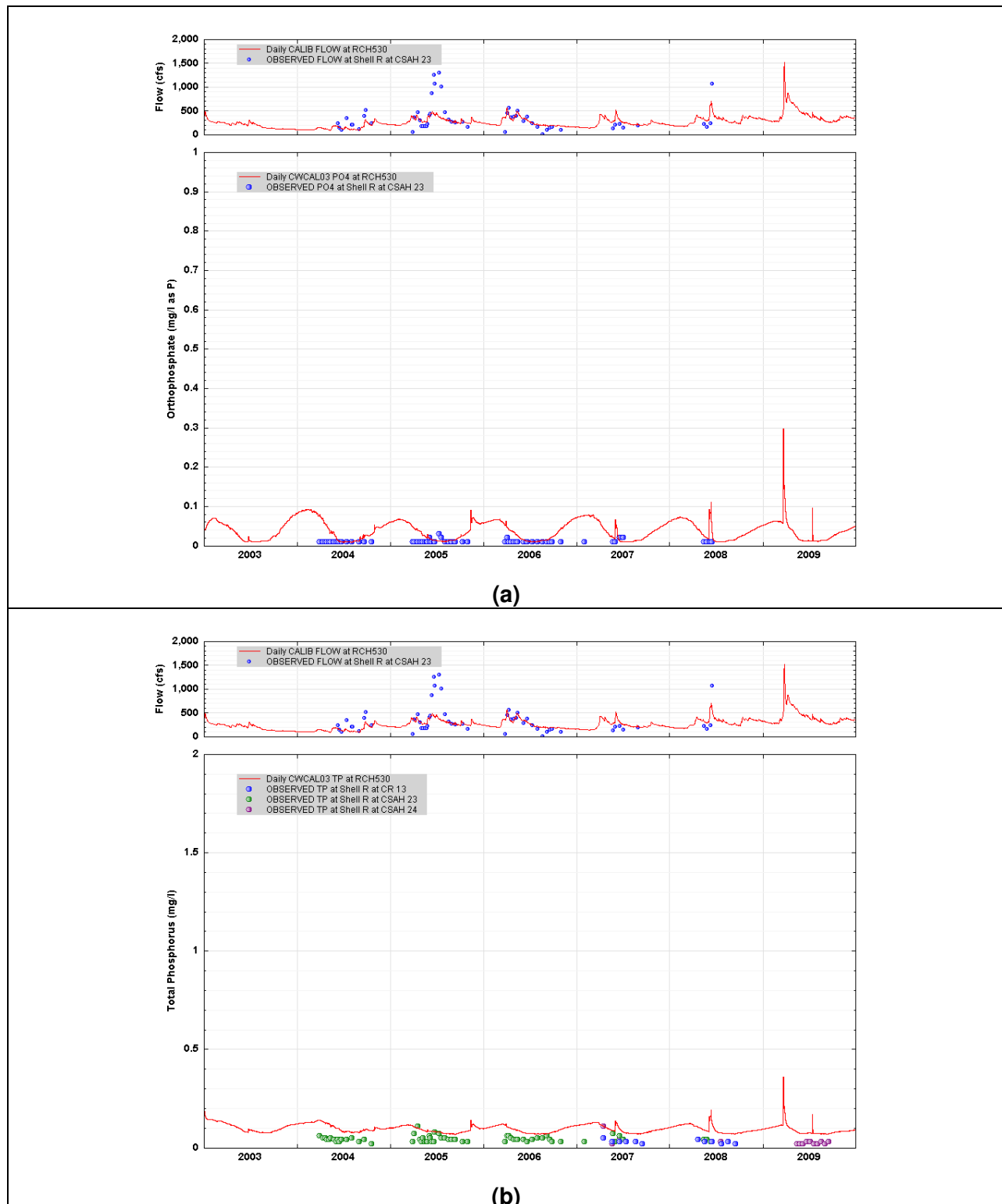


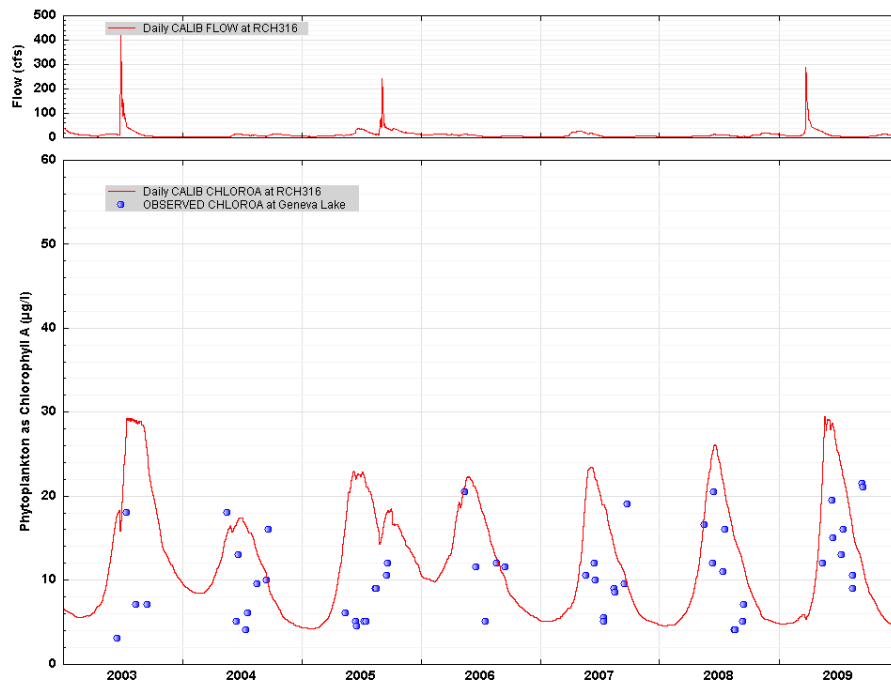
Figure 4.15 Observed and Simulated (a) Orthophosphorus as P, and (b) Total P at Shell River in Crow Wing River Watershed

4.5 PHYTOPLANKTON AS CHLOROPHYLL A

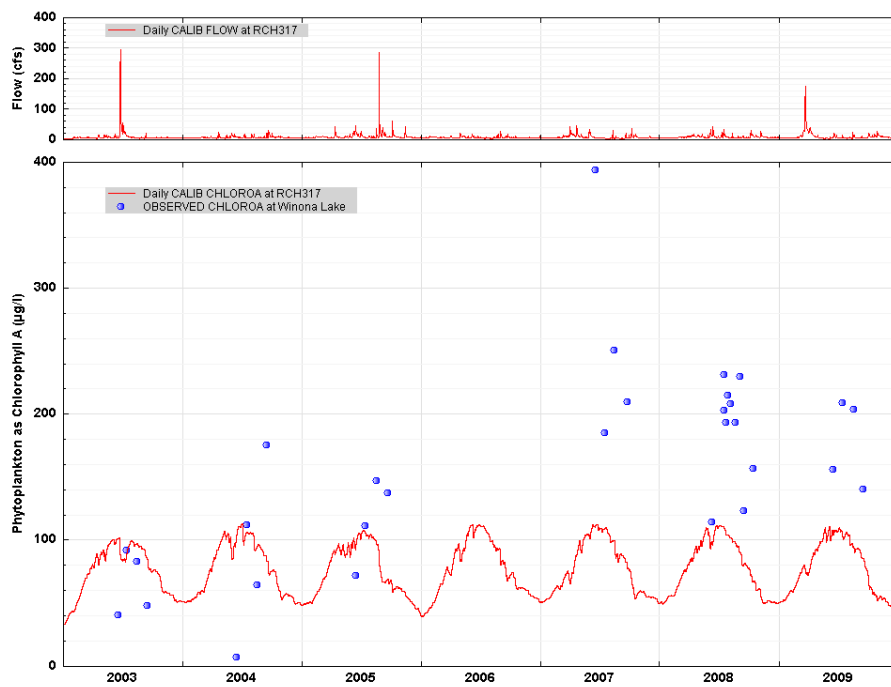
Phytoplankton is simulated in HSPF as a representation of algae that floats in the water of each RCHRES. Biological activity of the aquatic ecosystem depends upon the rate of primary production by these photosynthetic organisms, which in turn depends upon the physical environment, including nutrient availability, temperature, light, etc. The process of photosynthesis consumes carbon-dioxide (CO_2) and releases oxygen (O_2), while the process of respiration consumes O_2 and releases CO_2 . Phytoplankton consume the nutrients in water, and through assimilation, these nutrients are transformed into organic materials. These organic materials serve as a food source for higher trophic levels. The portion of organic matter not used for food decomposes, which further affects the nutrient and organic level in the water.

With excessive phytoplankton growth, much of the oxygen supply in the water may be depleted by decomposition of dead algae and by respiration. Phytoplankton, when excessive, can place a serious stress on the system. HSPF assumes that the entire phytoplankton population consists of a single species whose mean behavior is defined through a series of generalized mathematical formulations. The details on these formulations can be obtained in the HSPF Manual (Bicknell, 2005).

Calibration of the concentration of phytoplankton is achieved through several parameters that control the conversion of one nutrient form to another and the release of these nutrients from the bed of the RCHRES. As with other water quality constituents, the calibration of phytoplankton is conducted in tandem with other nutrients as these nutrients interact with each other, and influence the phytoplankton simulation. Figure 4.16 and Figure 4.17 show the observed and simulated concentration of Phytoplankton as Chlorophyll A in two lakes in the Long Prairie and Crow Wing River watersheds. Winona Lake in the Long Prairie watershed is especially interesting as it has the greatest amount of phytoplankton recorded in the three Crow Wing River Watersheds. This lake is downstream of a point source, so it is possible that a significant amount of nutrients has settled in the bed over time, which is being released regularly to cause such a high production of chlorophyll A. There are no waterbodies upstream of this lake. During calibration, we increased the simulated release of nutrients from the bed of Winona Lake, but were still unable to match the very high observed concentrations. To improve the simulation of Winona lake, additional information is need to accurately represent the hydraulics, hydrology, sediment bed depth, and sediment nutrient concentrations. For most other lakes, and waterbodies, the simulation of phytoplankton is acceptable. Remaining graphs are available in APPENDIX Q and APPENDIX R.

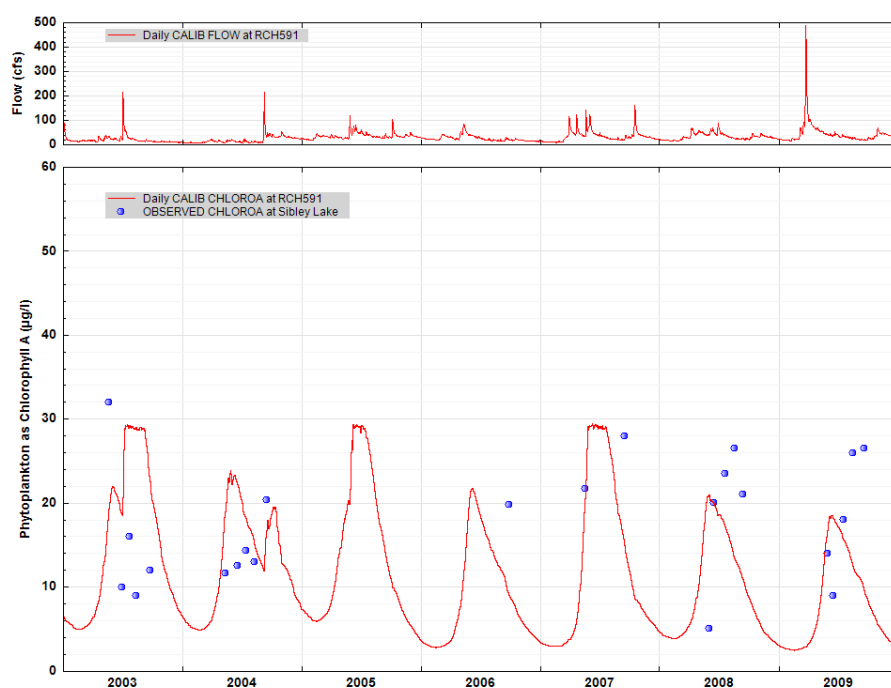


(a)

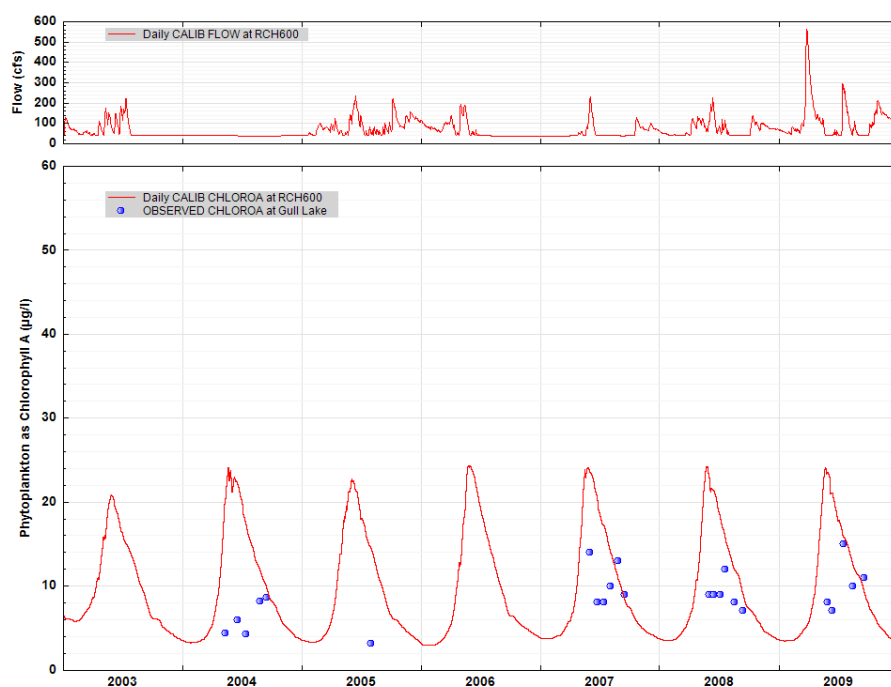


(b)

Figure 4.16 Observed and simulated Chlorophyll A as Phytoplankton in (a) Geneva Lake, and (b) Winona Lake in the Long Prairie River Watershed



(a)



(b)

Figure 4.17 Observed and simulated Chlorophyll A as Phytoplankton in (a) Sibley Lake, and (b) Gull Lake in the Crow Wing River Watershed

SECTION 5.0 SUMMARY AND CONCLUSIONS

To support the TMDL development of several impaired waterbodies in Minnesota, MPCA has decided to develop watershed models of all the HUC-8 watersheds in MN. As a part of this ongoing effort, watershed models were developed for the Redeye, Long Prairie, and Crow Wing River Watersheds. The project was divided into several phases with a concluding phase that required AQUA TERRA Consultants to develop fully functional water quality models, and to calibrate and validate them. This report presents the details of hydrology and water quality calibration and validation results. The model files are submitted separately as part of this phase.

Overall, the hydrology calibration and validation was fair to good at all of the gages where continuous data was available. One of the long term gages, Straight River directly downstream of Straight Lake, was difficult to calibrate and validate due to seasonal input of groundwater into the system. Detailed information about the groundwater interaction can be used to improve the hydrology simulation results. Some other lakes were also suspected of having regular groundwater input, the amount of which was generally obtained by calibration. The USGS gages also have a regular issue of freezing in winter which makes flow estimation in winter very difficult. These watersheds have a detailed network of precipitation gages, but regular and reliable data at some of these gages was an issue.

The presence of a significant number of lakes affects the hydrology of the watershed. Some of these lakes are managed and their flow is altered based on local requirements. However, details of the lake management were not available or were difficult to obtain. In light of some of these limitations, the hydrology calibration and validation results were satisfactory.

The hydrology simulation was sufficiently sound to provide a strong basis for water quality simulation in these watersheds. Water quality calibration included the calibration of sediment, water temperature, dissolved oxygen, nitrogen, phosphorus, and phytoplankton as chlorophyll A. Water quality data was available for multiple locations in the watershed. Although the water quality data was not sufficient to conduct a detailed statistical analysis, it was sufficient to observe trends at different parts of the watershed. The water quality calibration and validation were satisfactory.

The final hydrology and water quality model for the Redeye, Long Prairie, and Crow Wing River watersheds can be used for TMDL development. As more water quality data becomes available, the model can be extended and refined to increase the confidence in the water quality simulation.

SECTION 6.0 REFERENCES

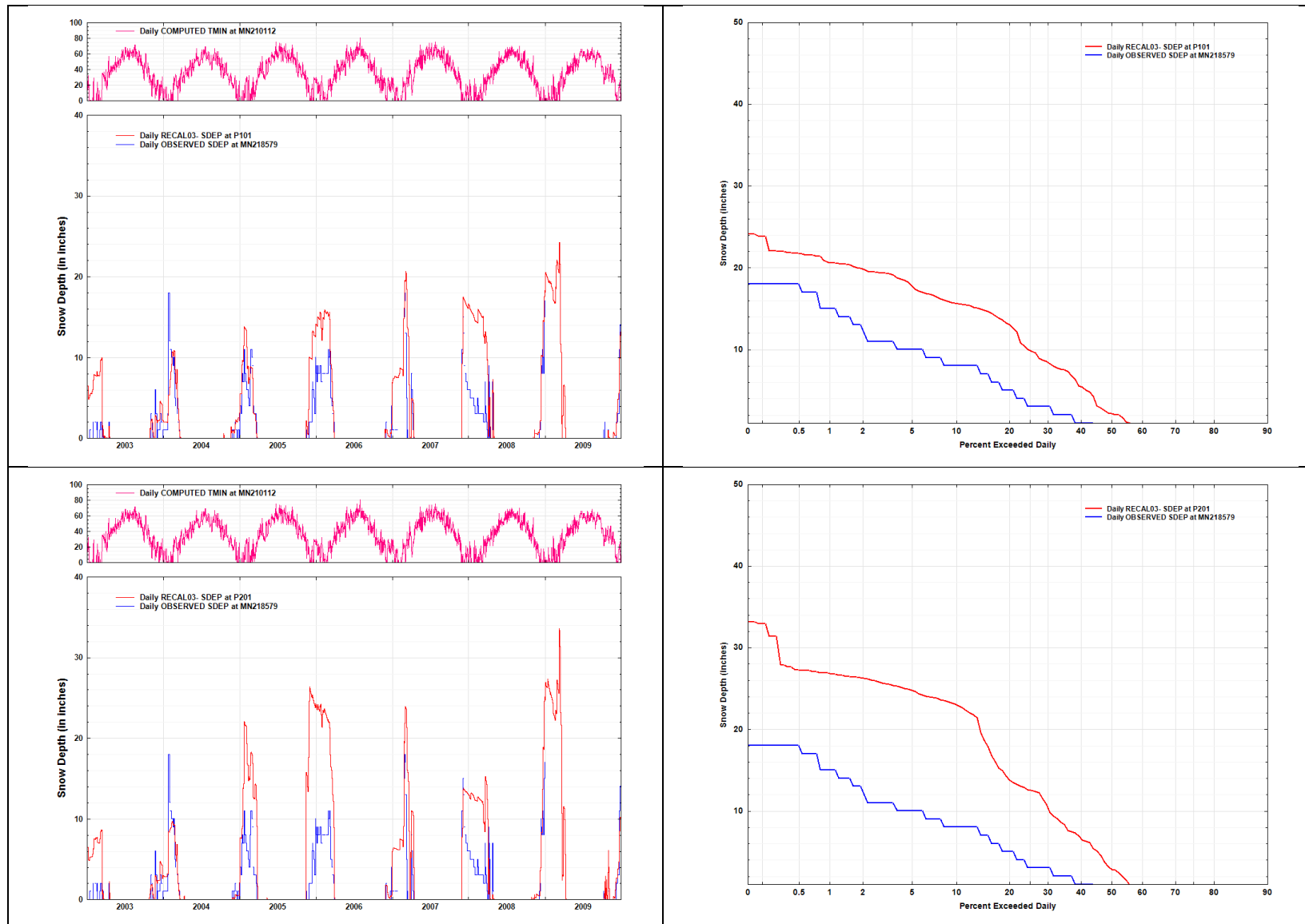
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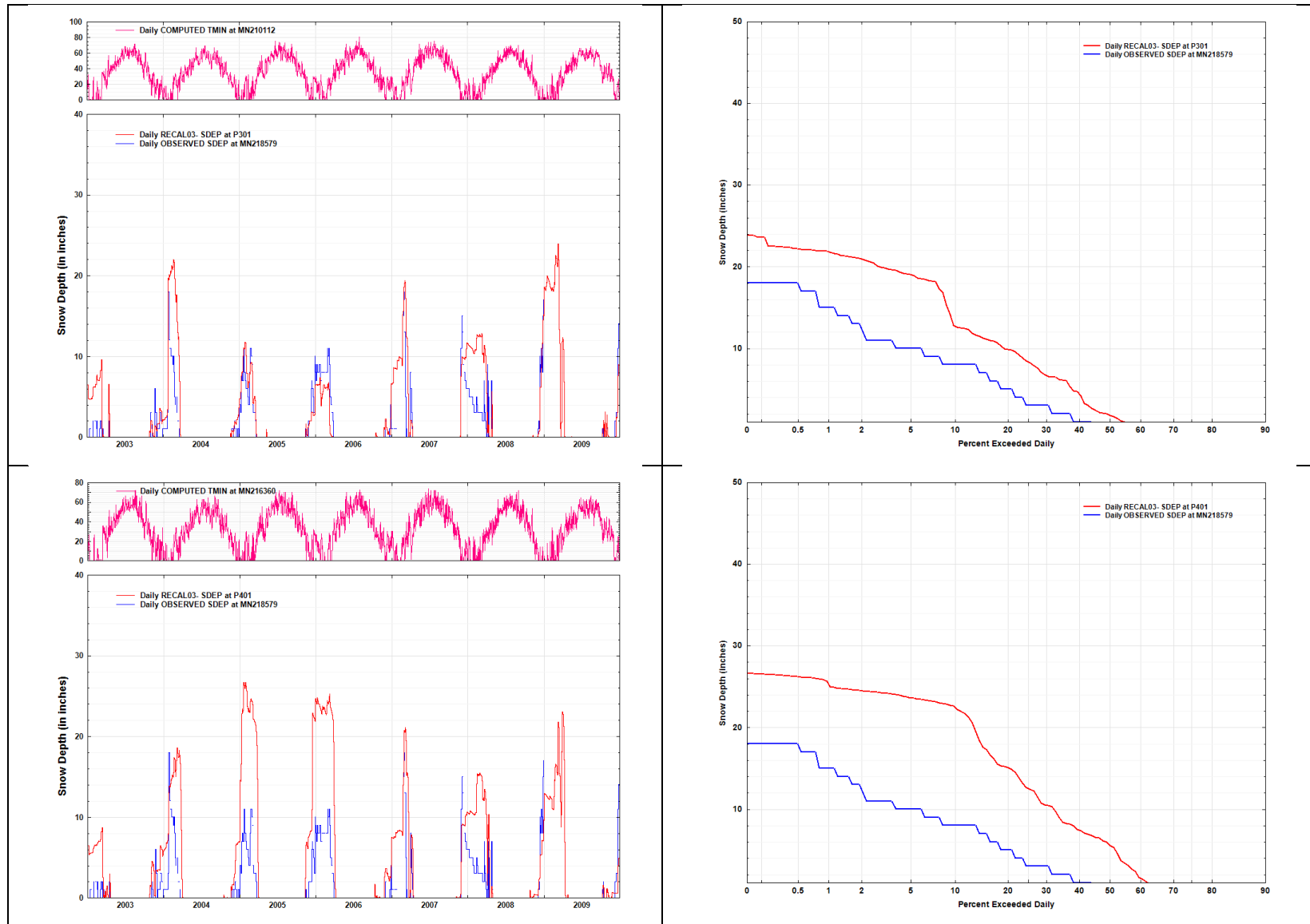
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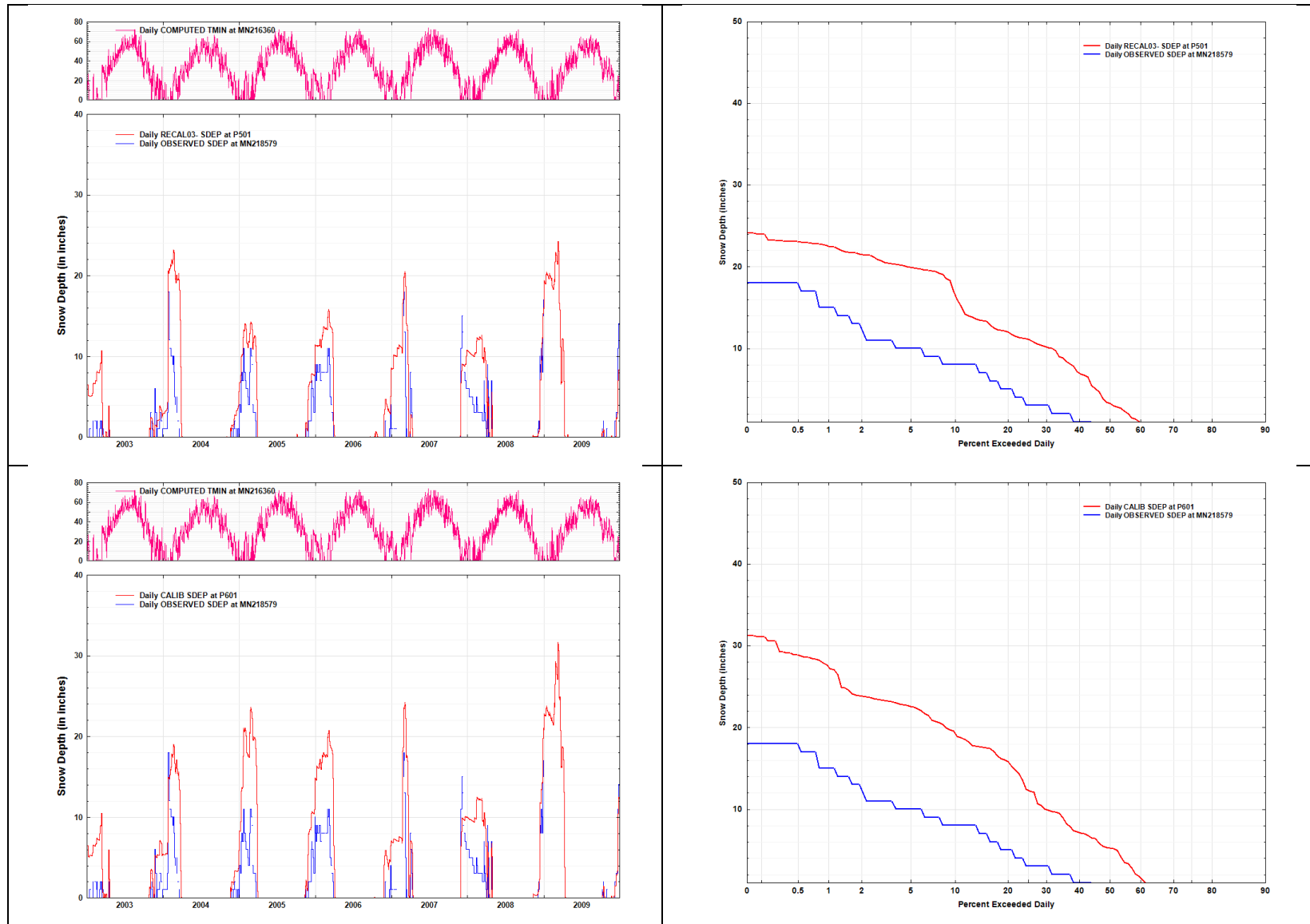
APPENDIX A

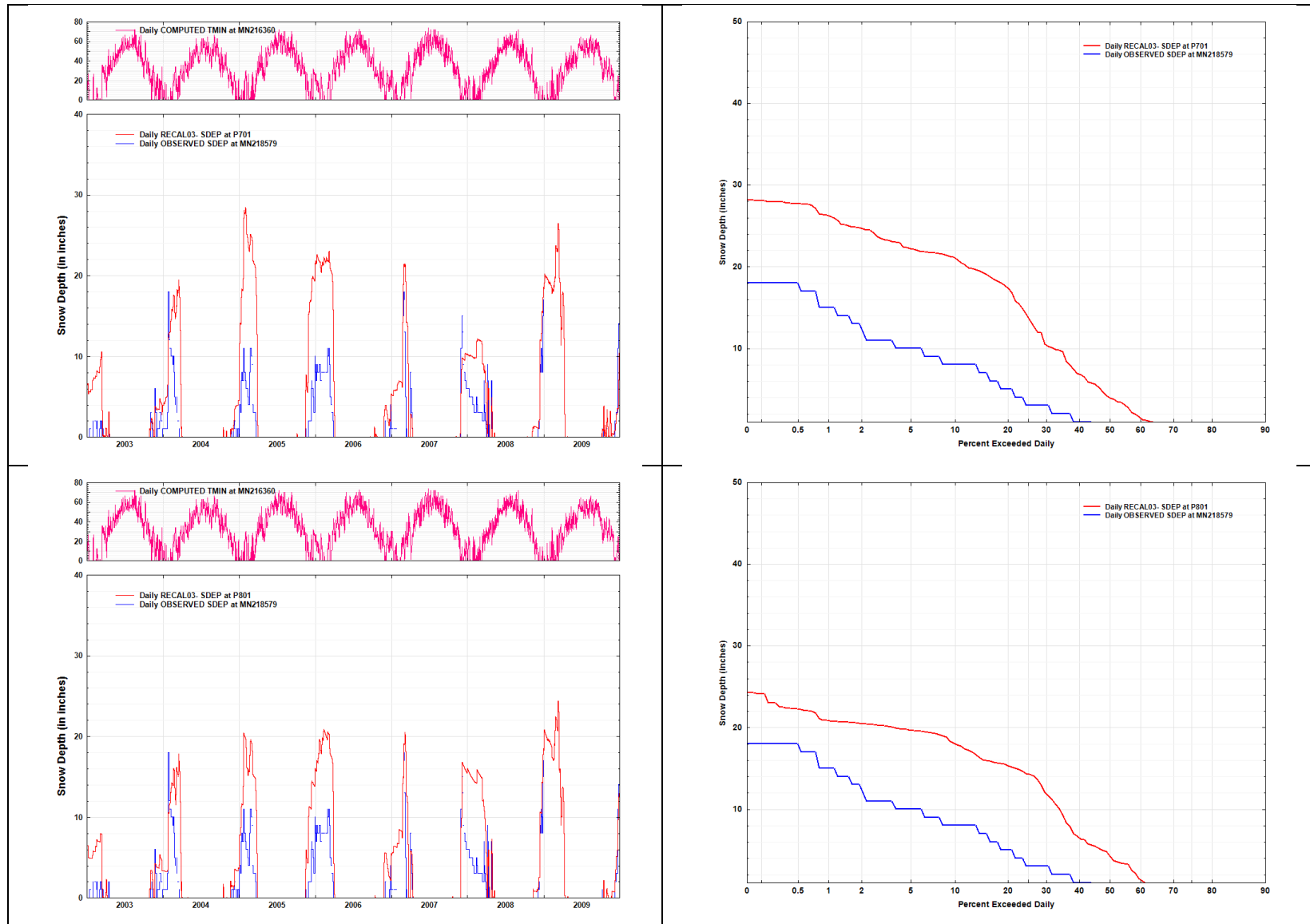
SNOW DEPTH AND FREQUENCY DURATION GRAPHS FOR THE CALIBRATION PERIOD

A.1 REDEYE RIVER WATERSHED

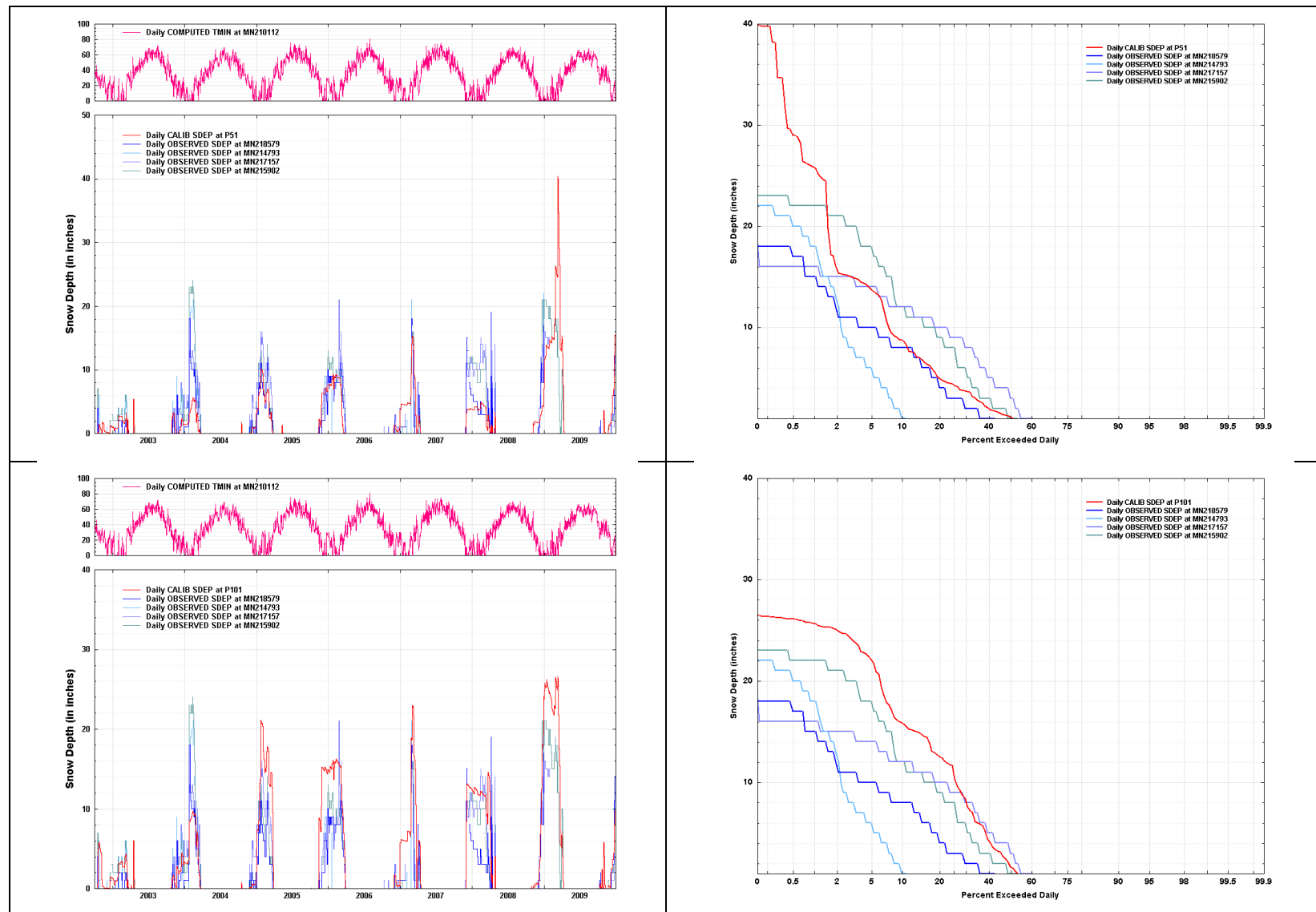


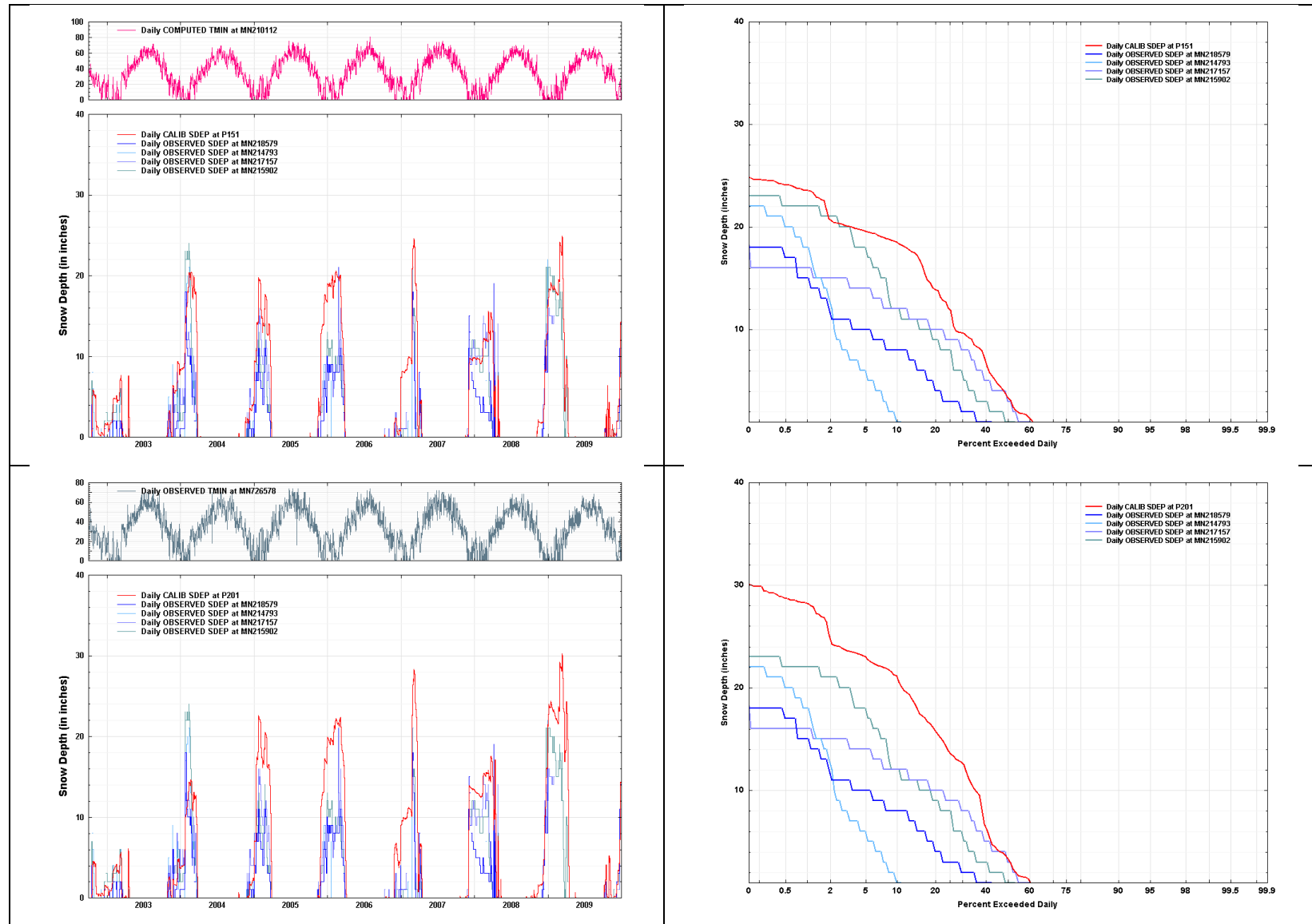


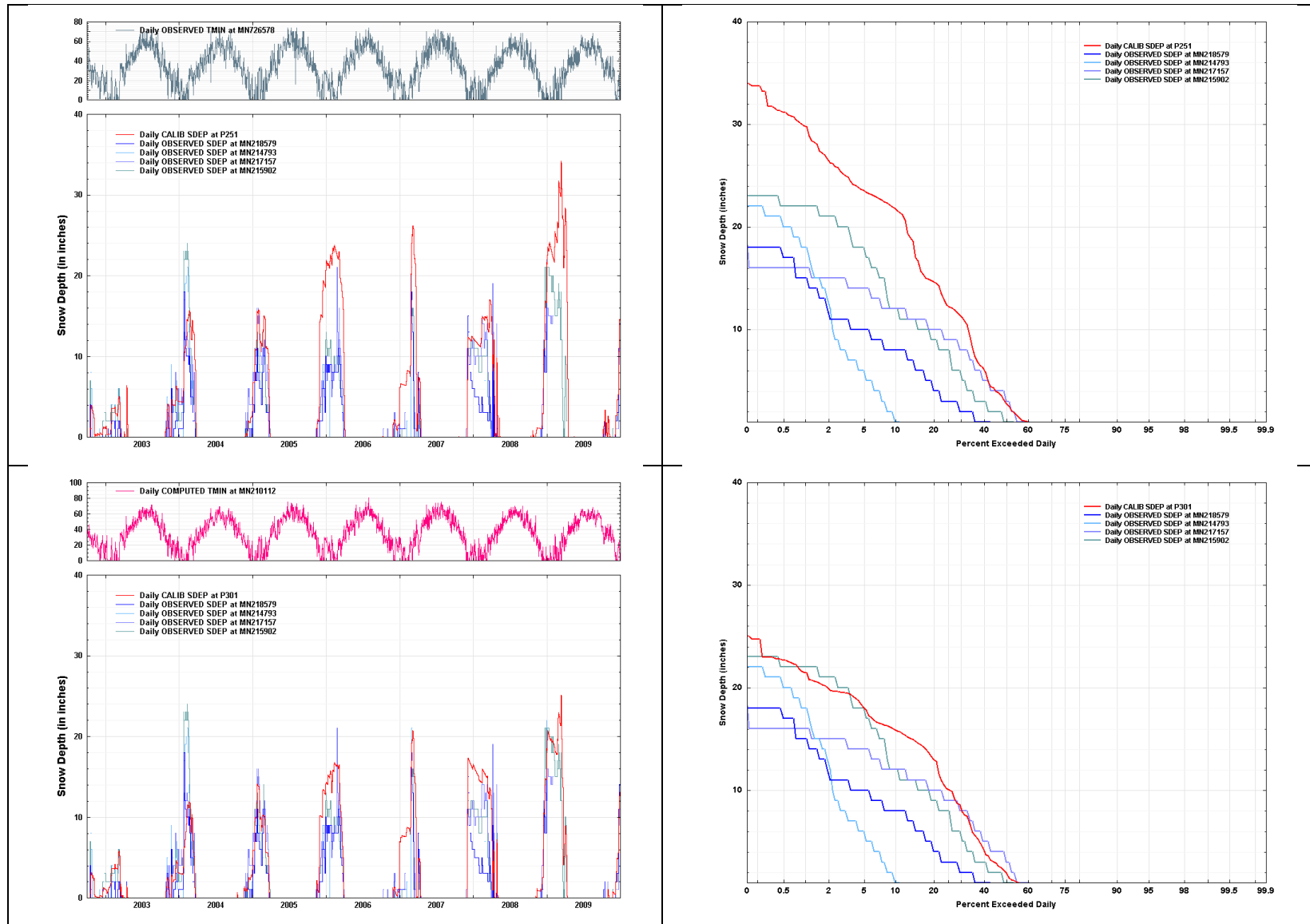


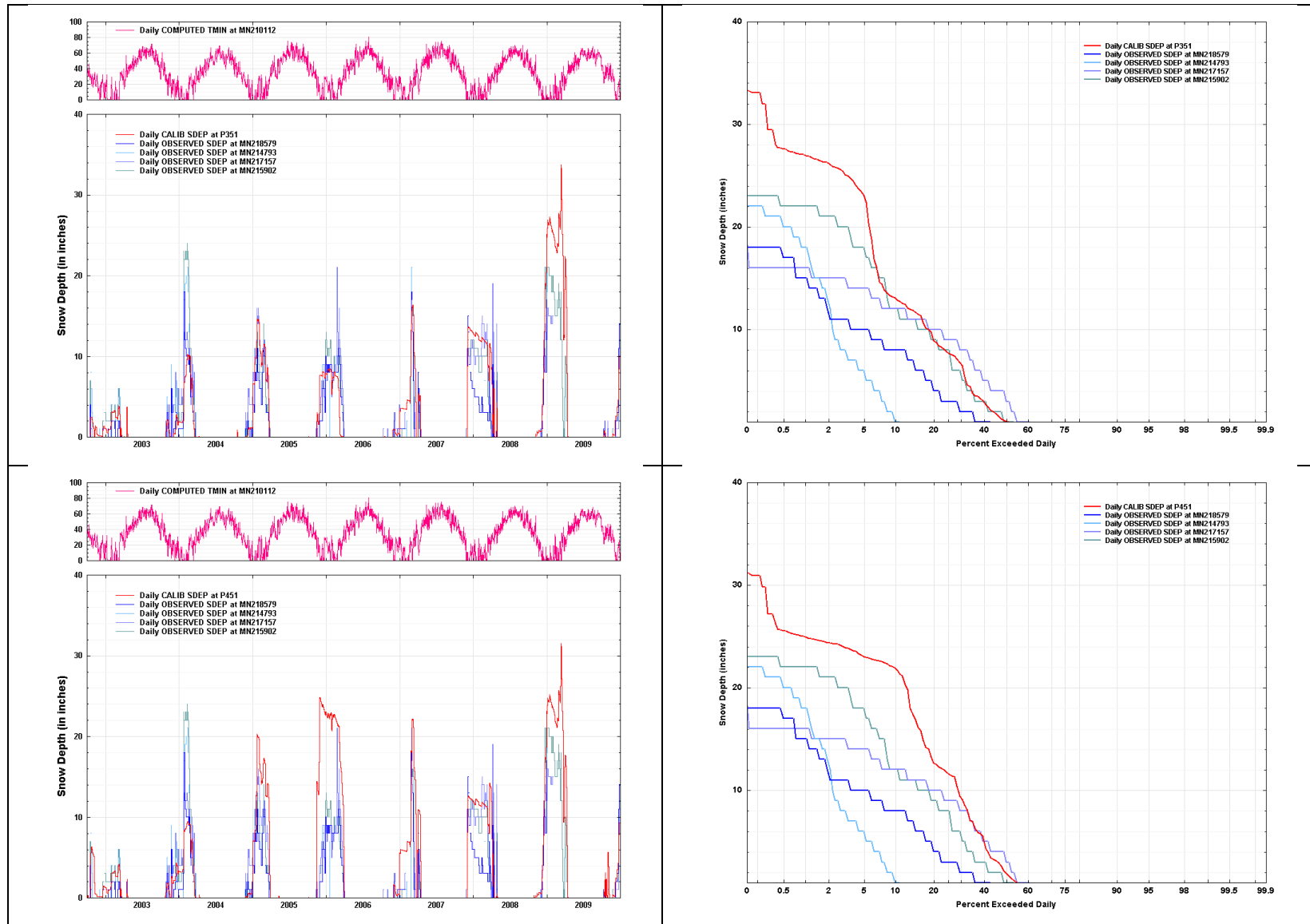


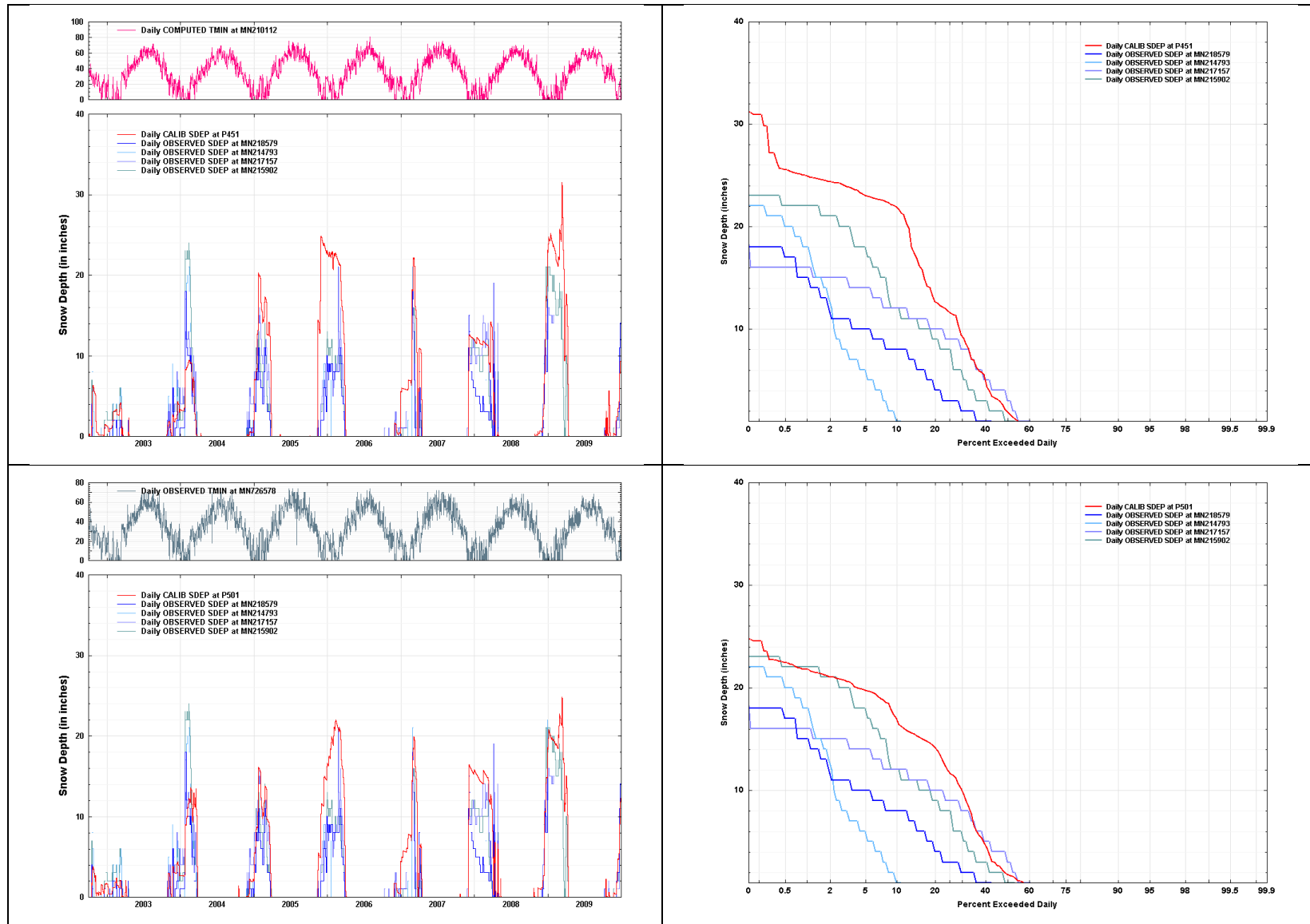
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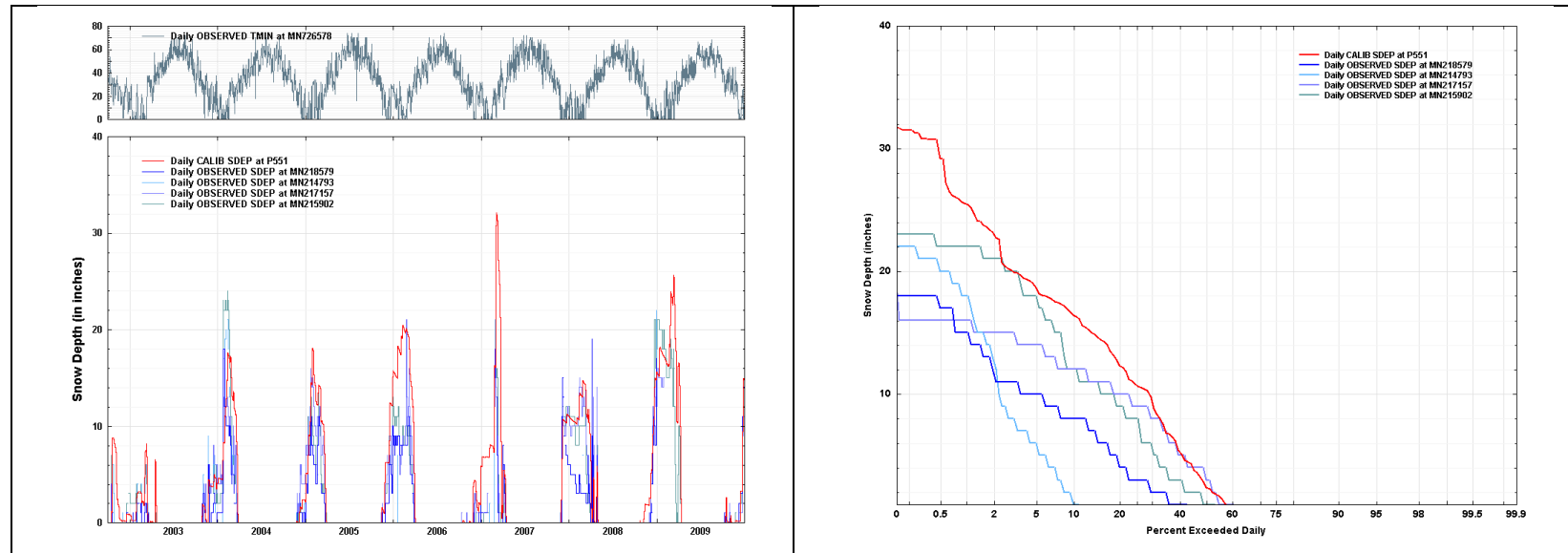




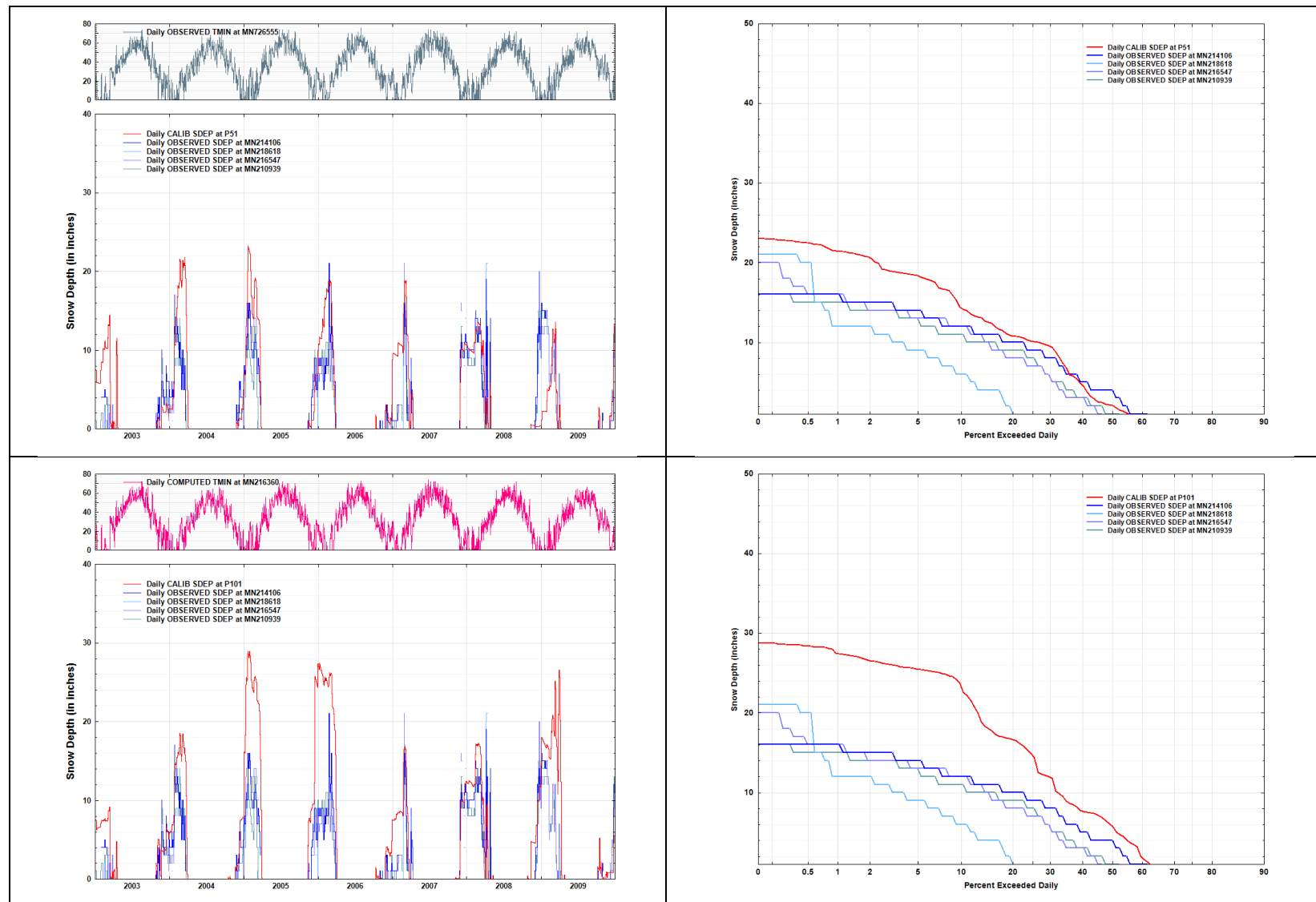


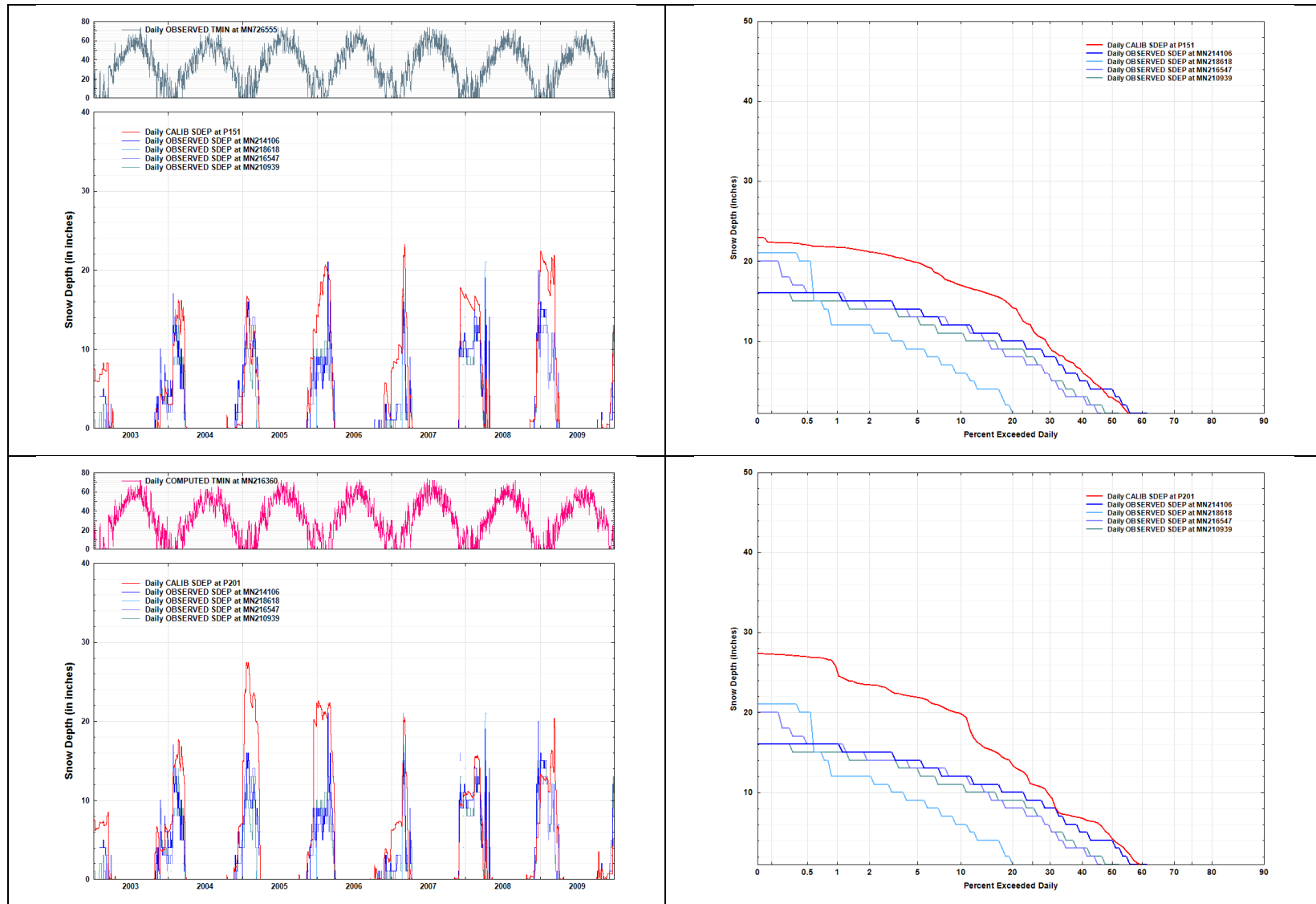


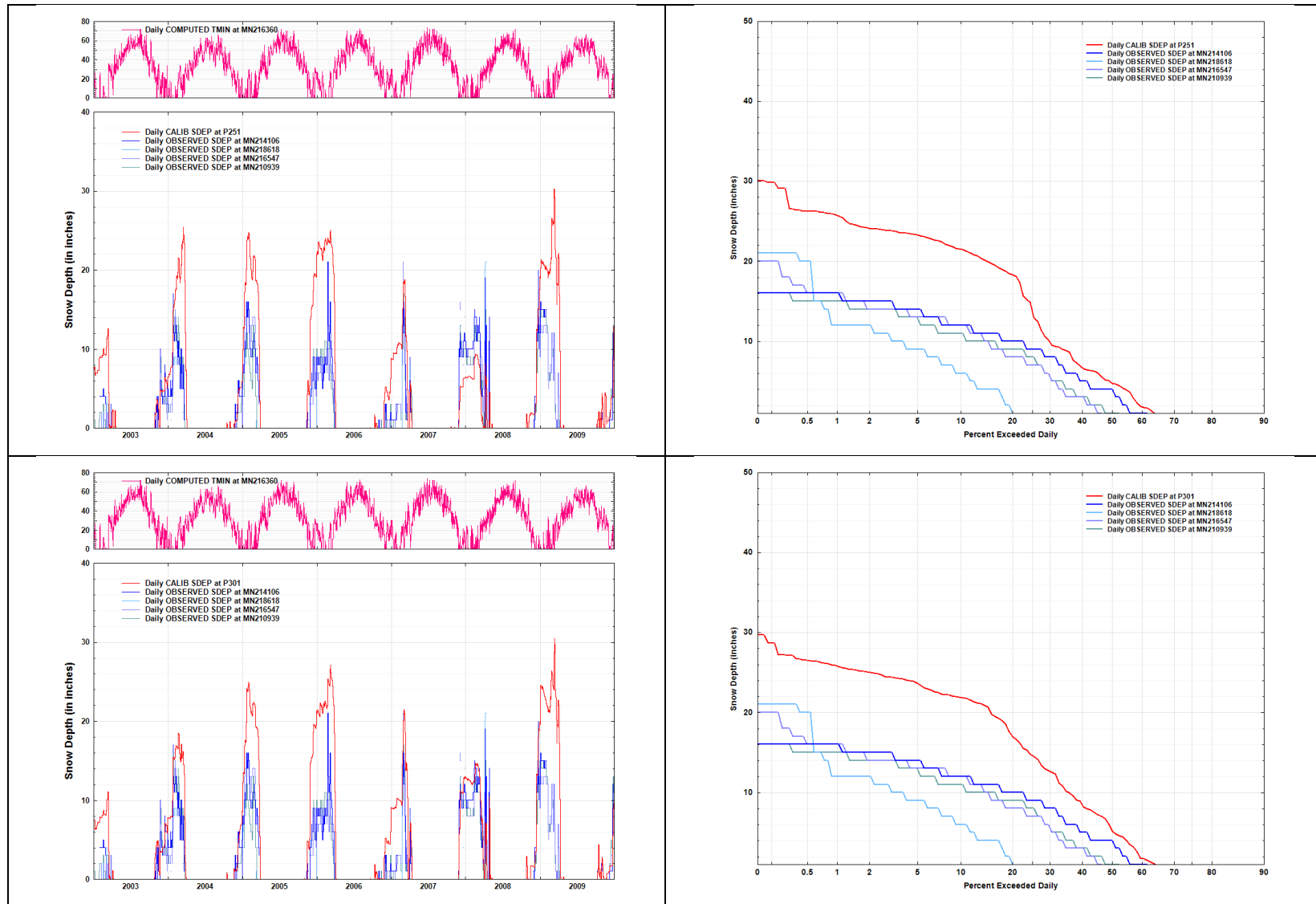


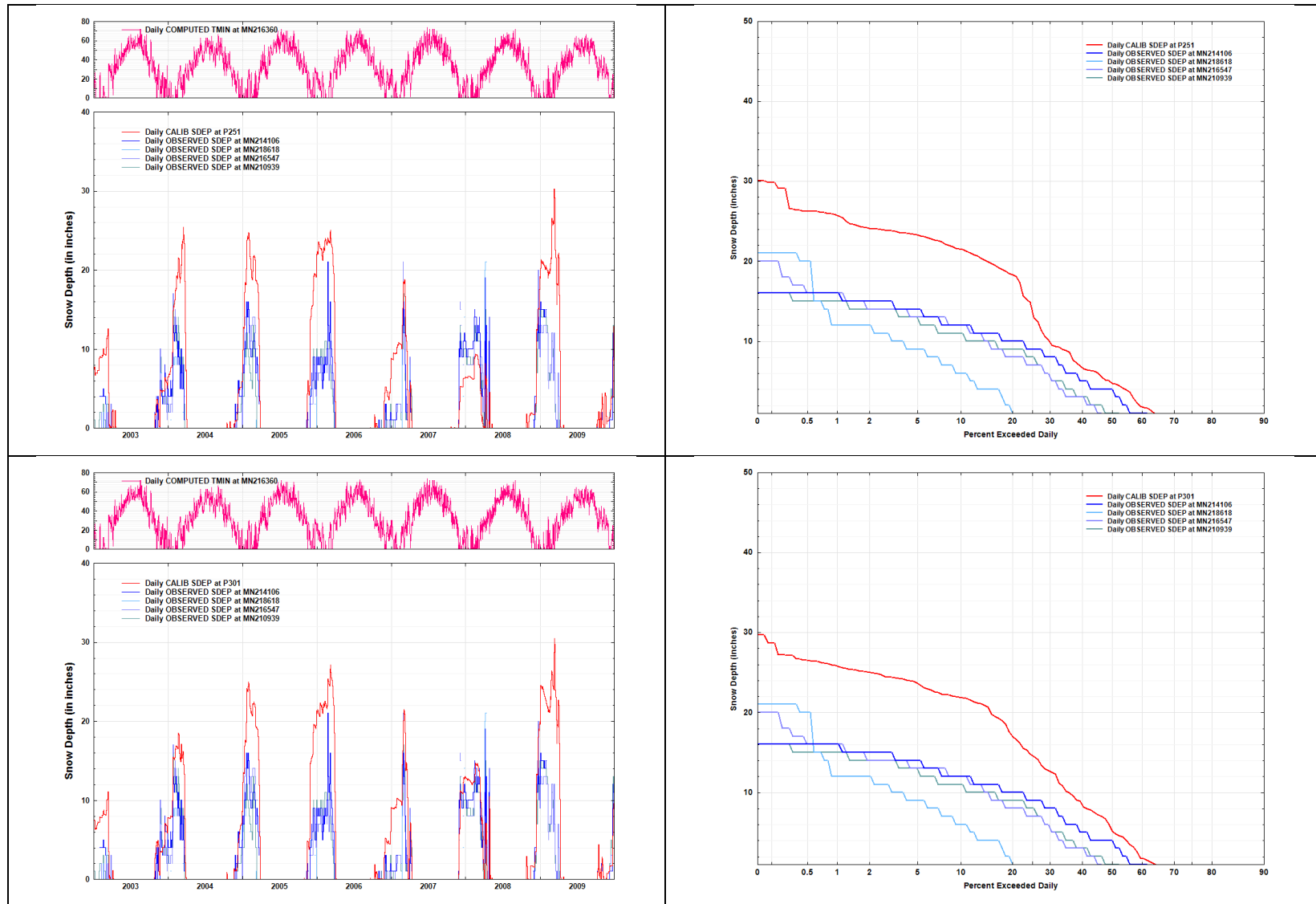


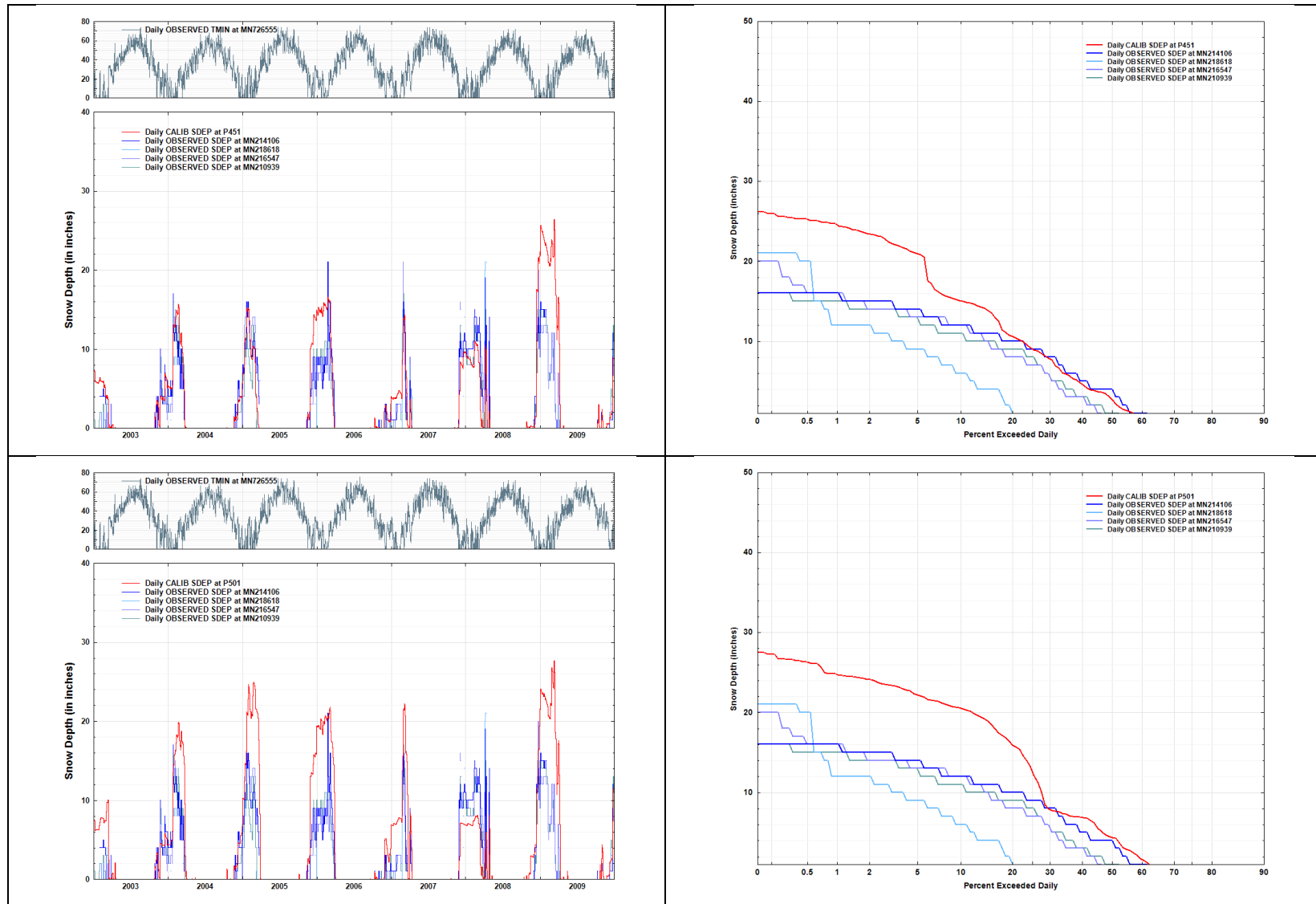
A.3 CROW WING RIVER WATERSHED

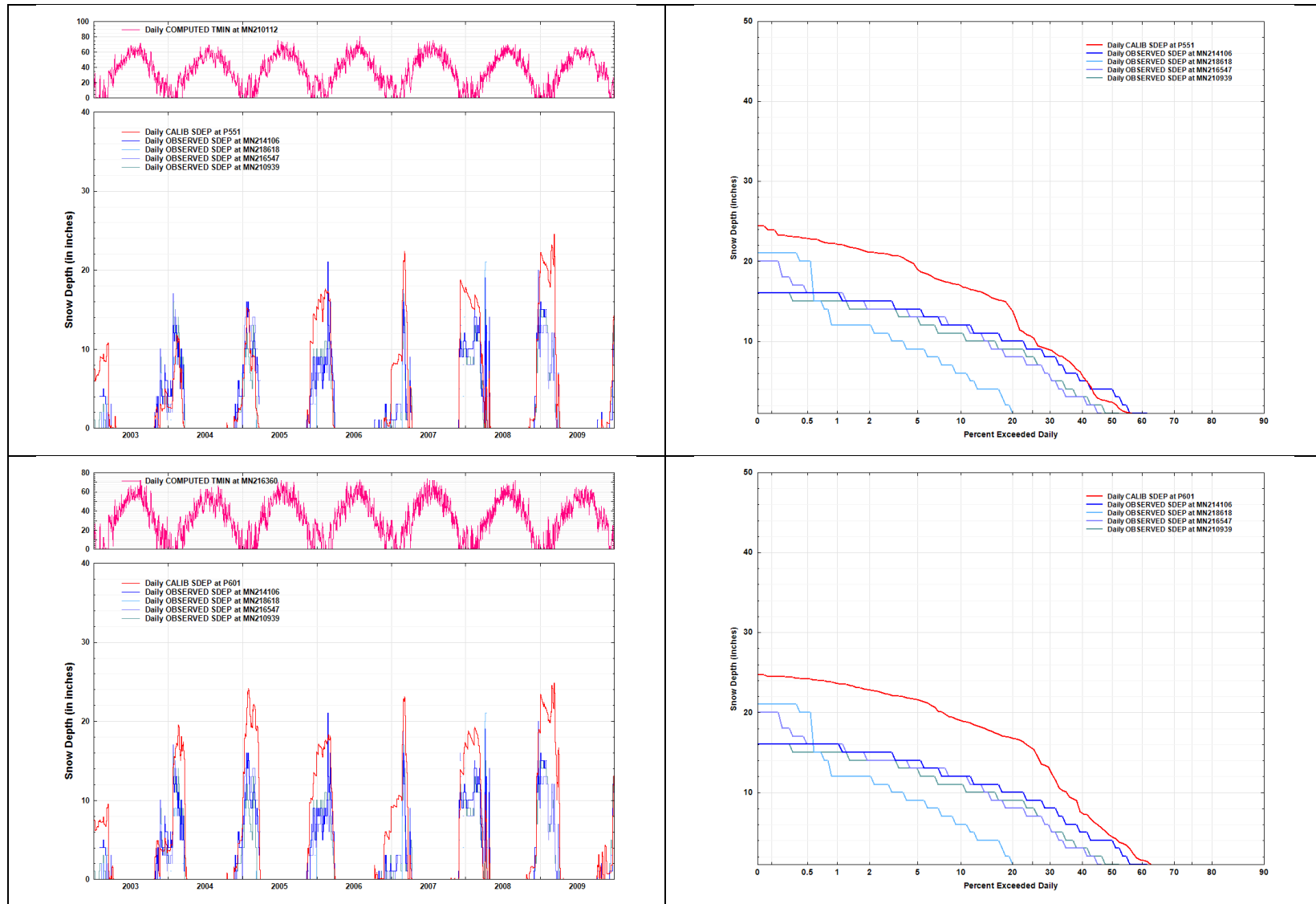


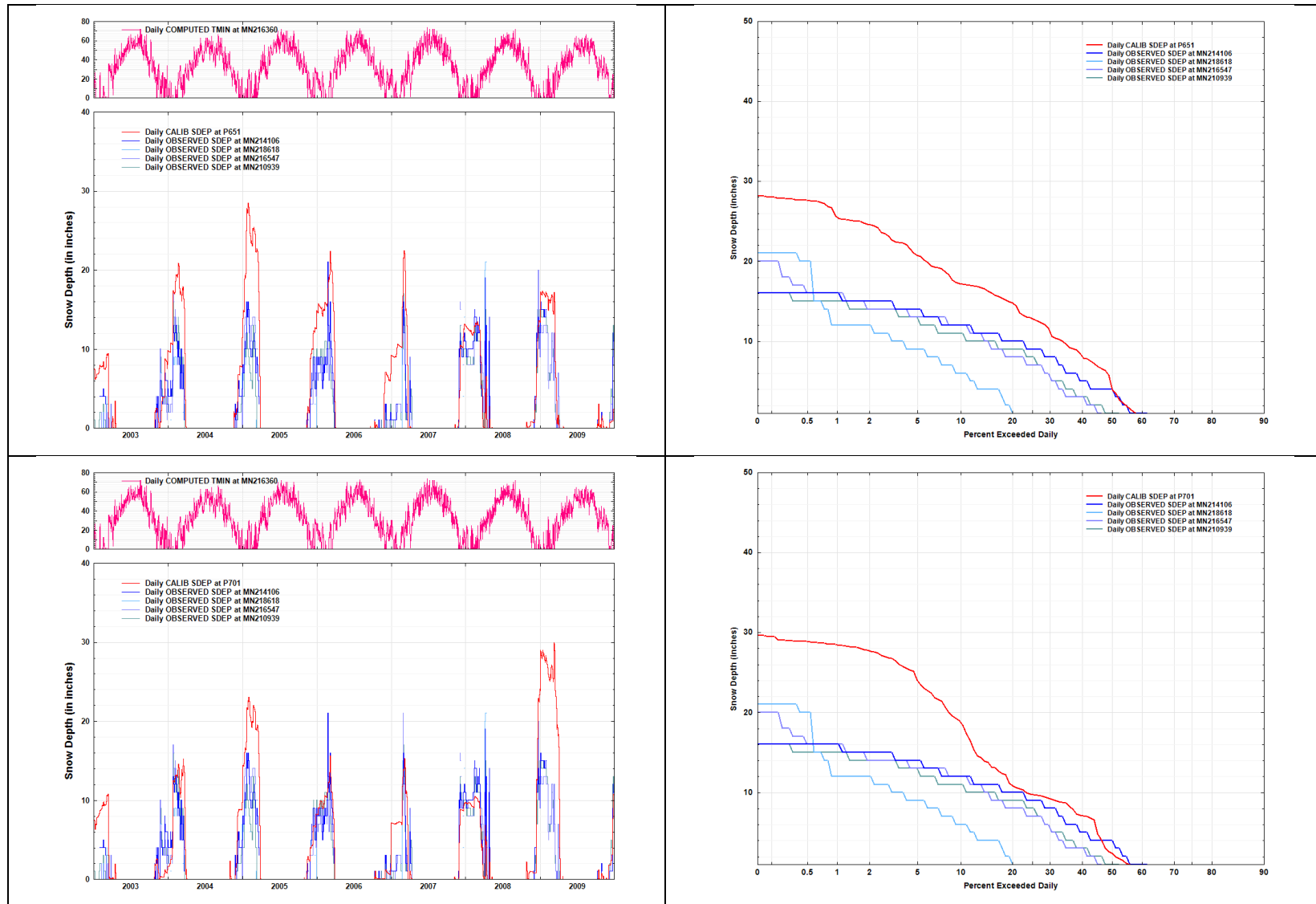


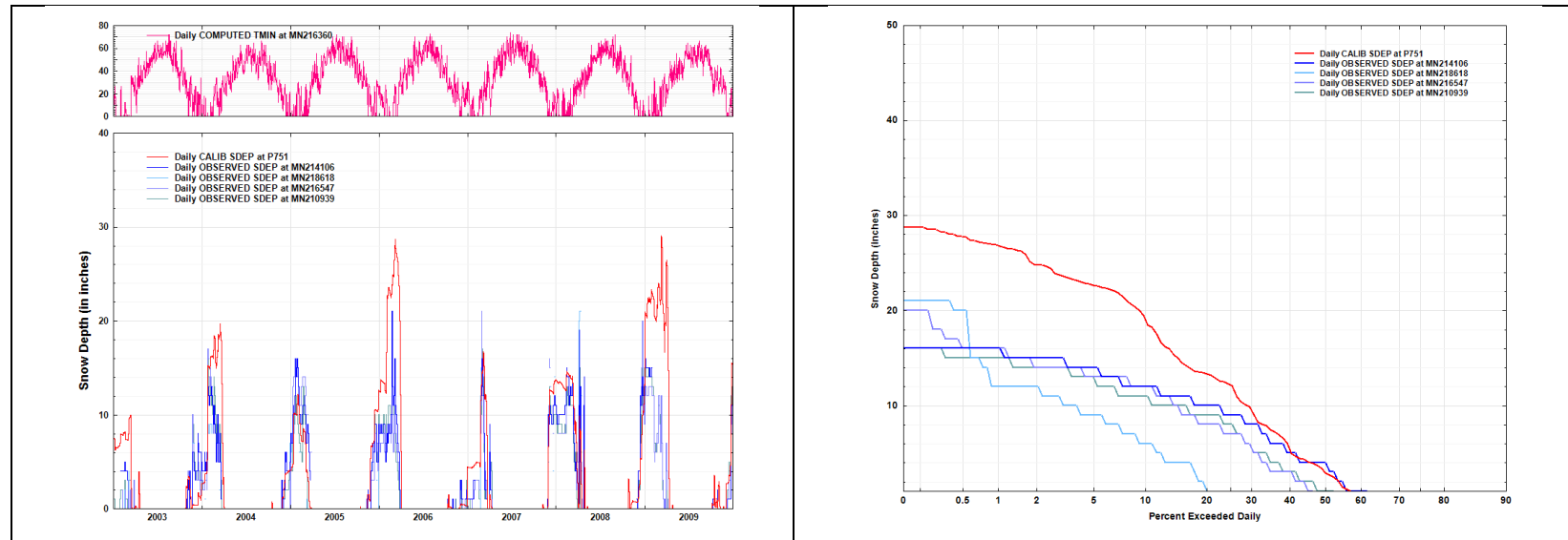








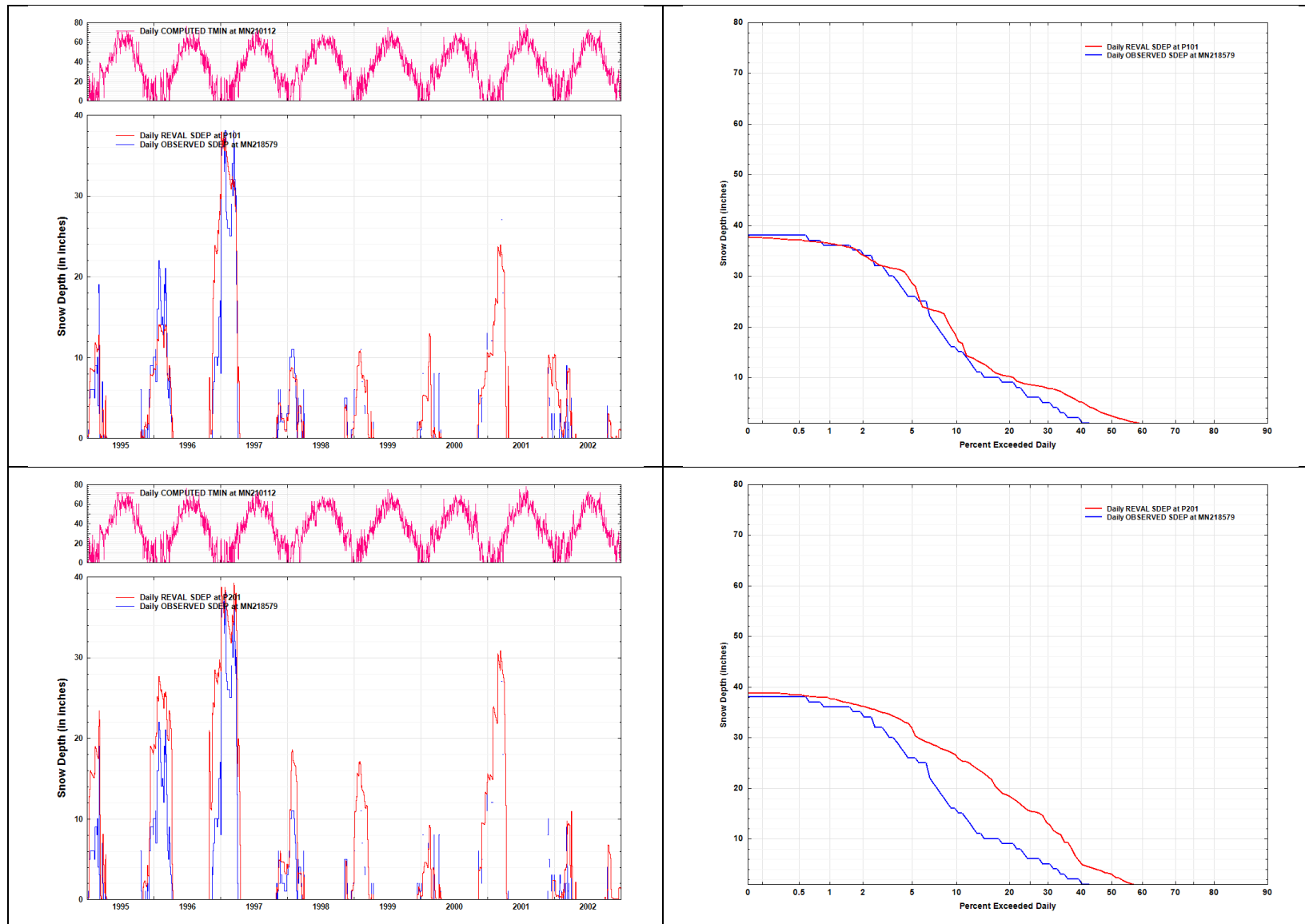


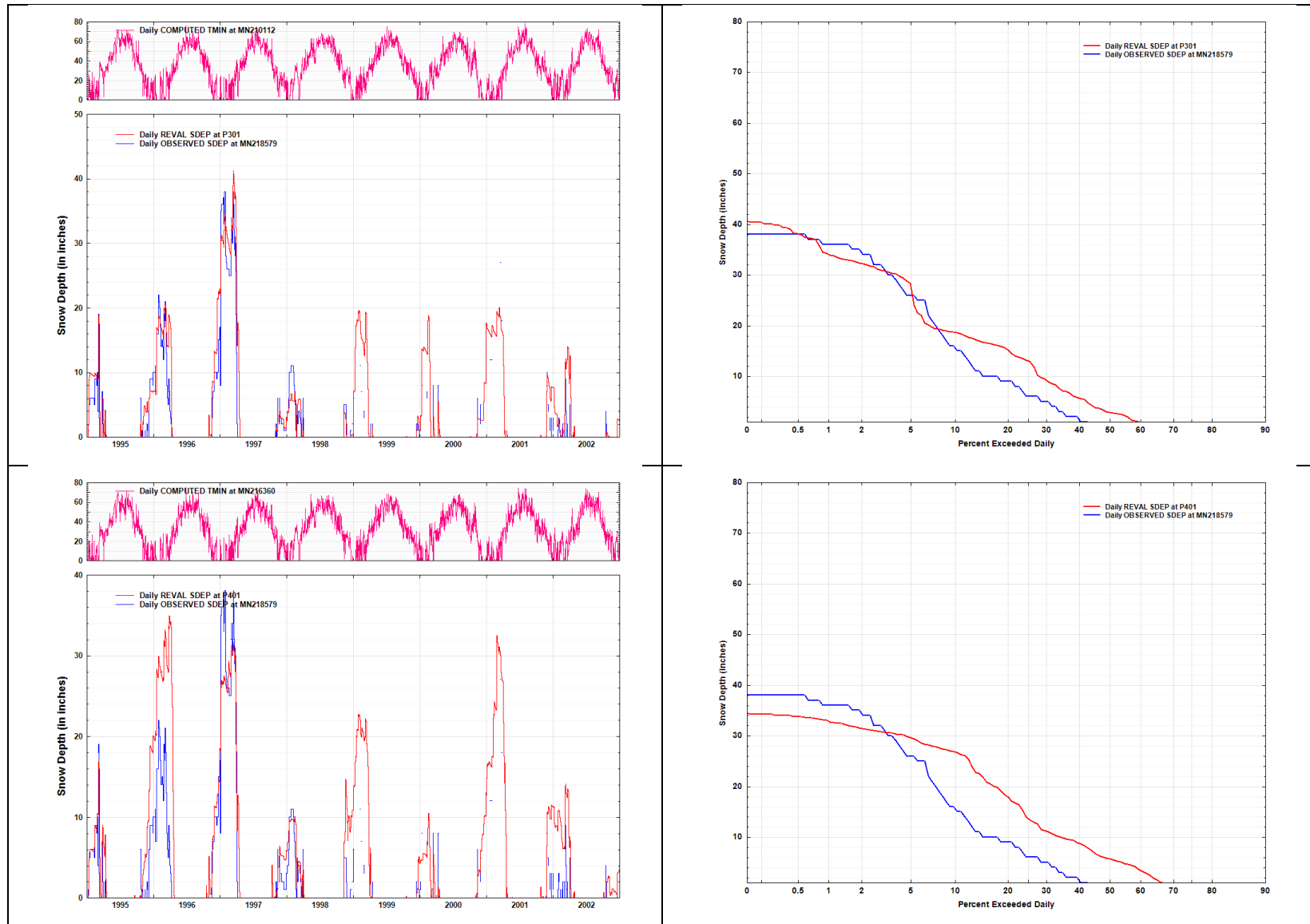


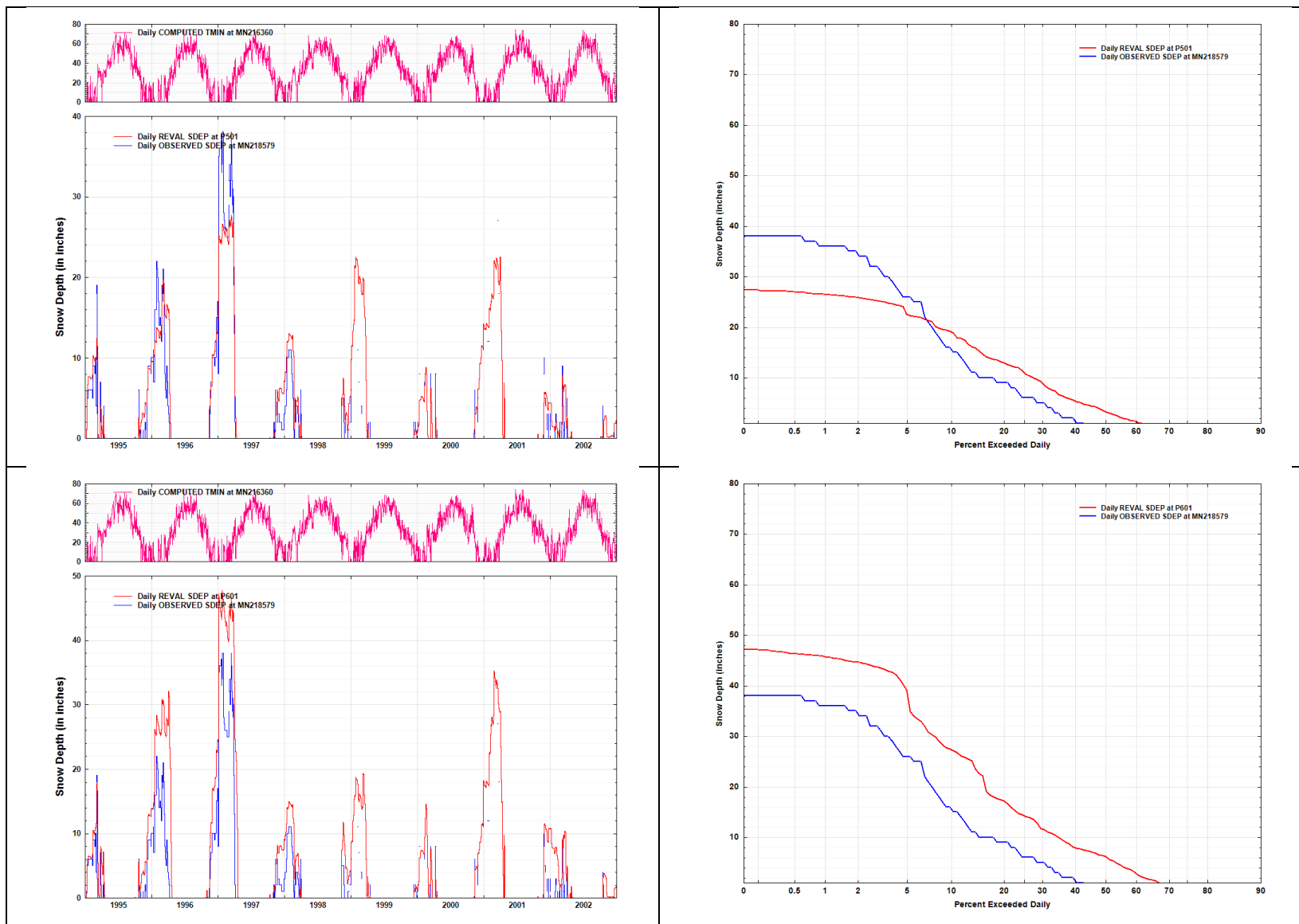
APPENDIX B

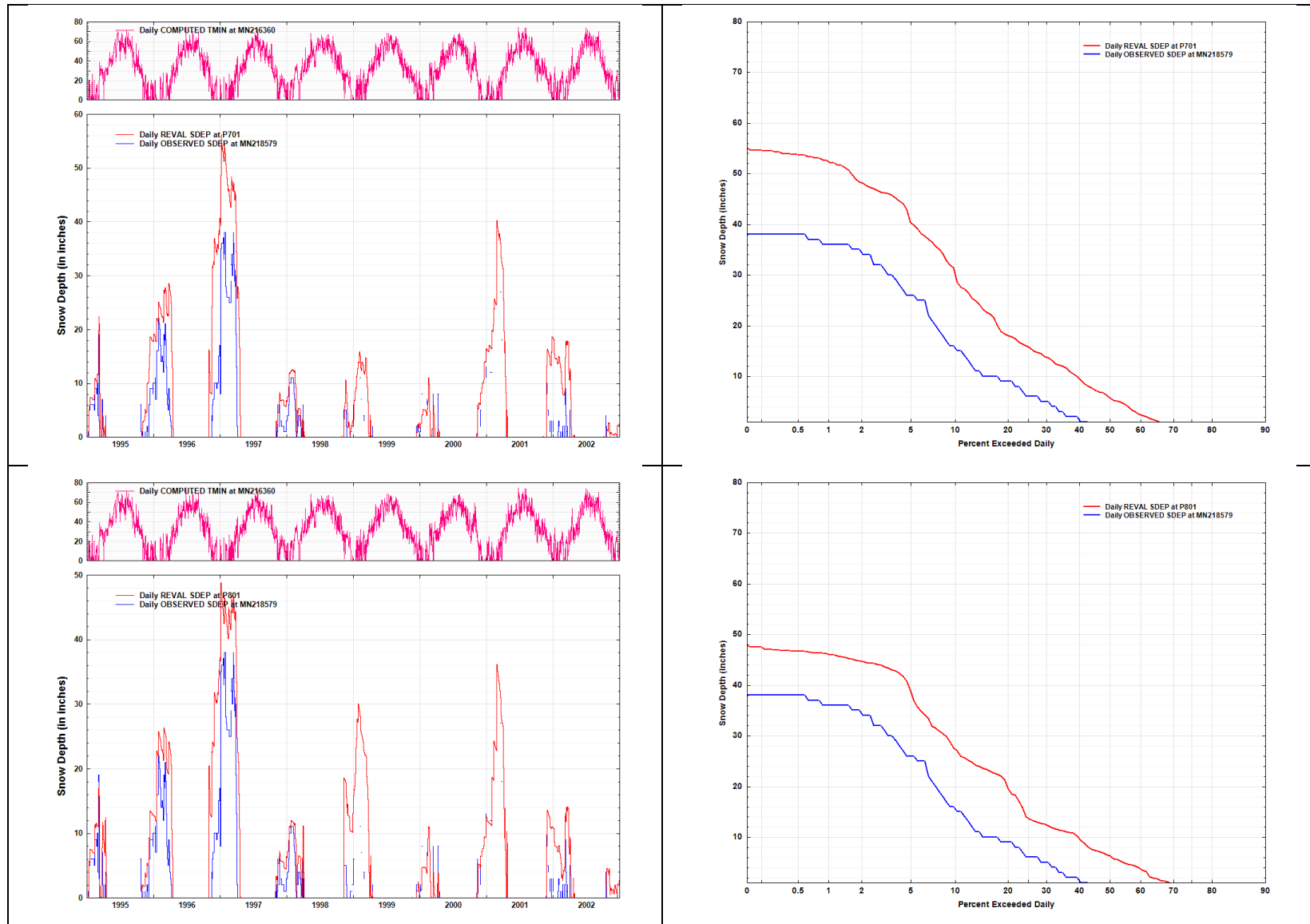
SNOW DEPTH AND FREQUENCY DURATION GRAPHS FOR THE VALIDATION PERIOD

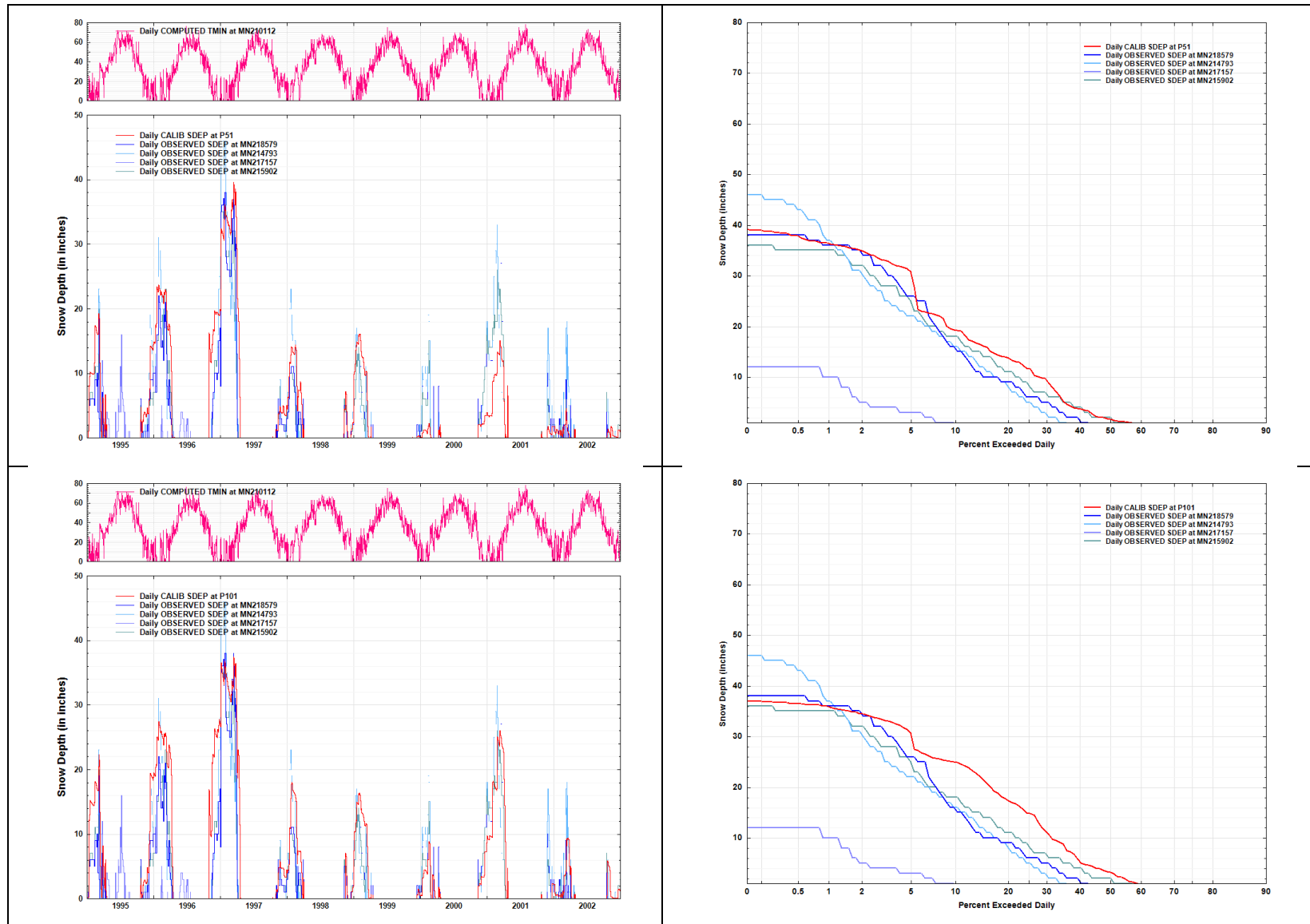
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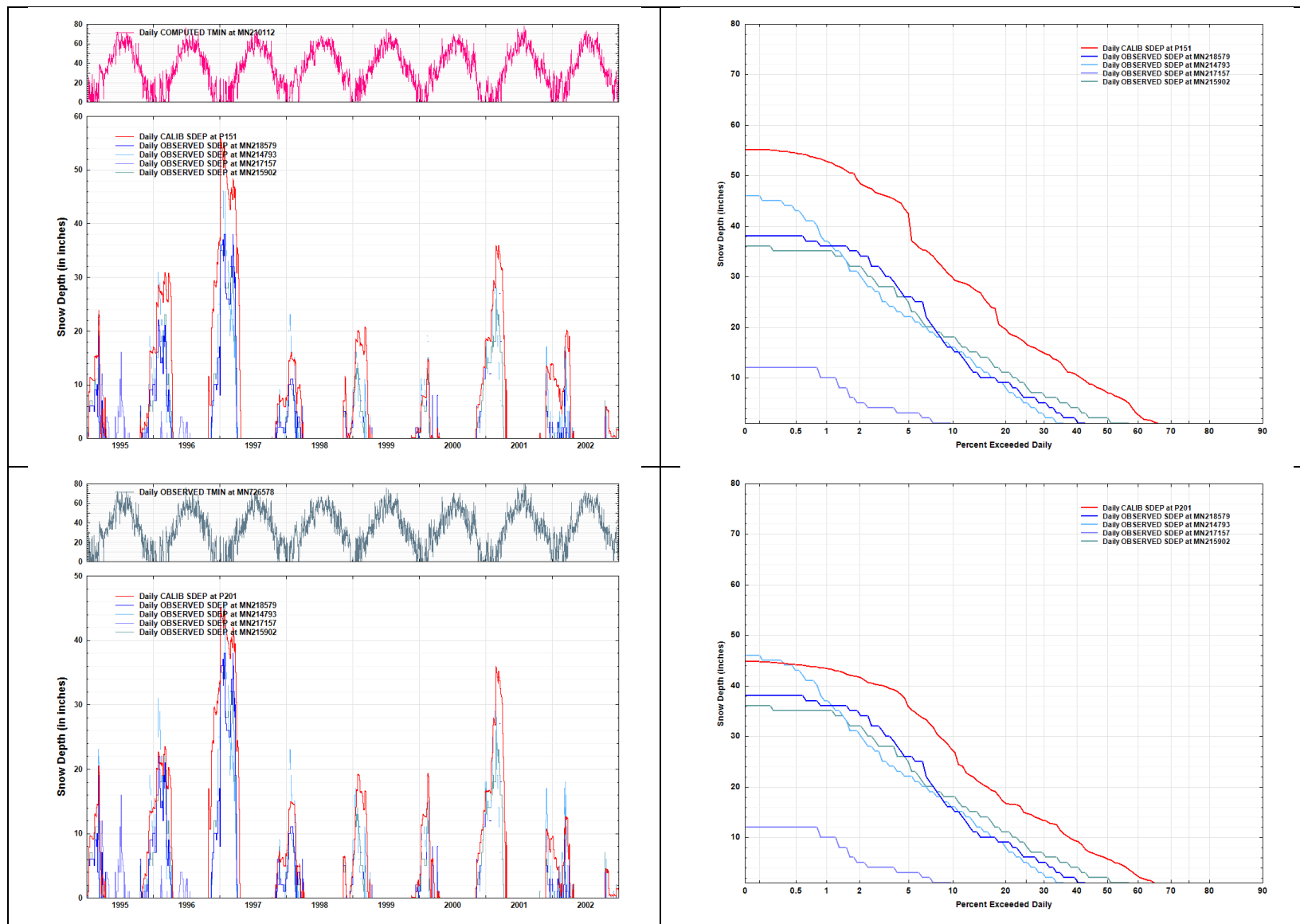


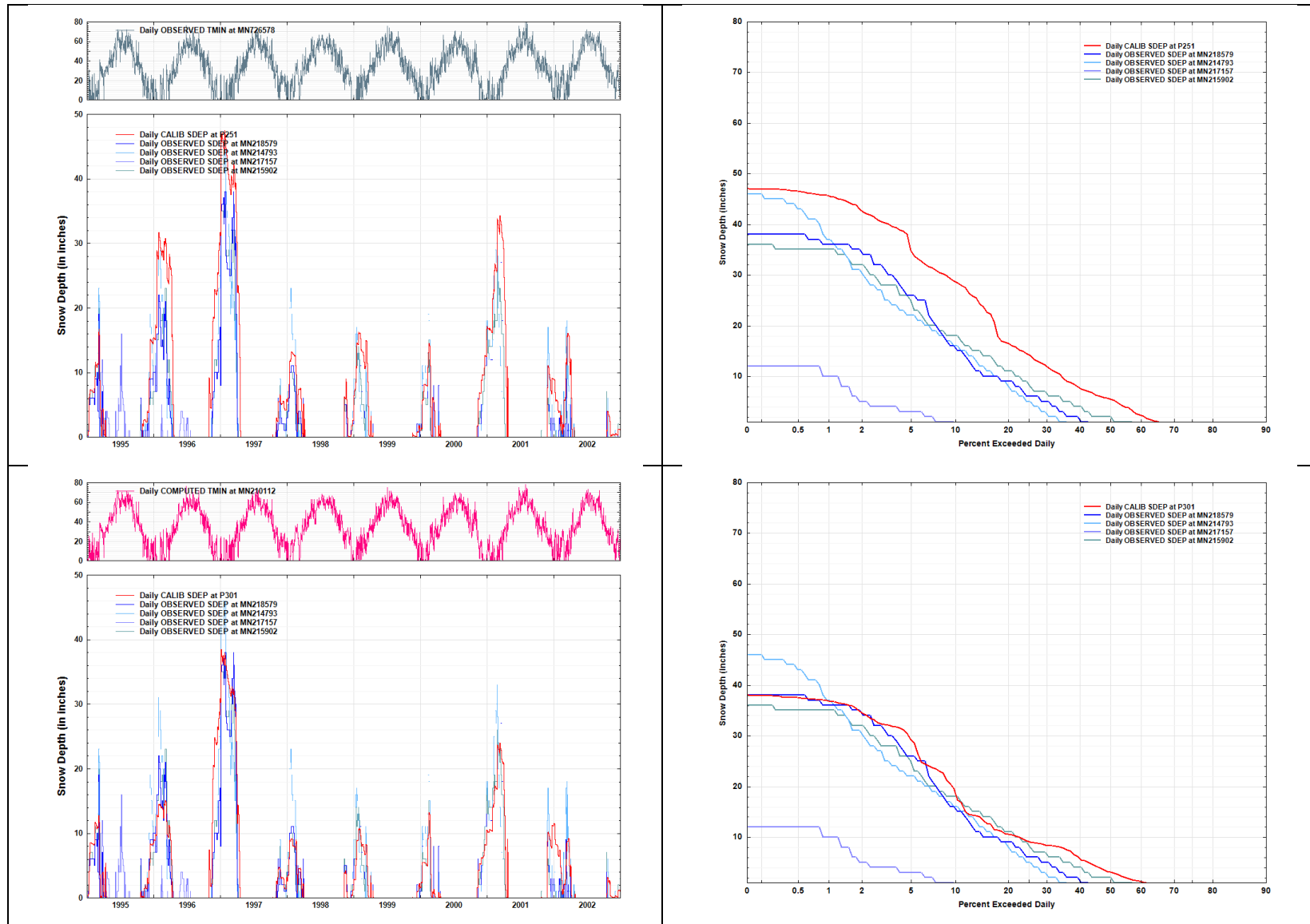


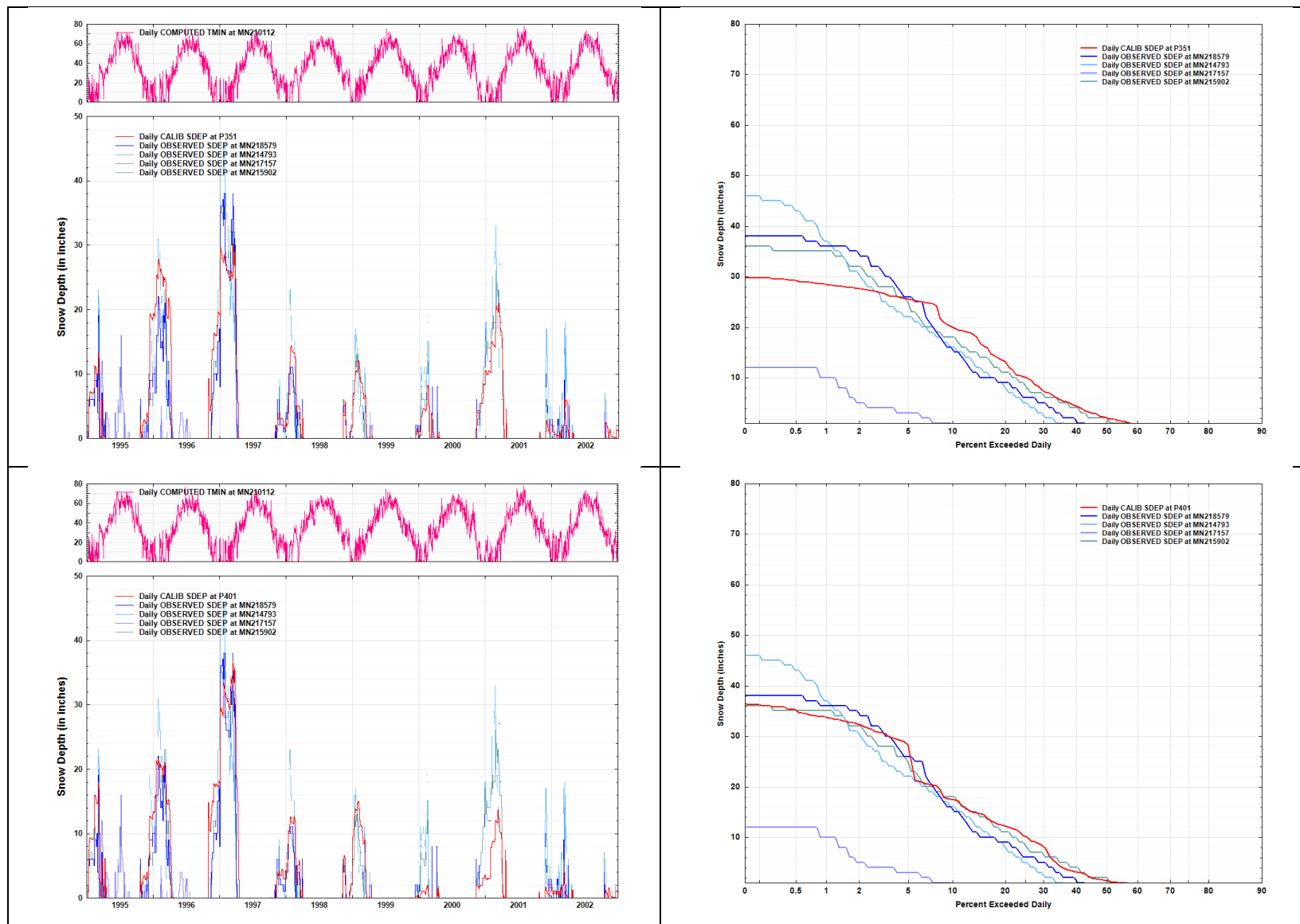


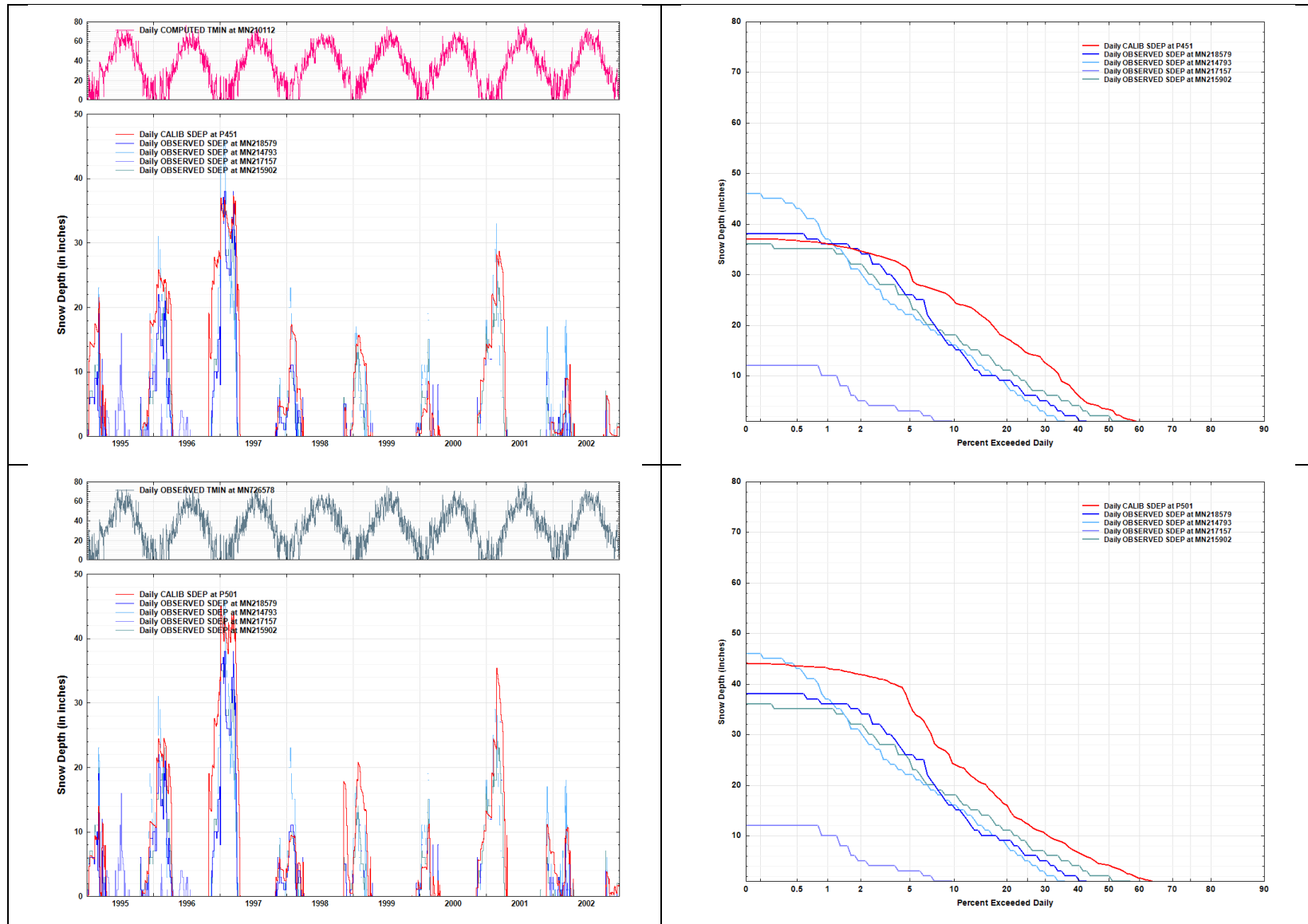


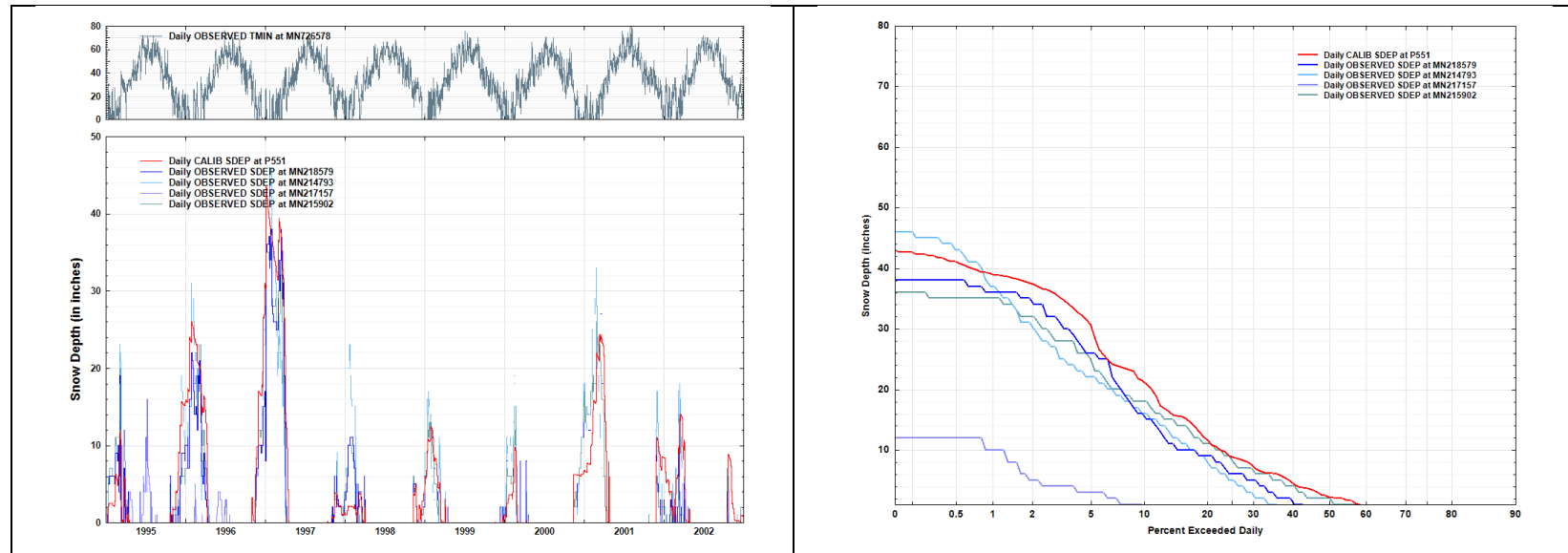
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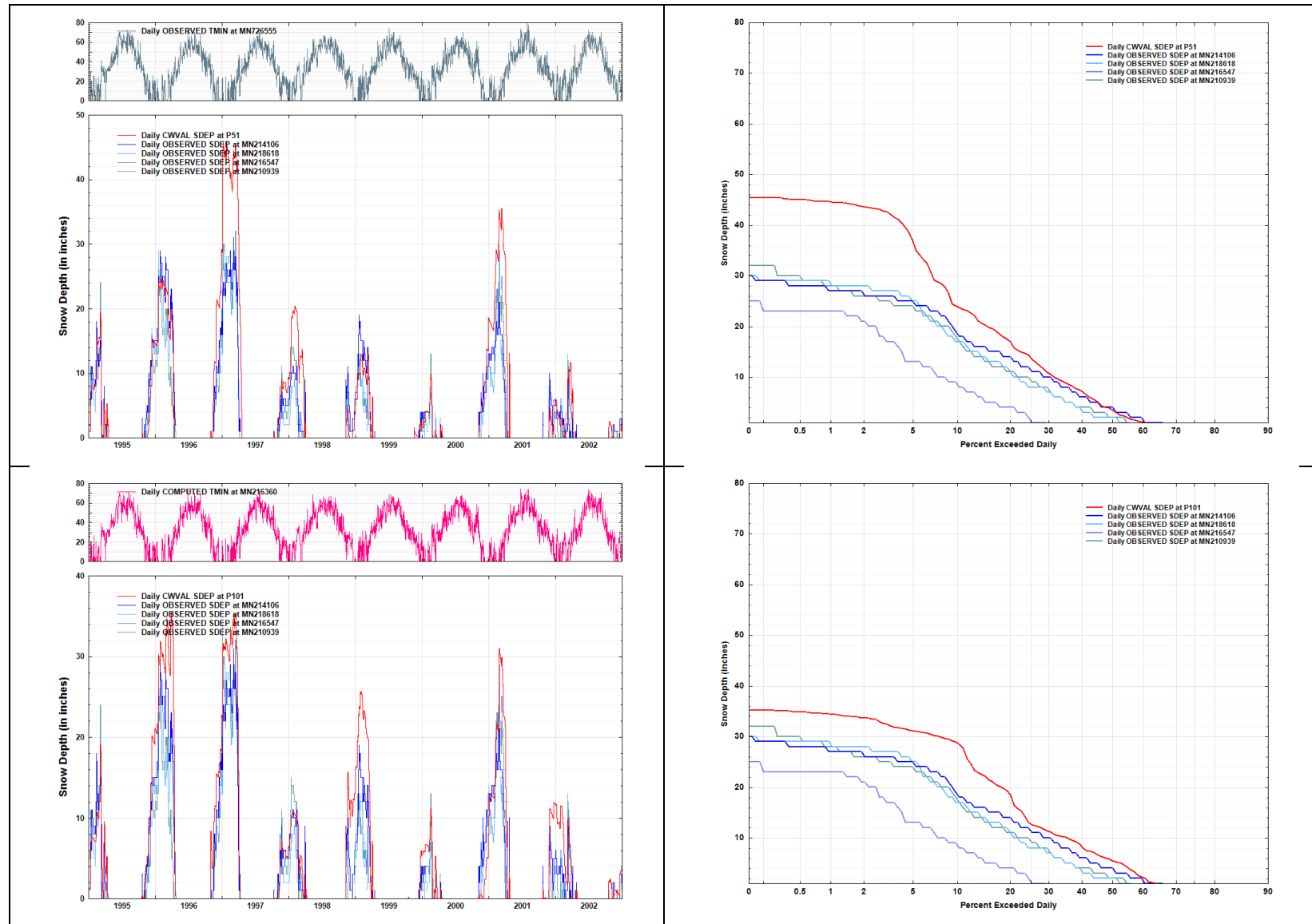


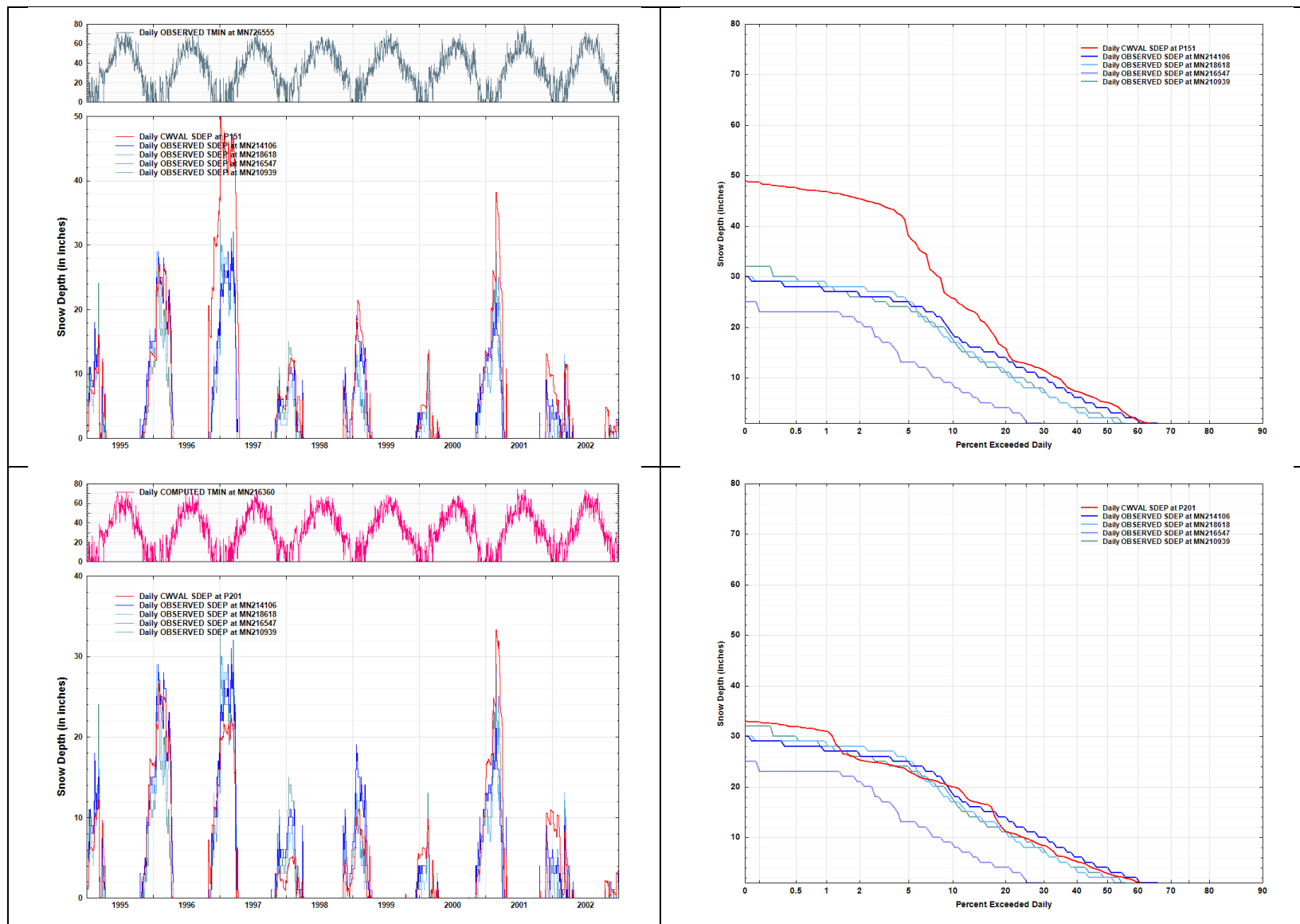


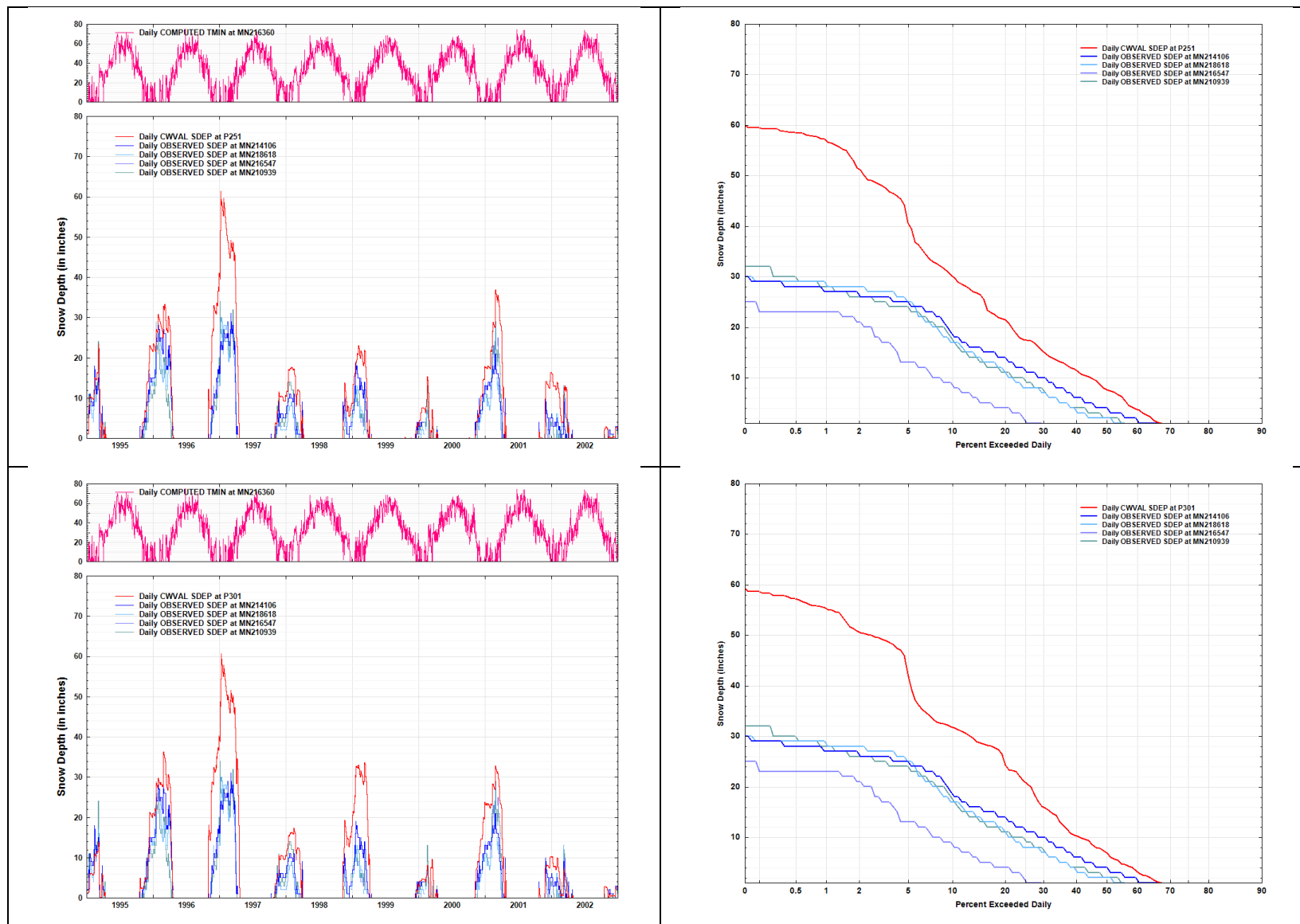


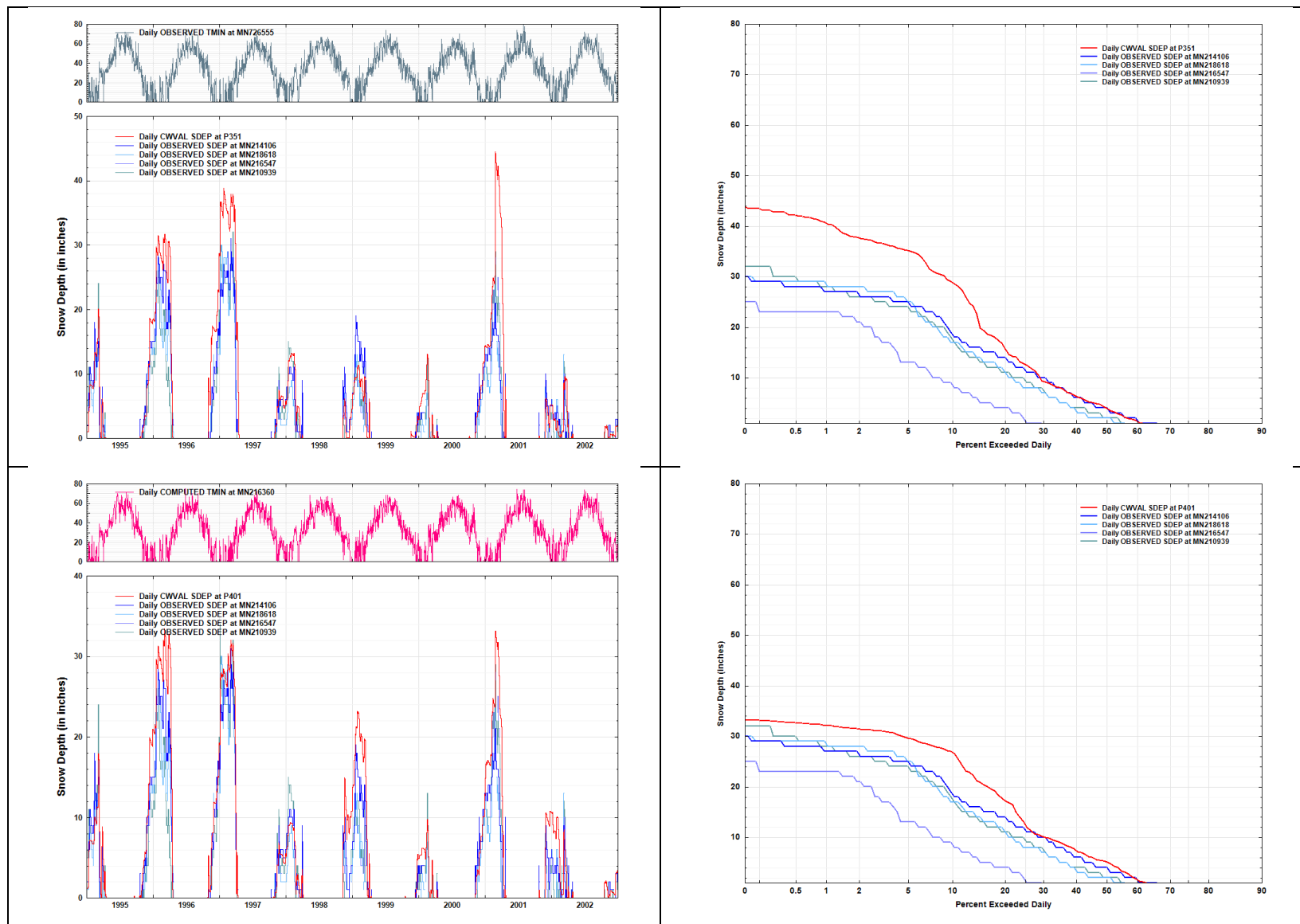


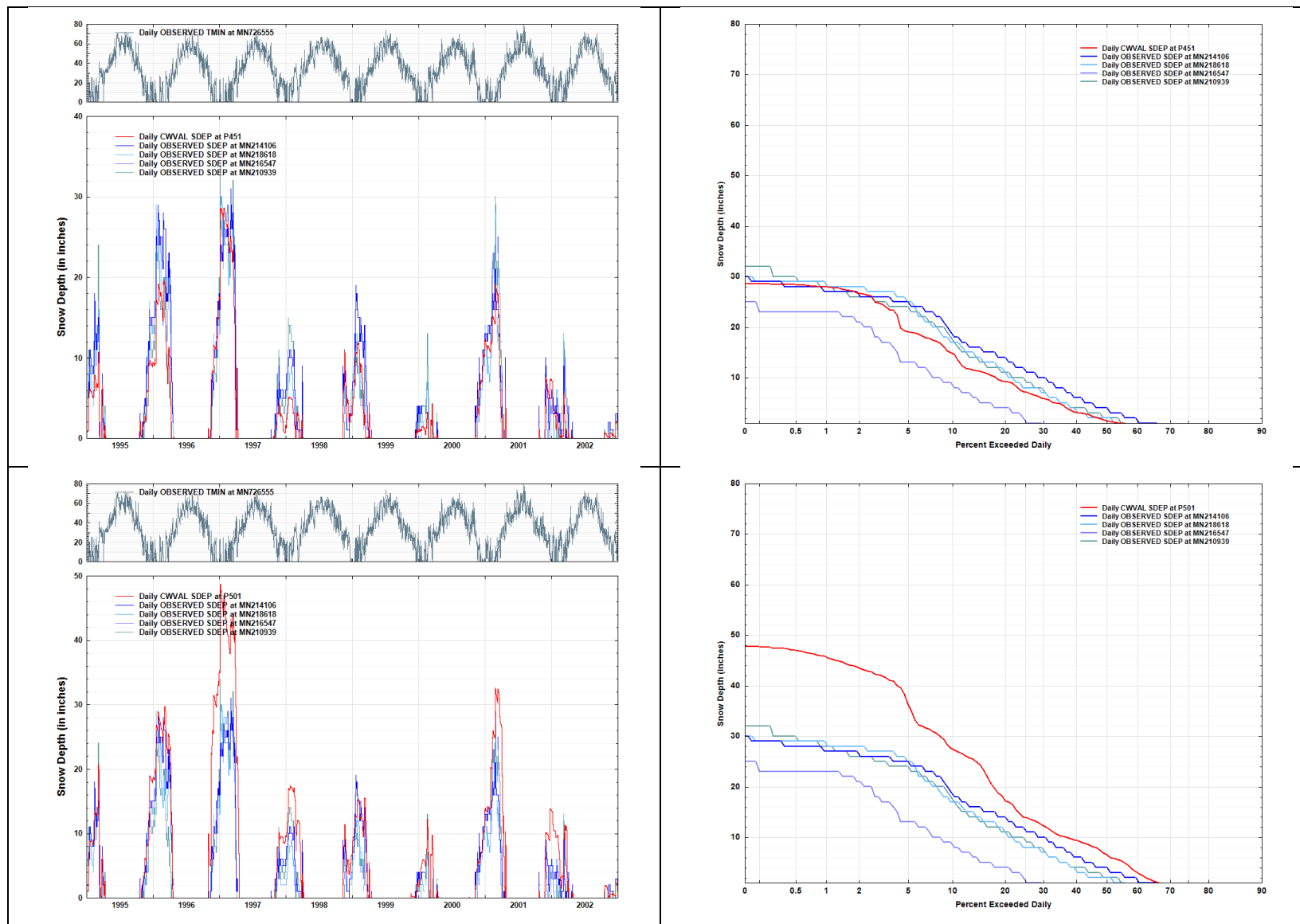


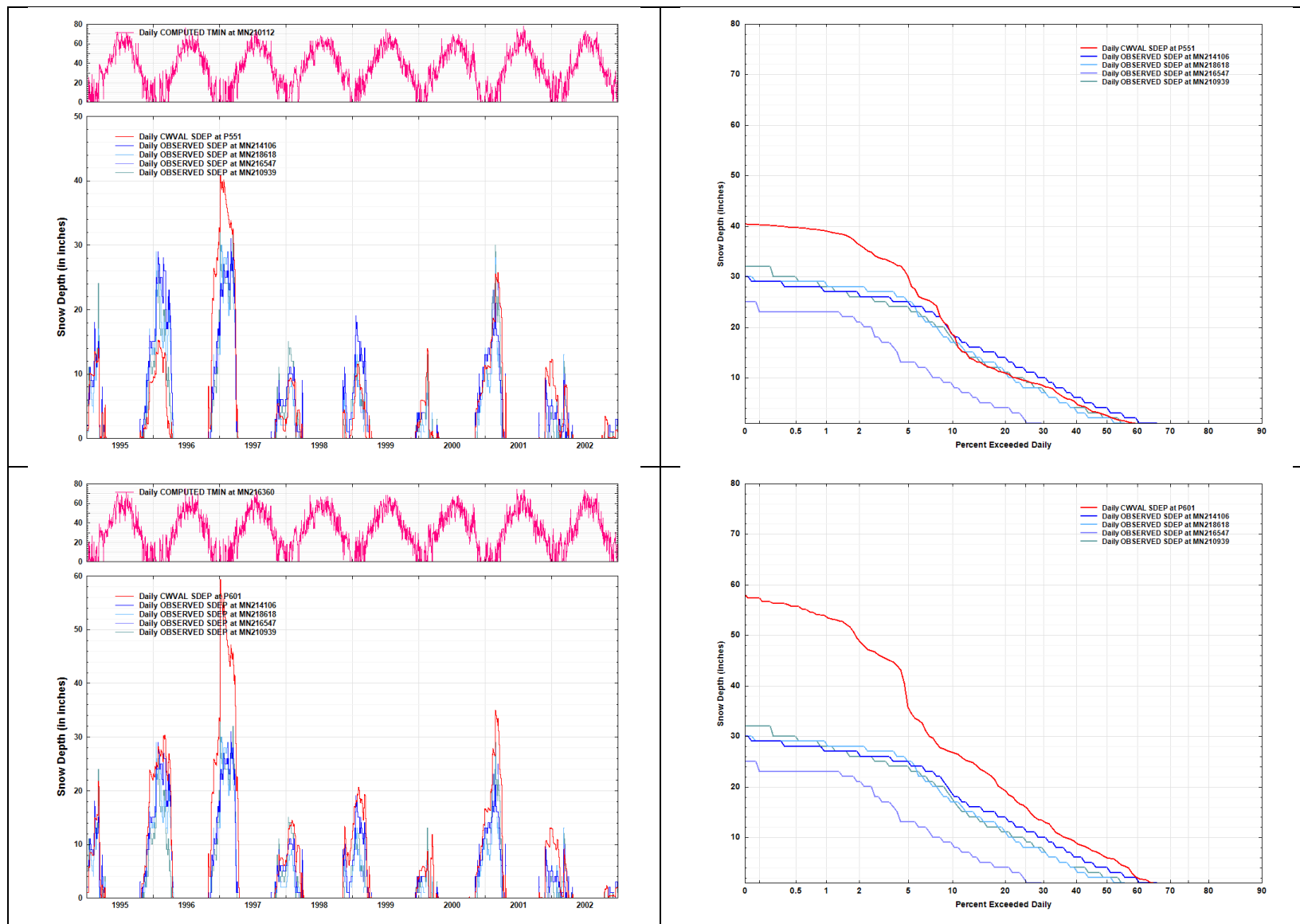
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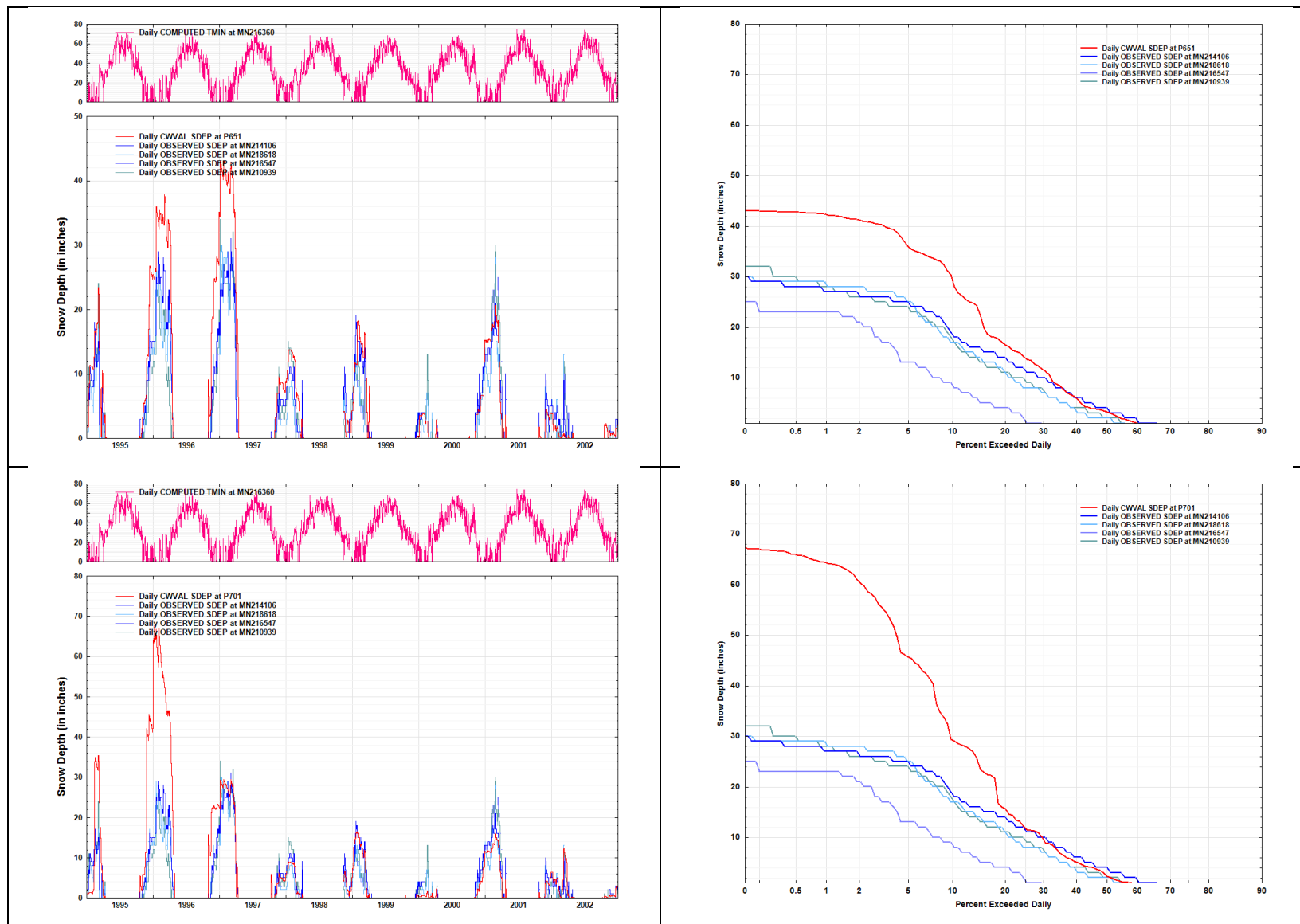


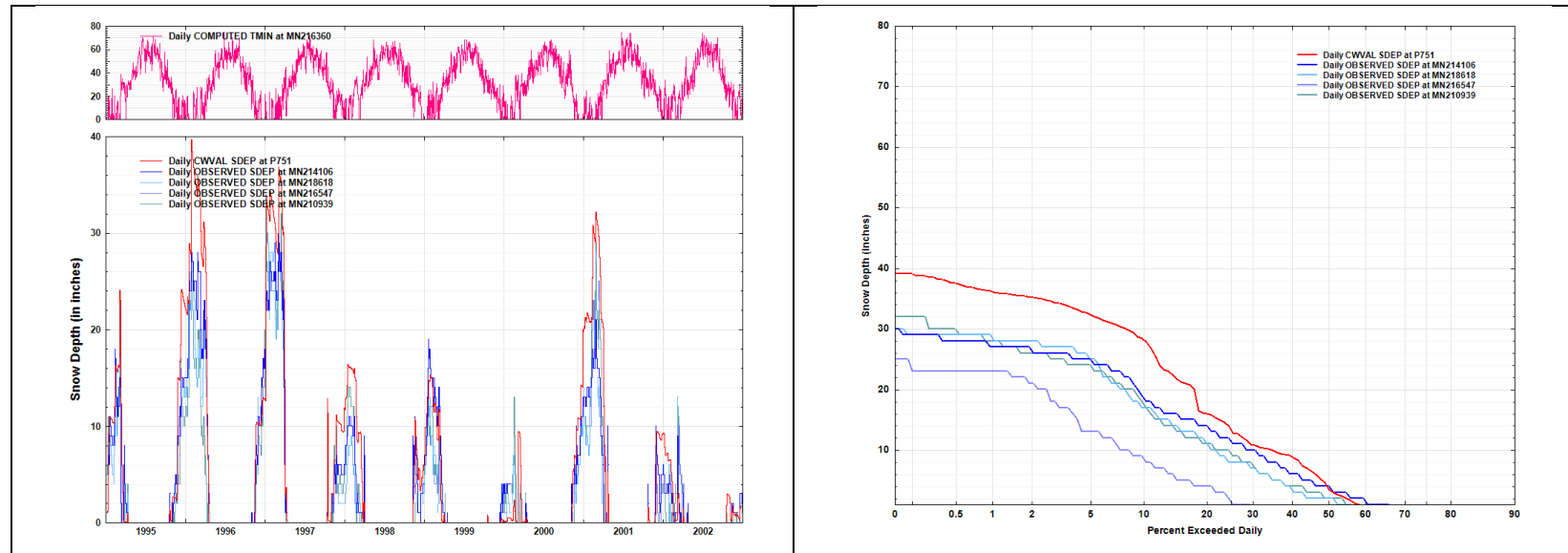








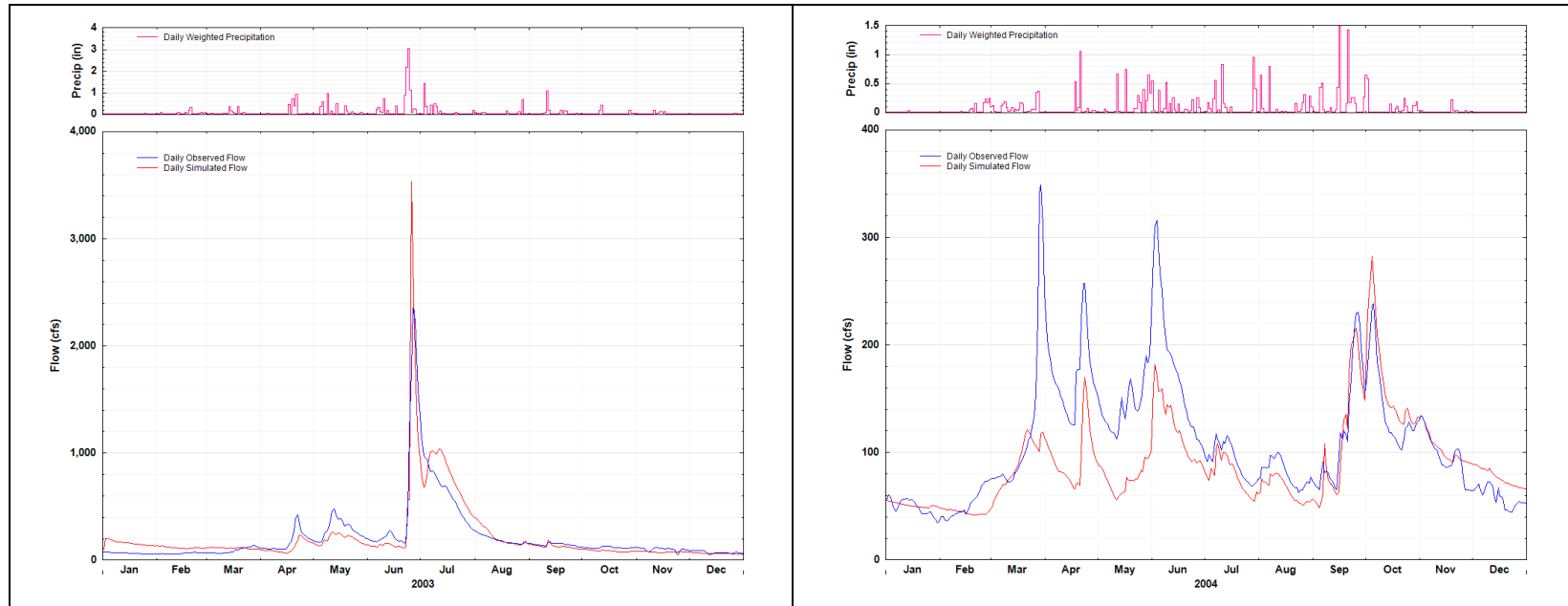


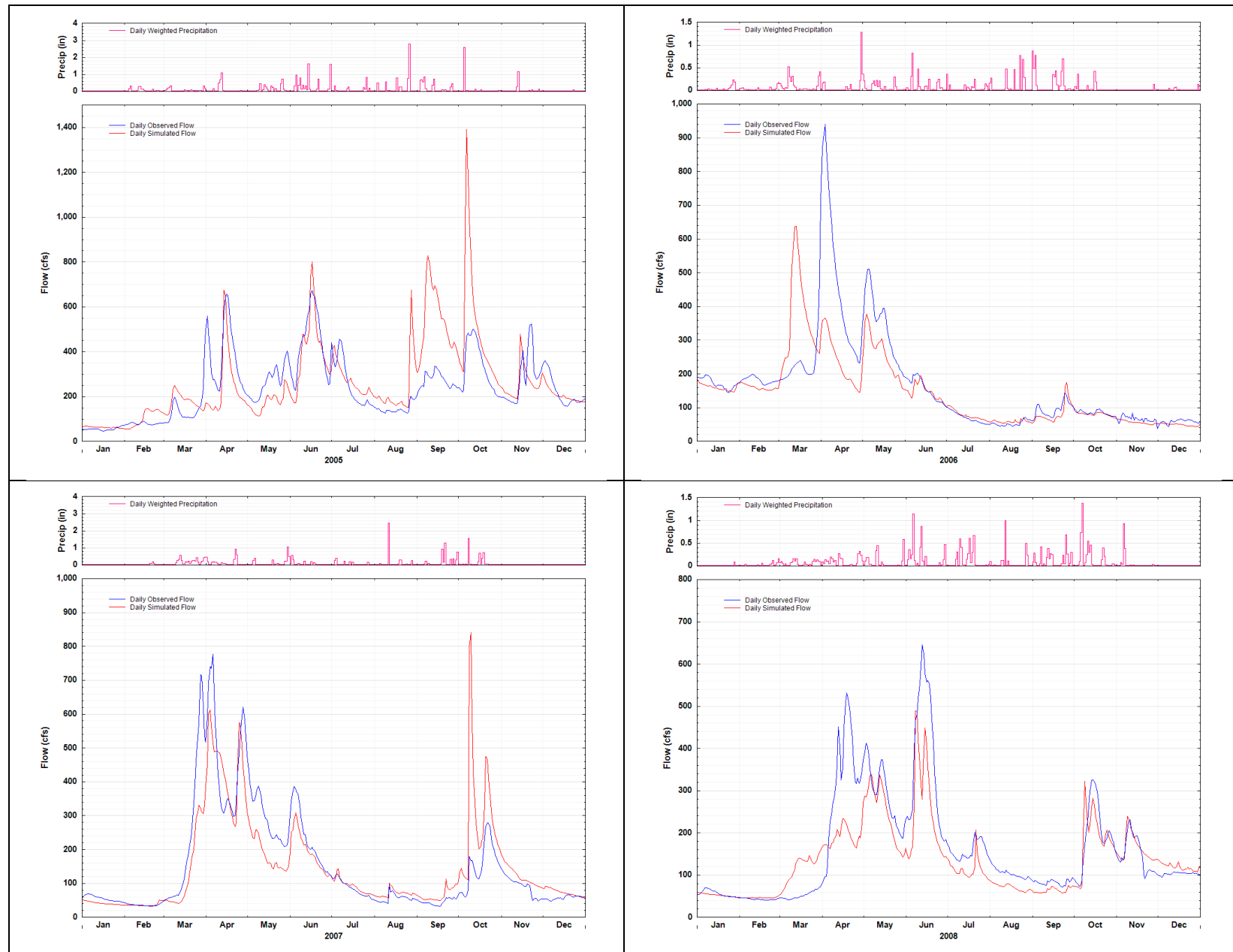


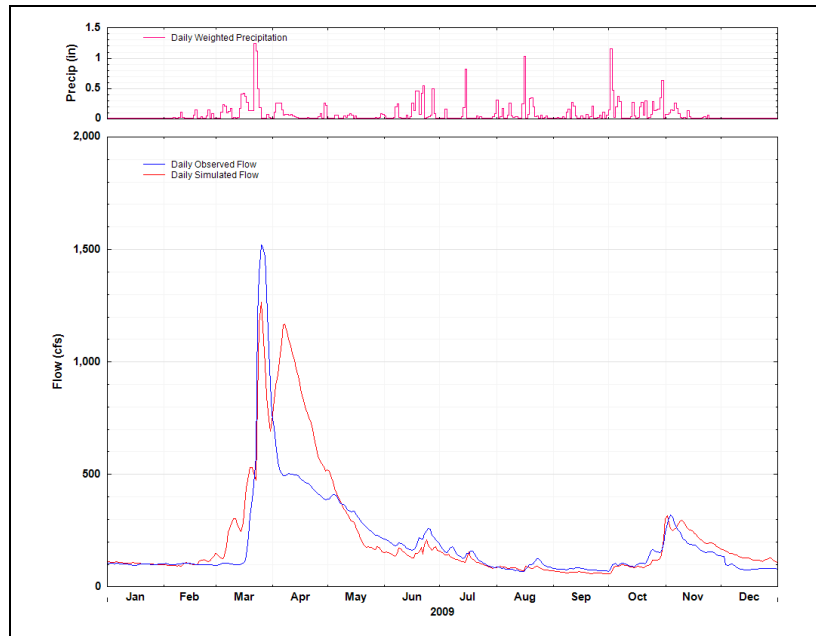
APPENDIX C YEARLY HYDROGRAPHS FOR THE CALIBRATION PERIOD

C.1 LONG PRAIRIE RIVER WATERSHED

C.1.1 USGS gage 05245100



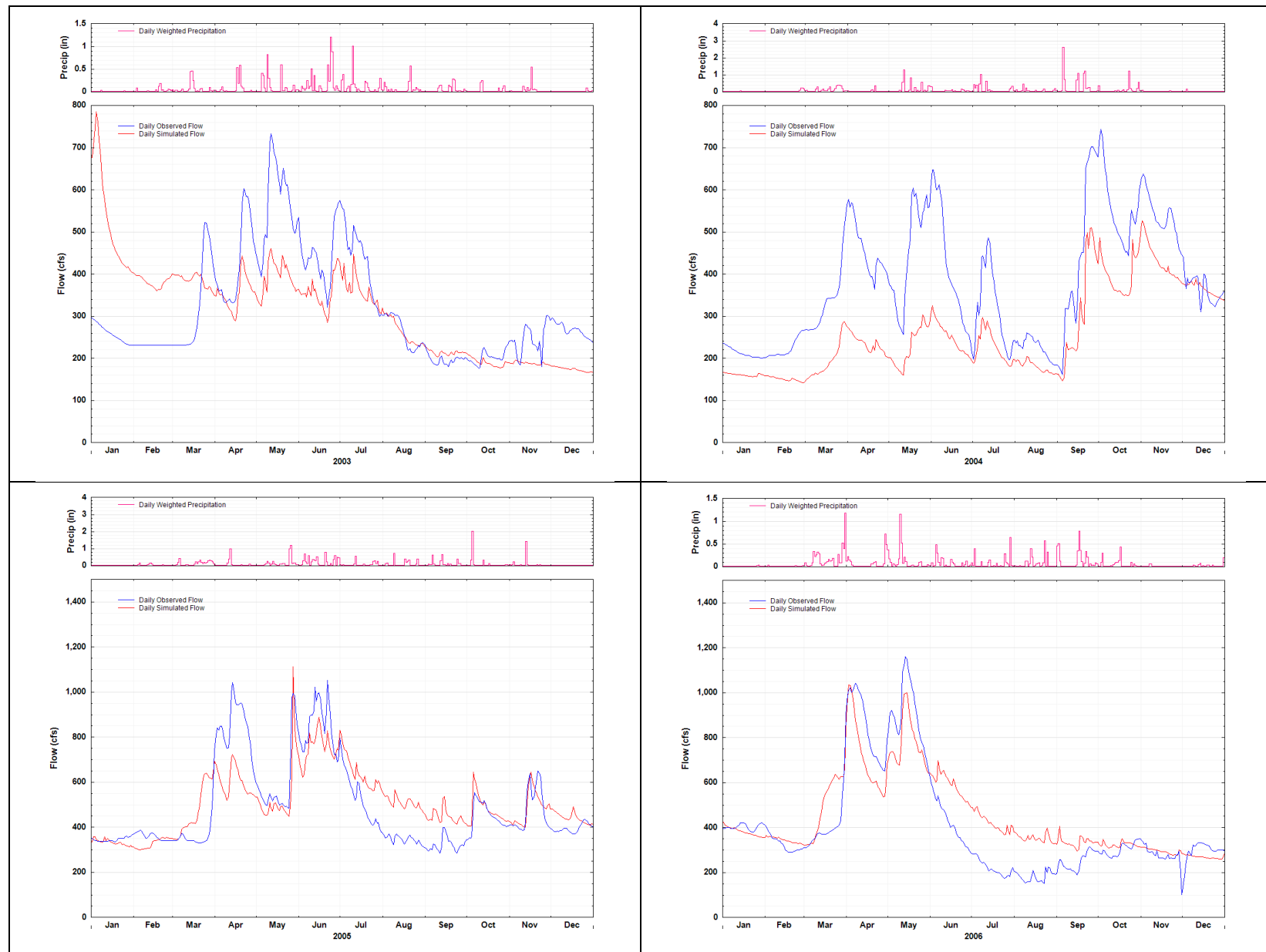




C.2 CROW WING RIVER WATERSHED**C.2.1 USGS gage 05243725**

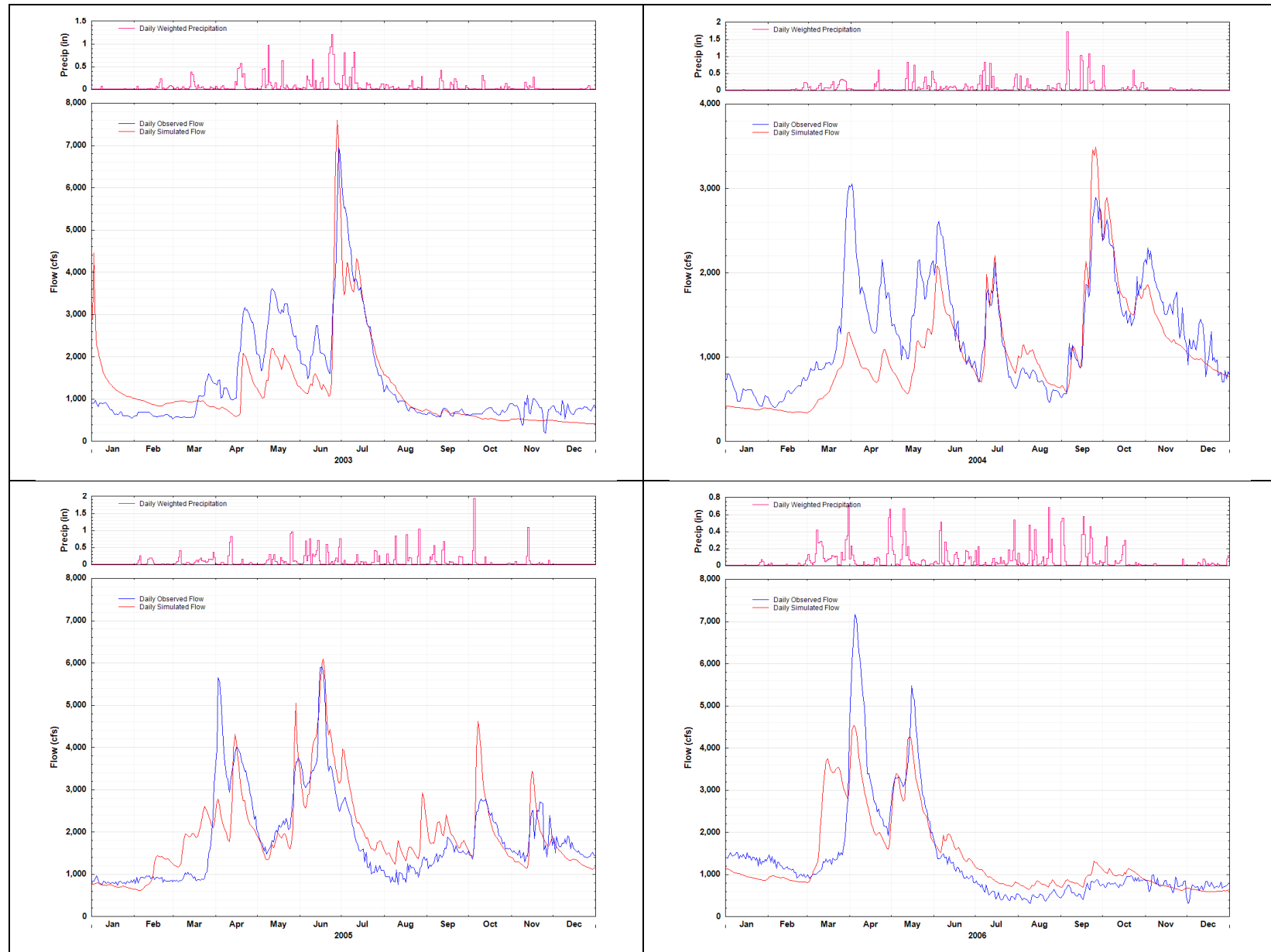


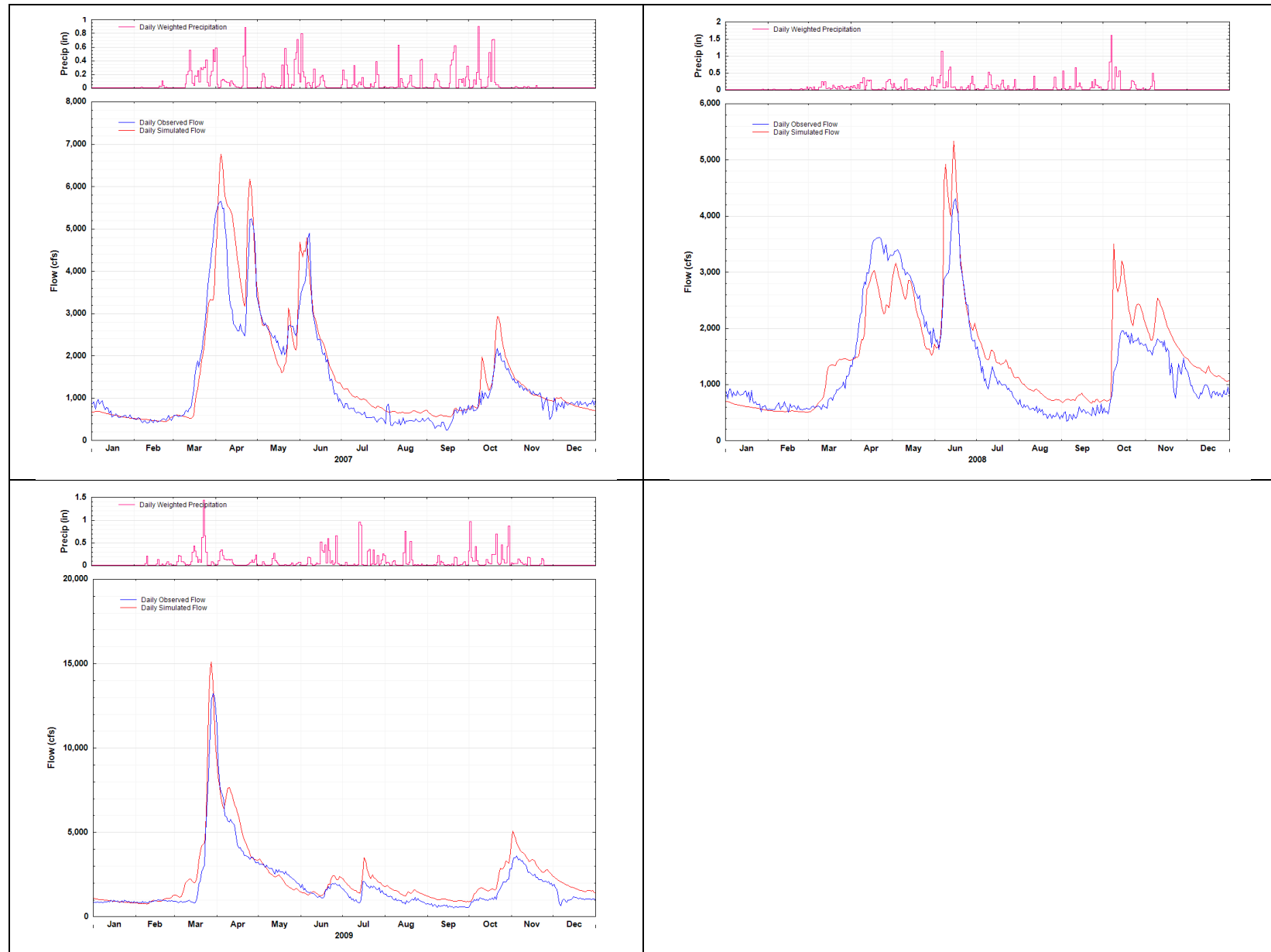
C.2.2 USGS gage 05244000





C.2.3 USGS gage 05247500

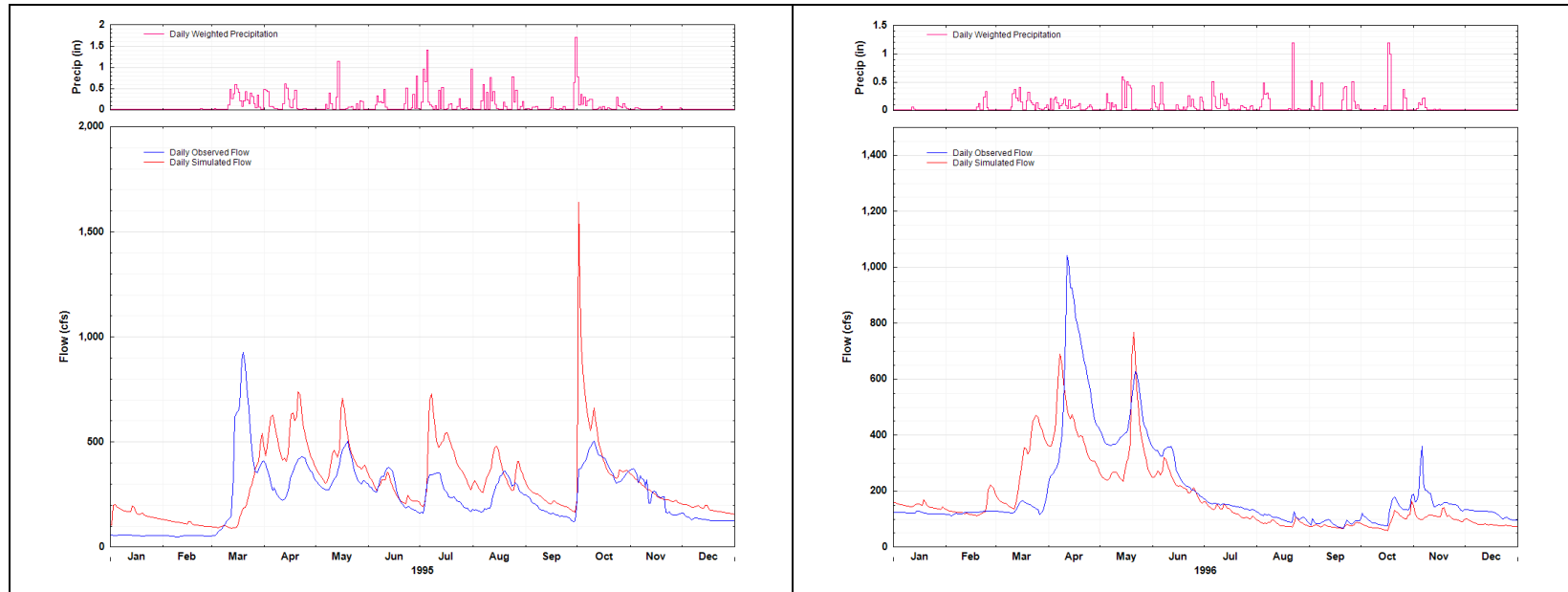


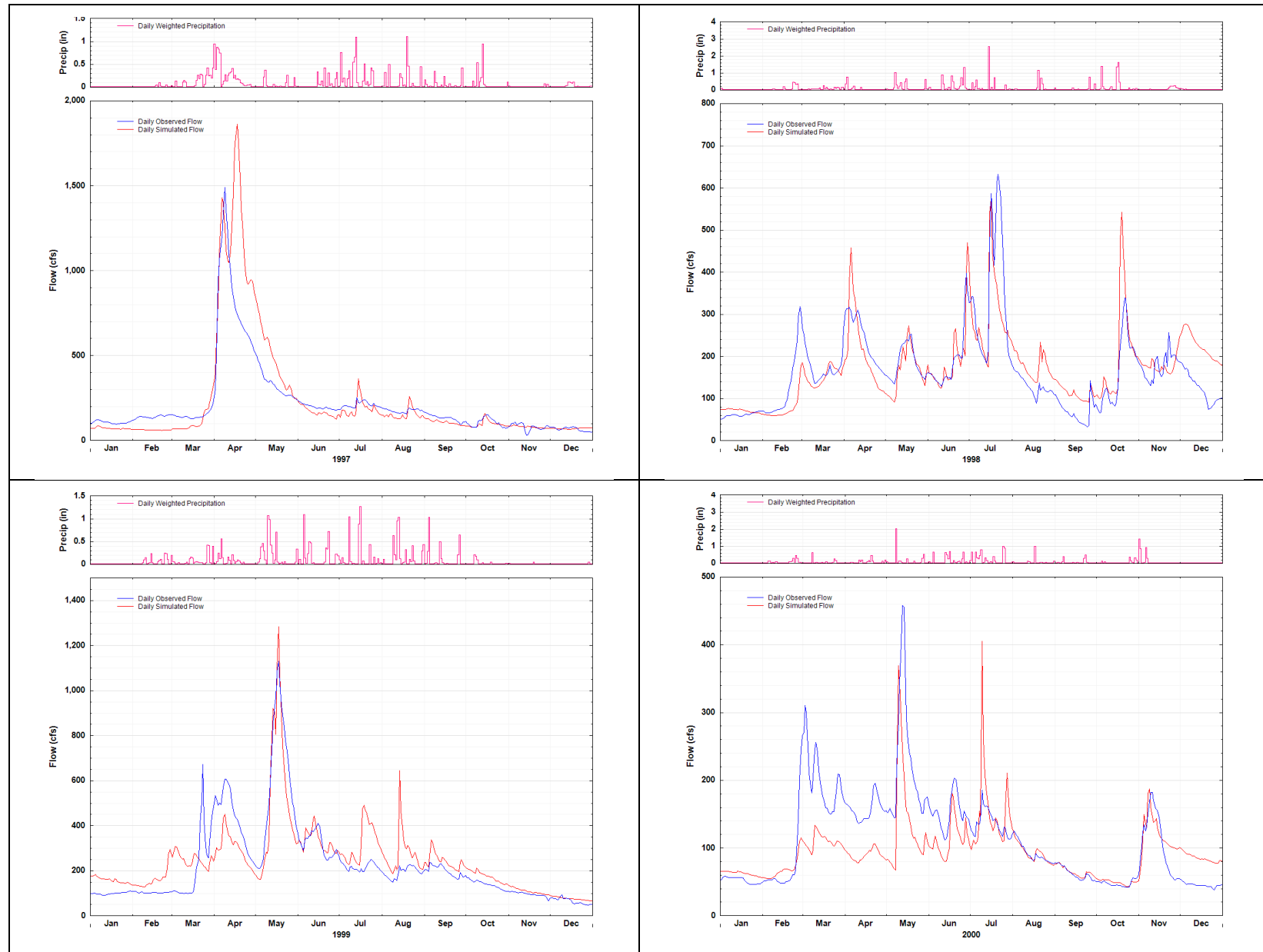


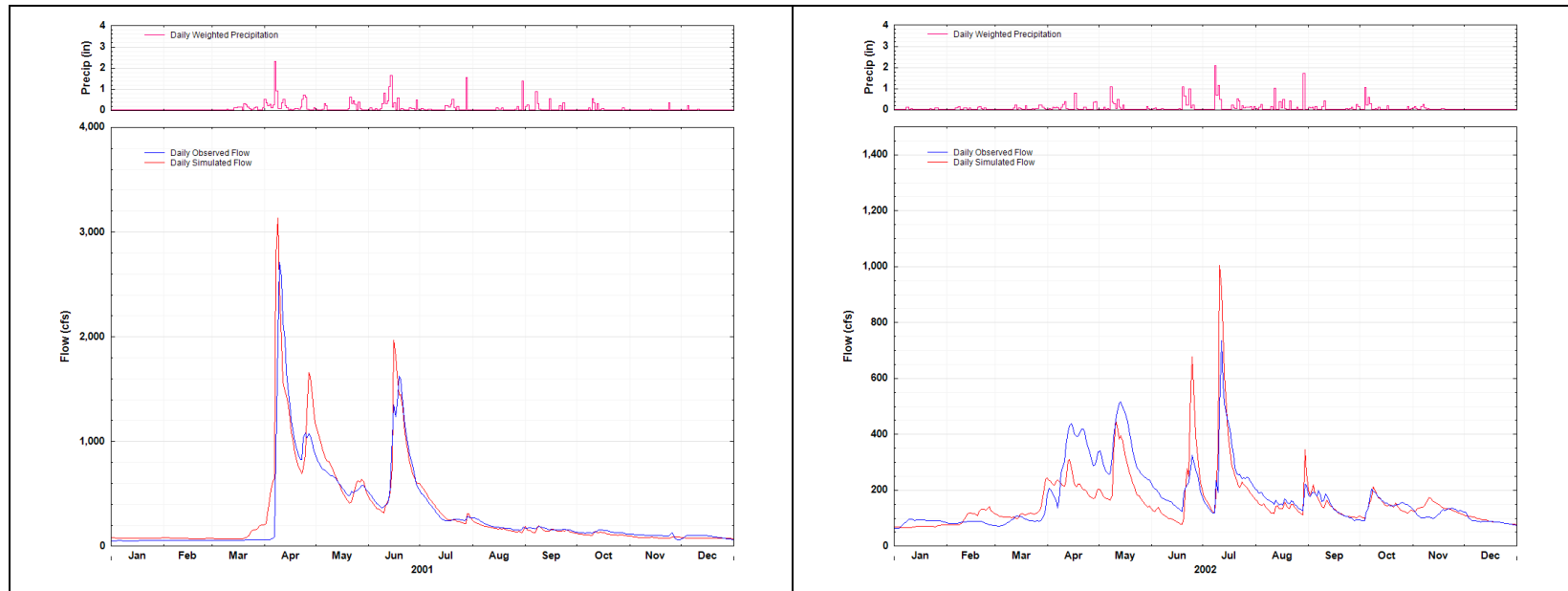
APPENDIX D YEARLY HYDROGRAPHS FOR THE VALIDATION PERIOD

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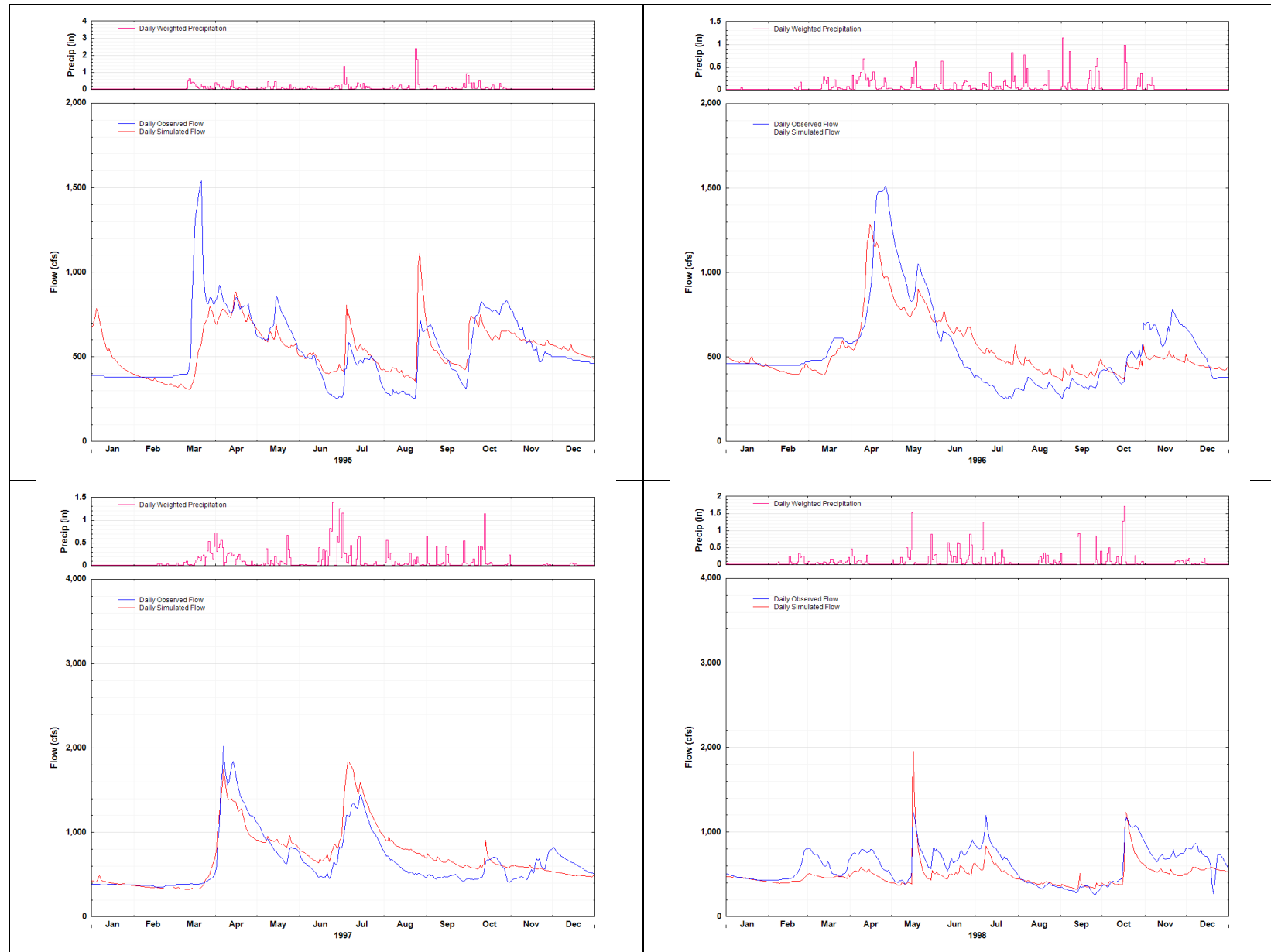


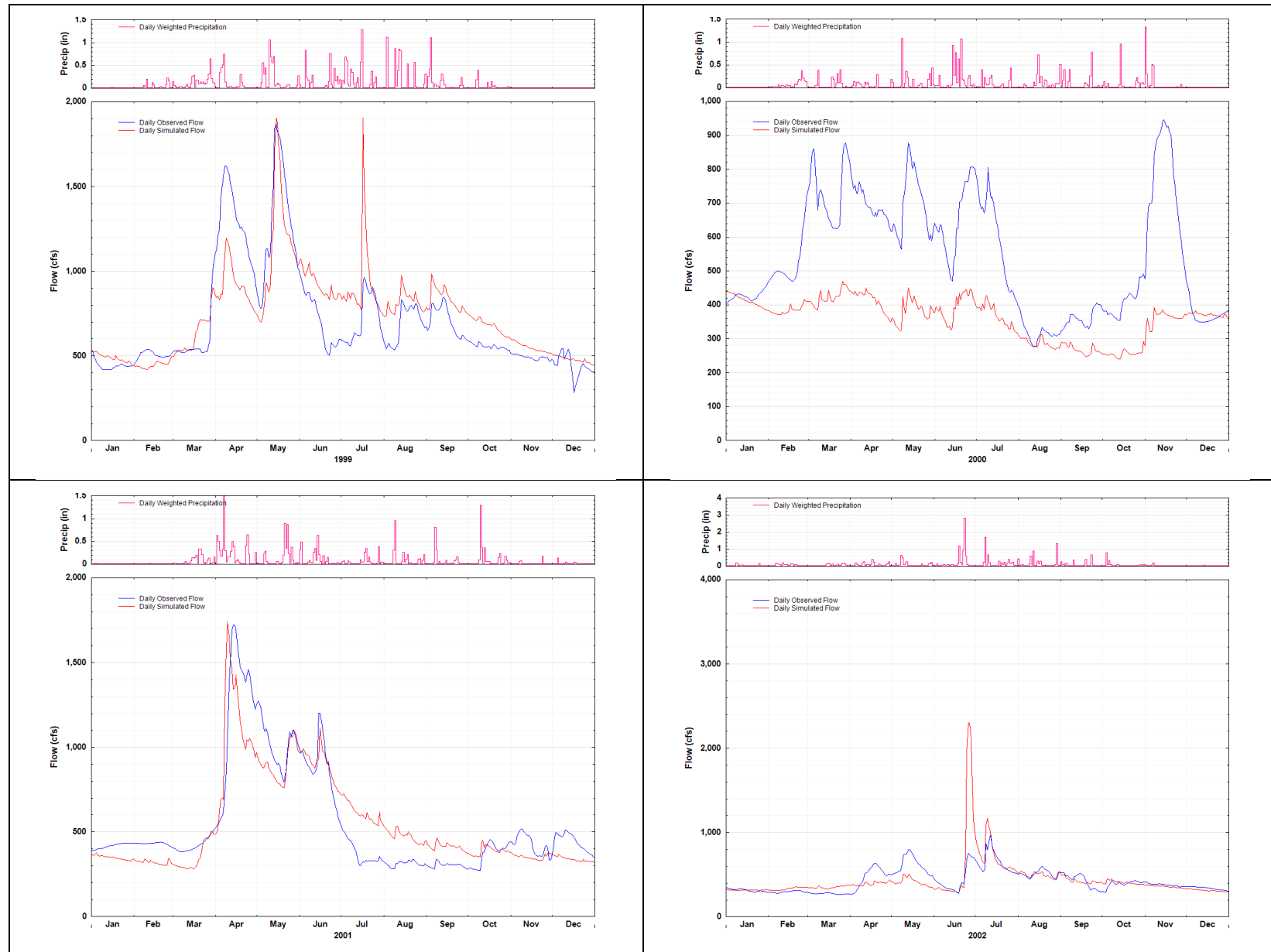


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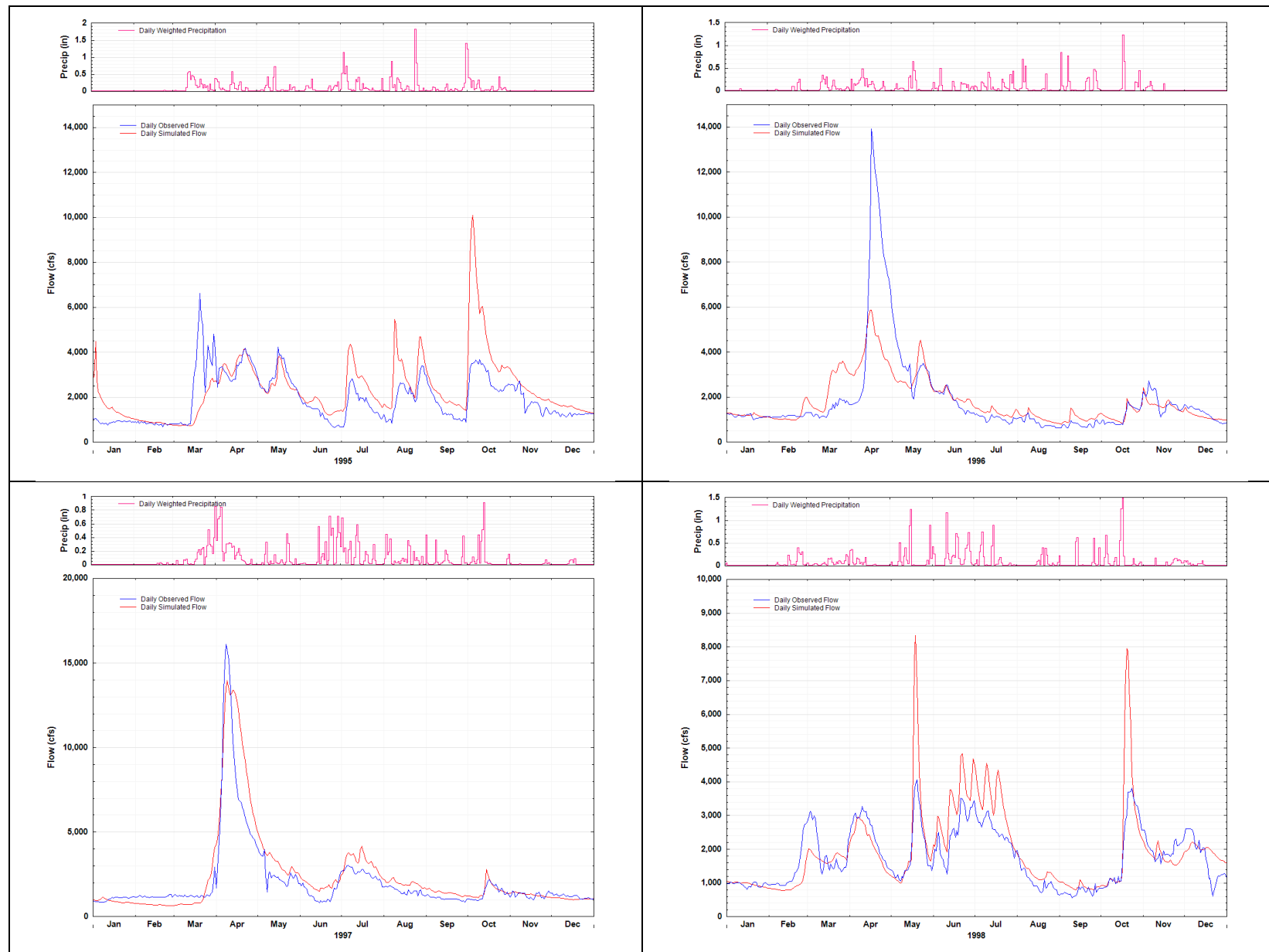


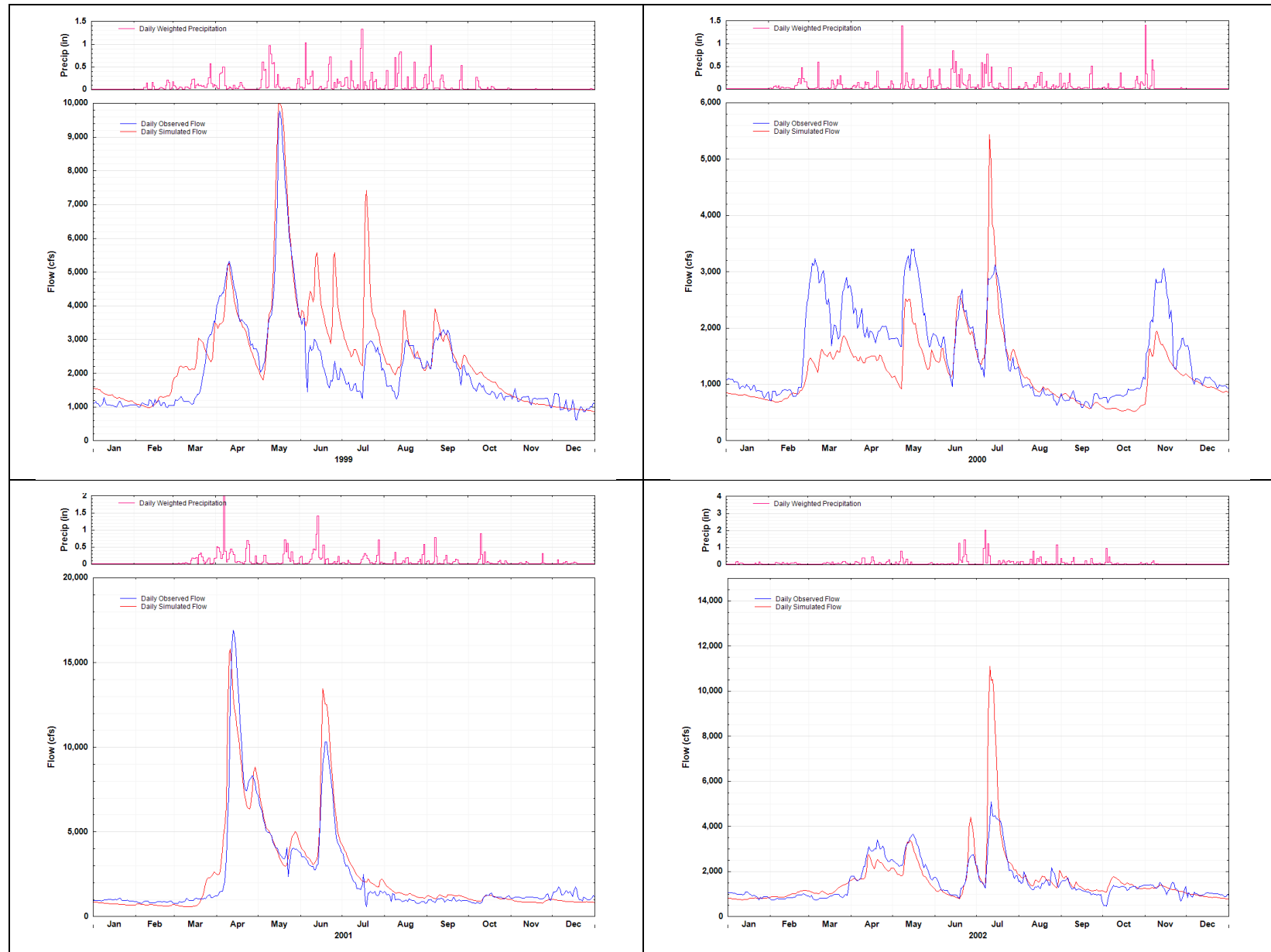
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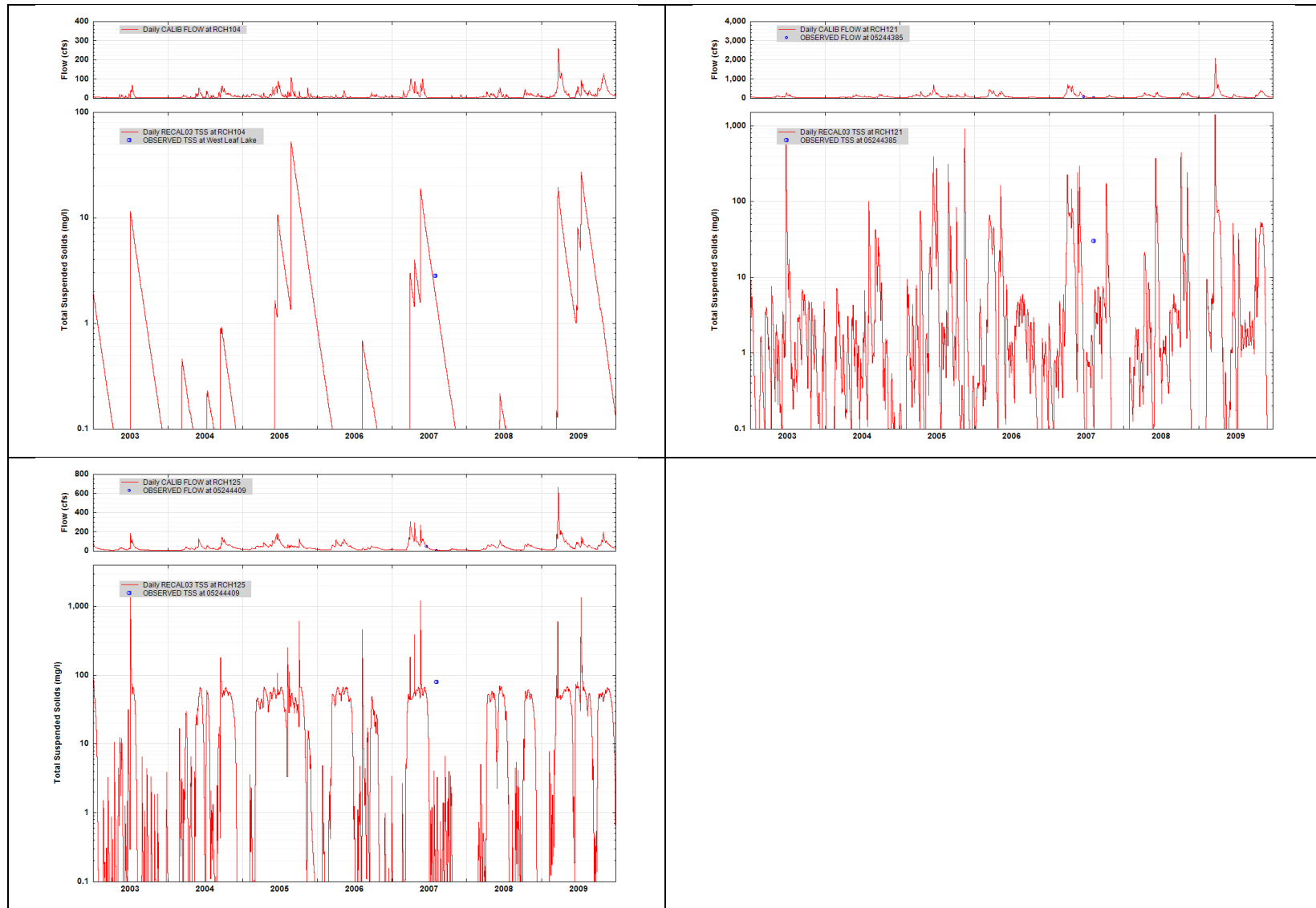
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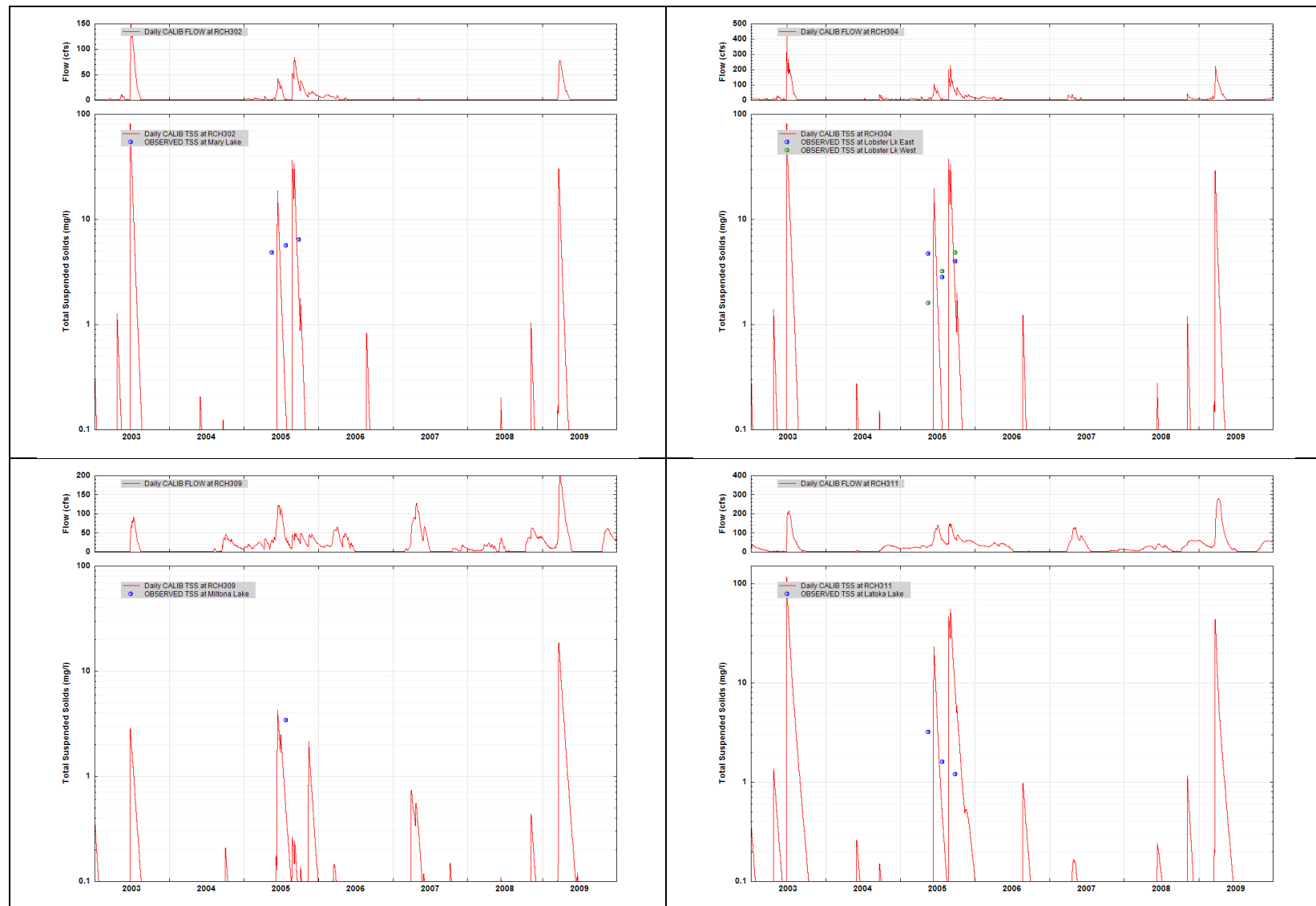


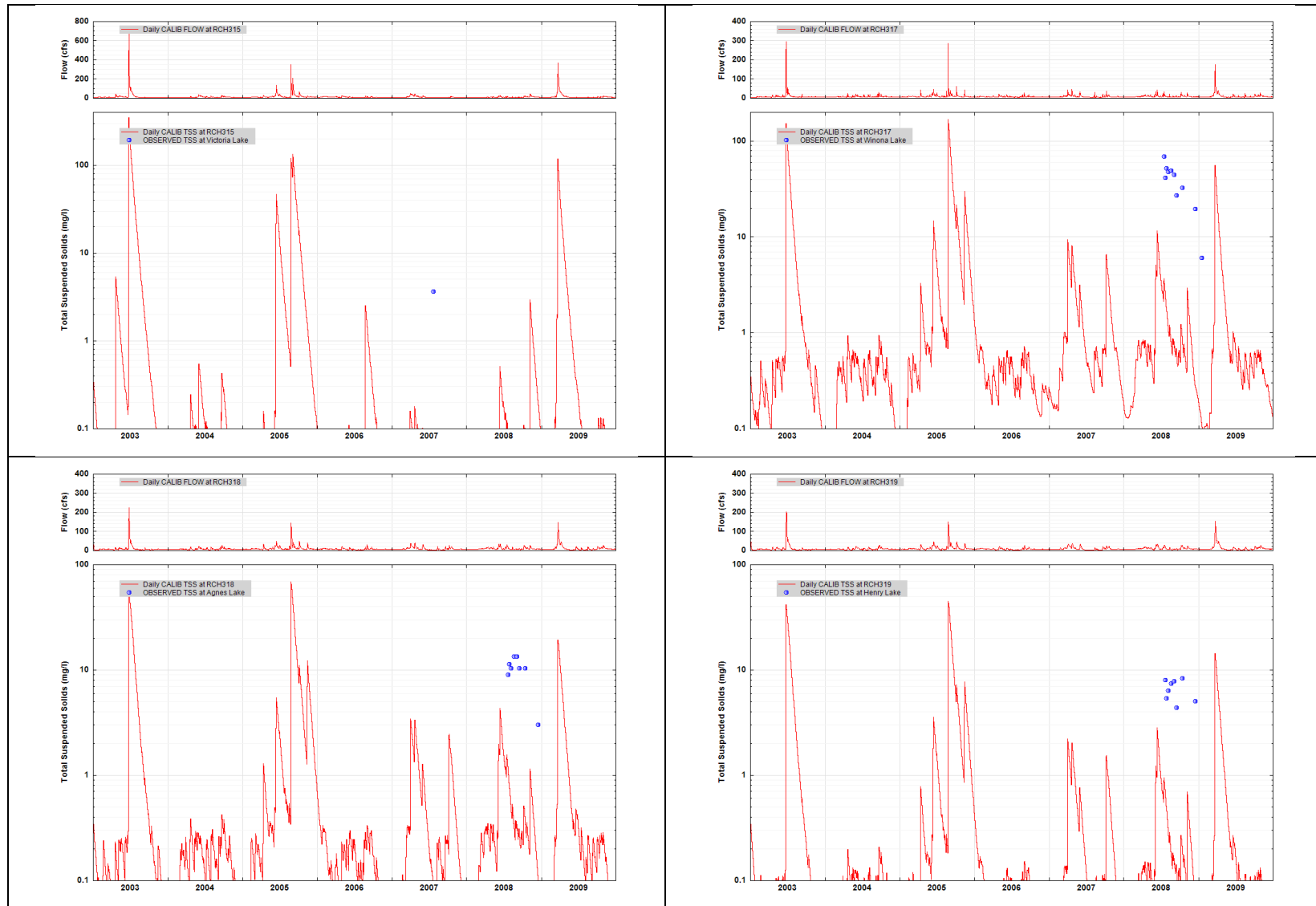


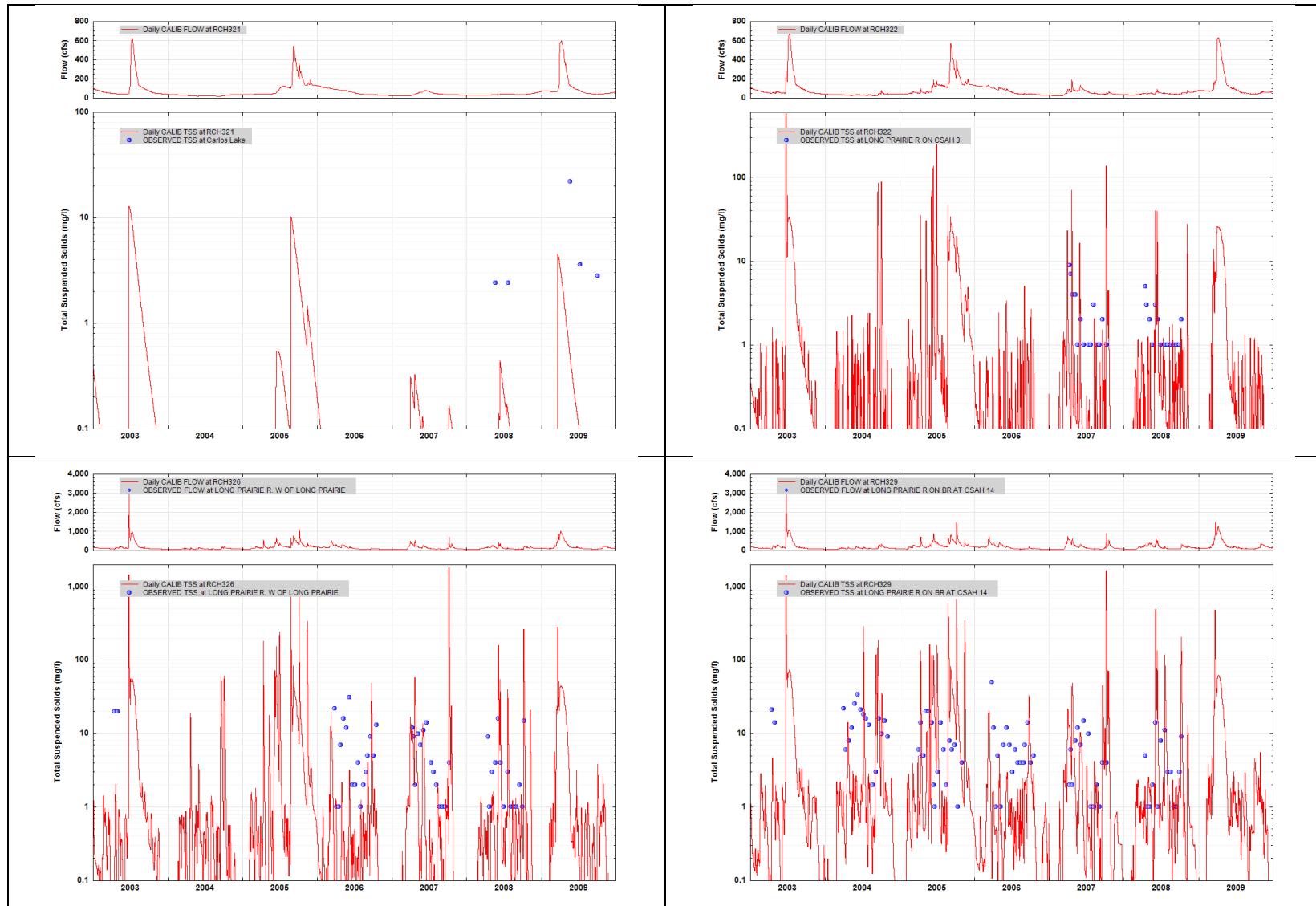
APPENDIX E OBSERVED AND SIMULATED WATER TSS GRAPHS FOR THE CALIBRATION PERIOD

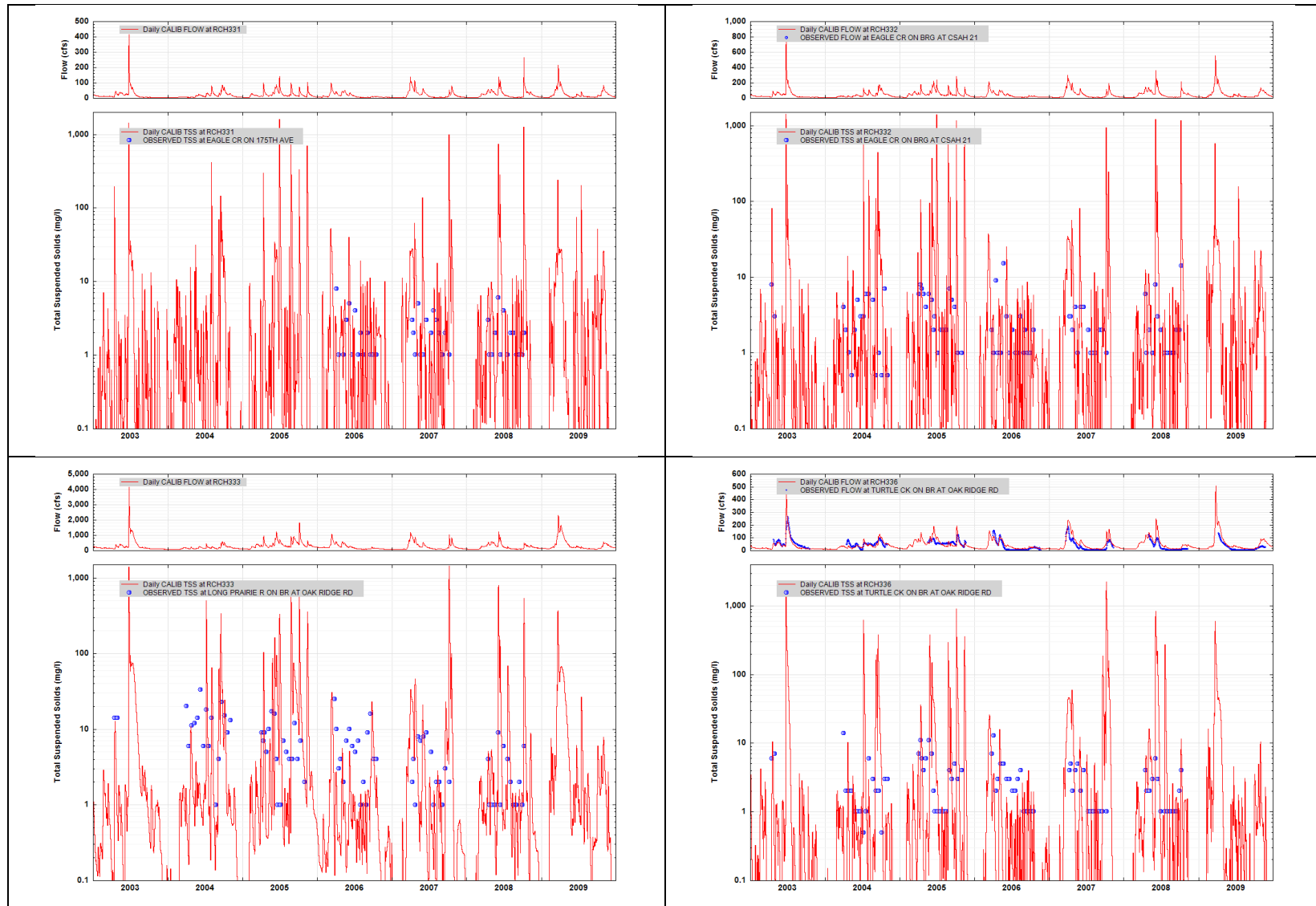
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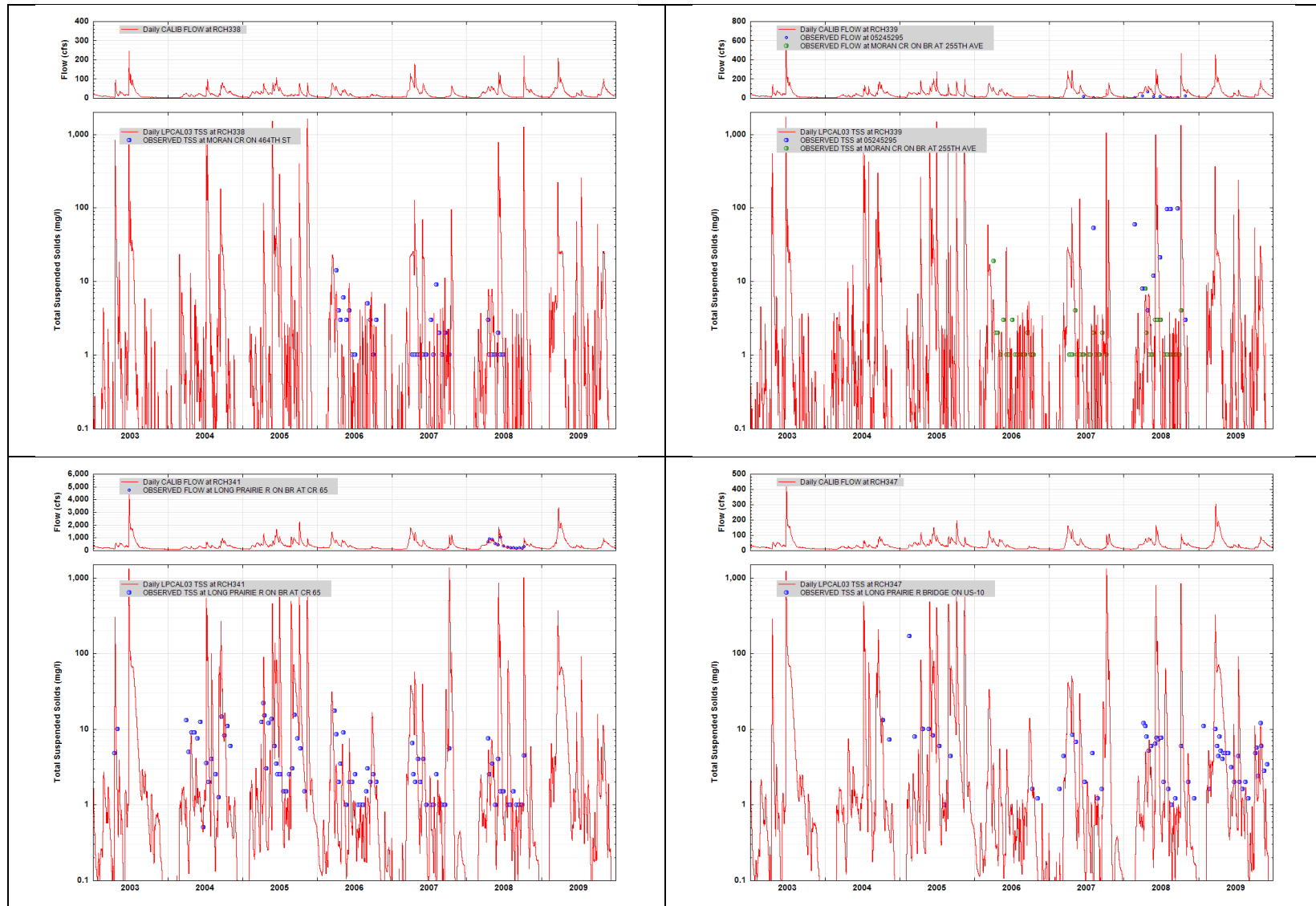


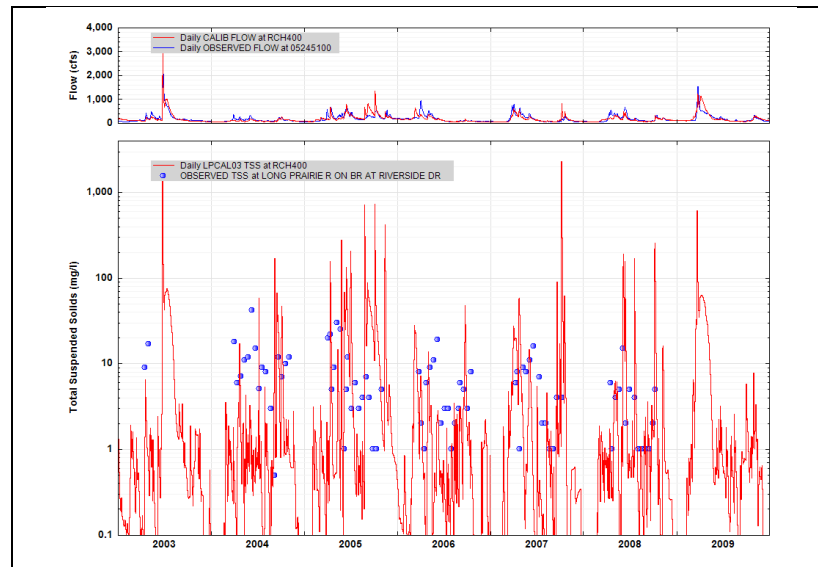
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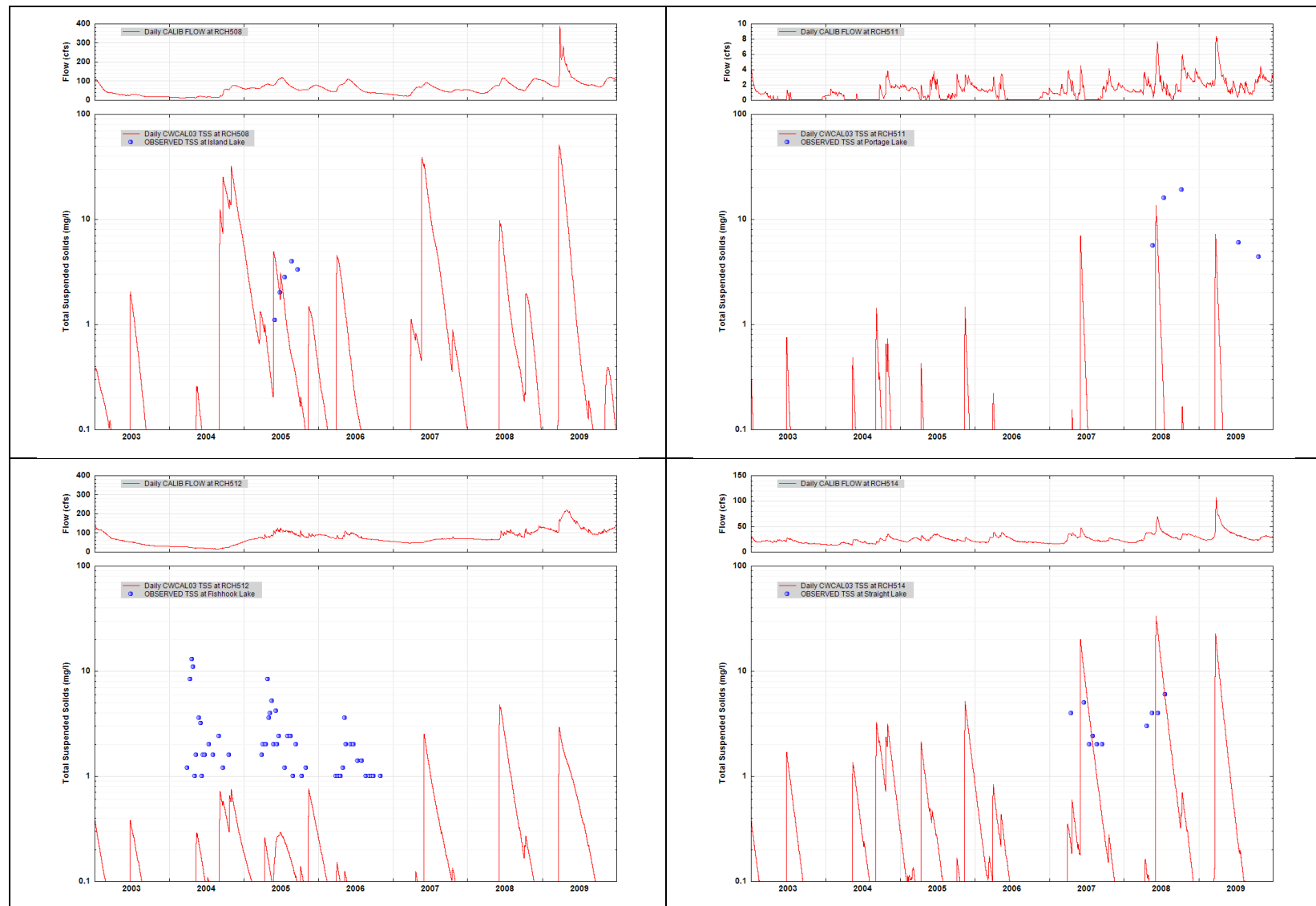


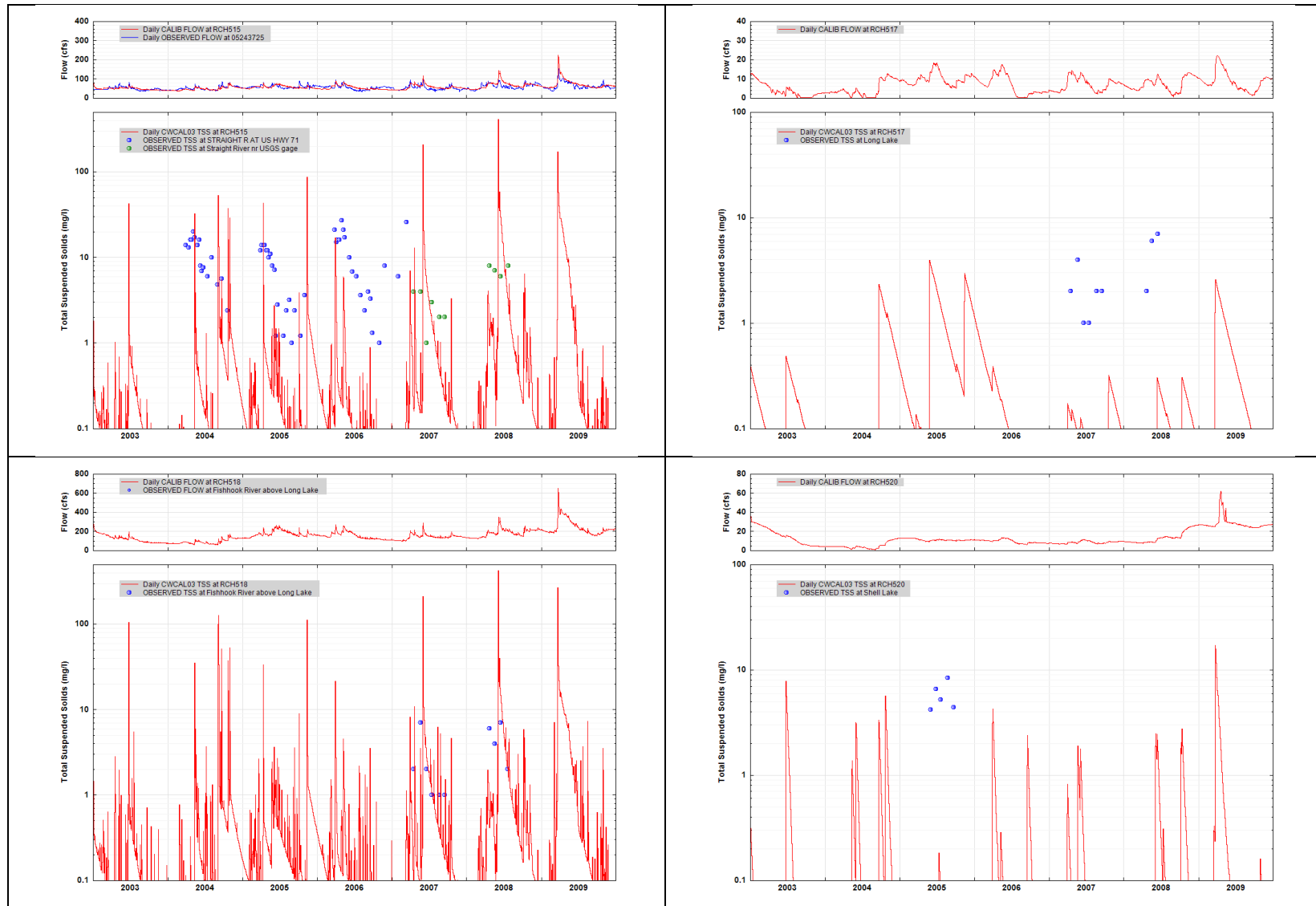


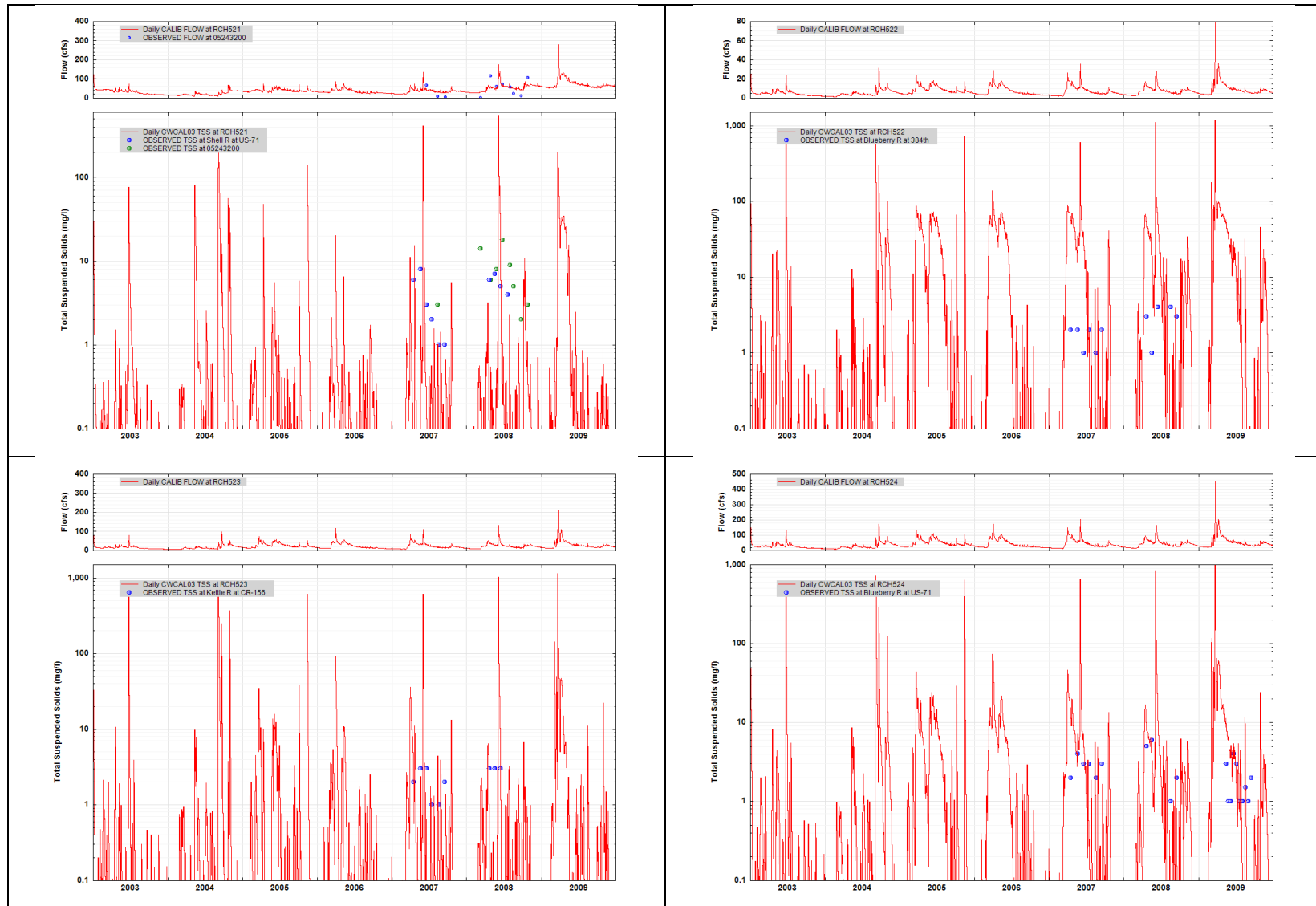


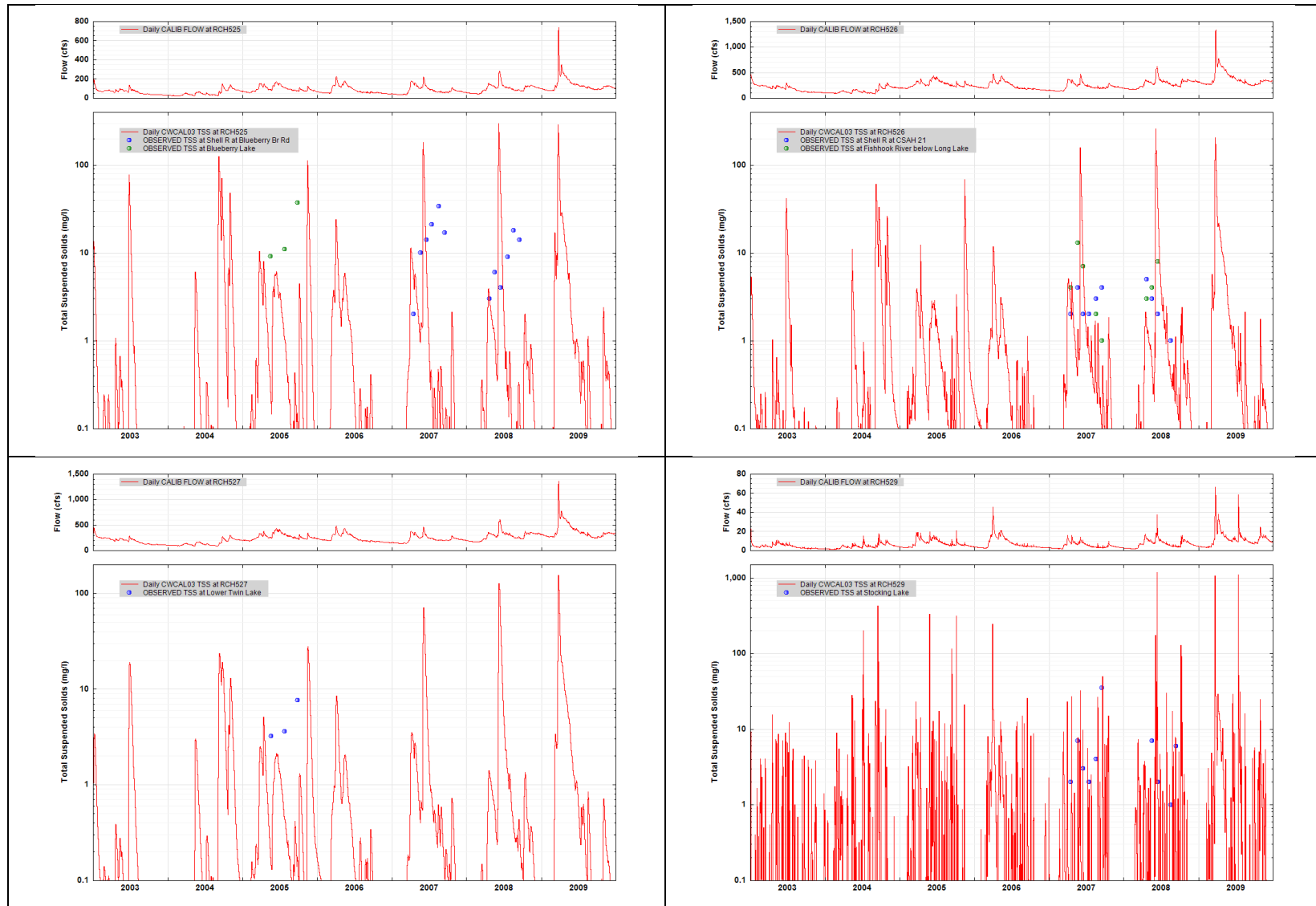


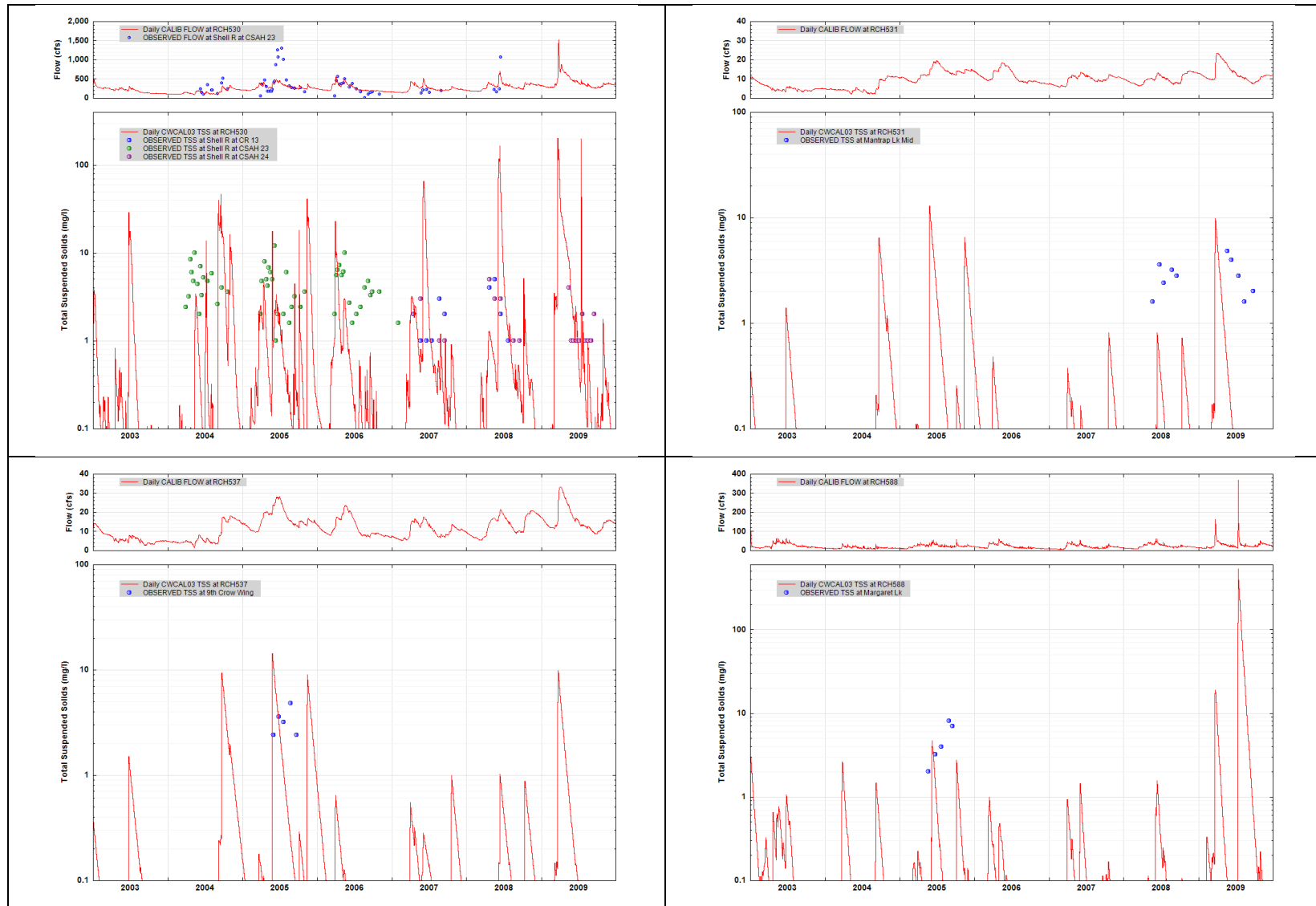


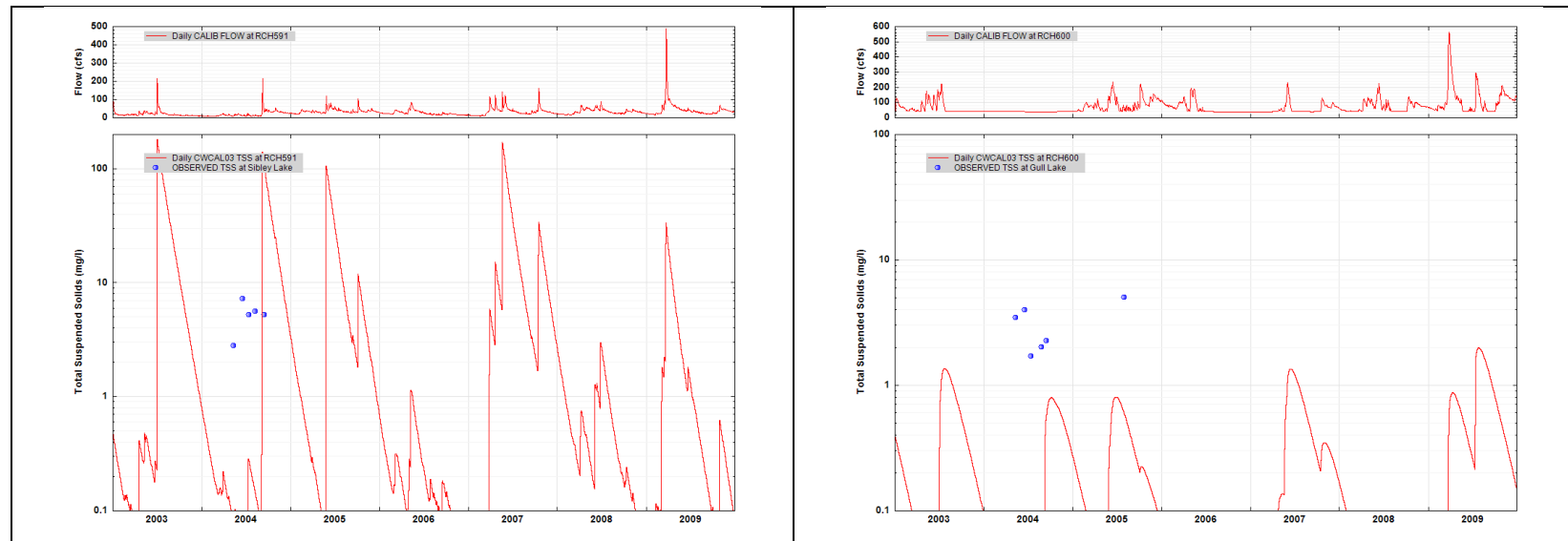
E.3 CROW WING RIVER WATERSHED





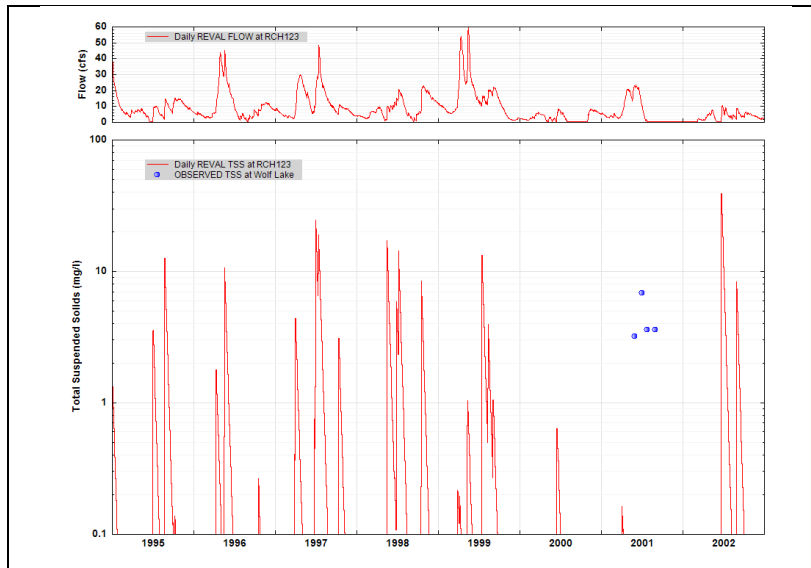


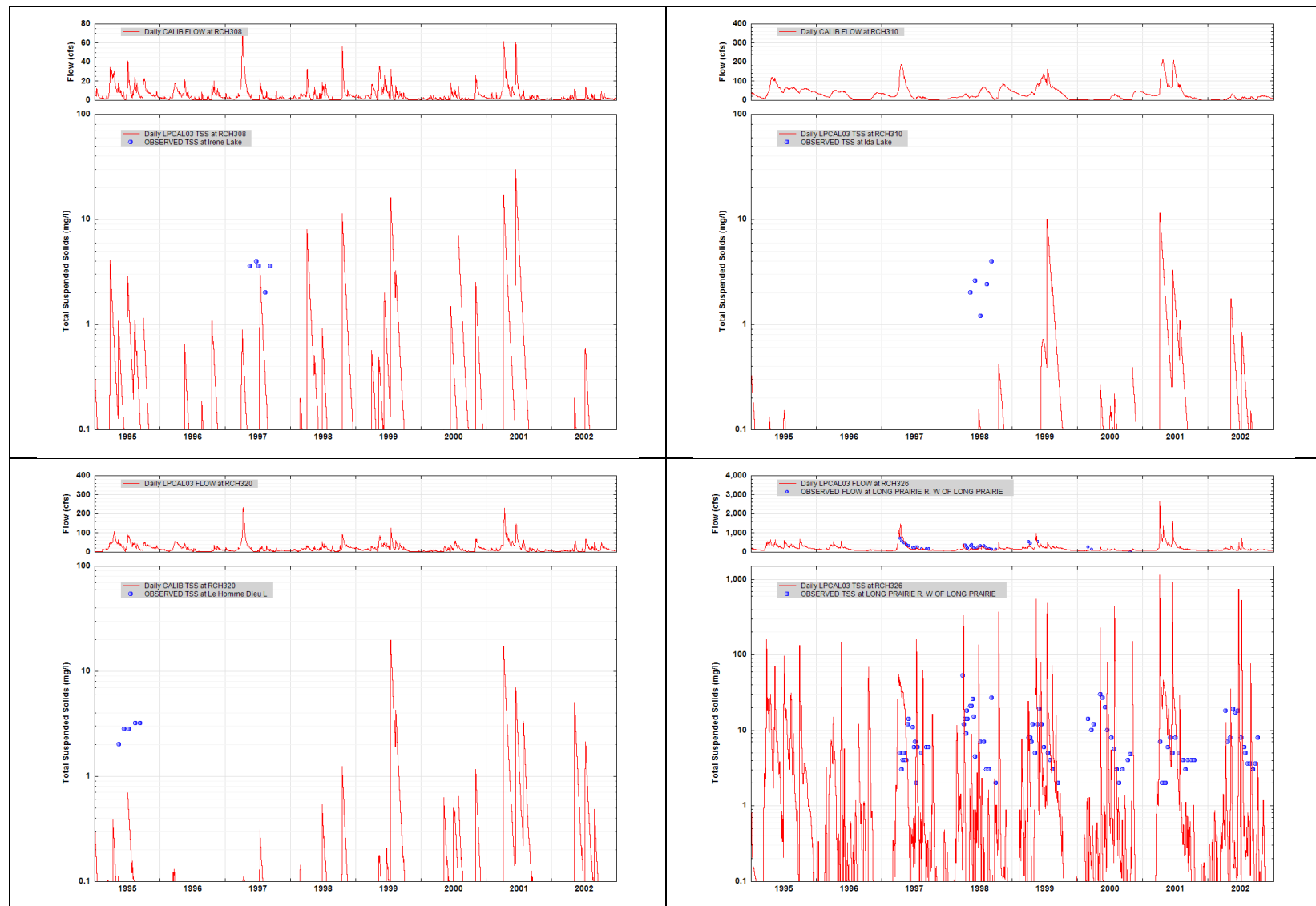


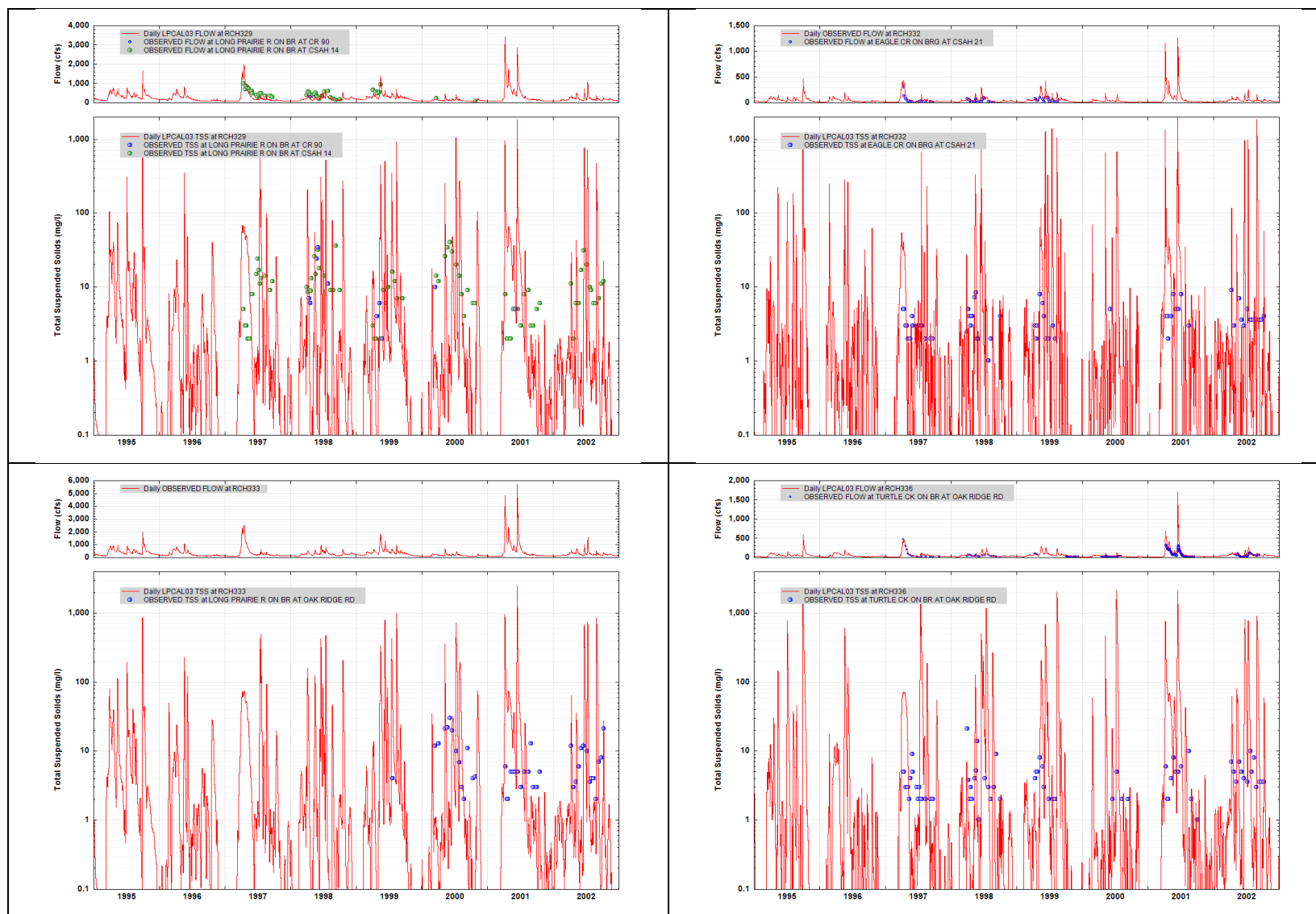


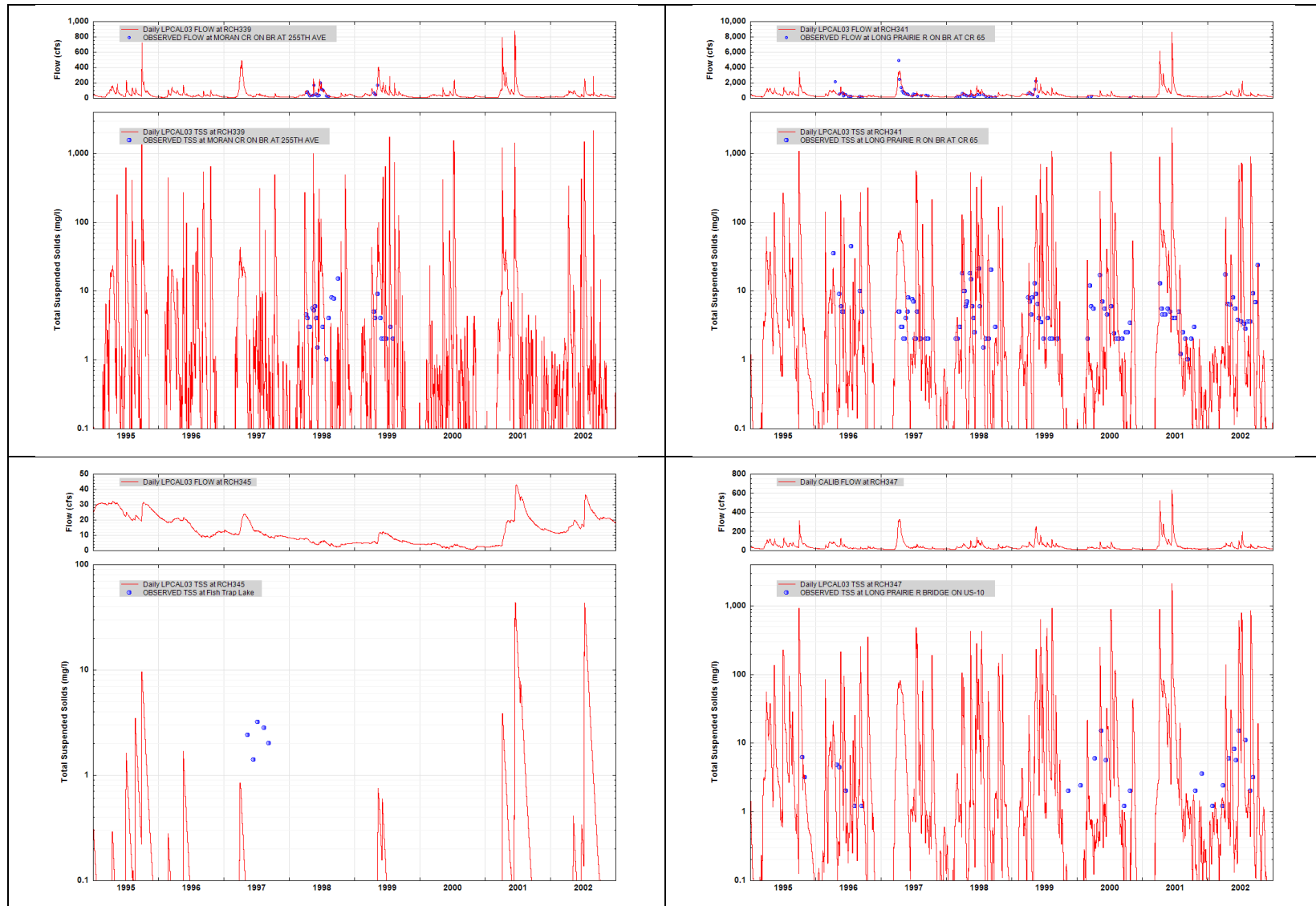
APPENDIX F OBSERVED AND SIMULATED WATER TSS GRAPHS FOR THE VALIDATION PERIOD

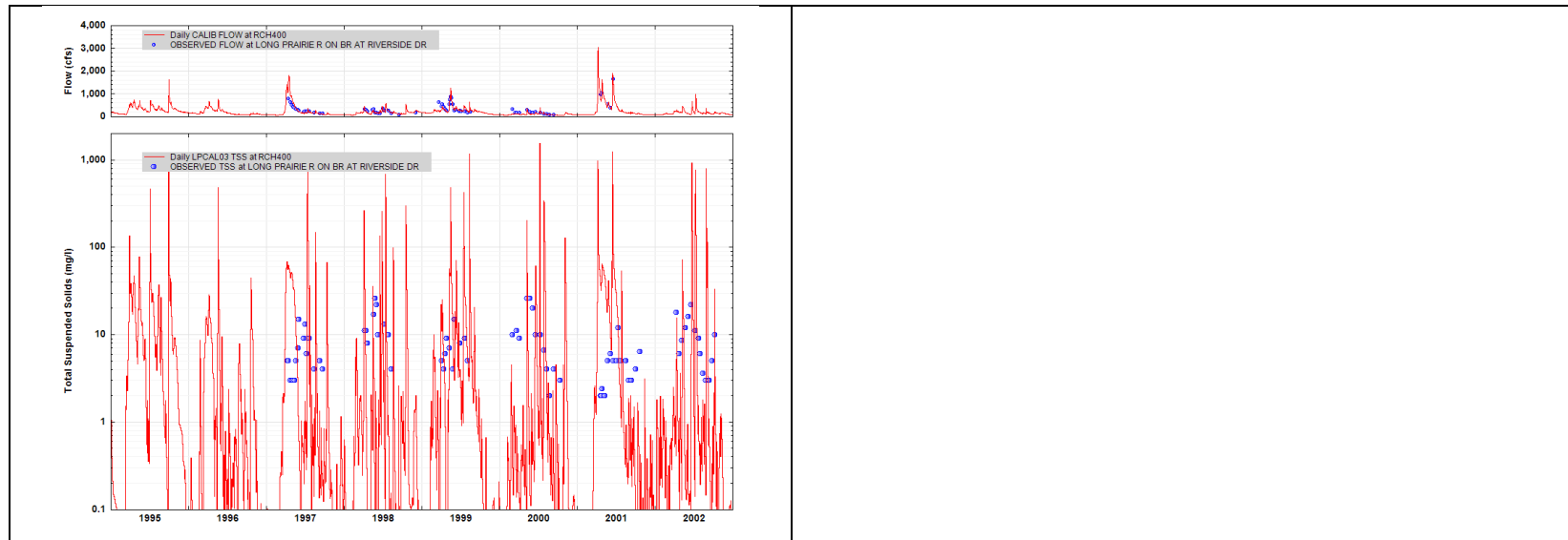
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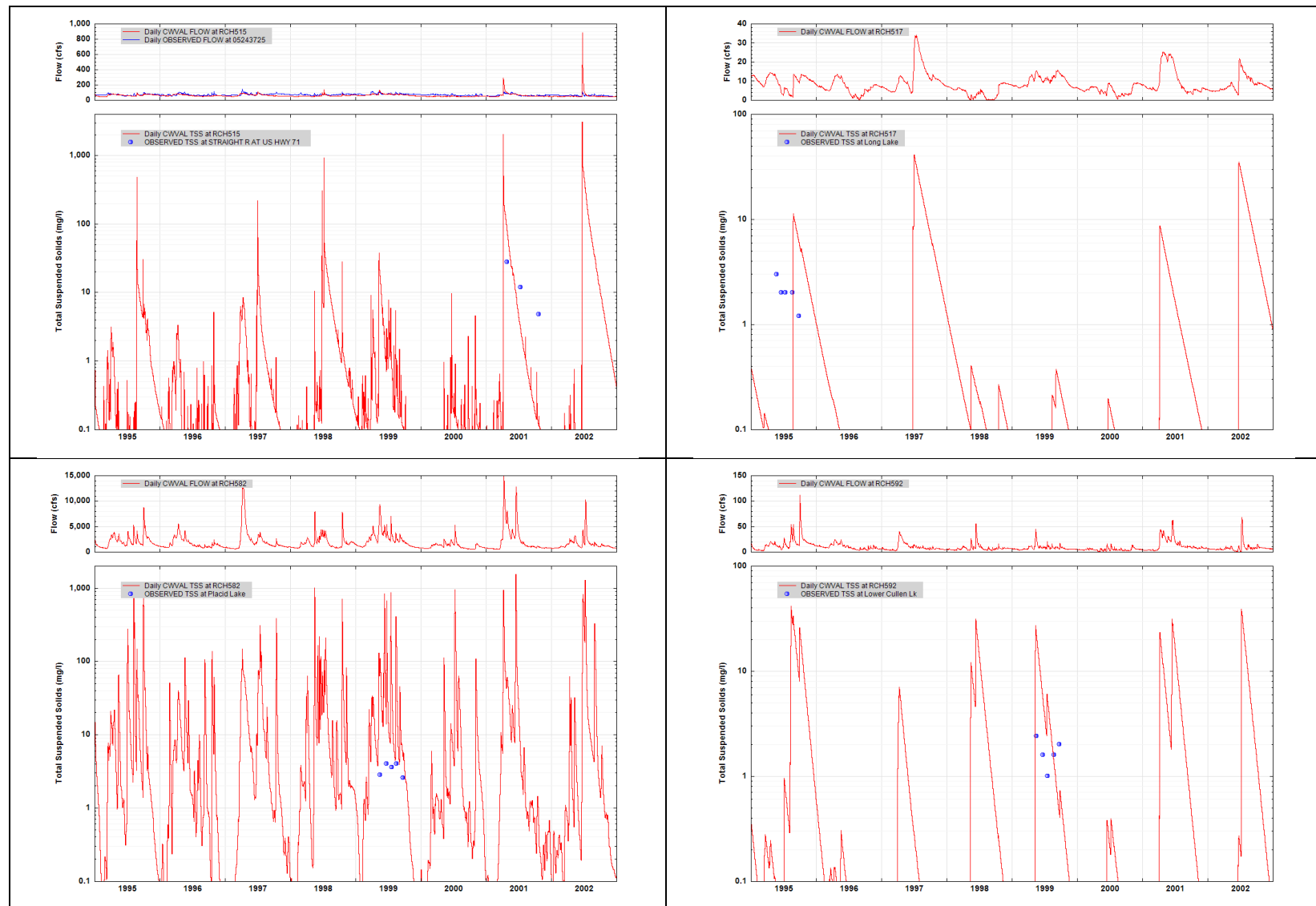
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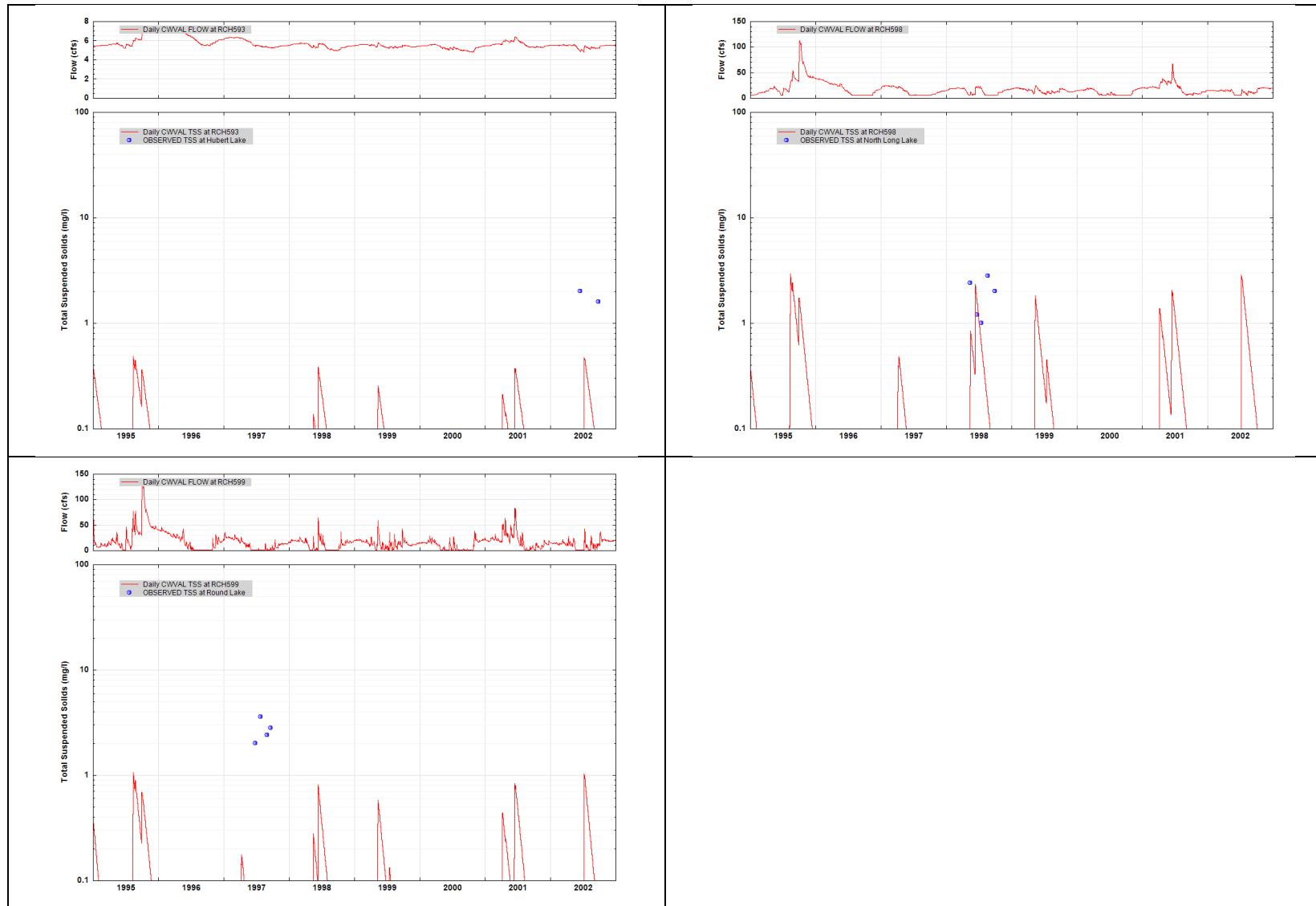






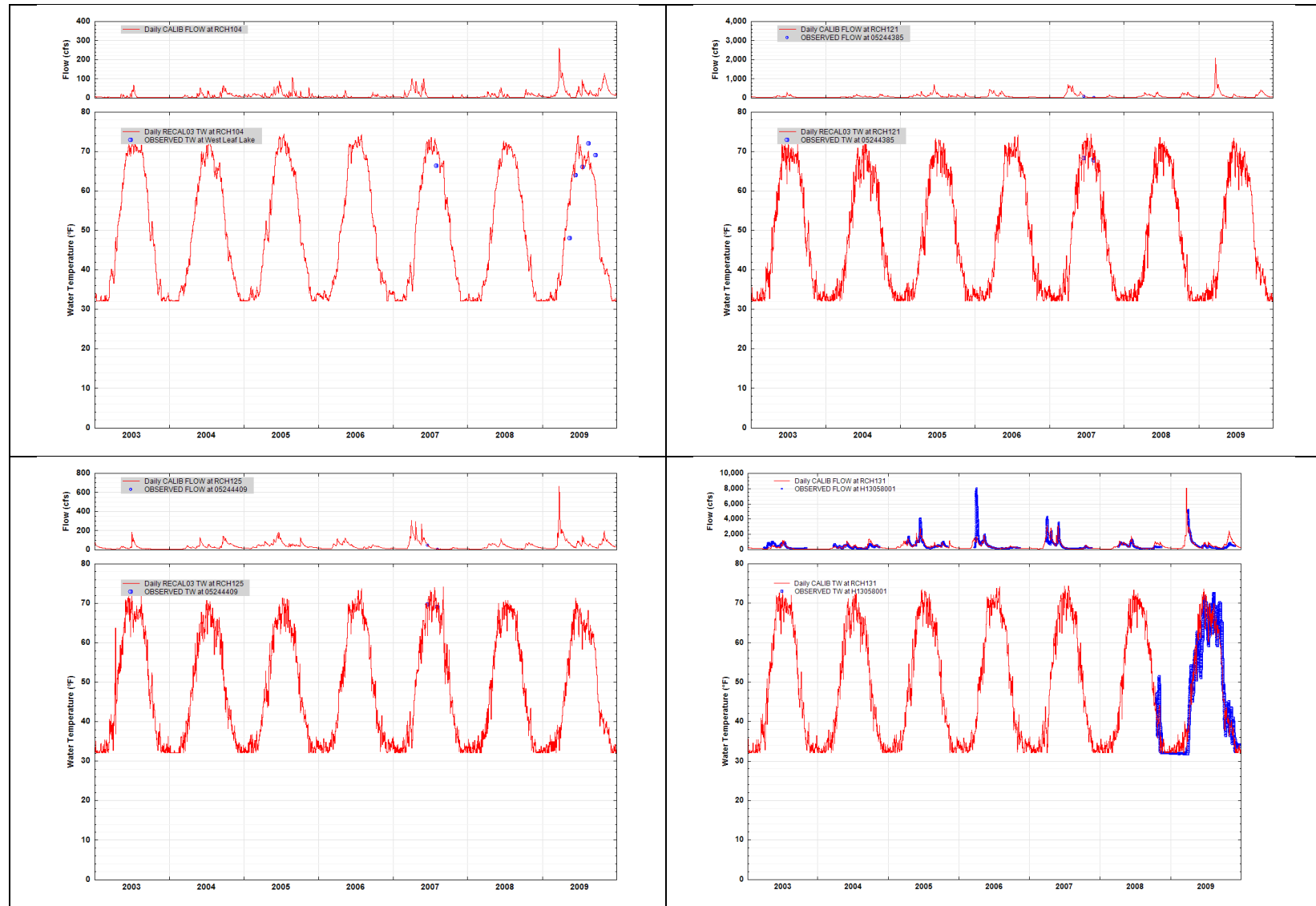
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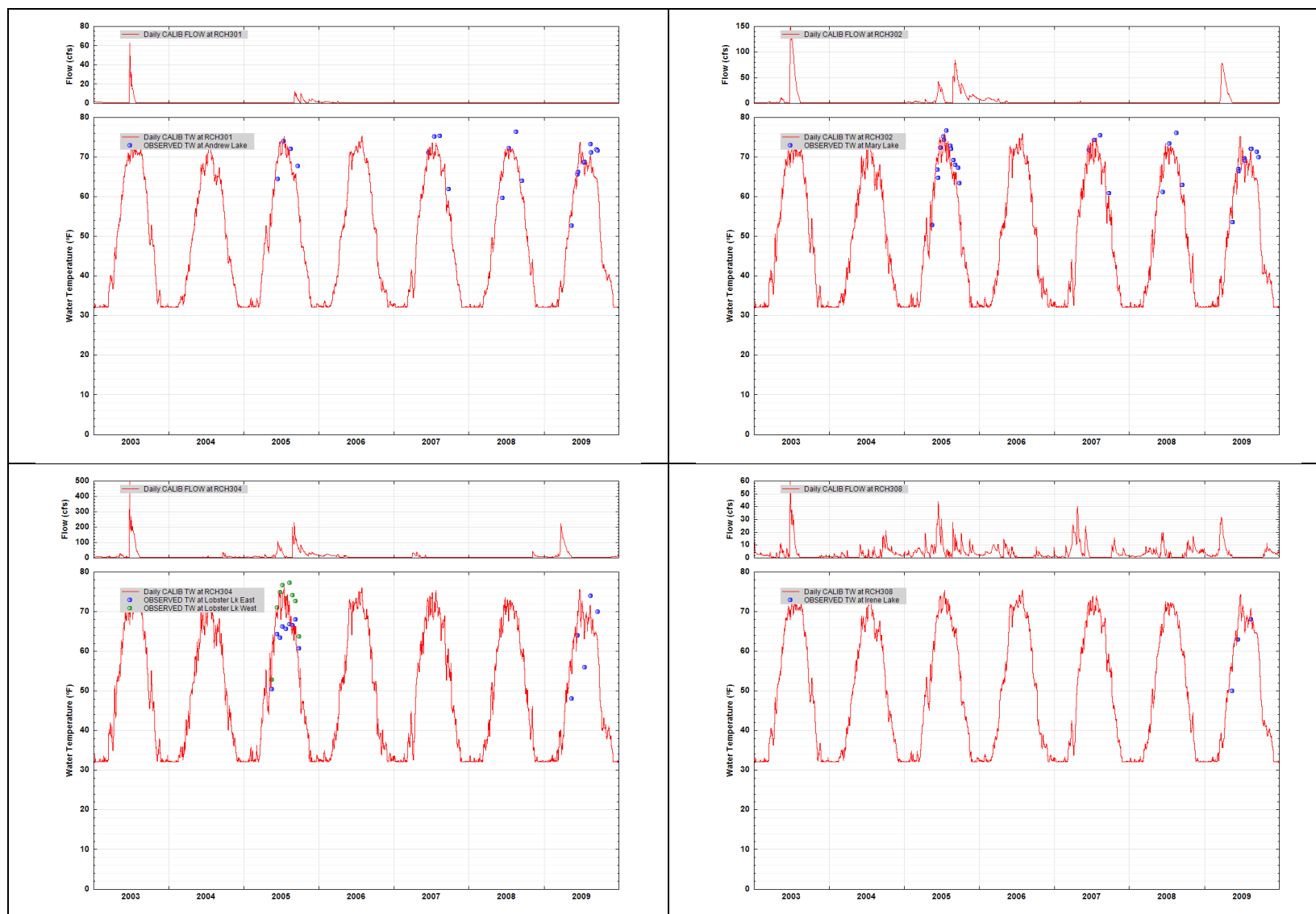


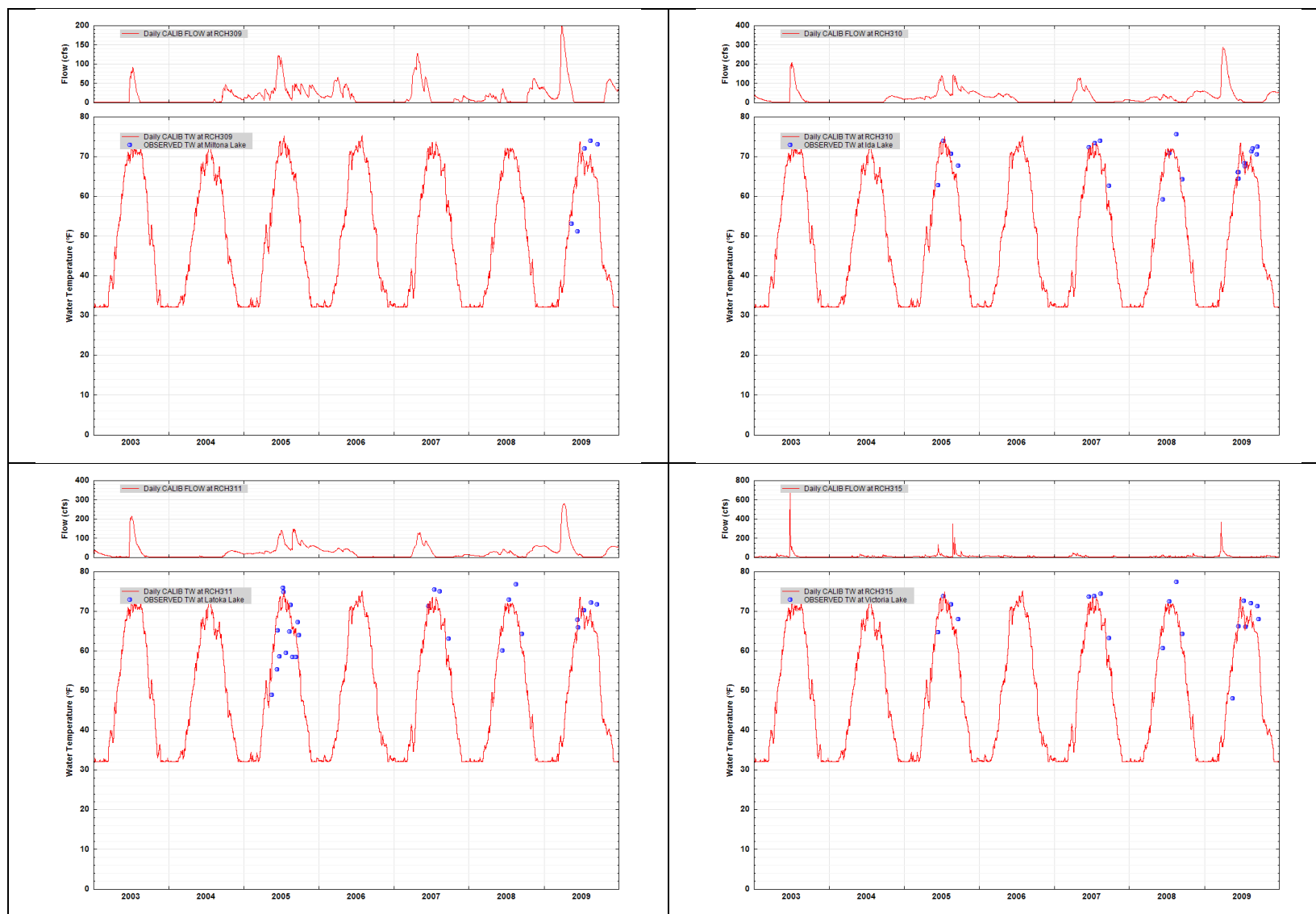
APPENDIX G OBSERVED AND SIMULATED WATER TEMPERATURE FOR THE CALIBRATION PERIOD

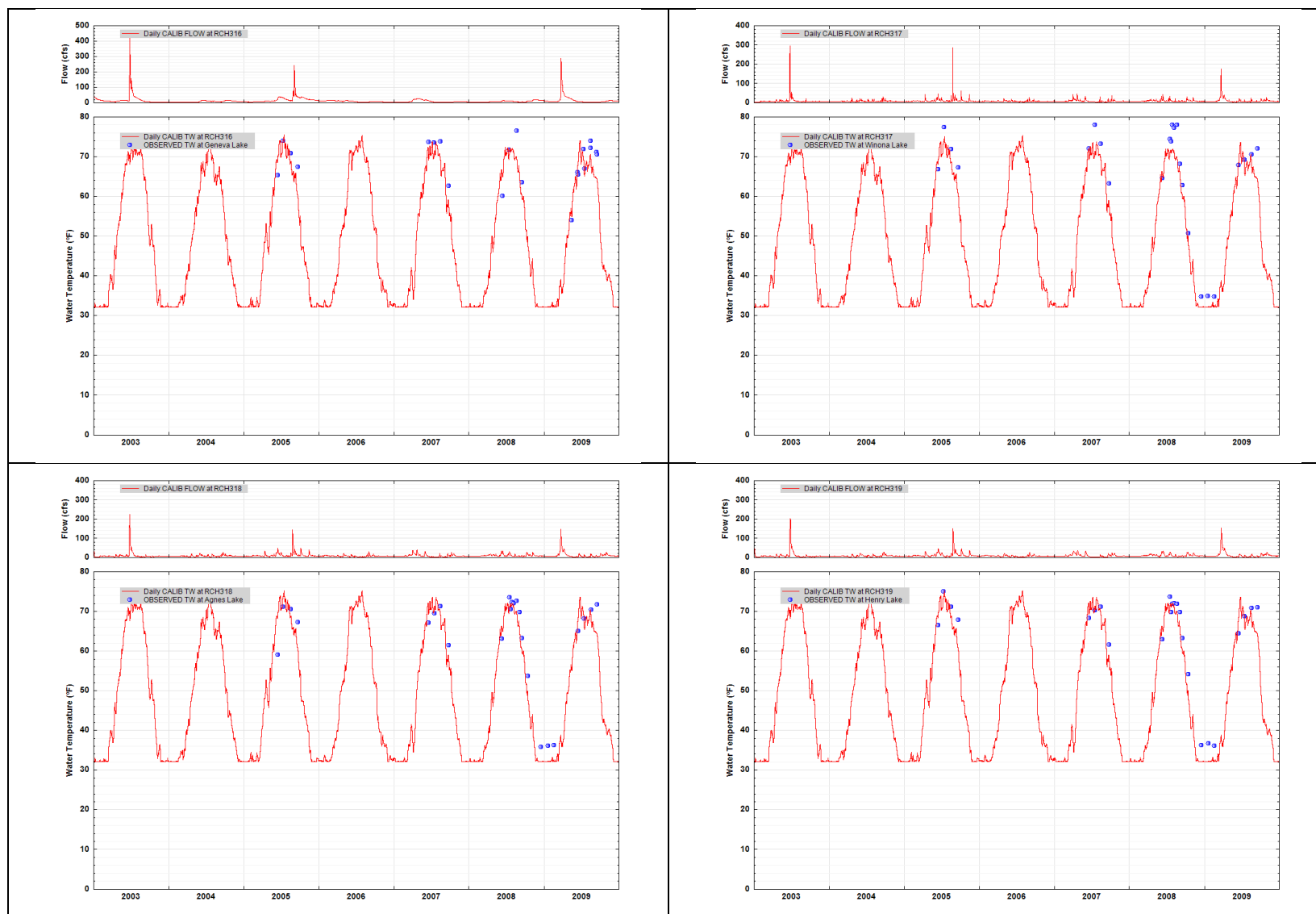
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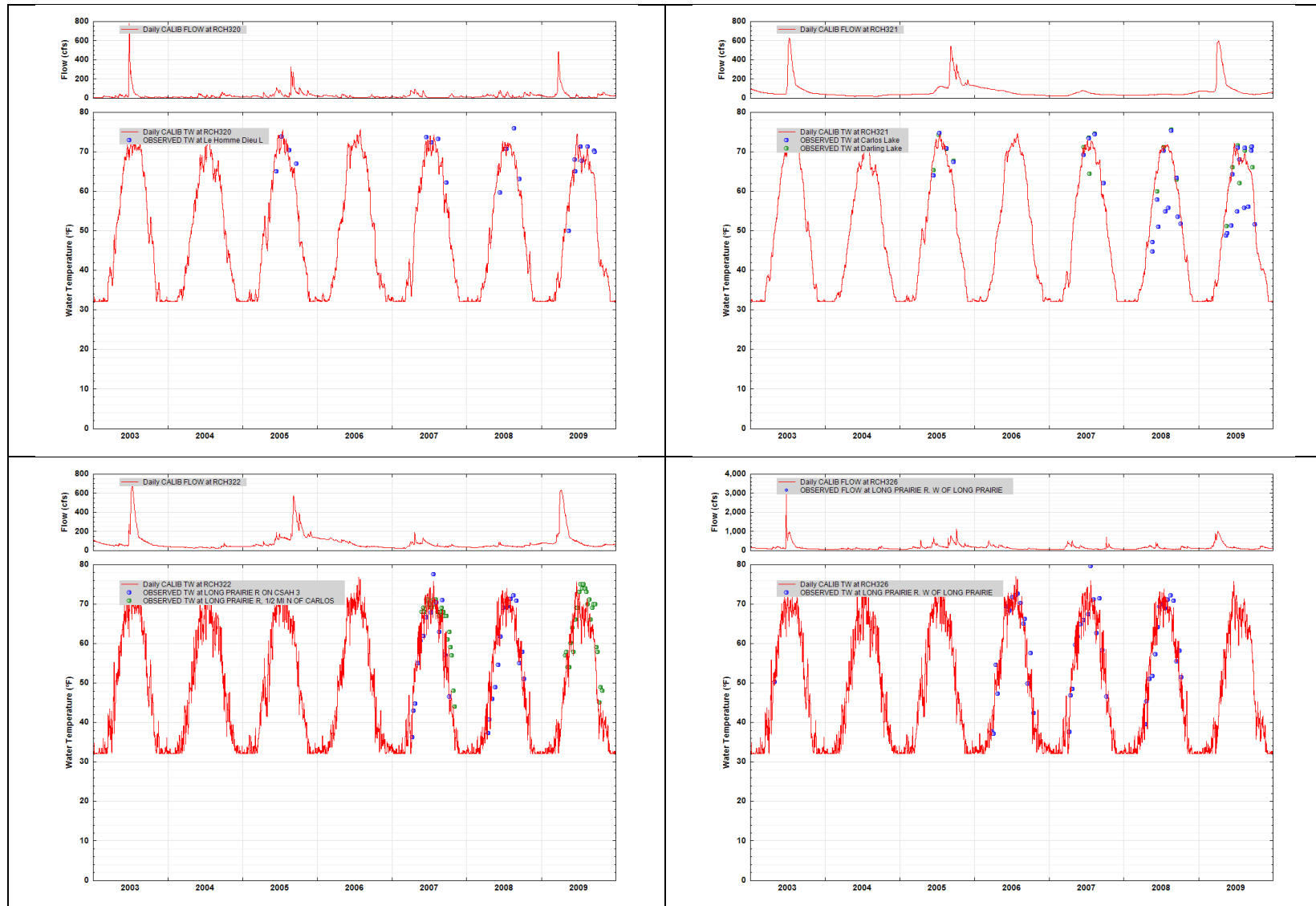


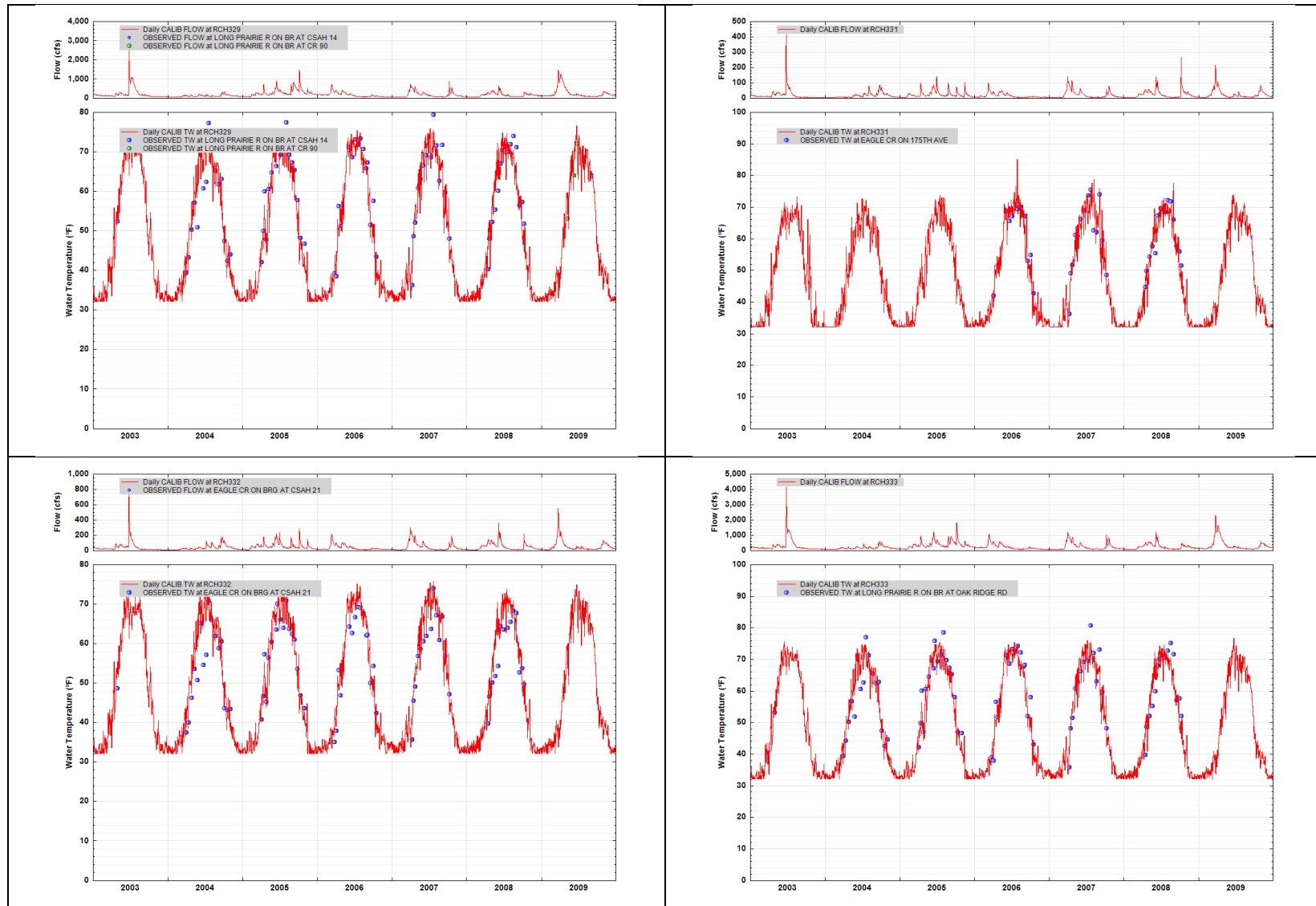
G.2 LONG PRAIRIE RIVER WATERSHED

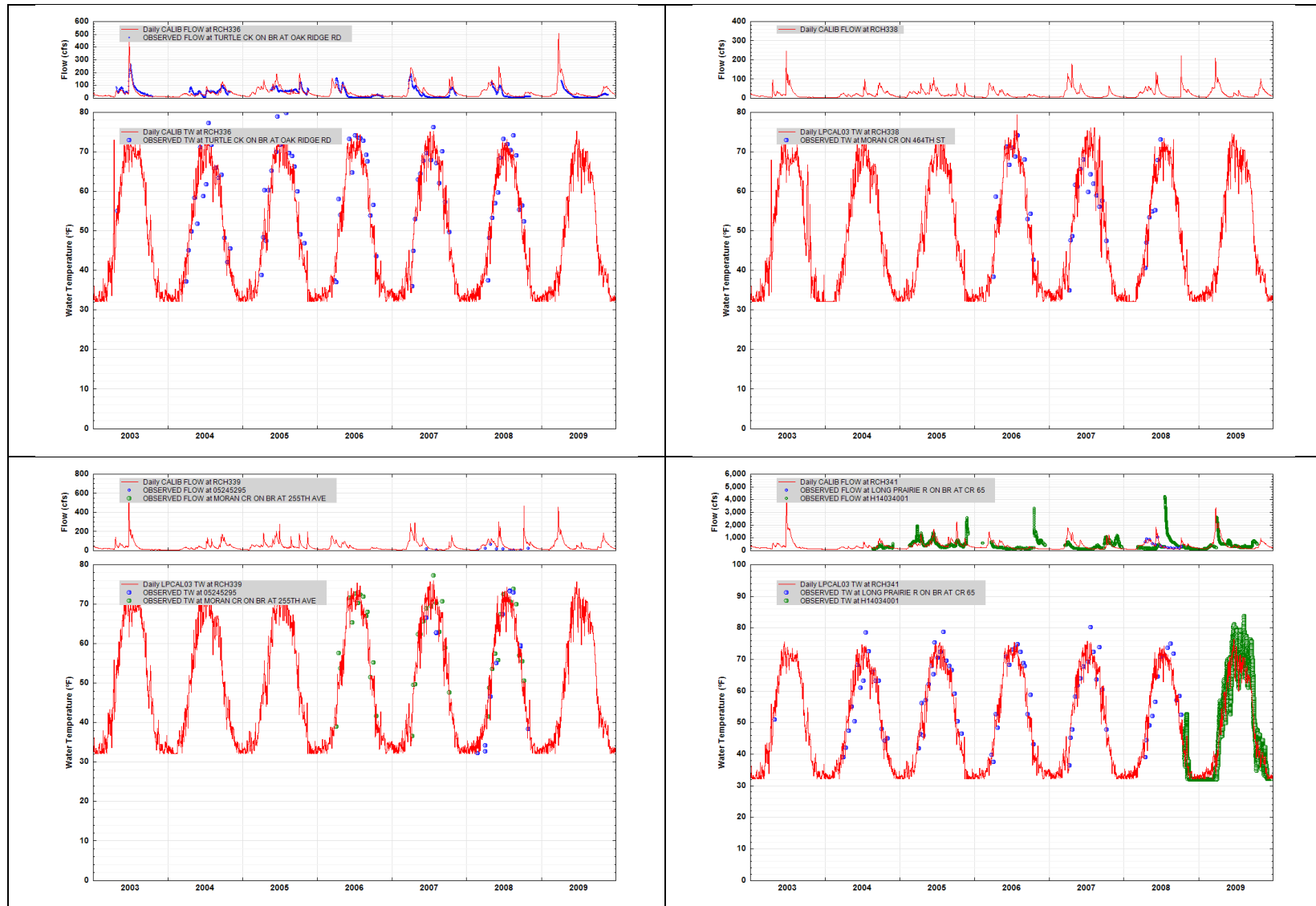


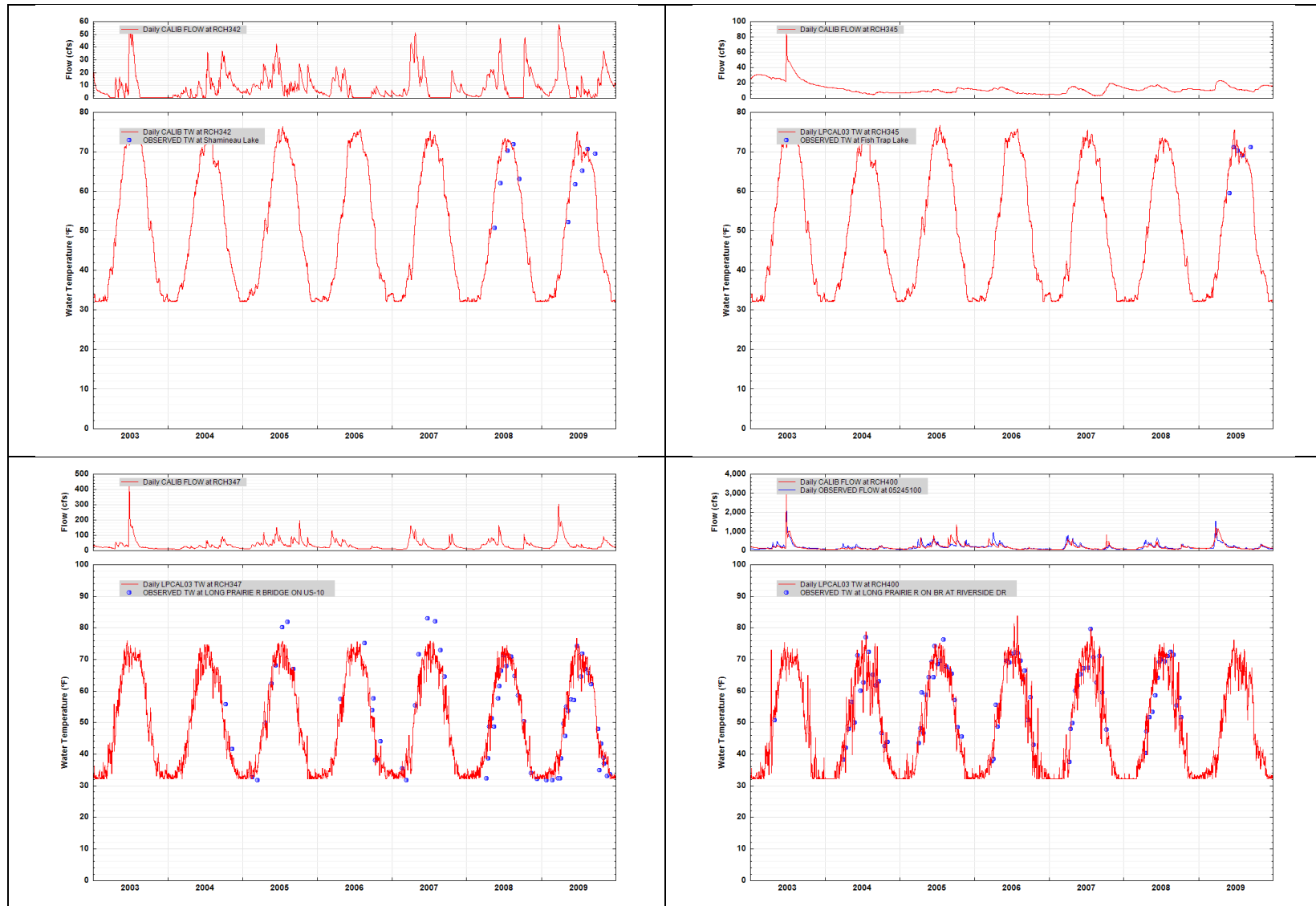


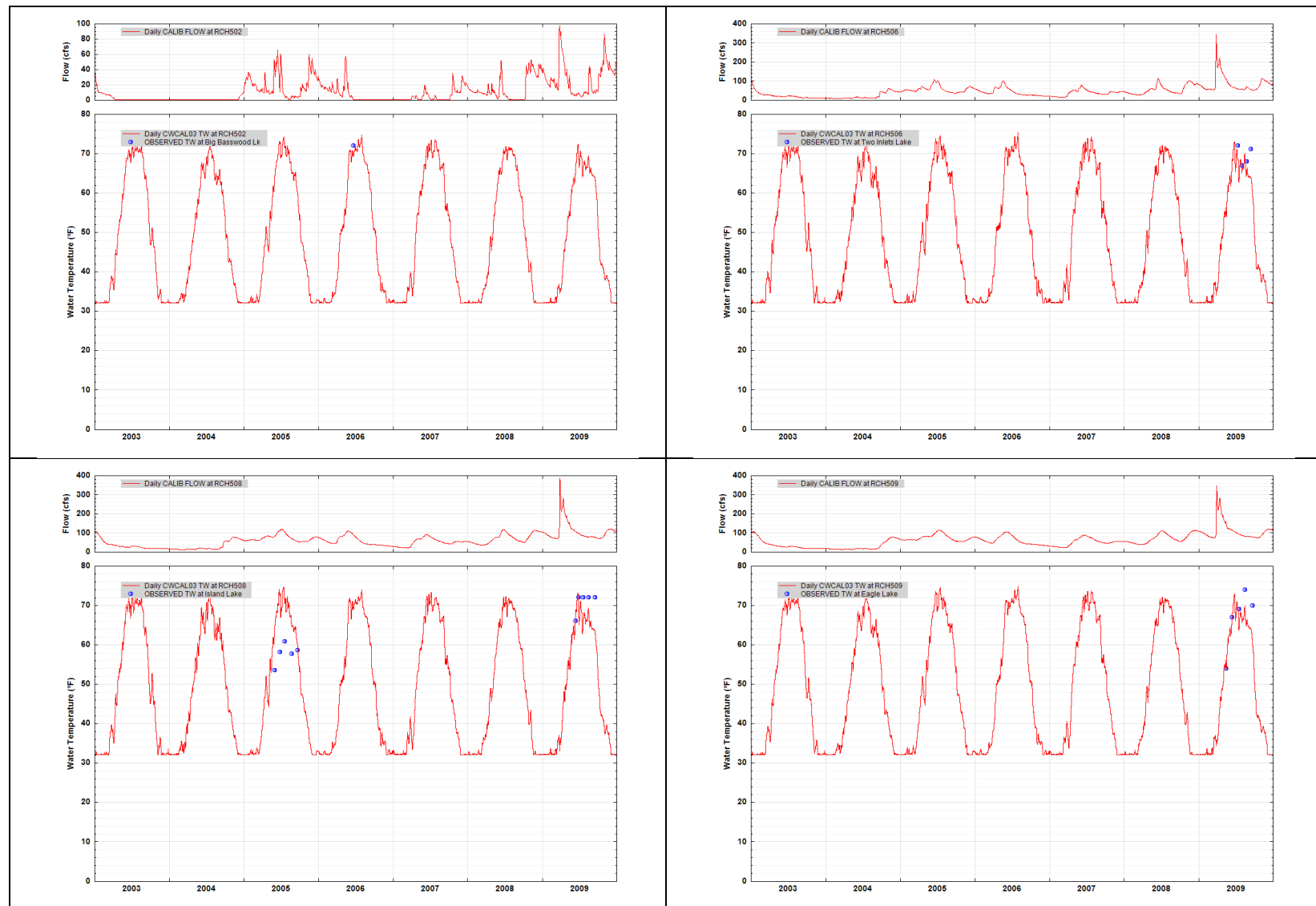


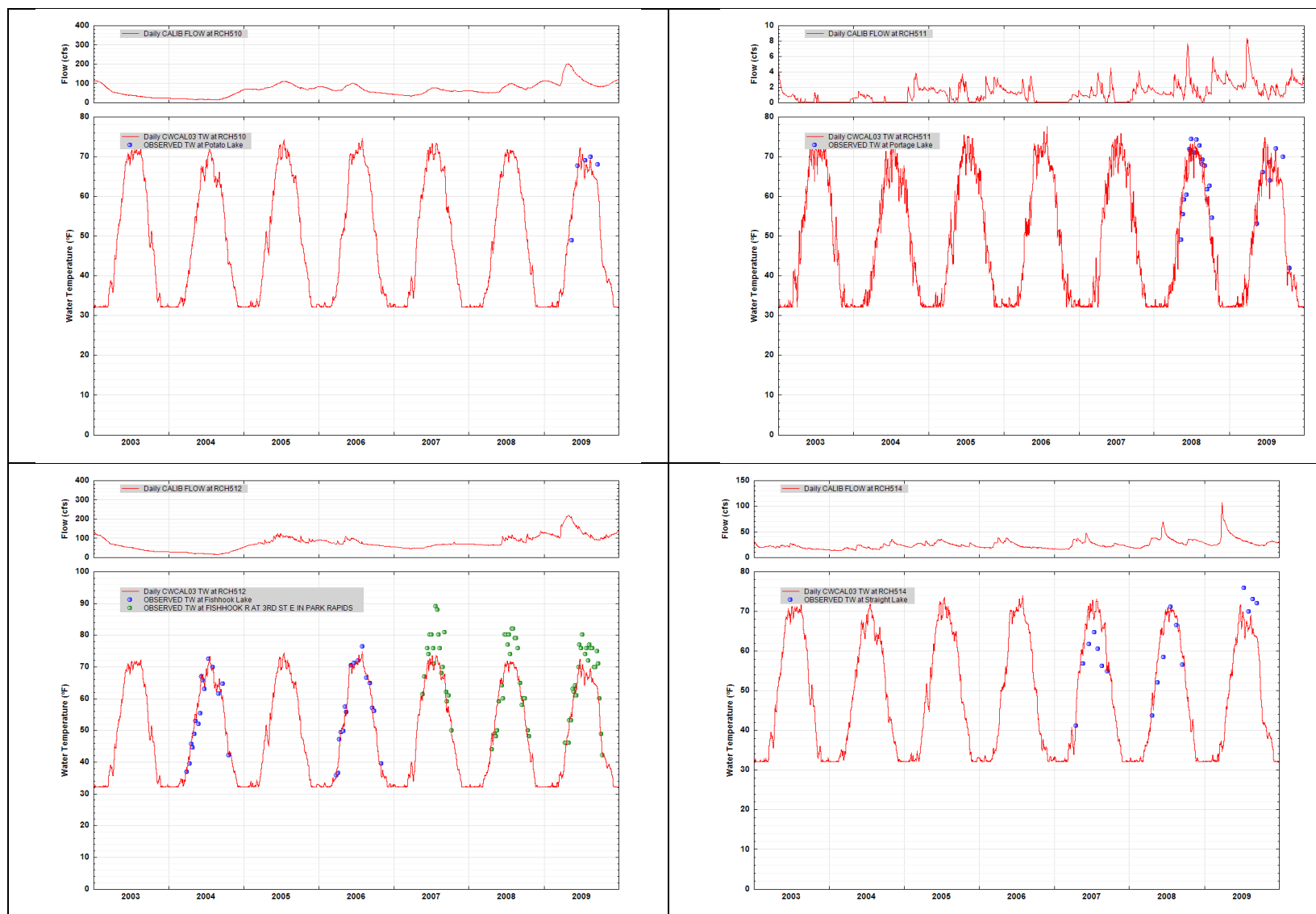


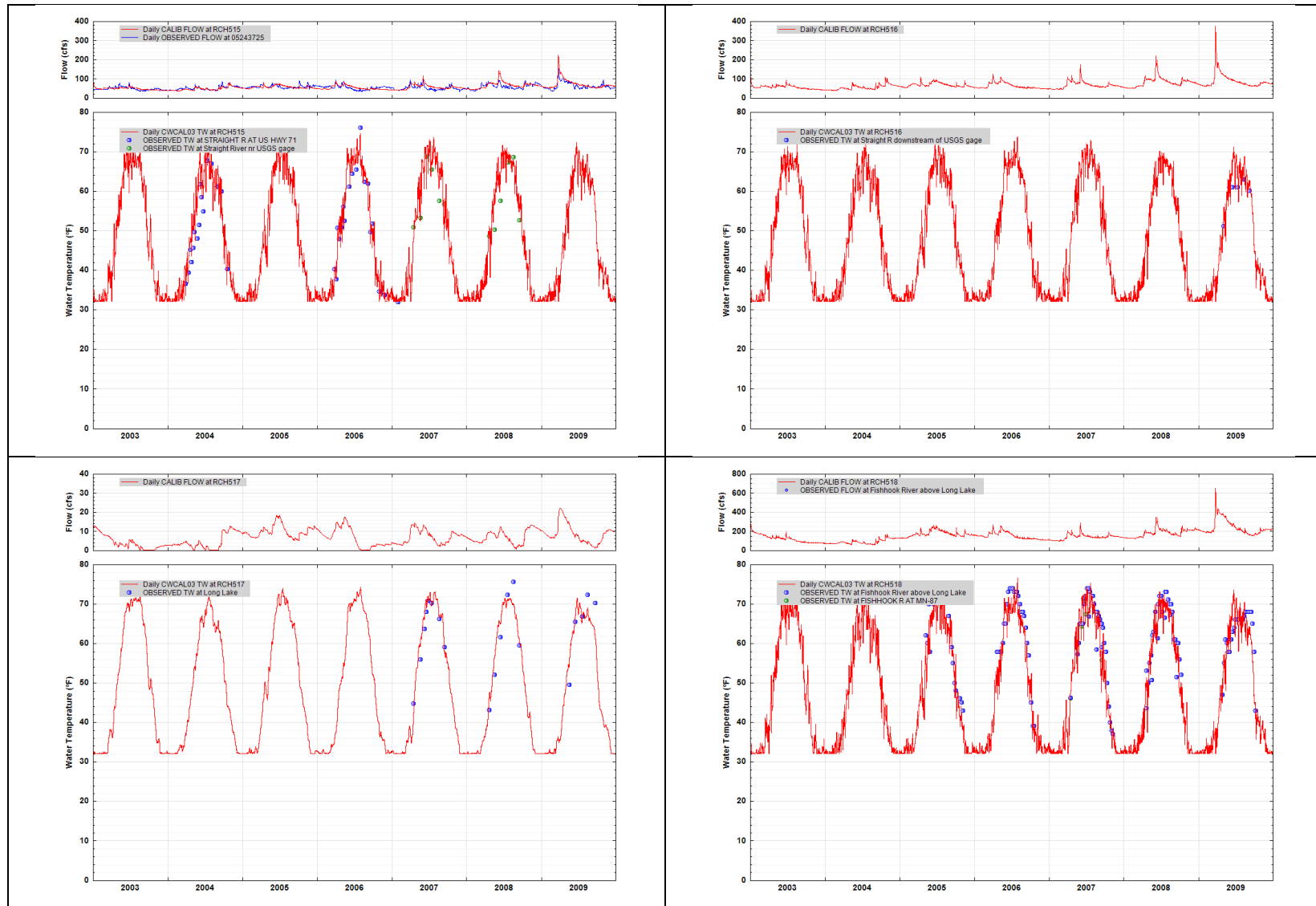


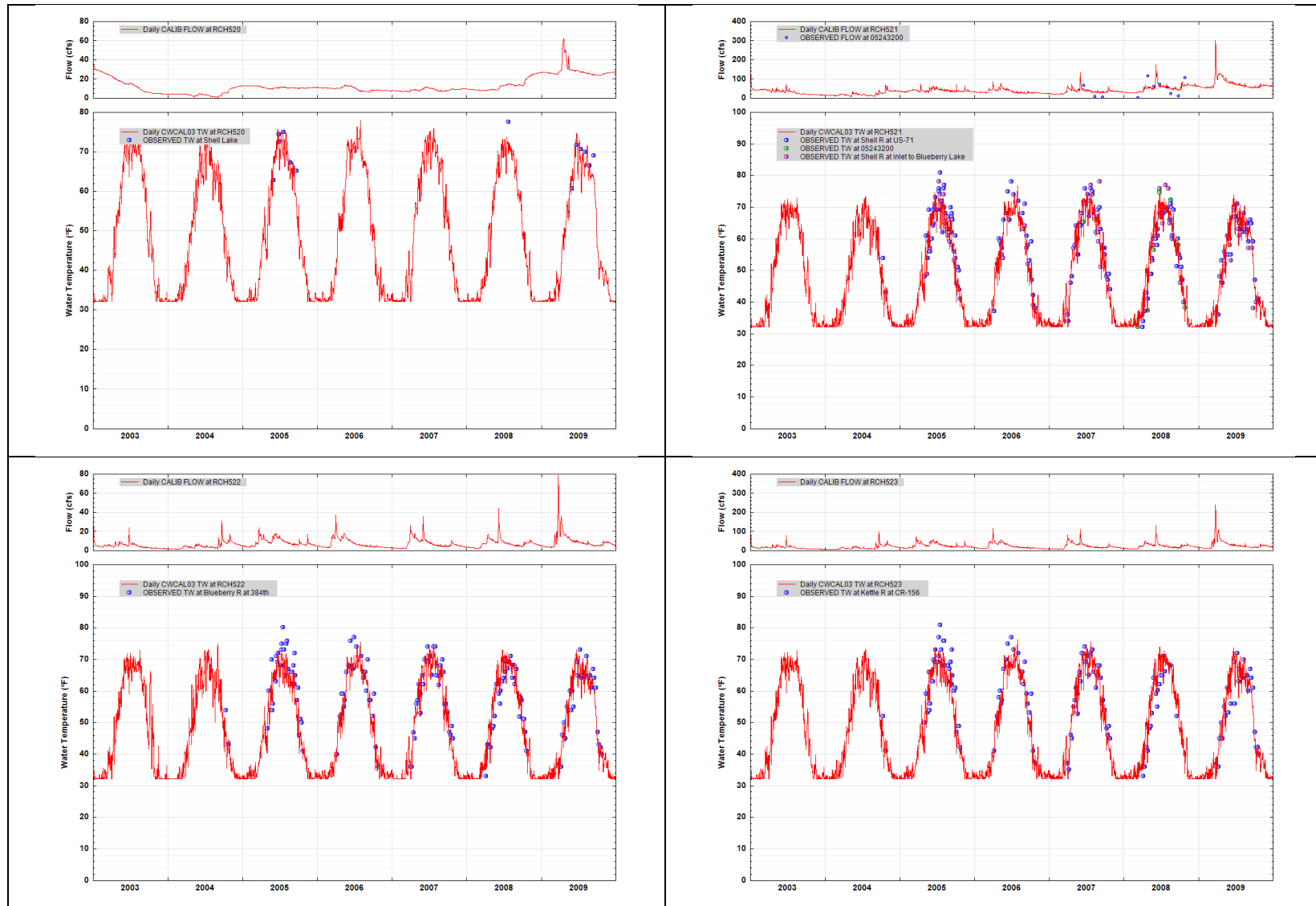


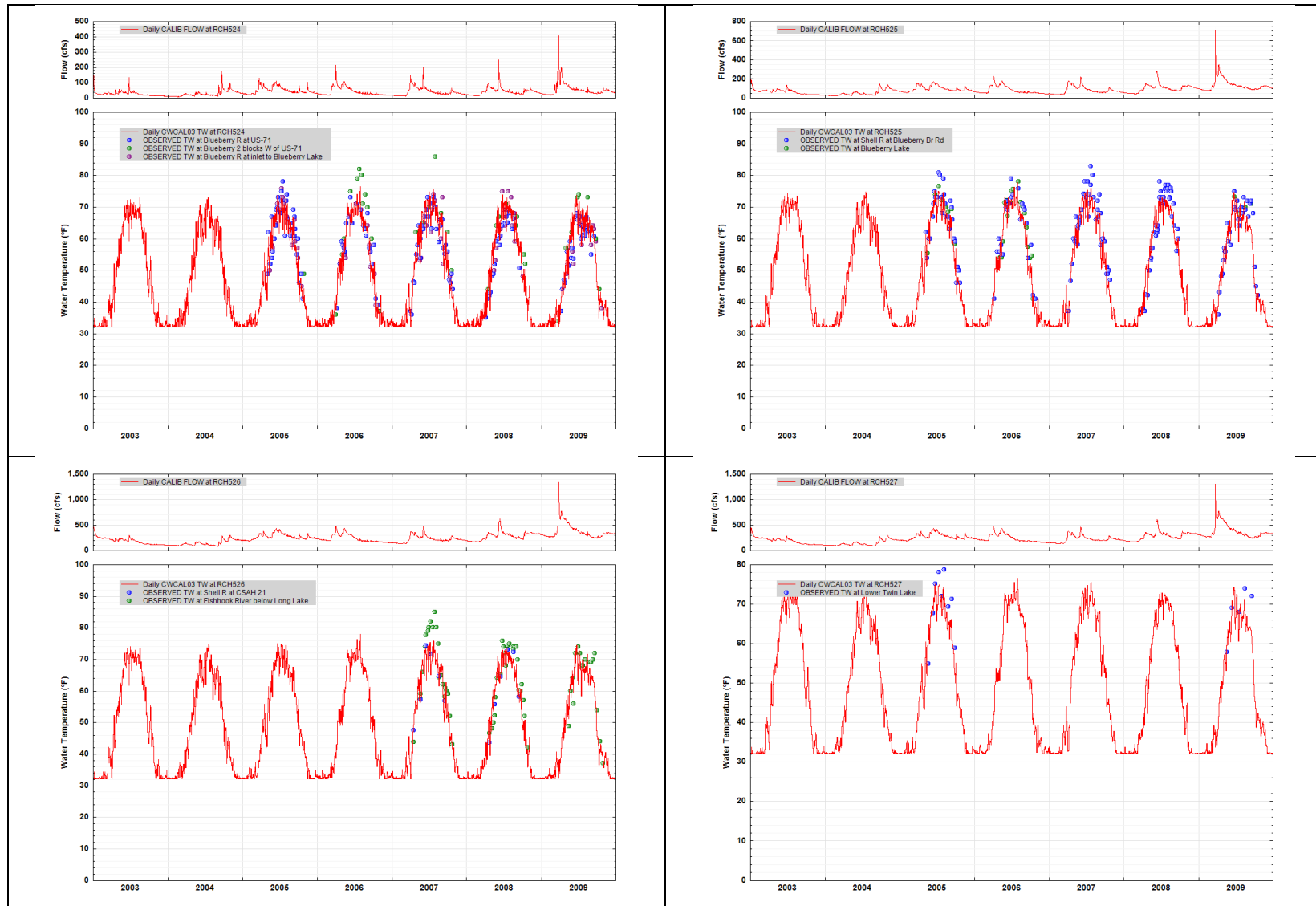


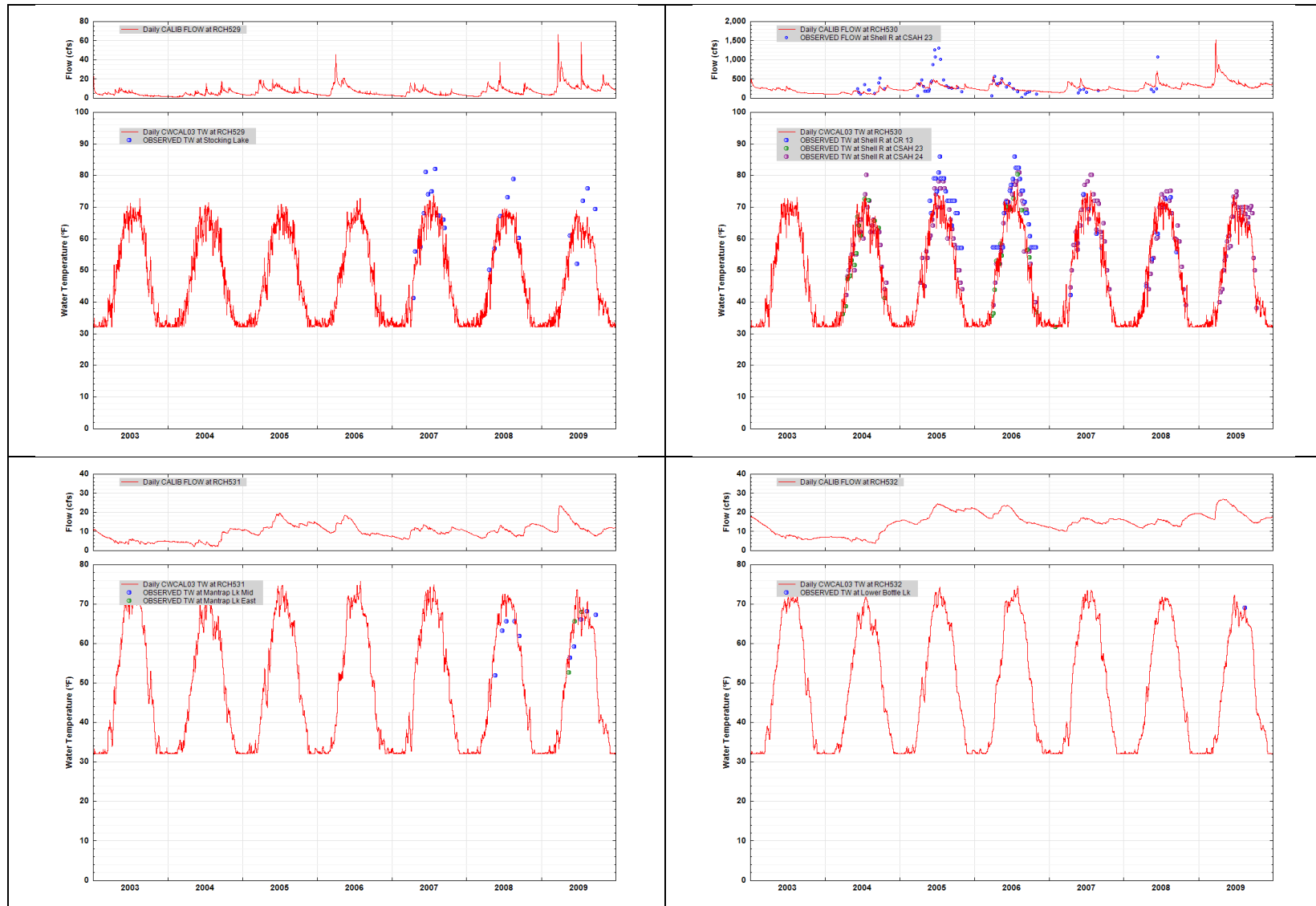
G.3 CROW WING RIVER WATERSHED

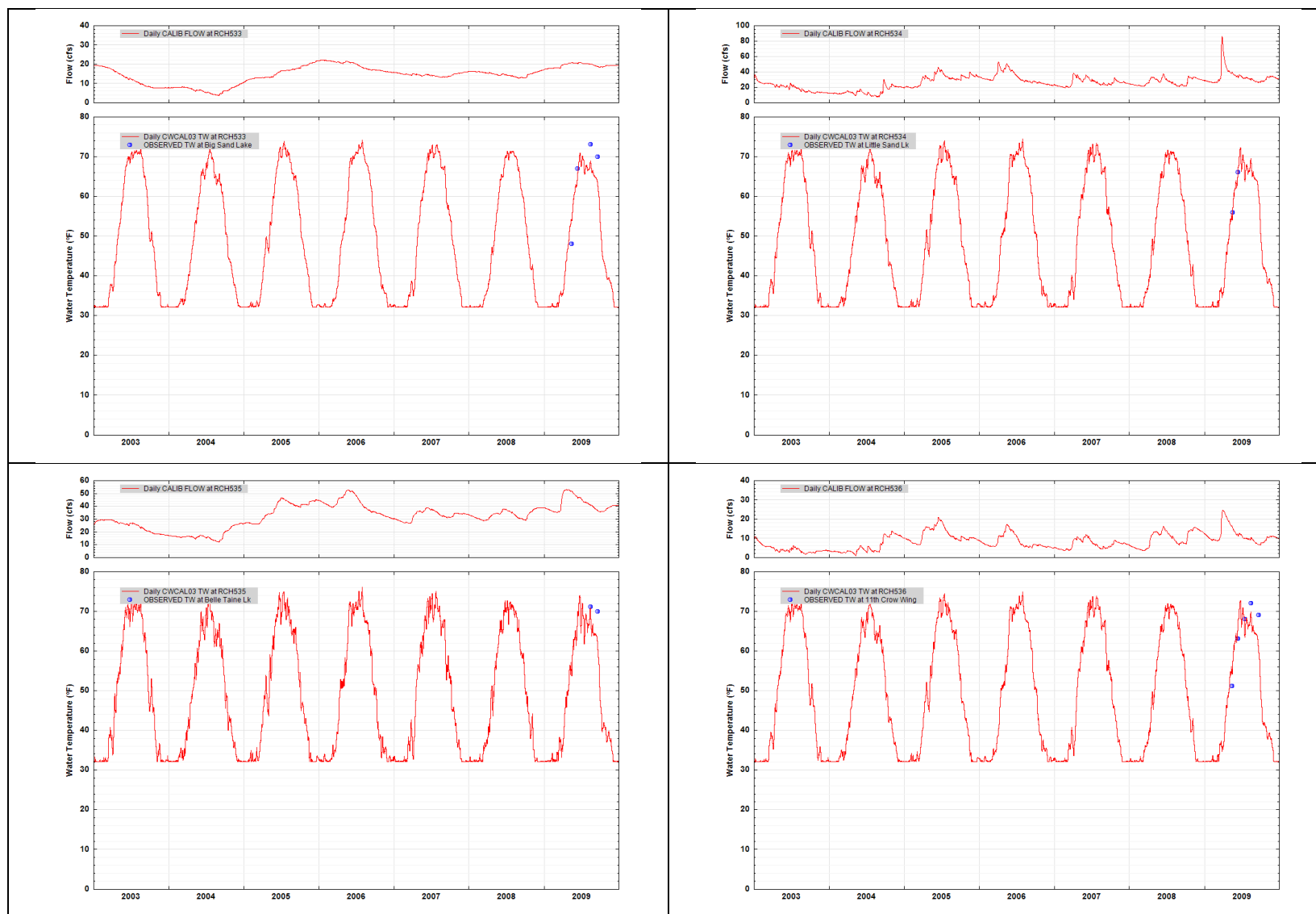


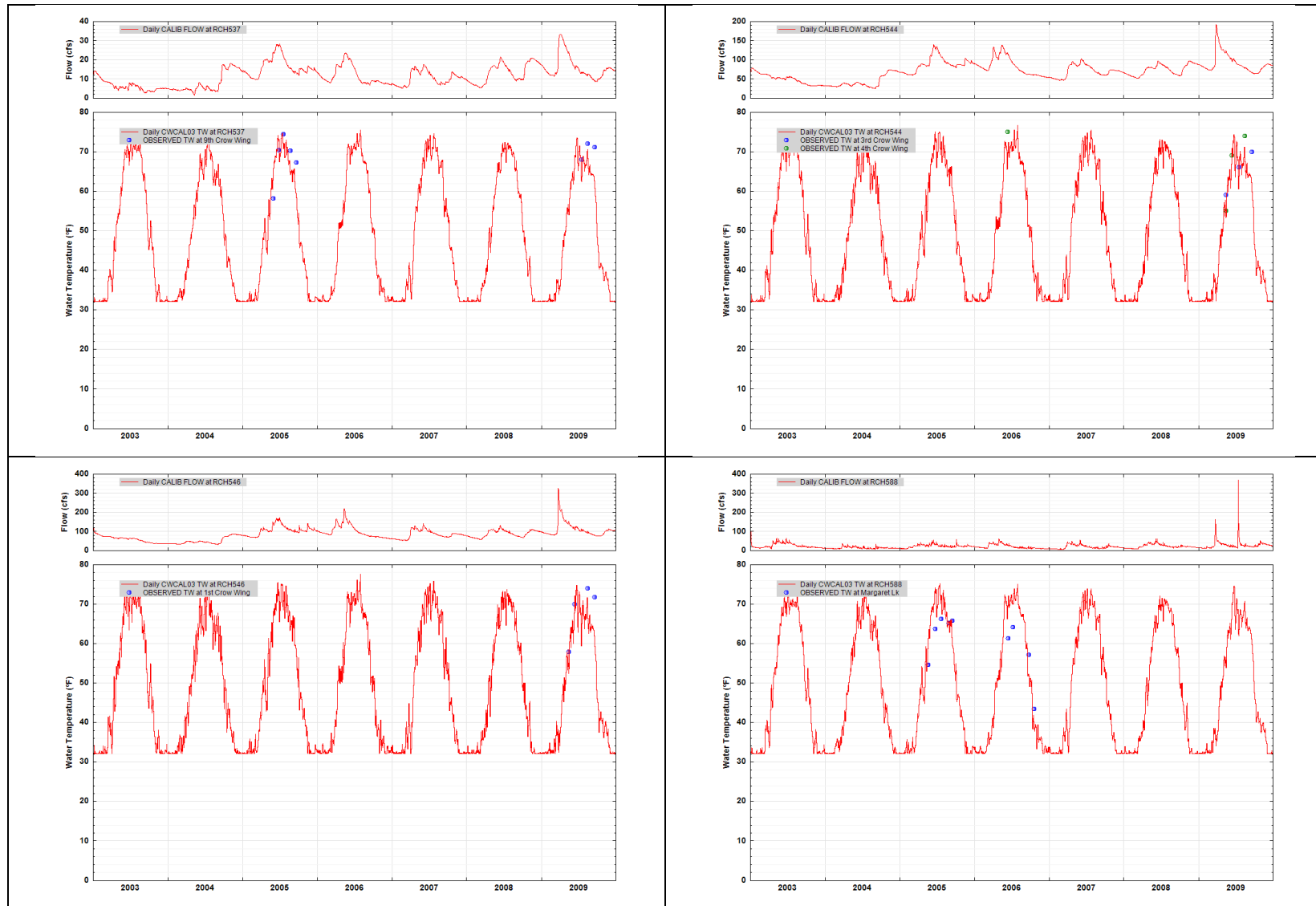


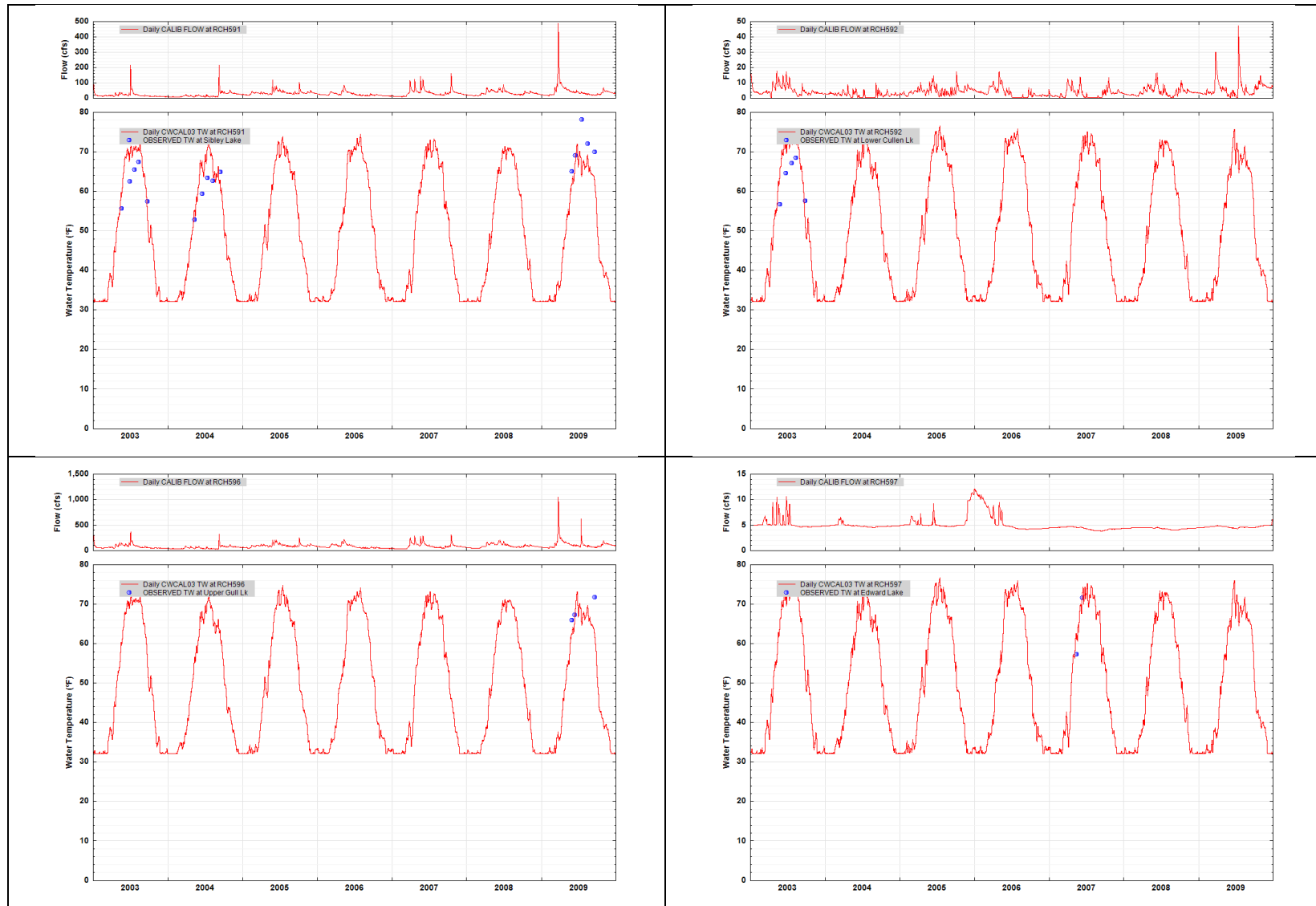


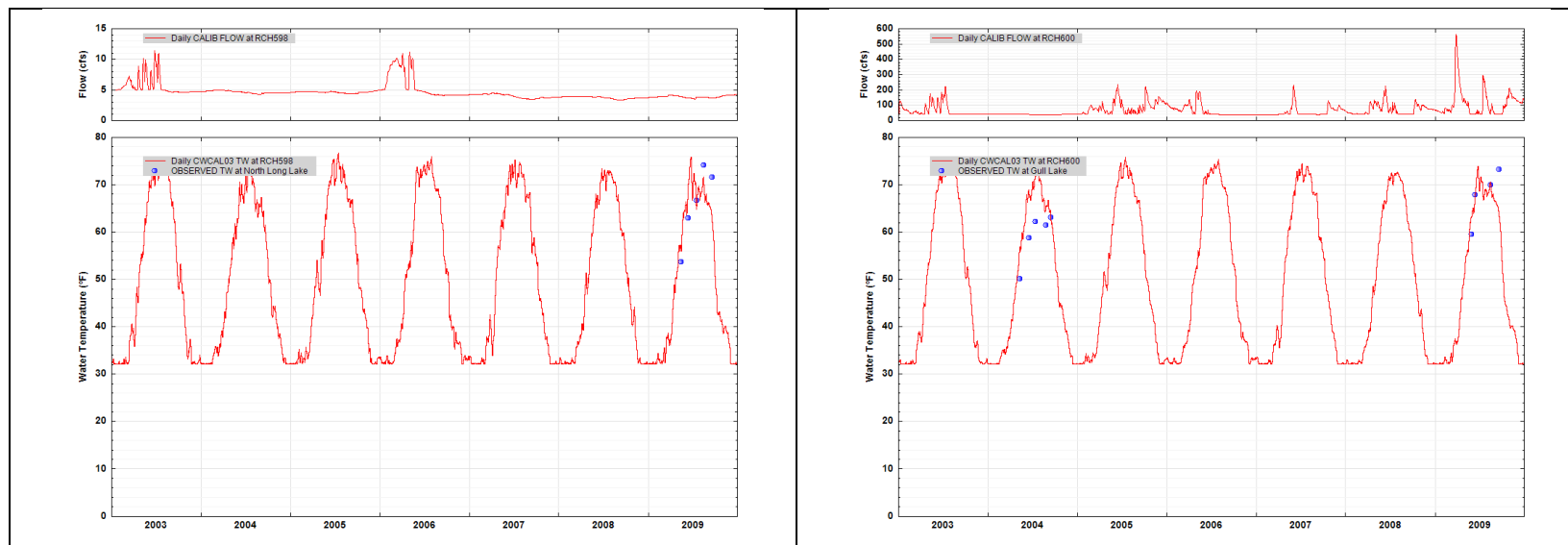






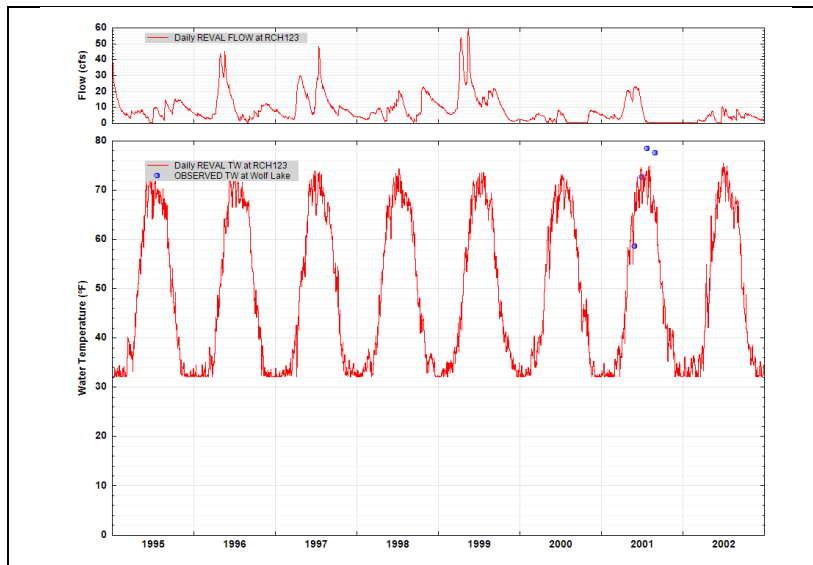


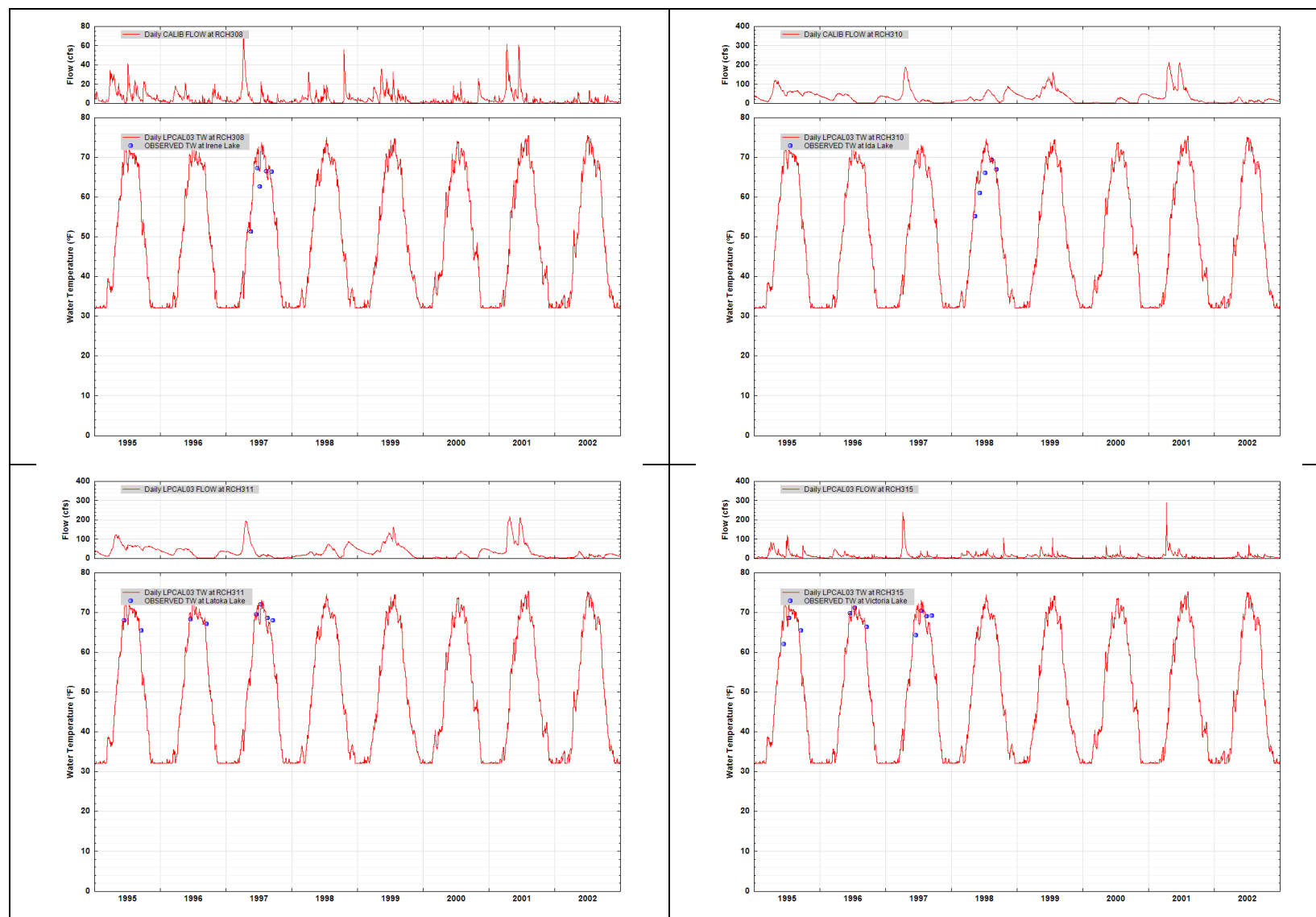


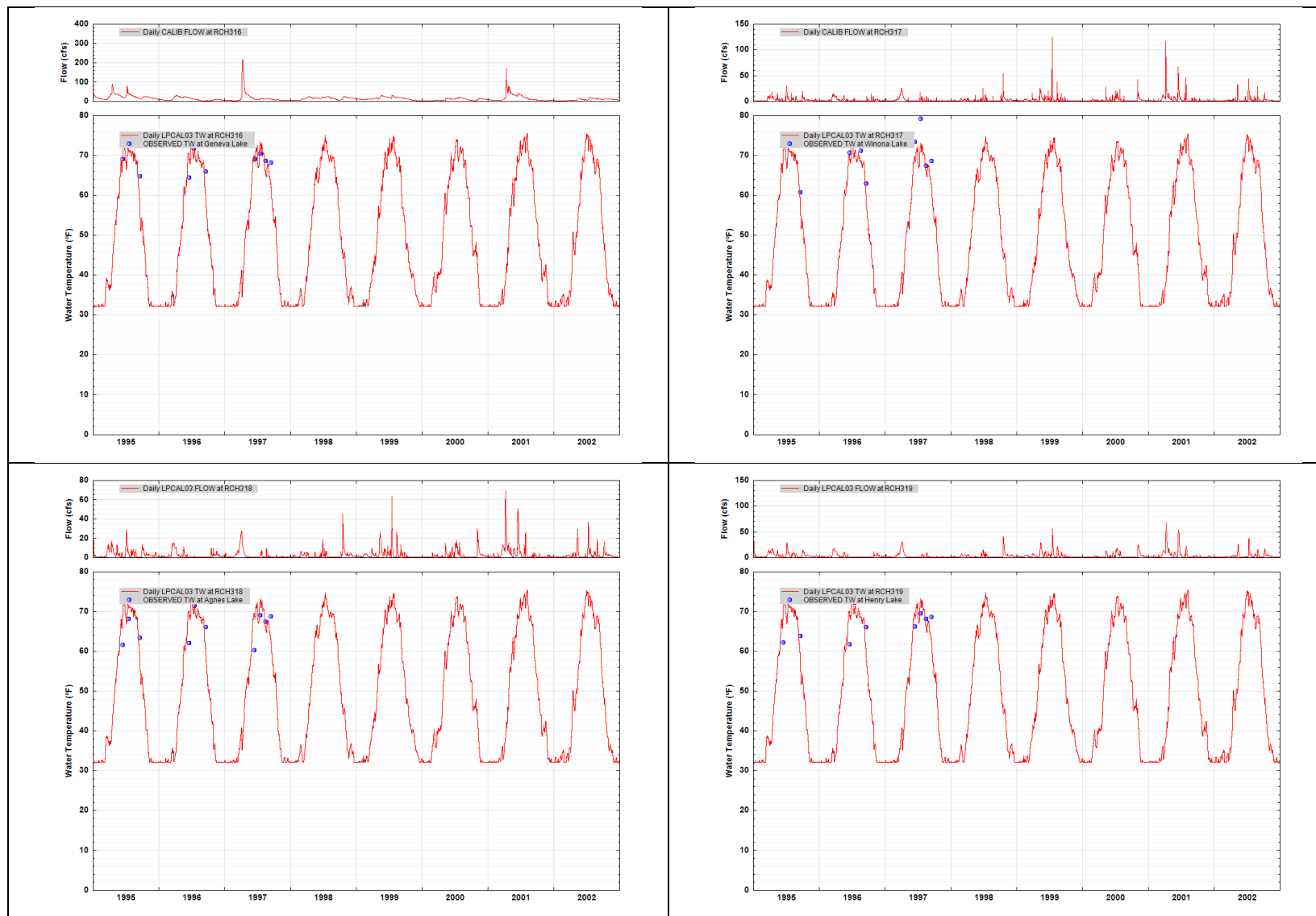


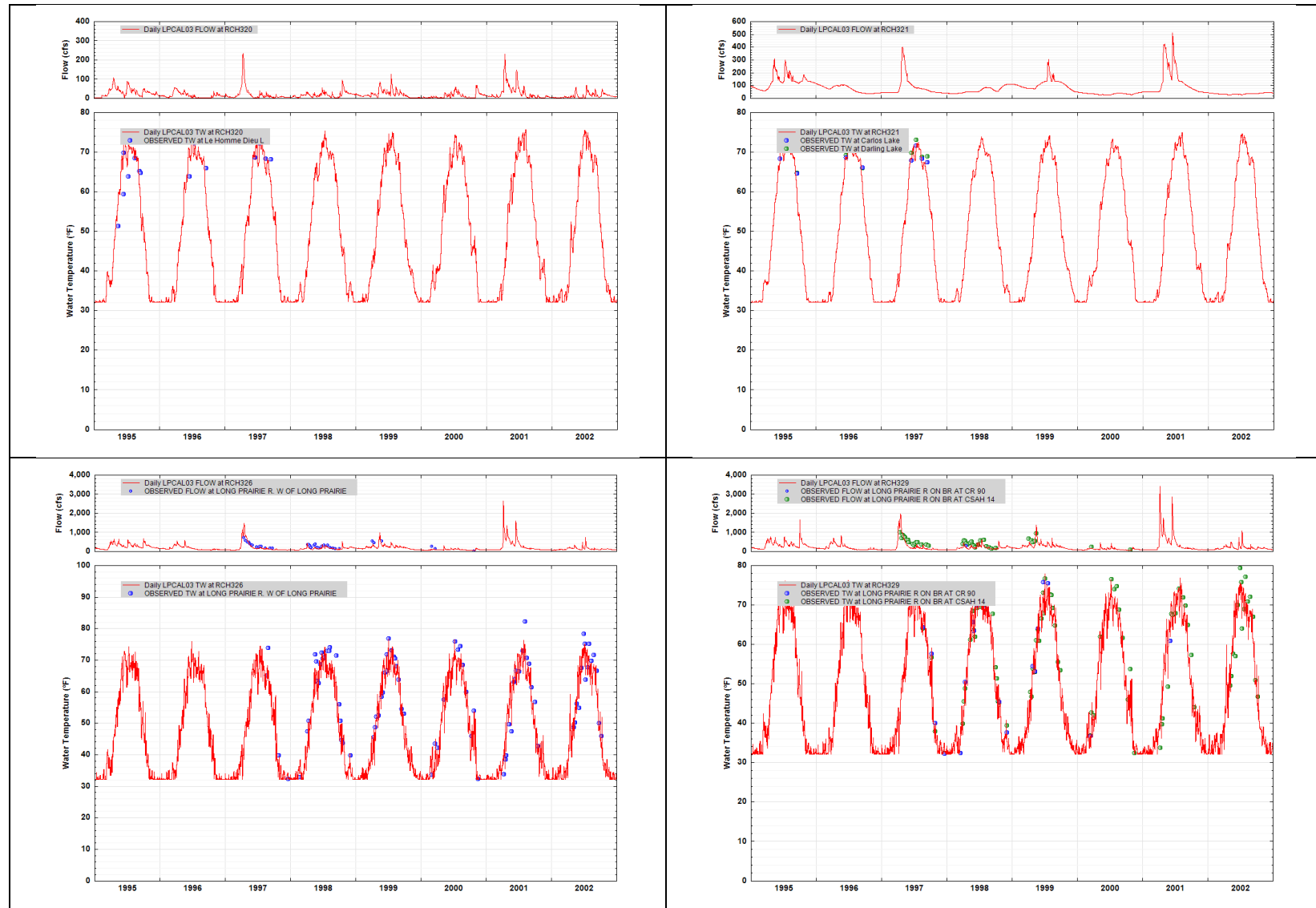
APPENDIX H OBSERVED AND SIMULATED WATER TEMPERATURE FOR THE VALIDATION PERIOD

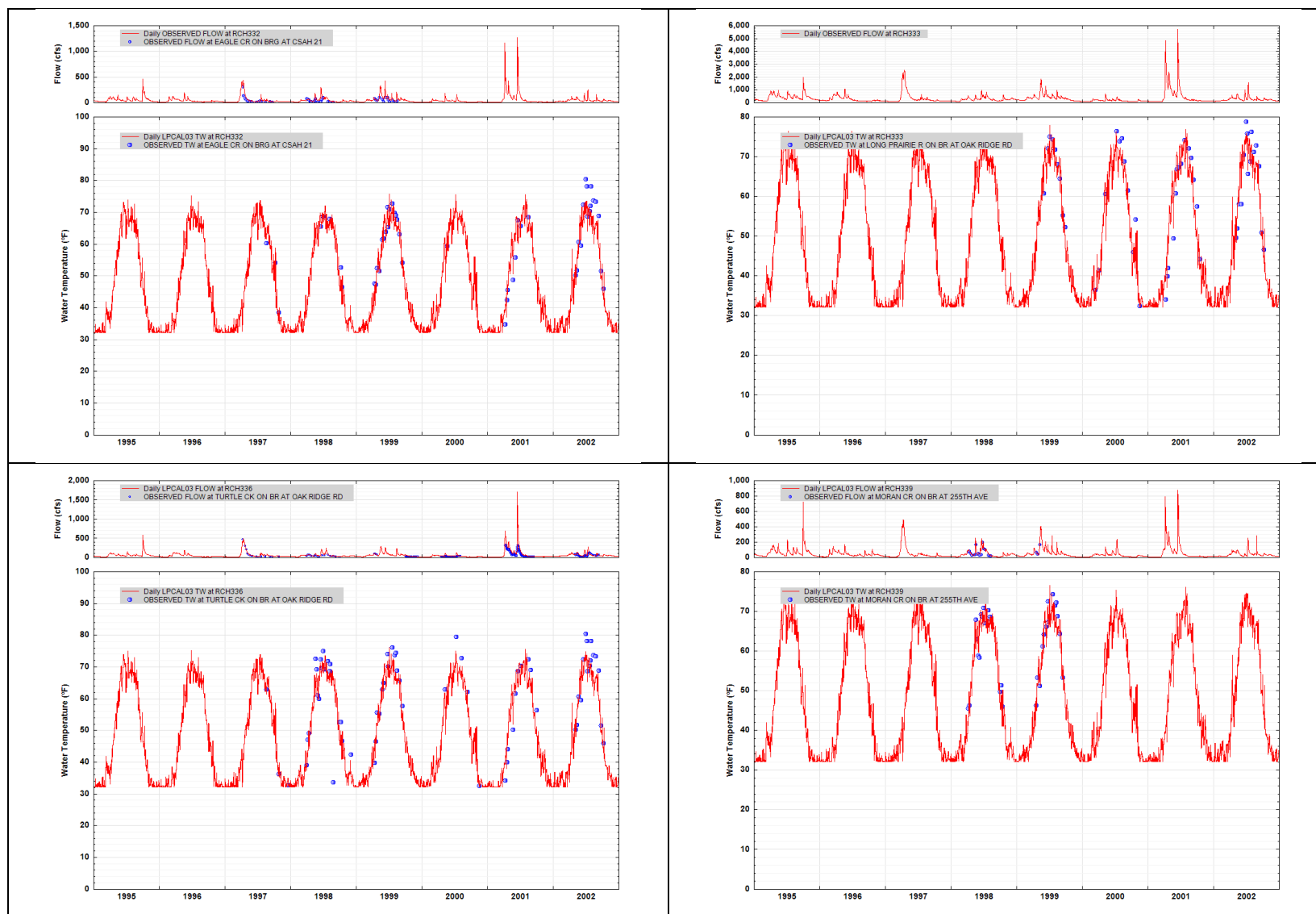
H.1 REDEYE RIVER WATERSHED

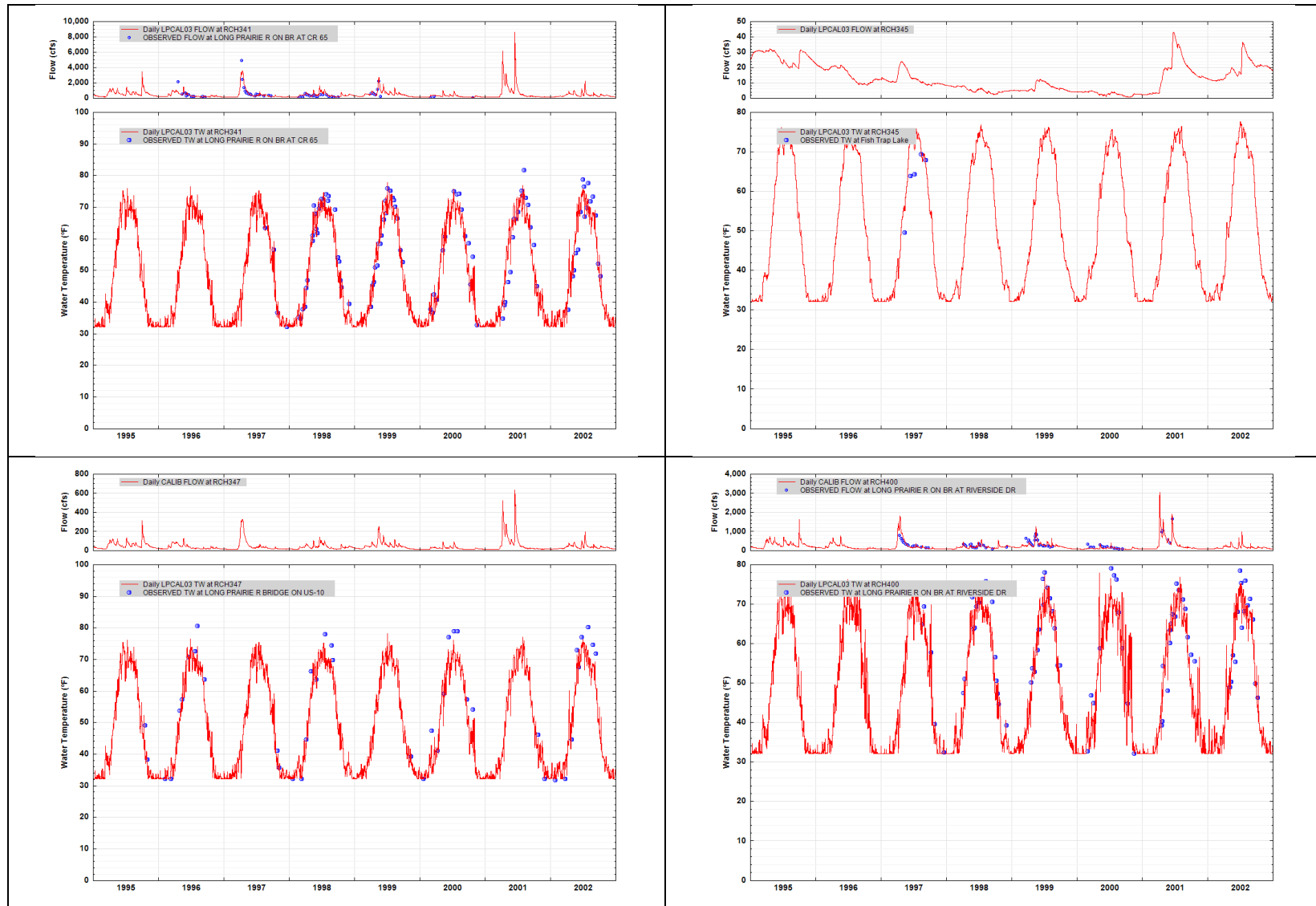


H.2 LONG PRAIRIE RIVER WATERSHED

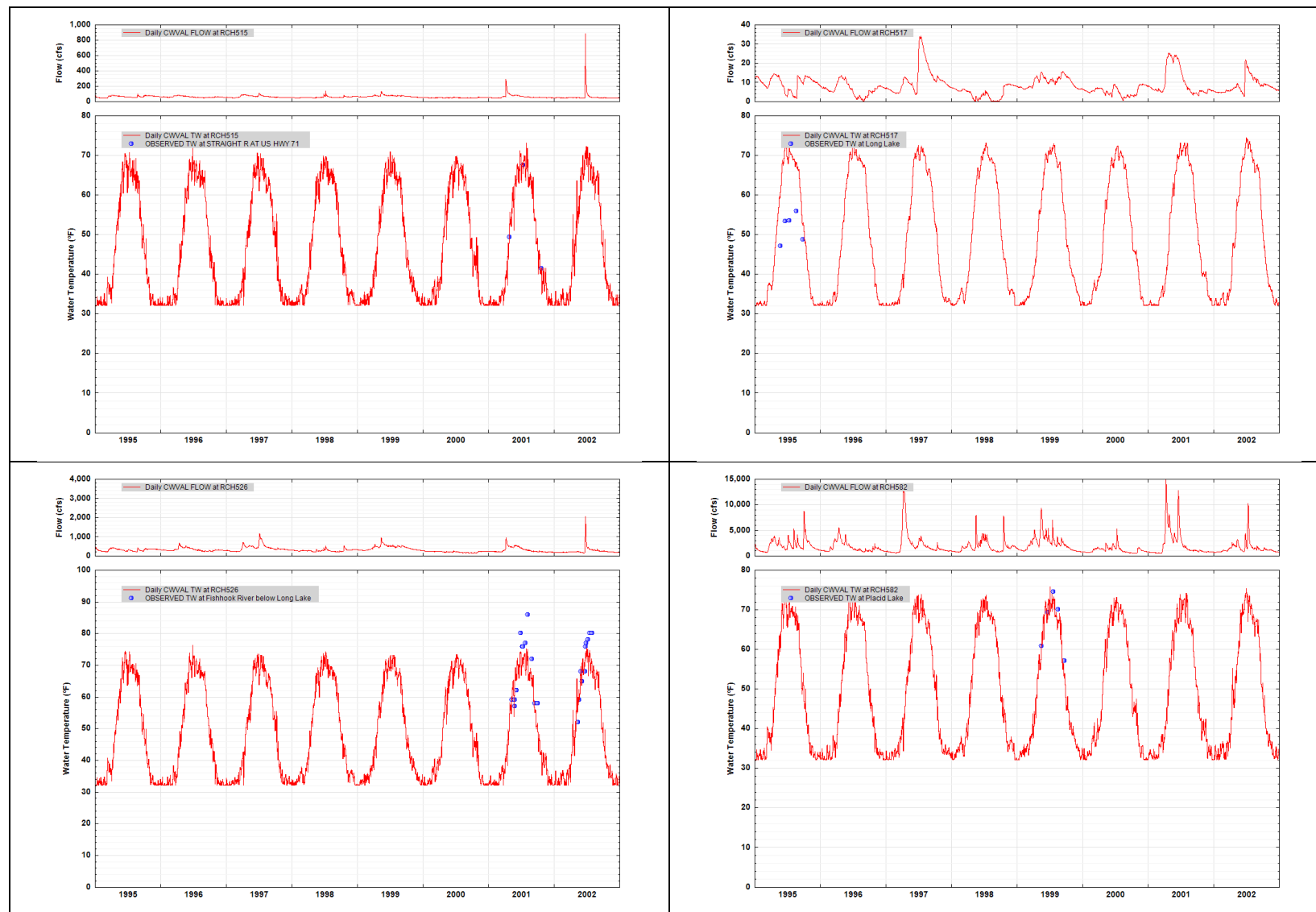


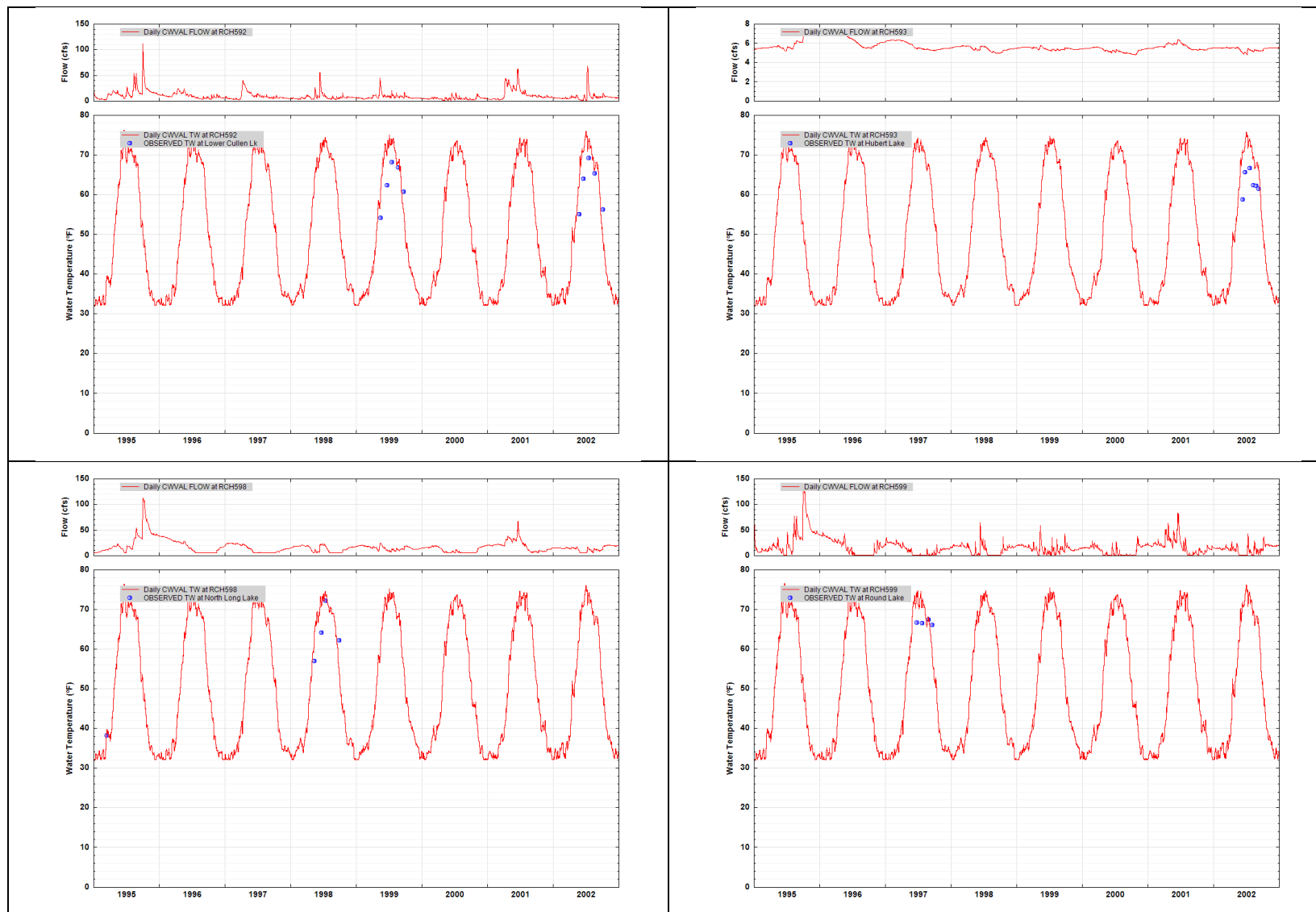






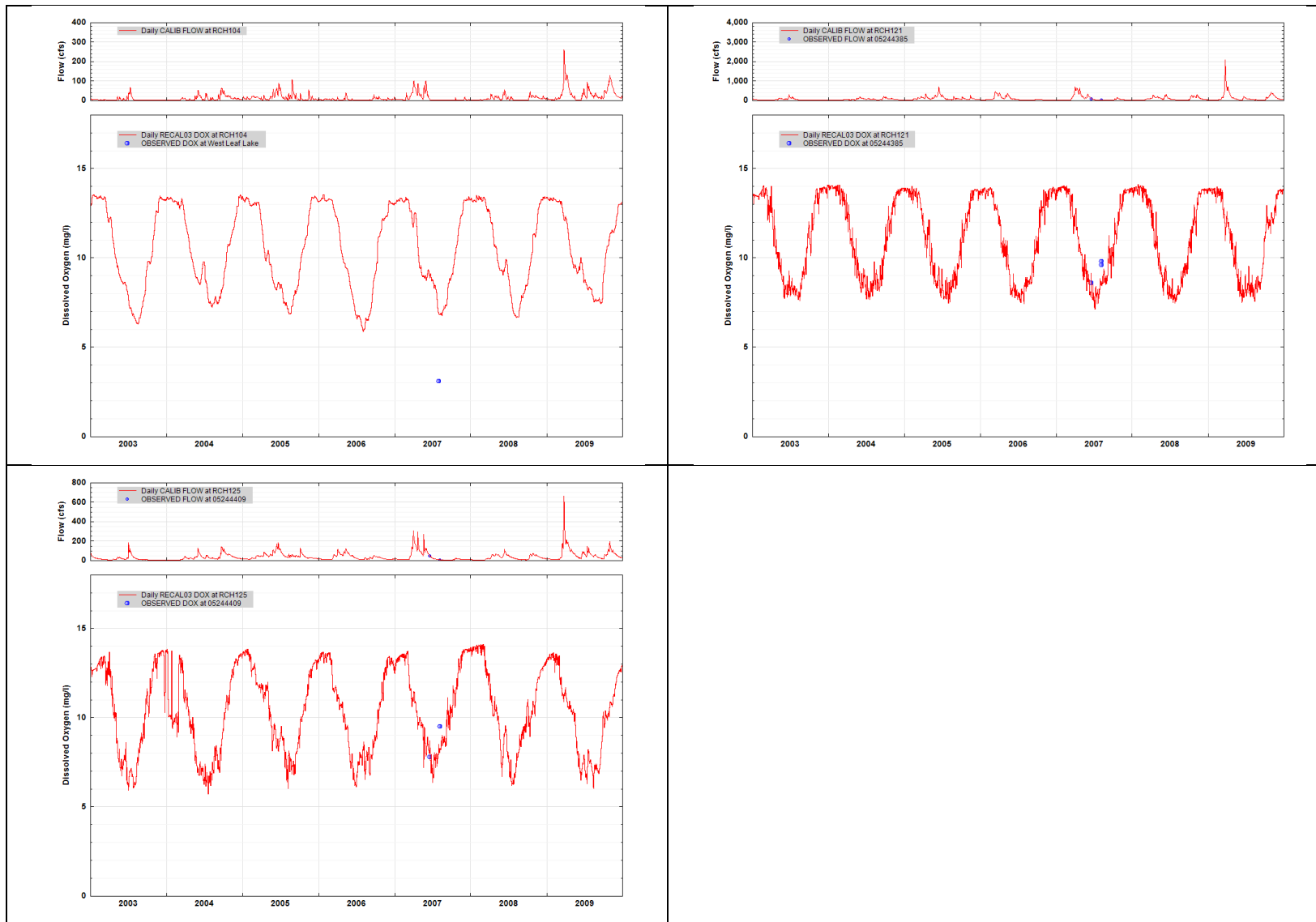
H.3 CROW WING RIVER WATERSHED



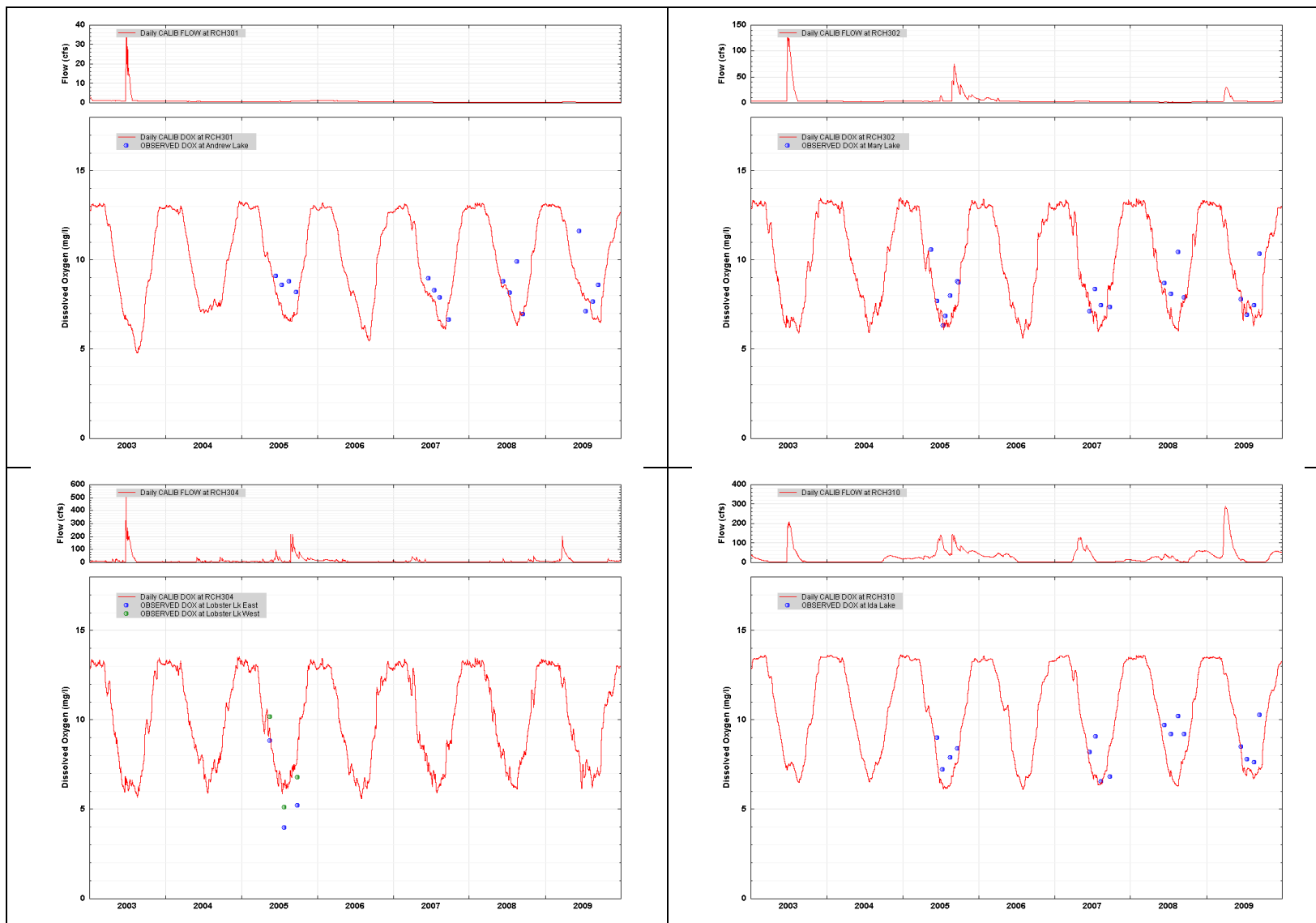


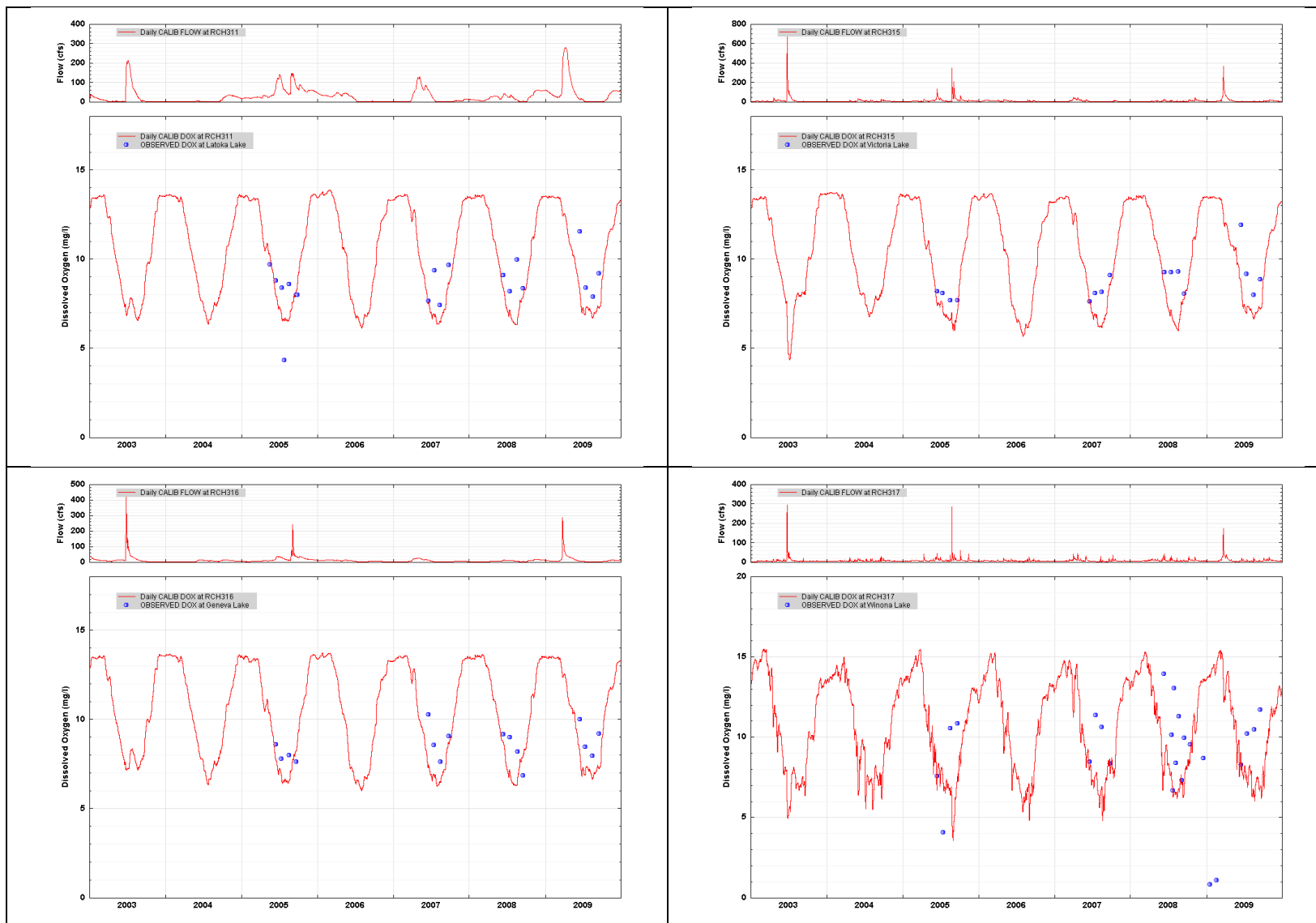
APPENDIX I OBSERVED AND SIMULATED DISSOLVED OXYGEN FOR THE CALIBRATION PERIOD

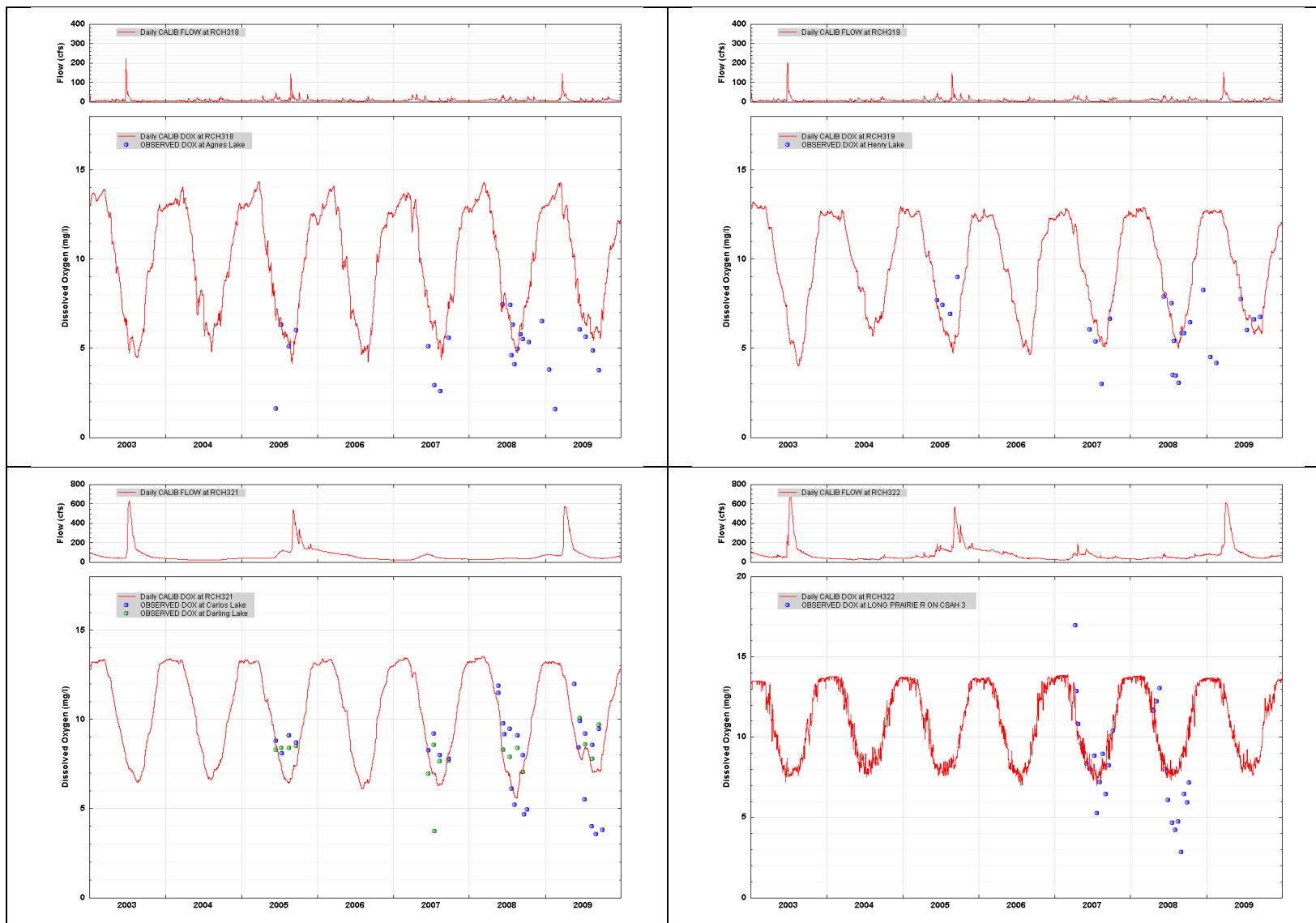
I.1 REDEYE RIVER WATERSHED

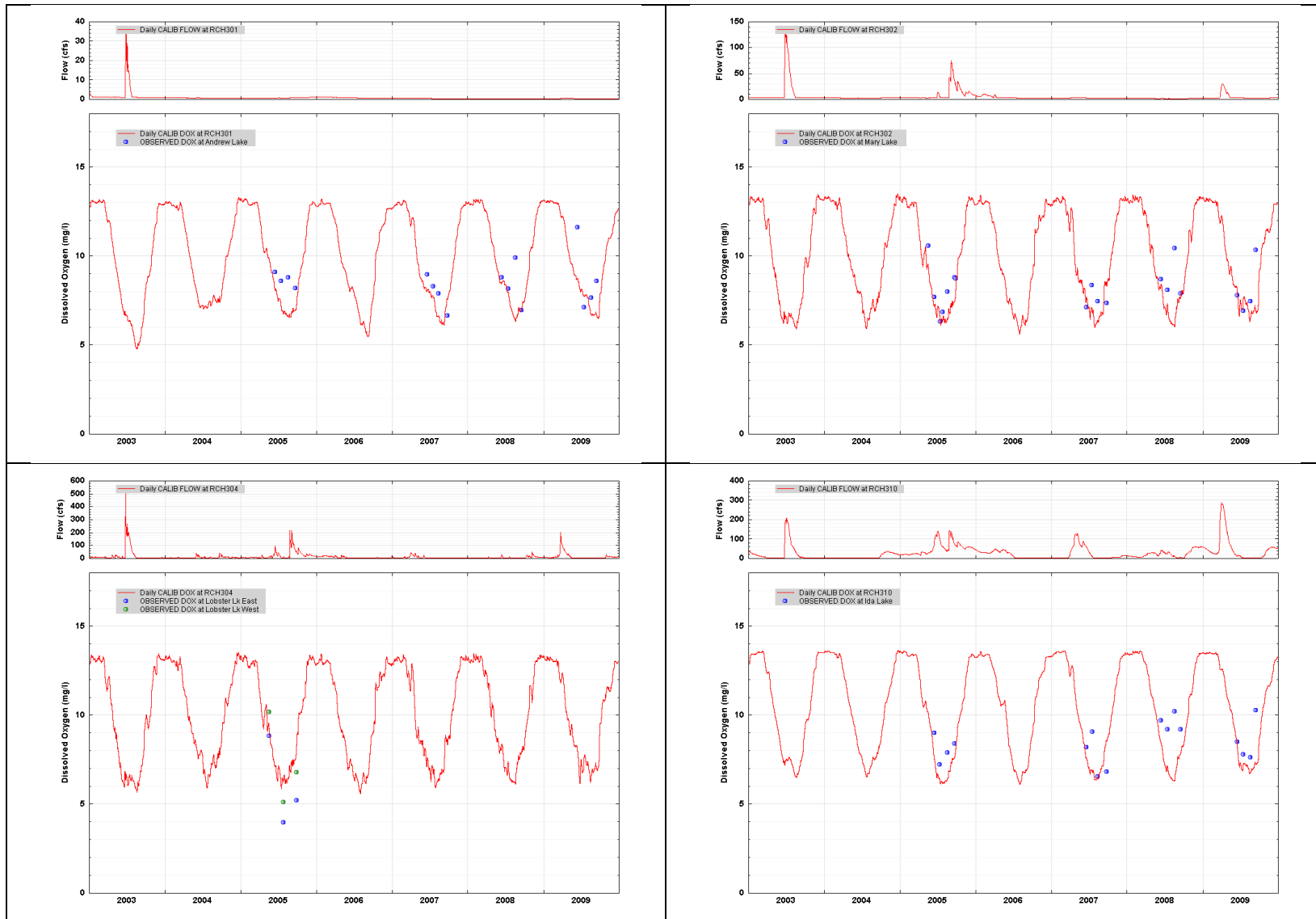


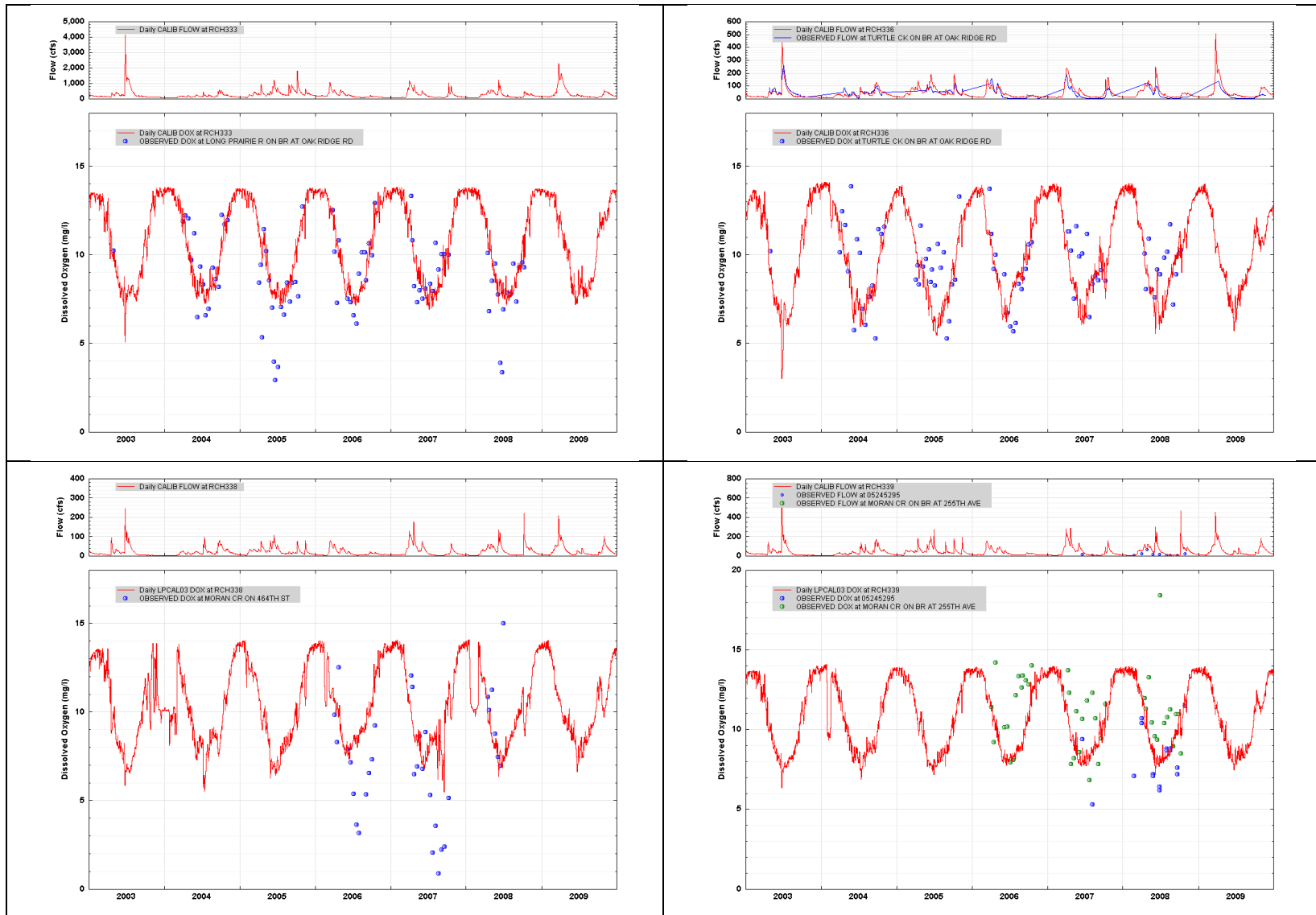
I.2 LONG PRAIRIE RIVER WATERSHED

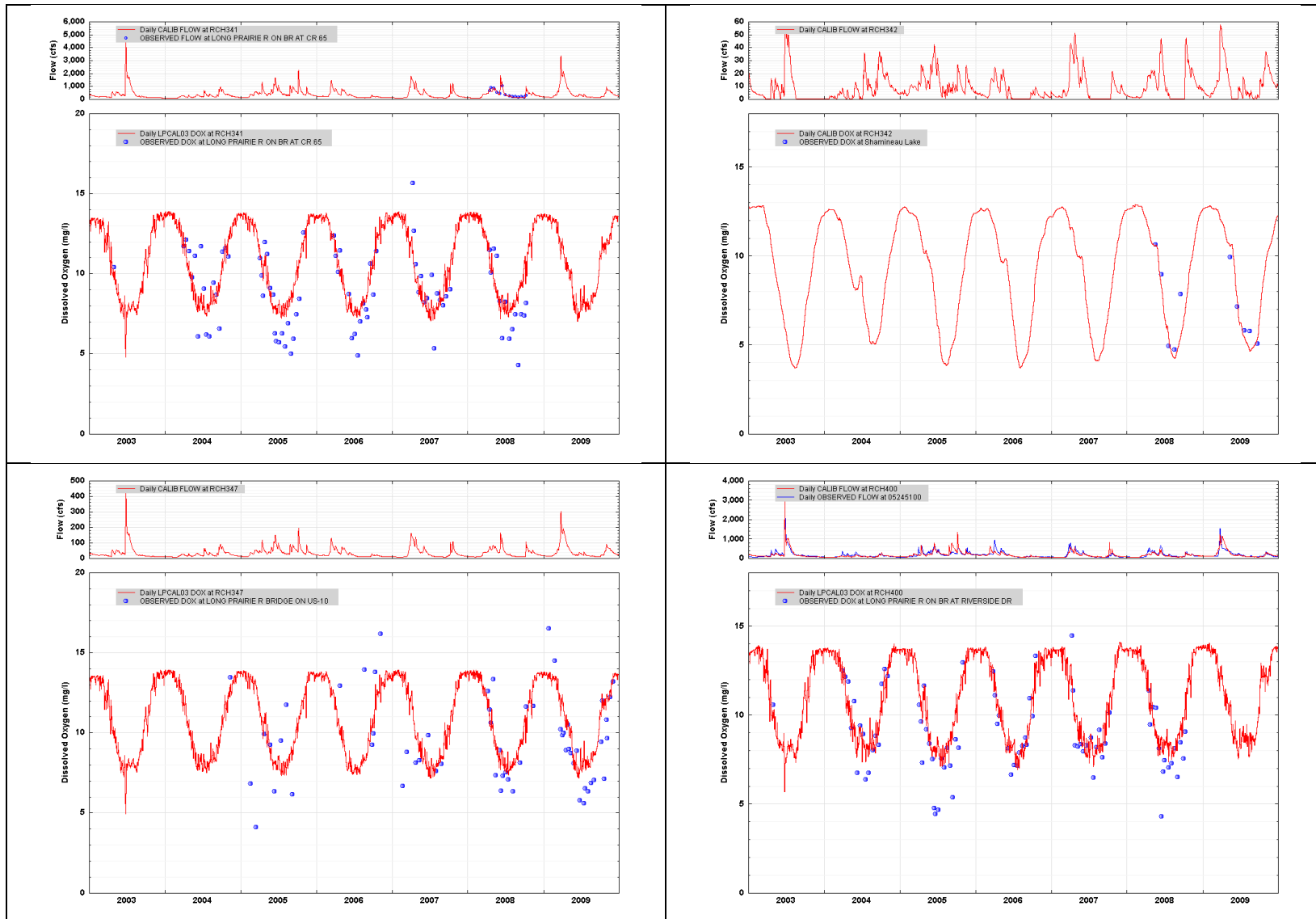




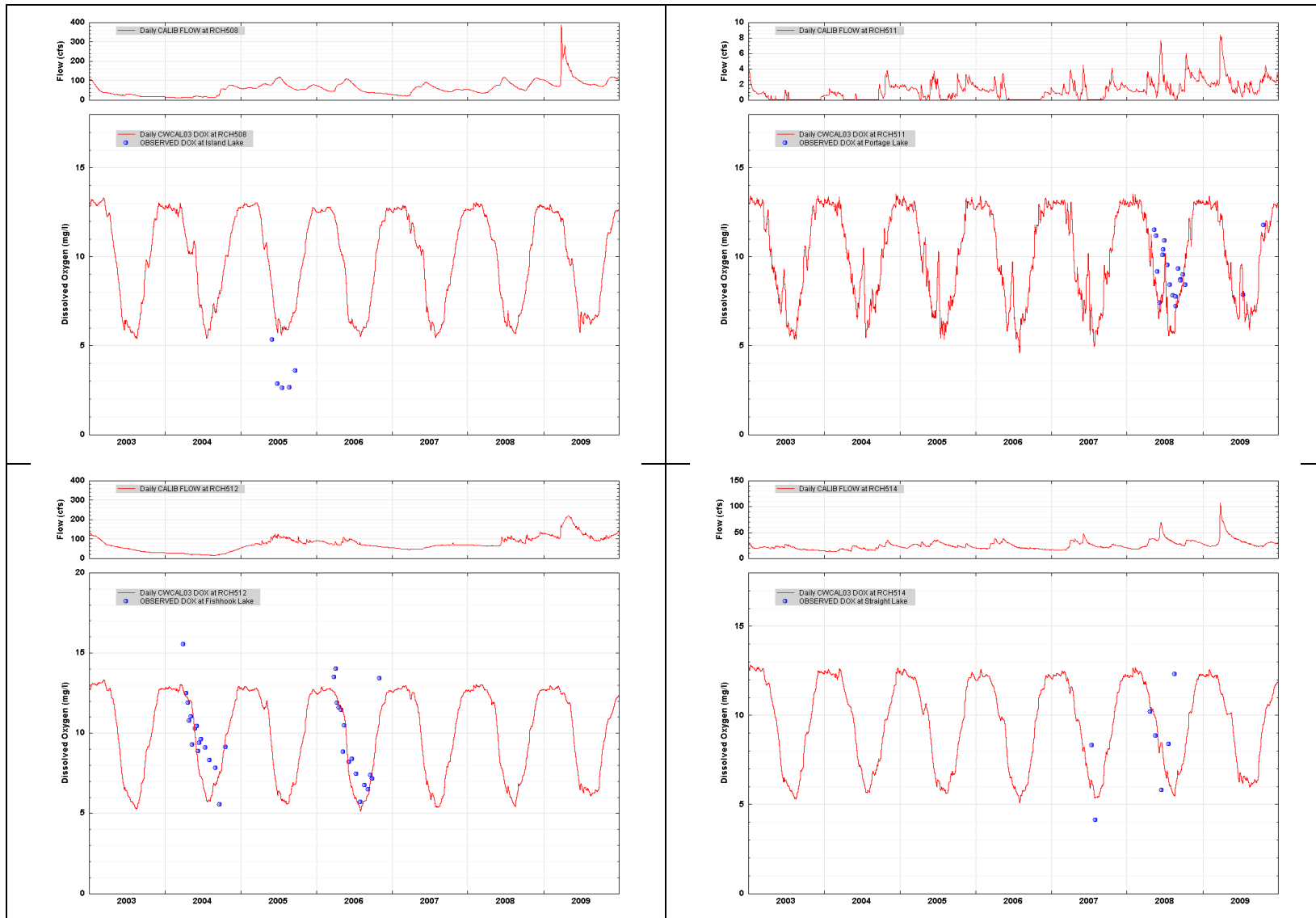


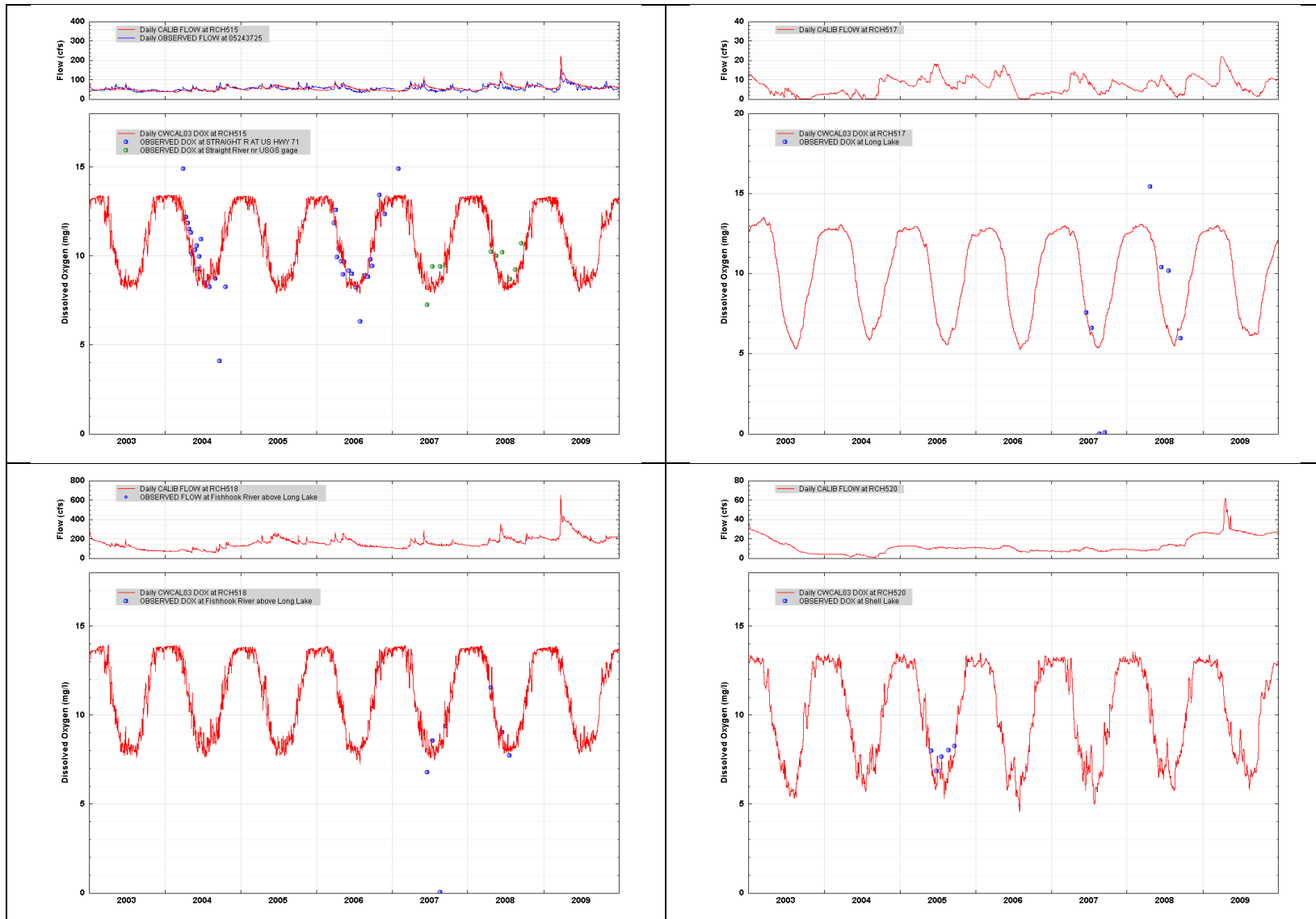


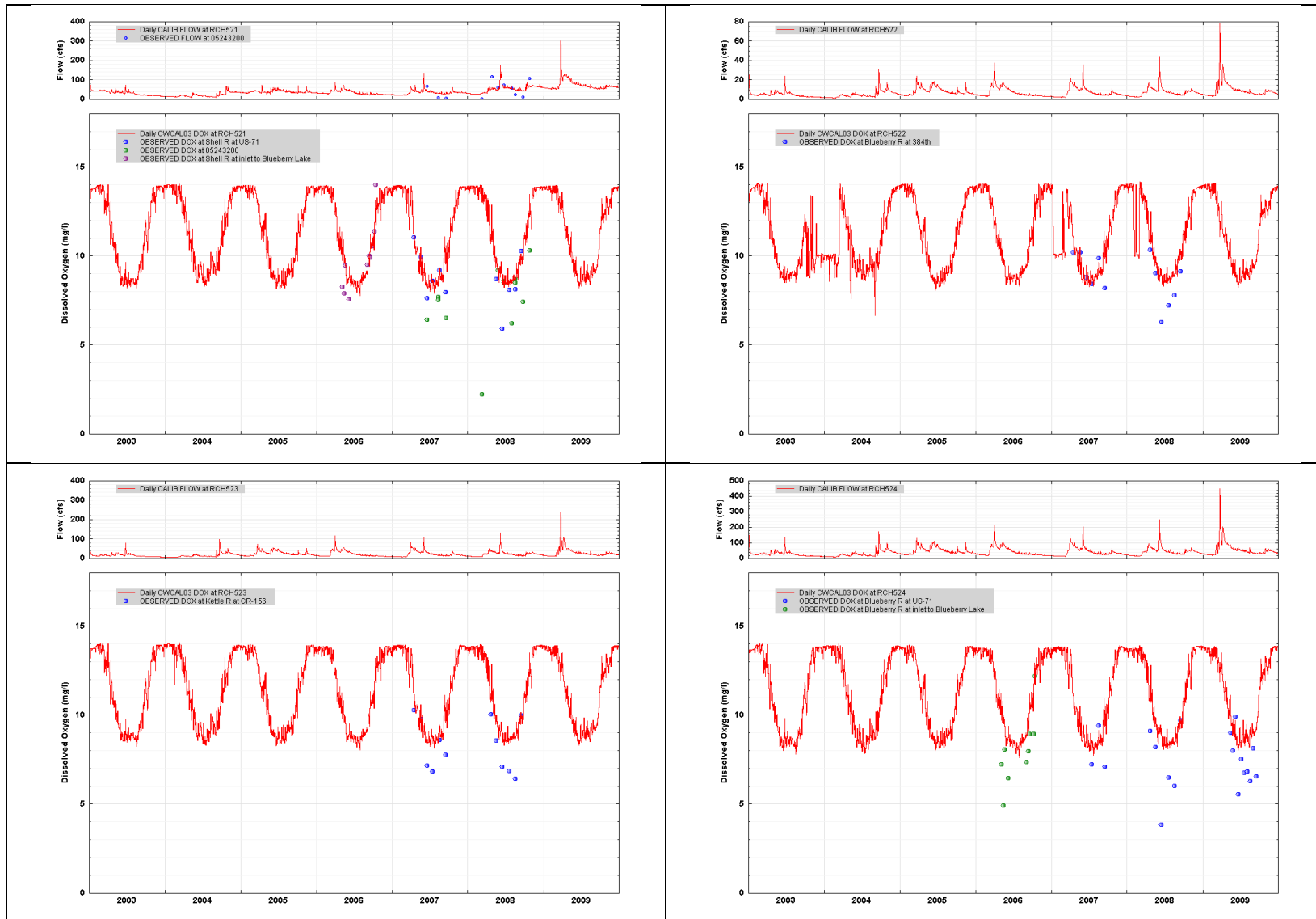


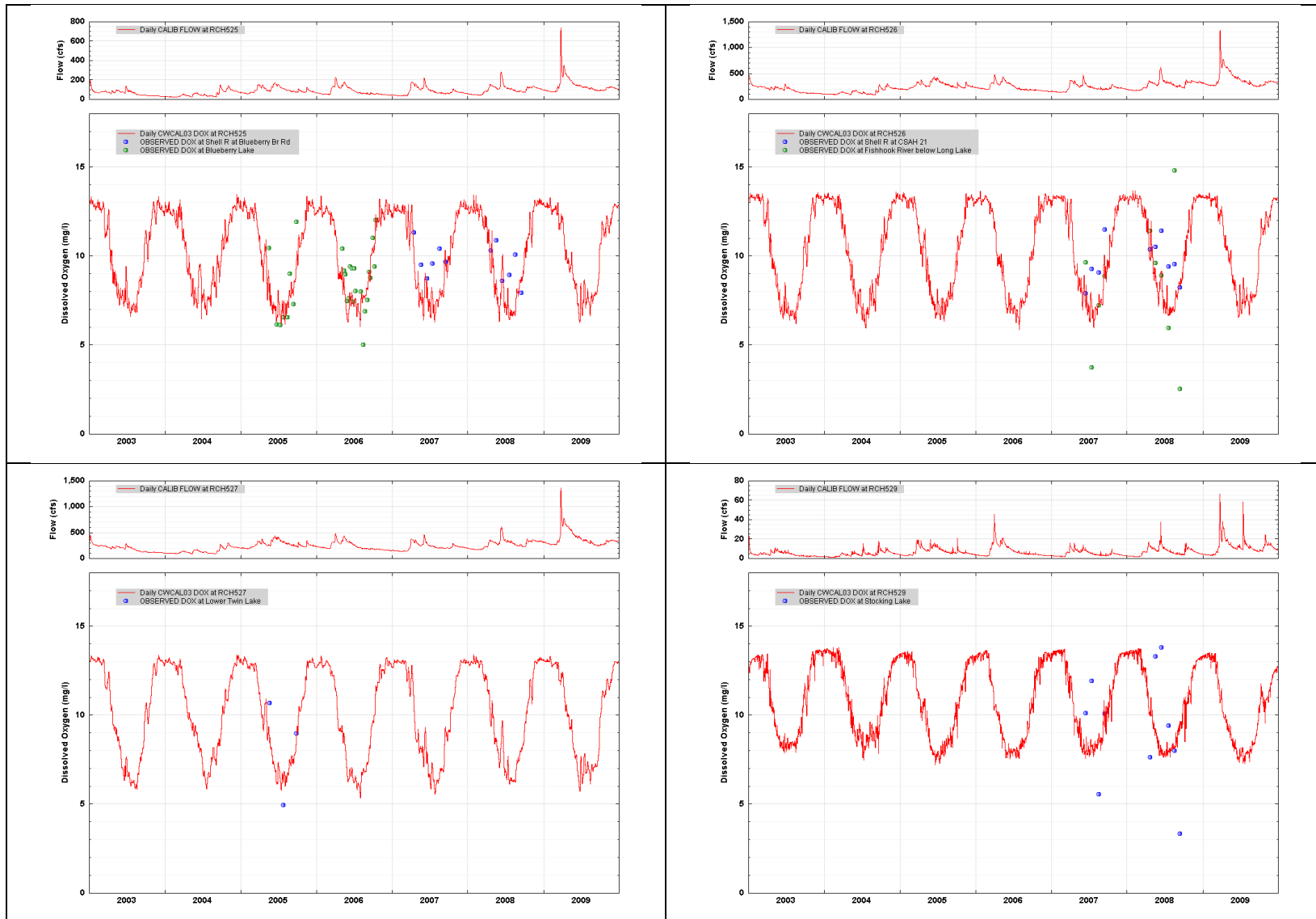


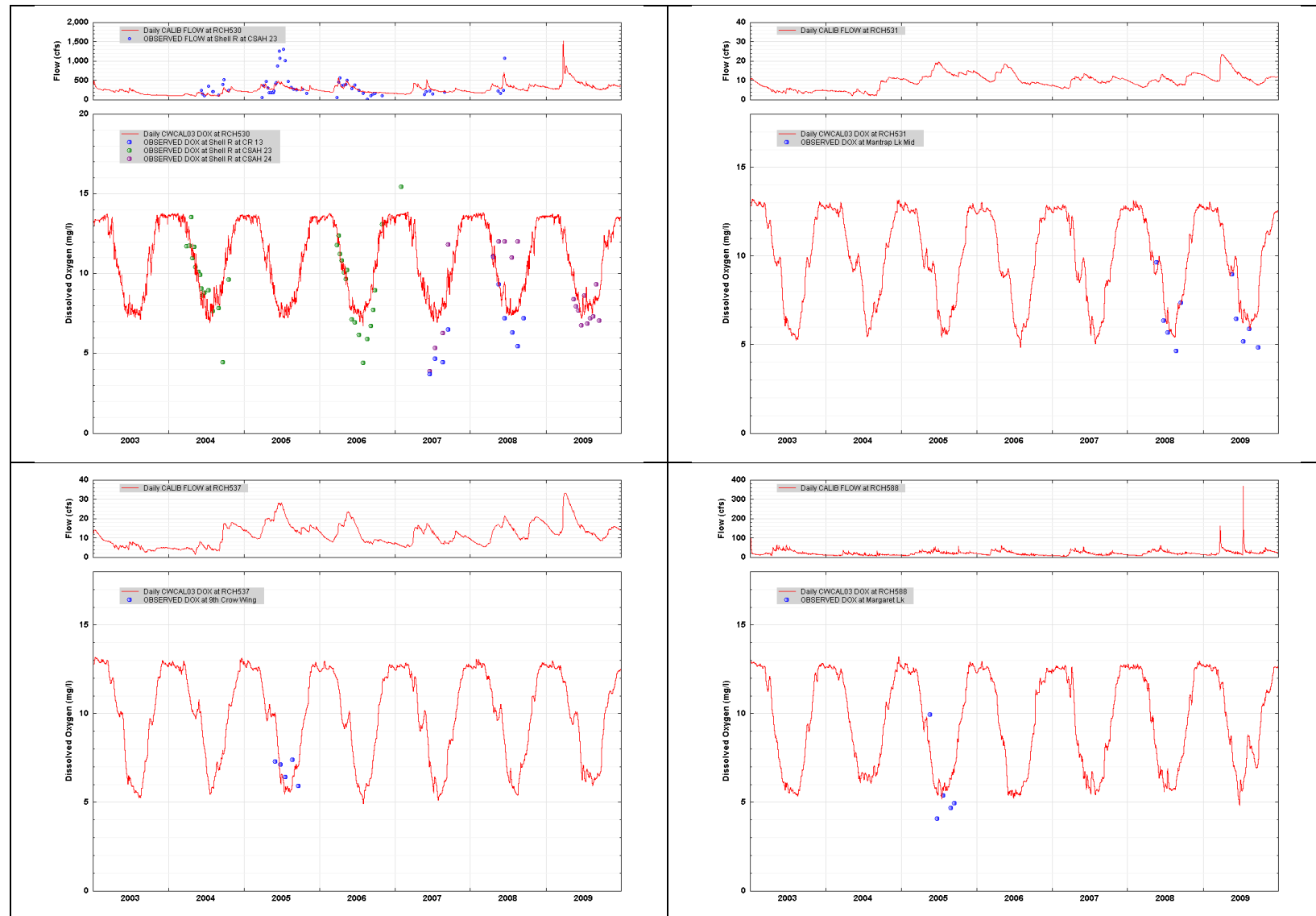
I.3 CROW WING RIVER WATERSHED

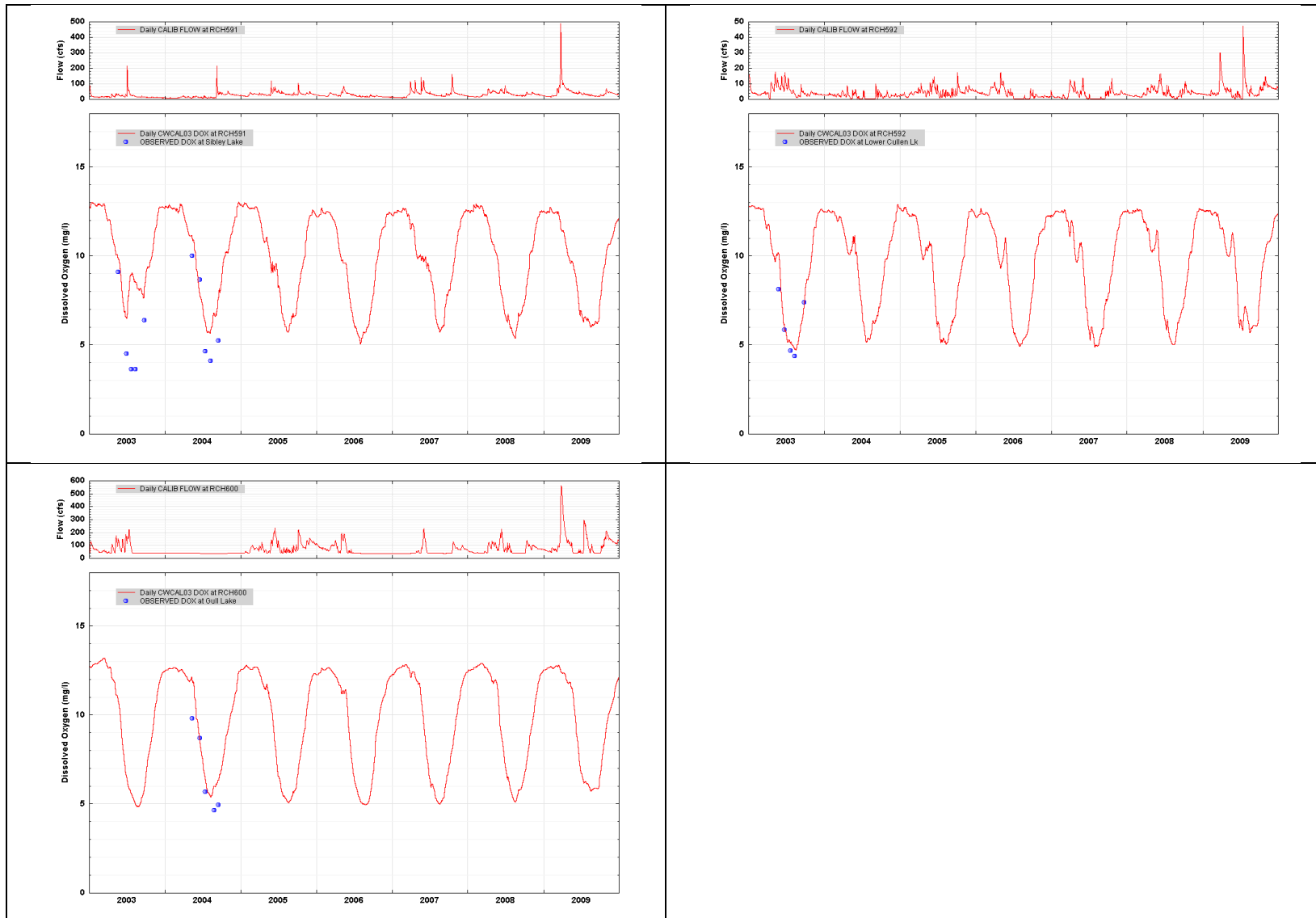








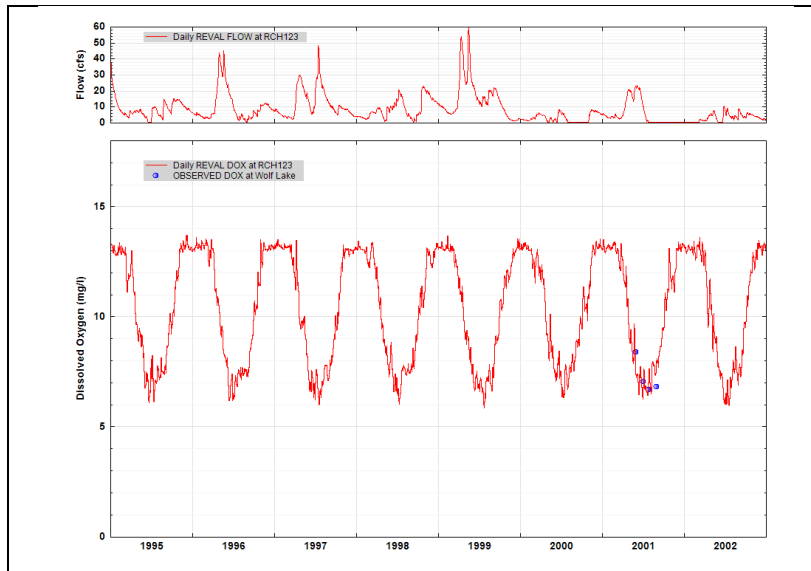


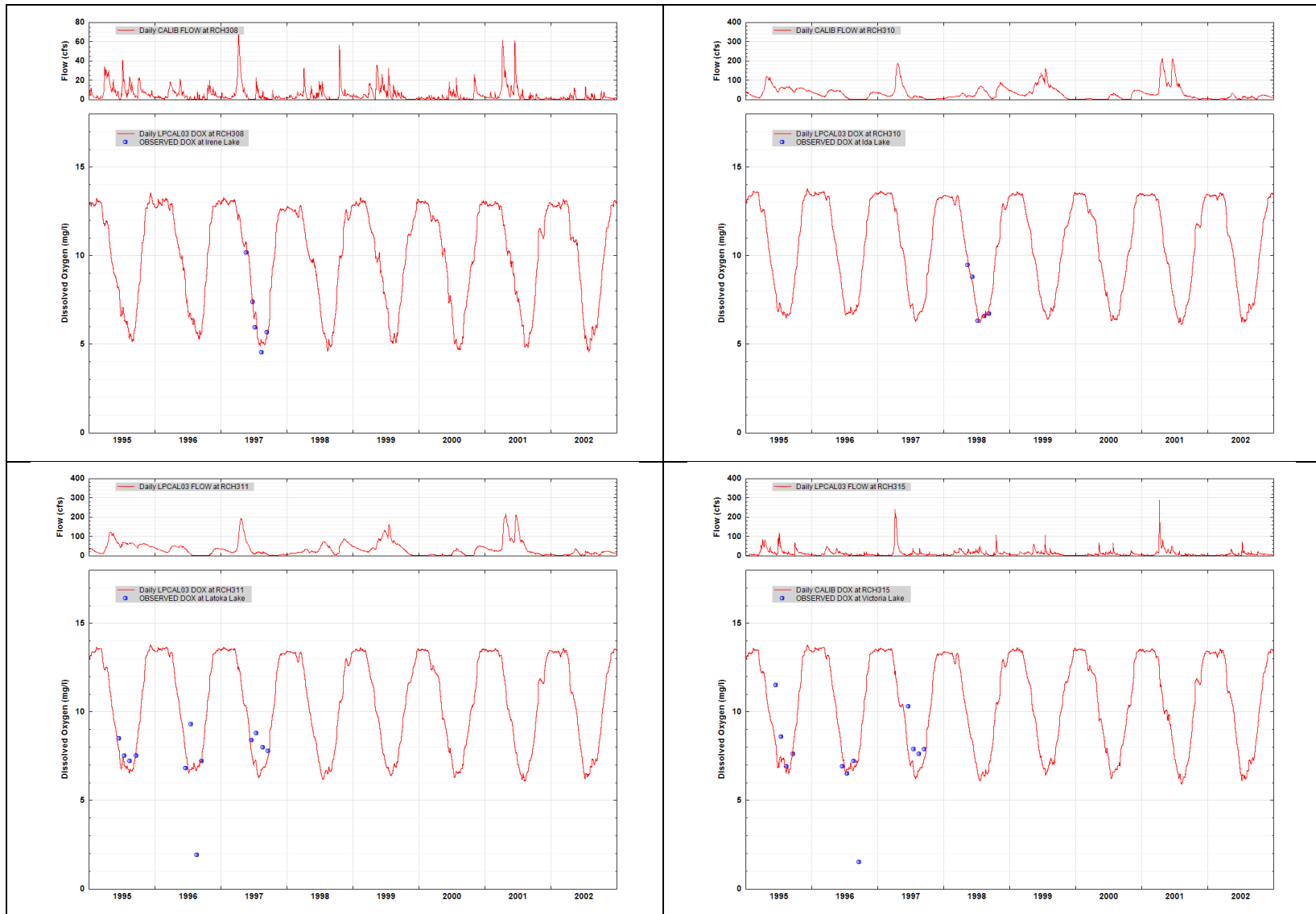


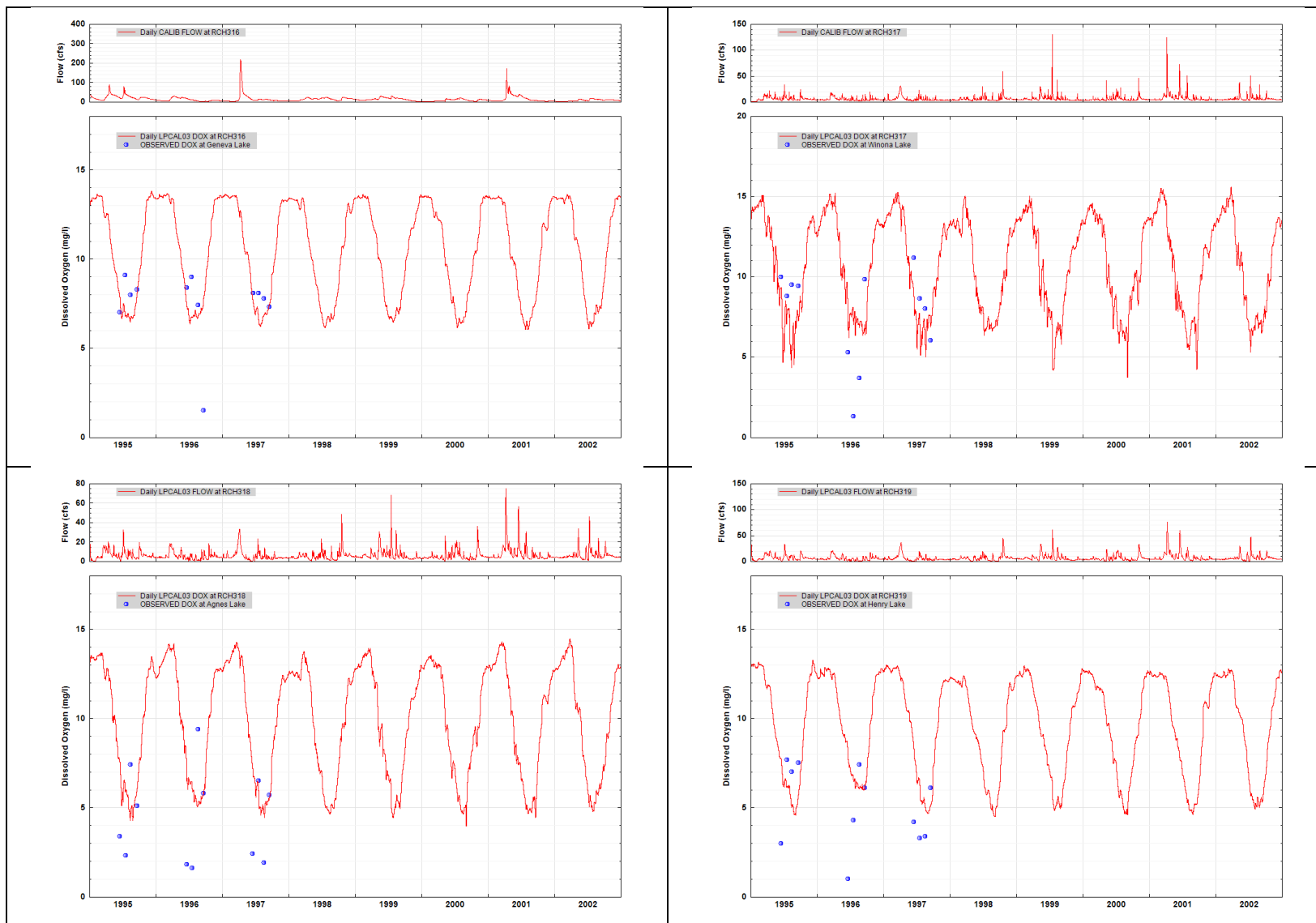
APPENDIX J

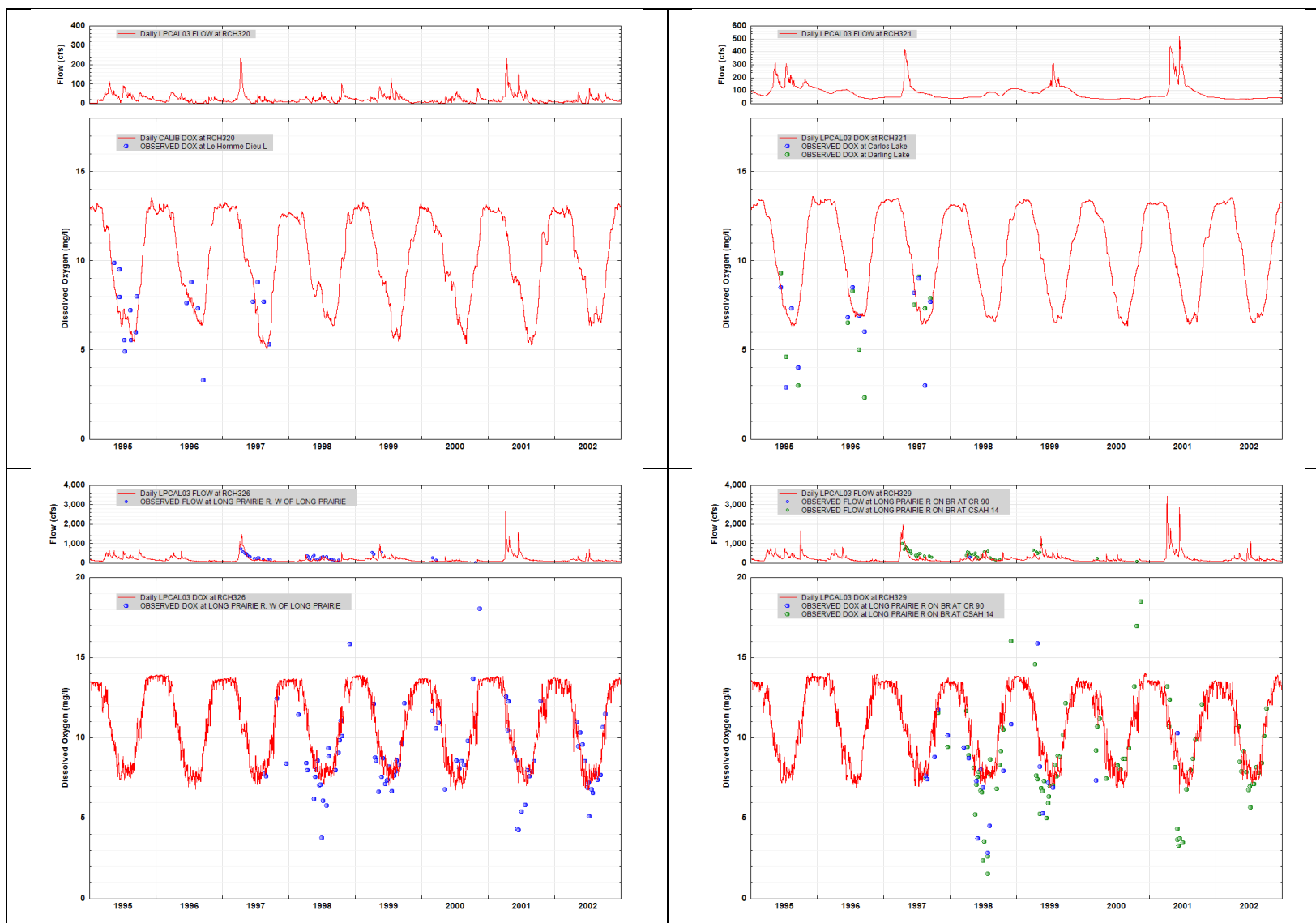
OBSERVED AND SIMULATED DISSOLVED OXYGEN FOR THE VALIDATION PERIOD

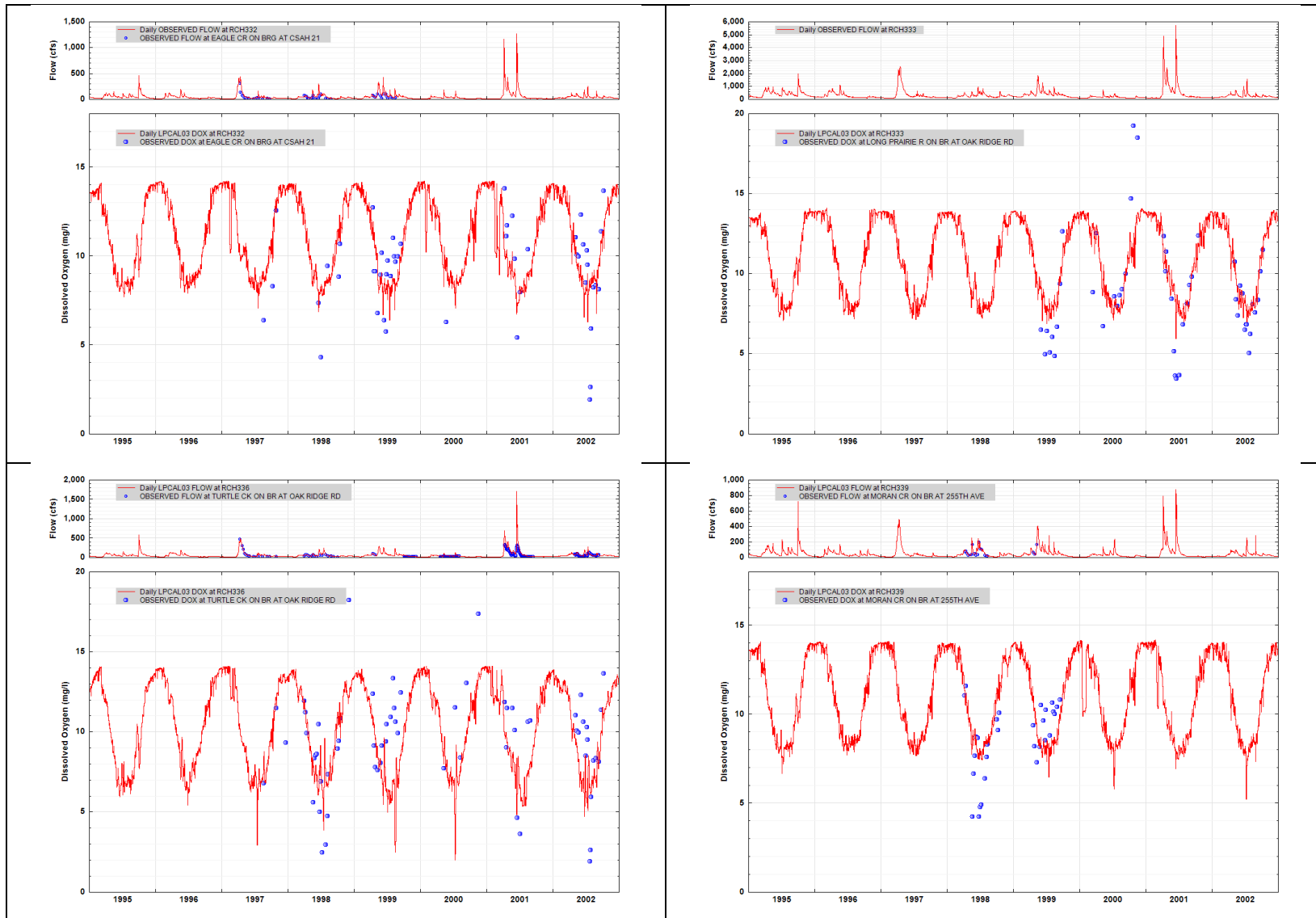
J.1 REDEYE RIVER WATERSHED

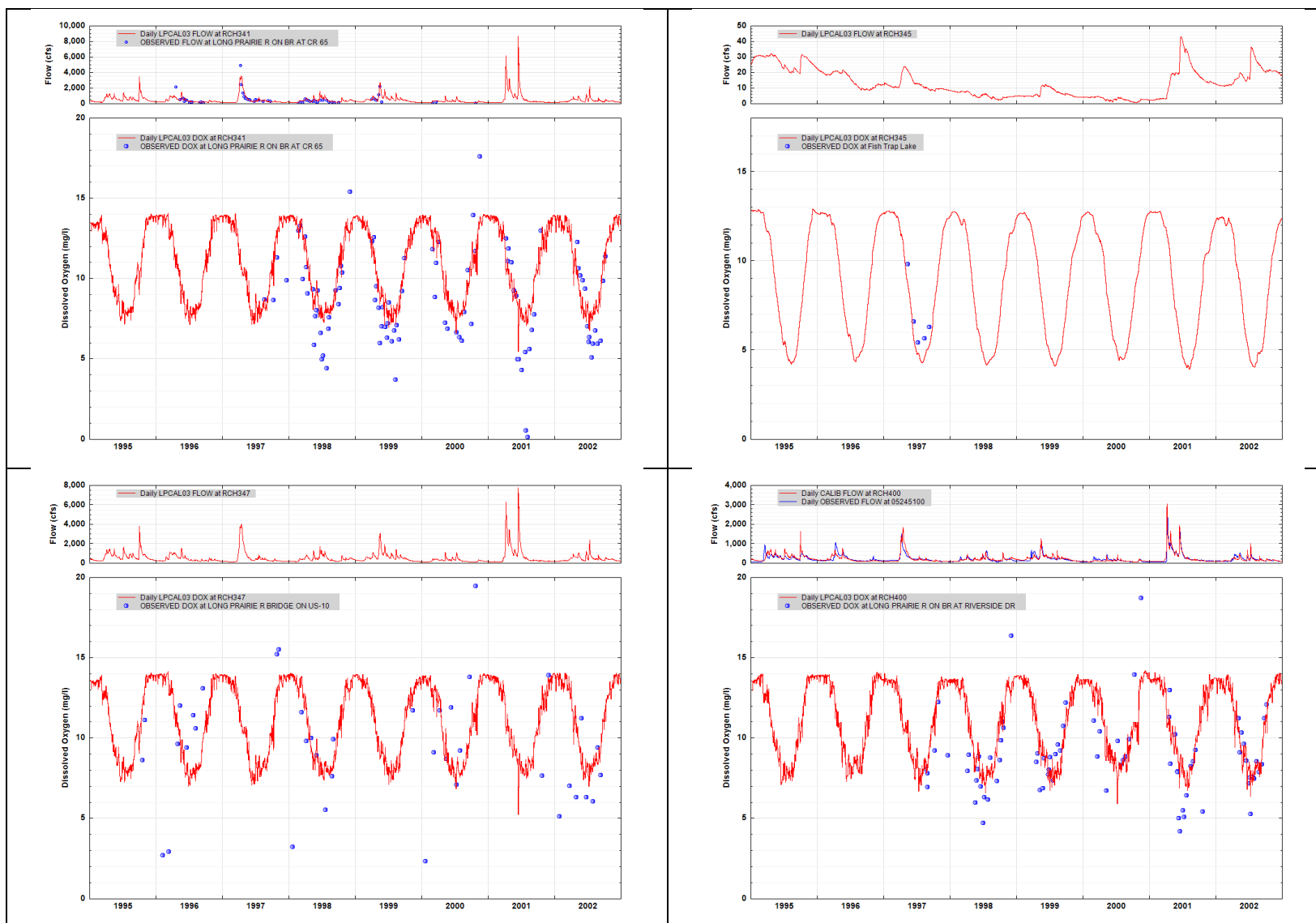


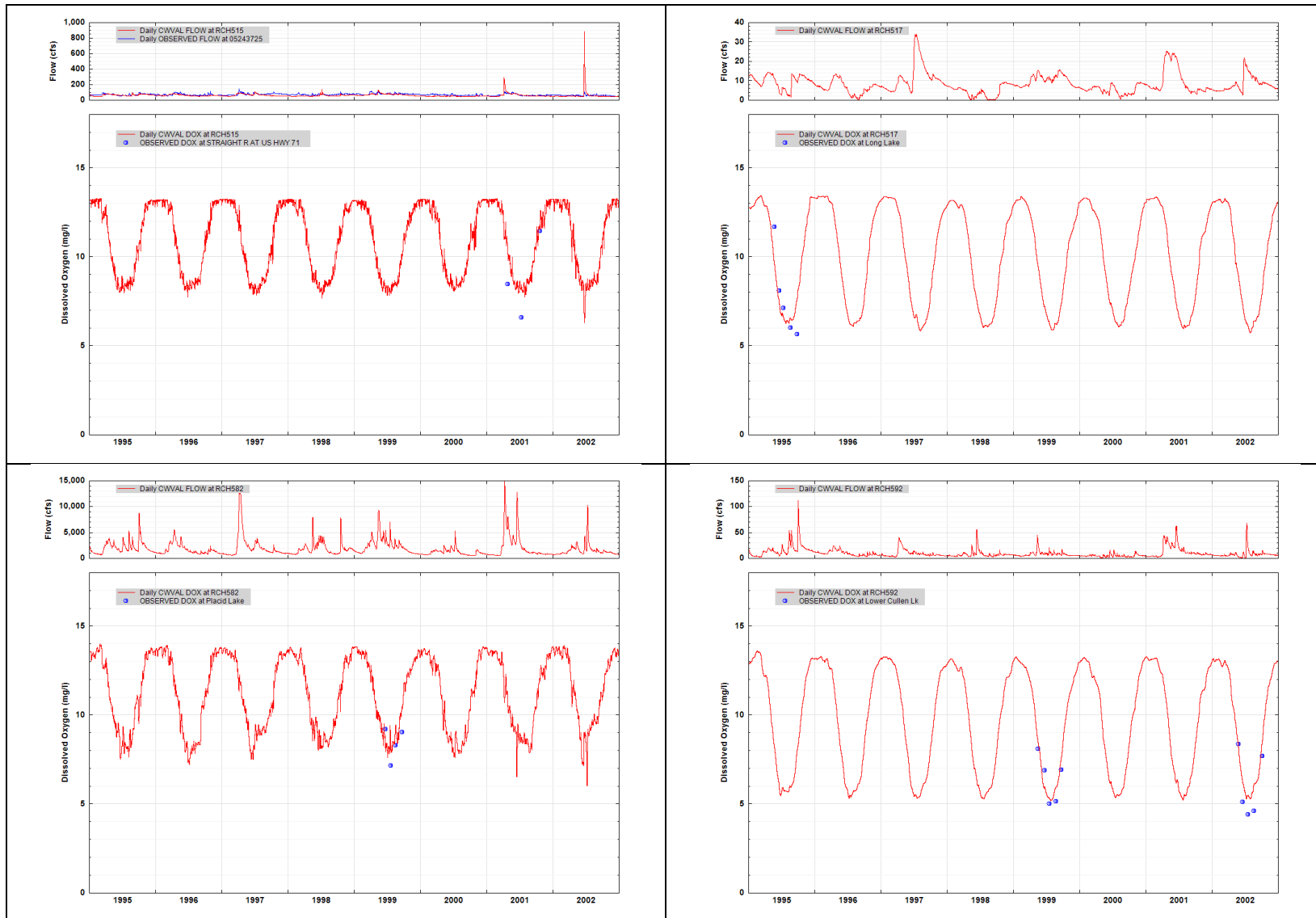
J.2 LONG PRAIRIE RIVER WATERSHED

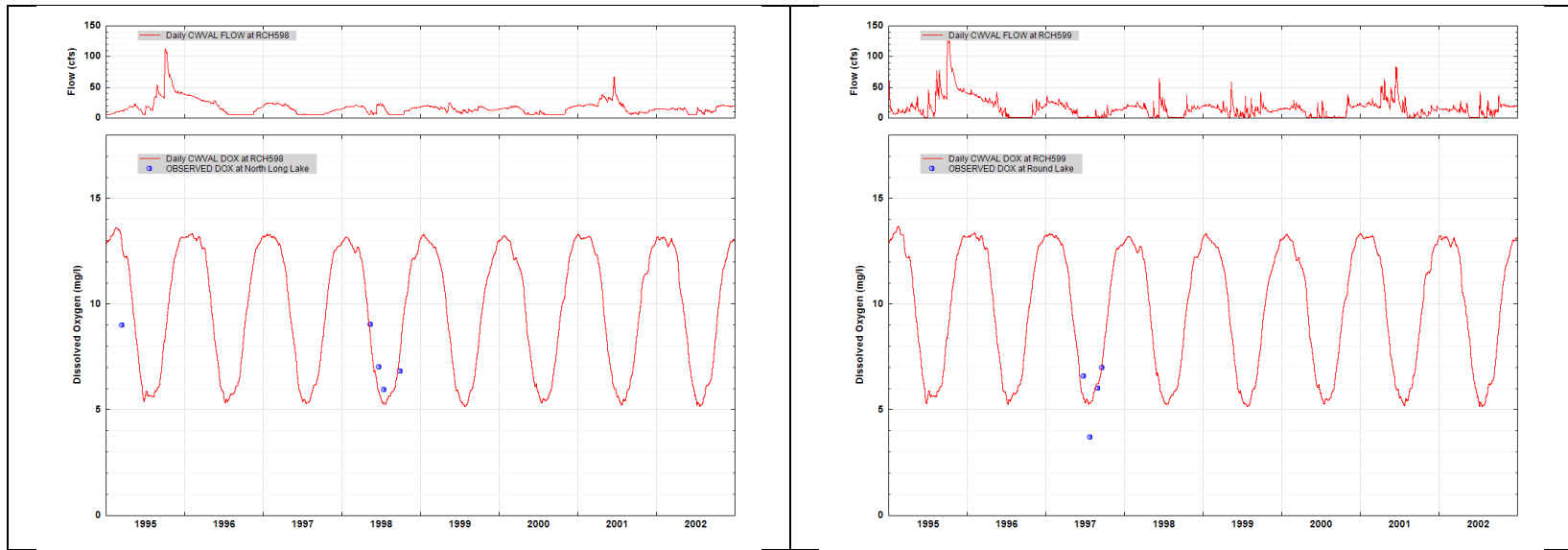








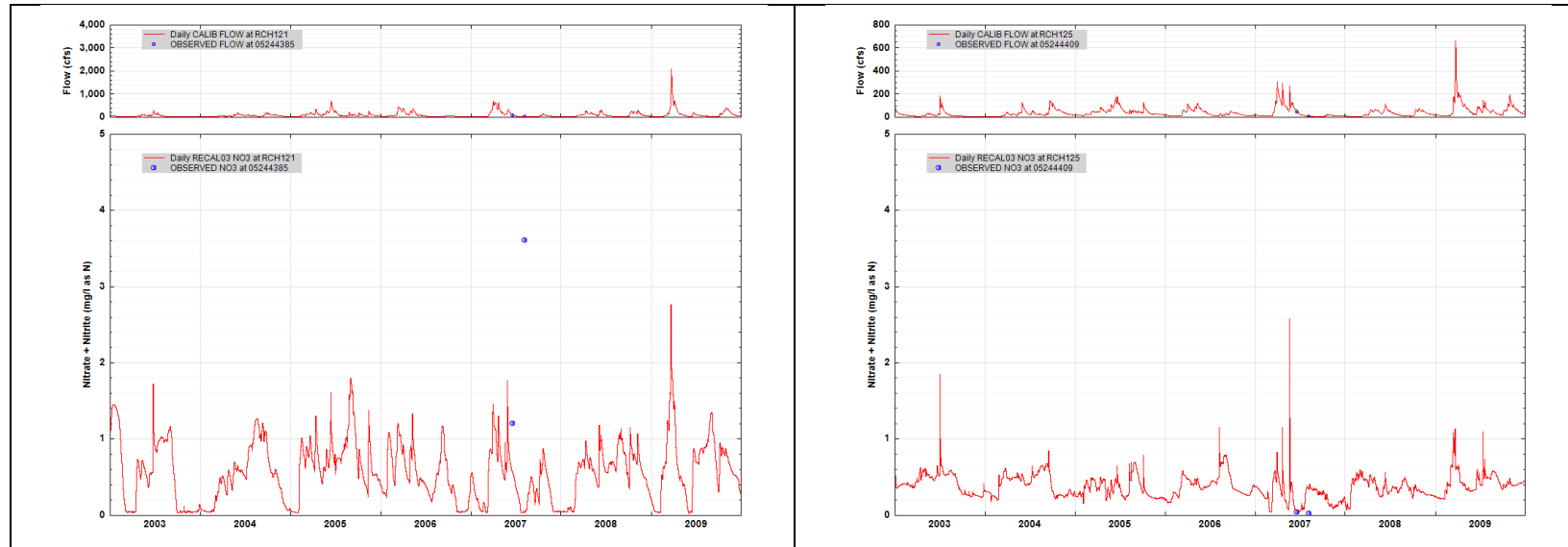
J.3 CROW WING RIVER WATERSHED



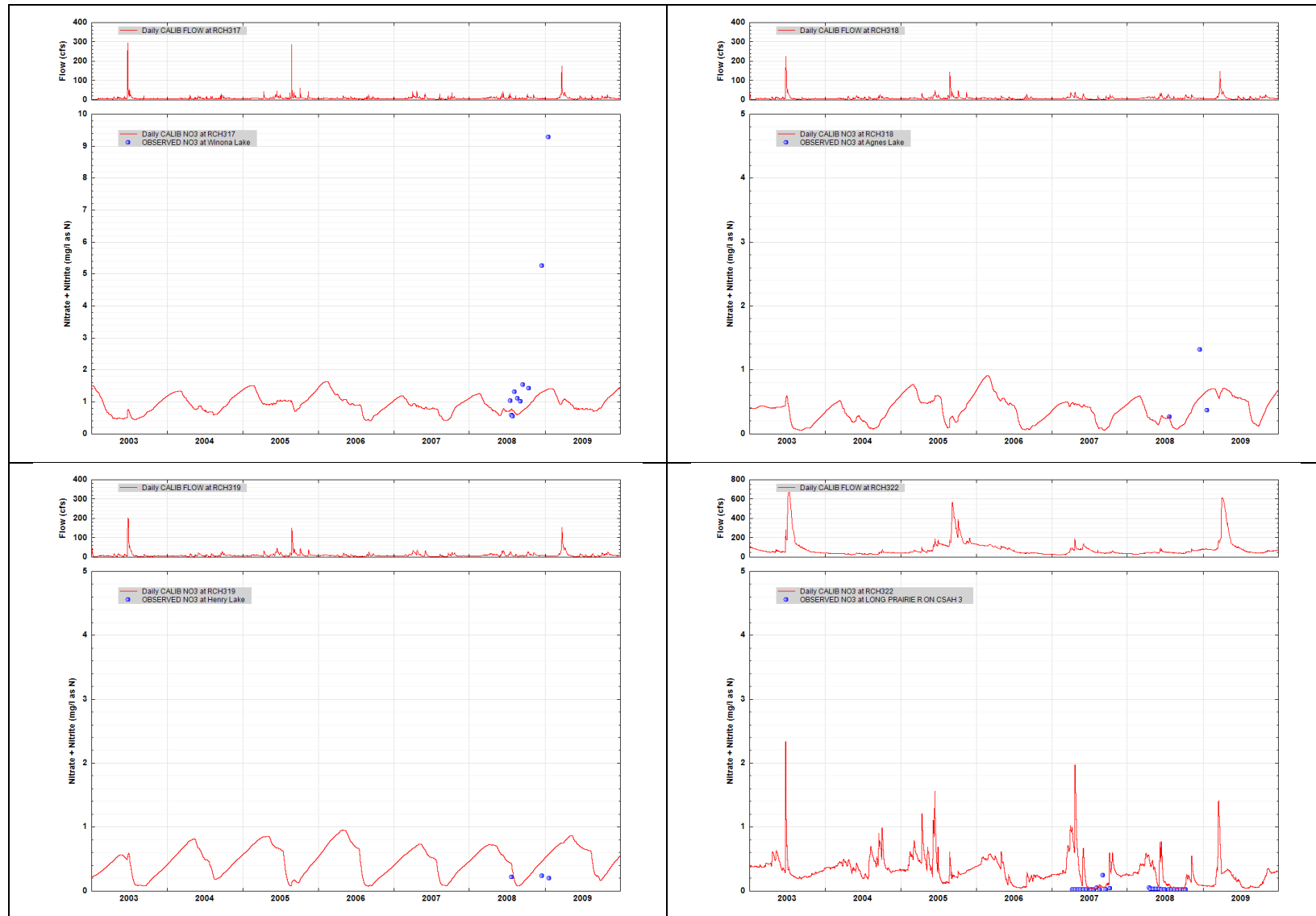
APPENDIX K OBSERVED AND SIMULATED NITROGEN CONSTITUENTS FOR THE CALIBRATION PERIOD

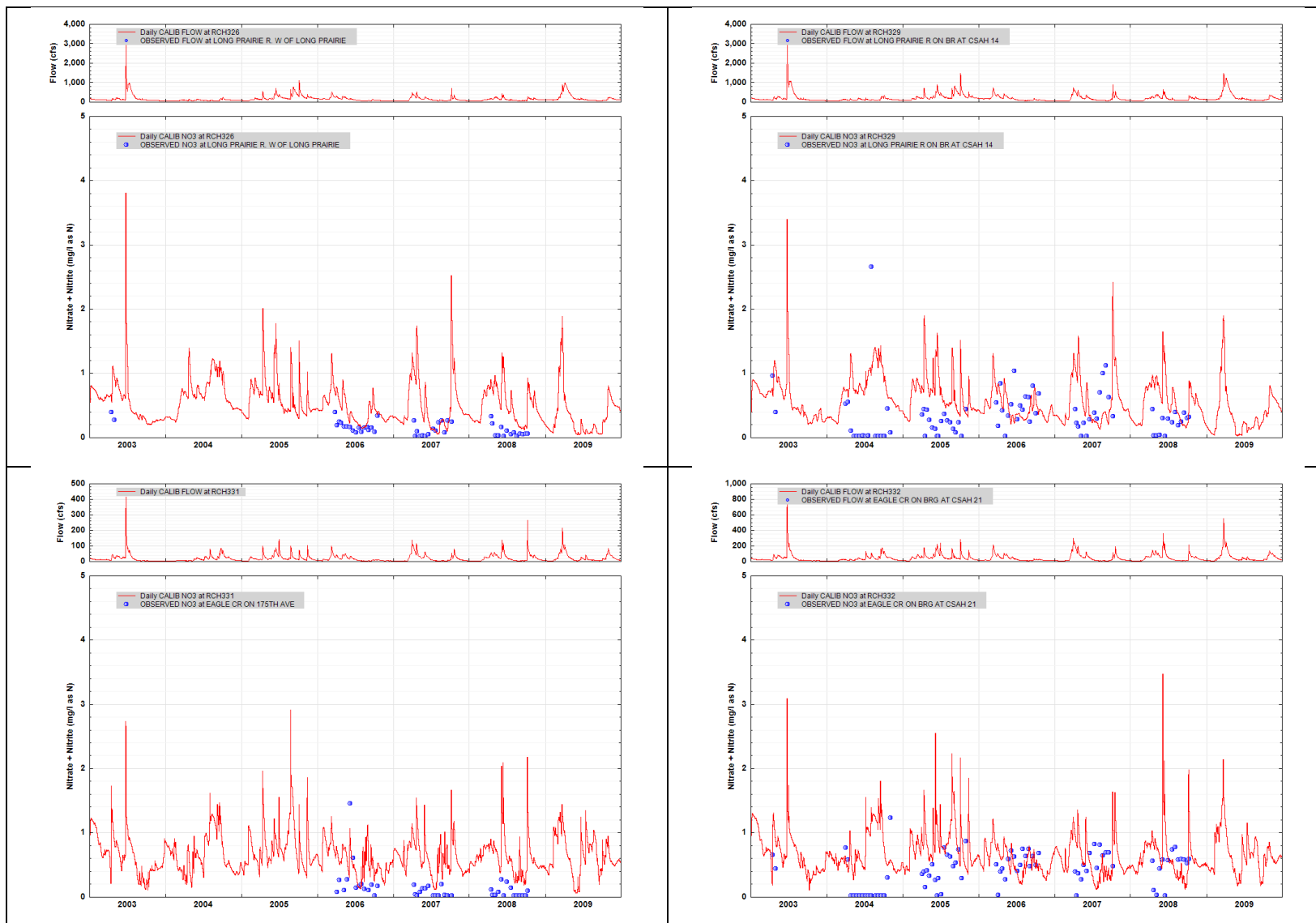
K.1 NITRATE

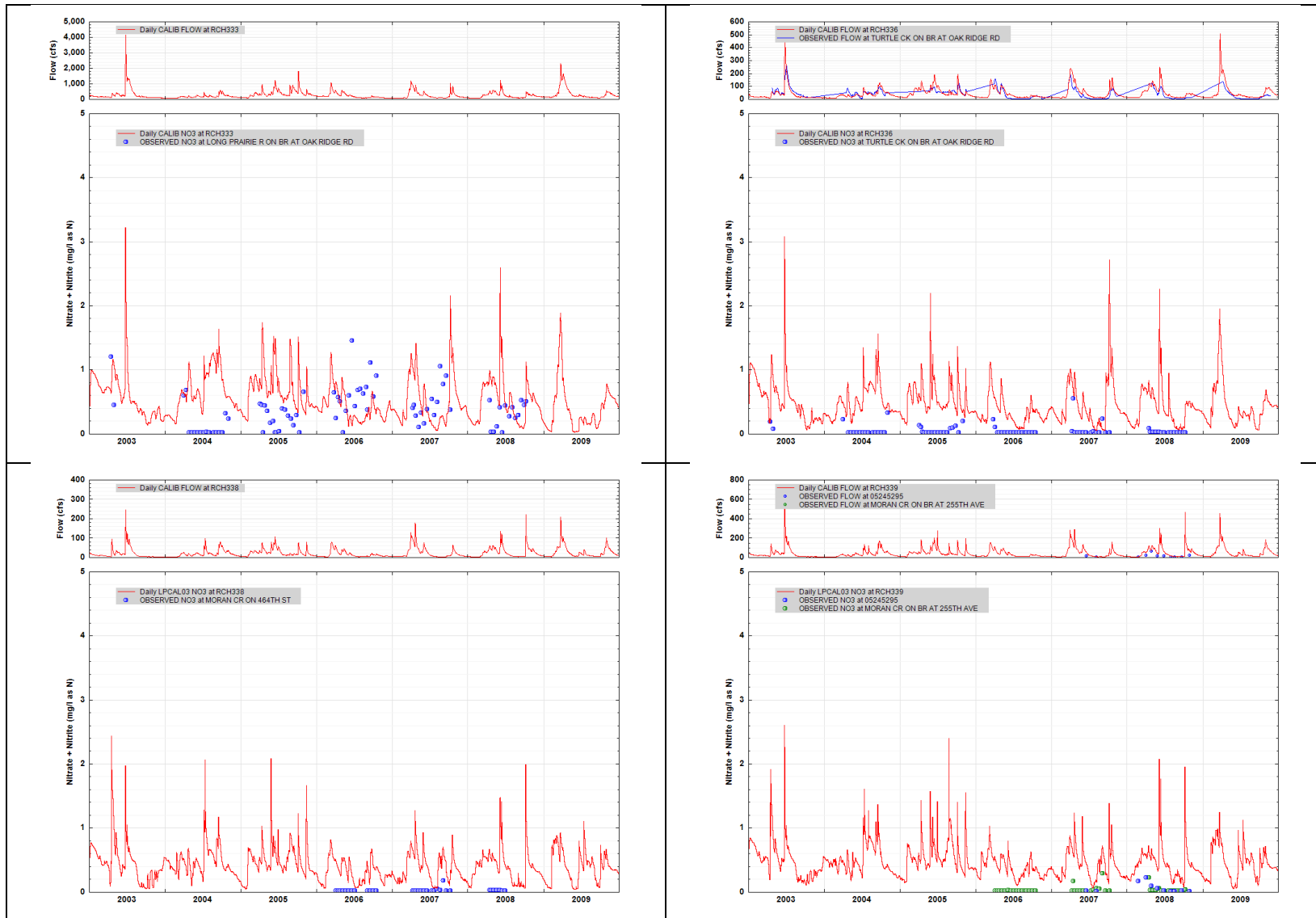
K.1.1 Redeye River Watershed

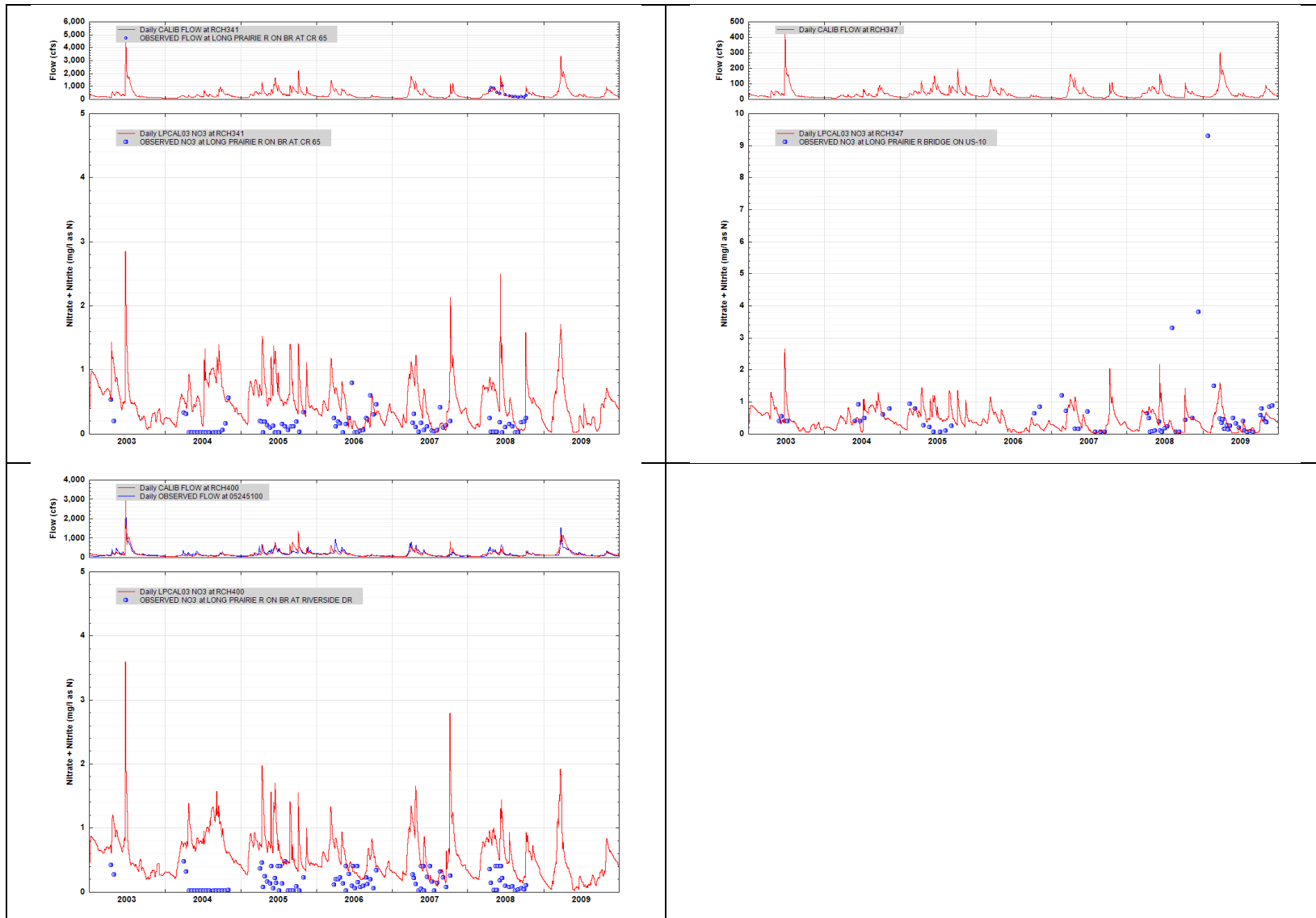


K.1.2 Long Prairie River Watershed

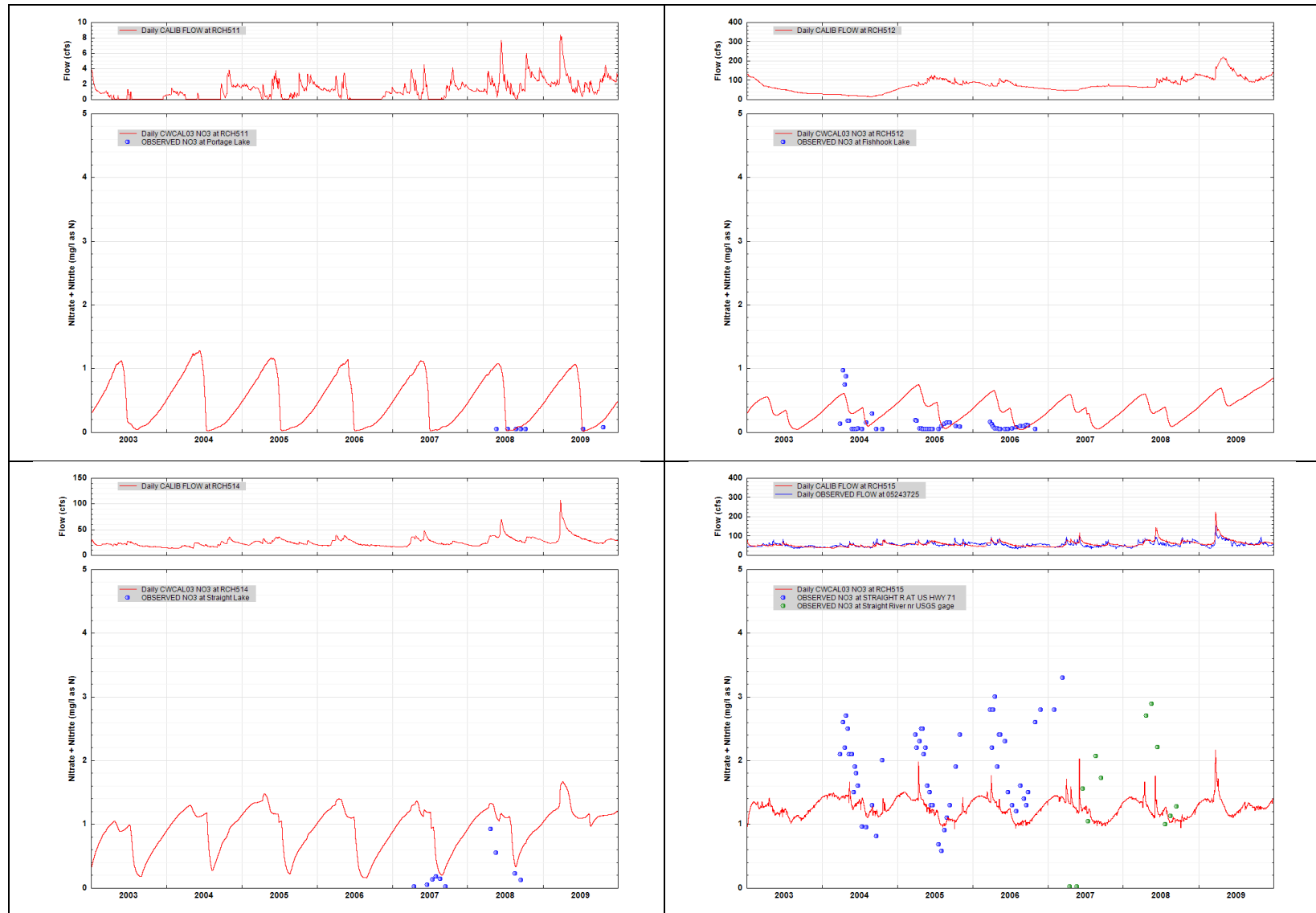


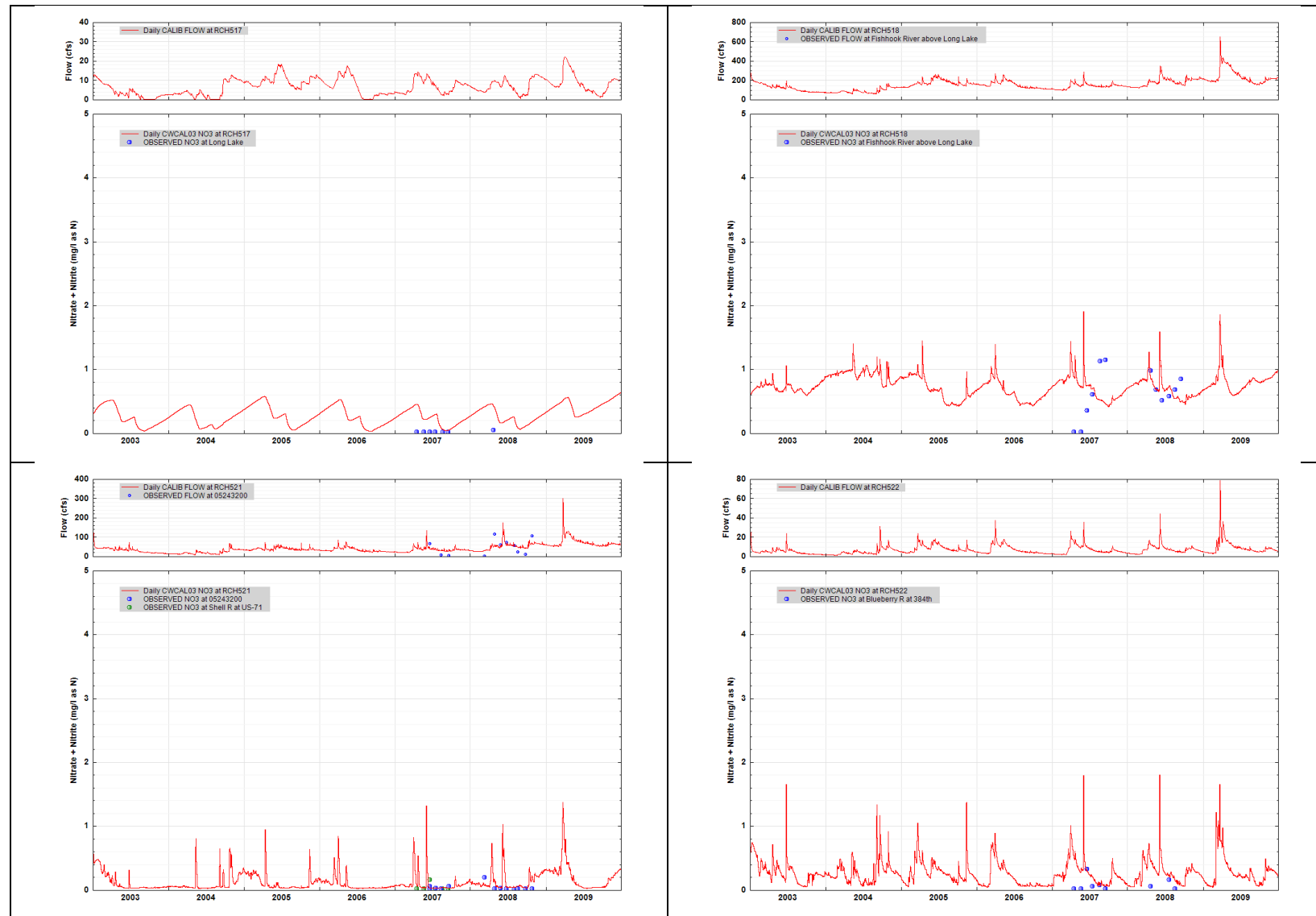


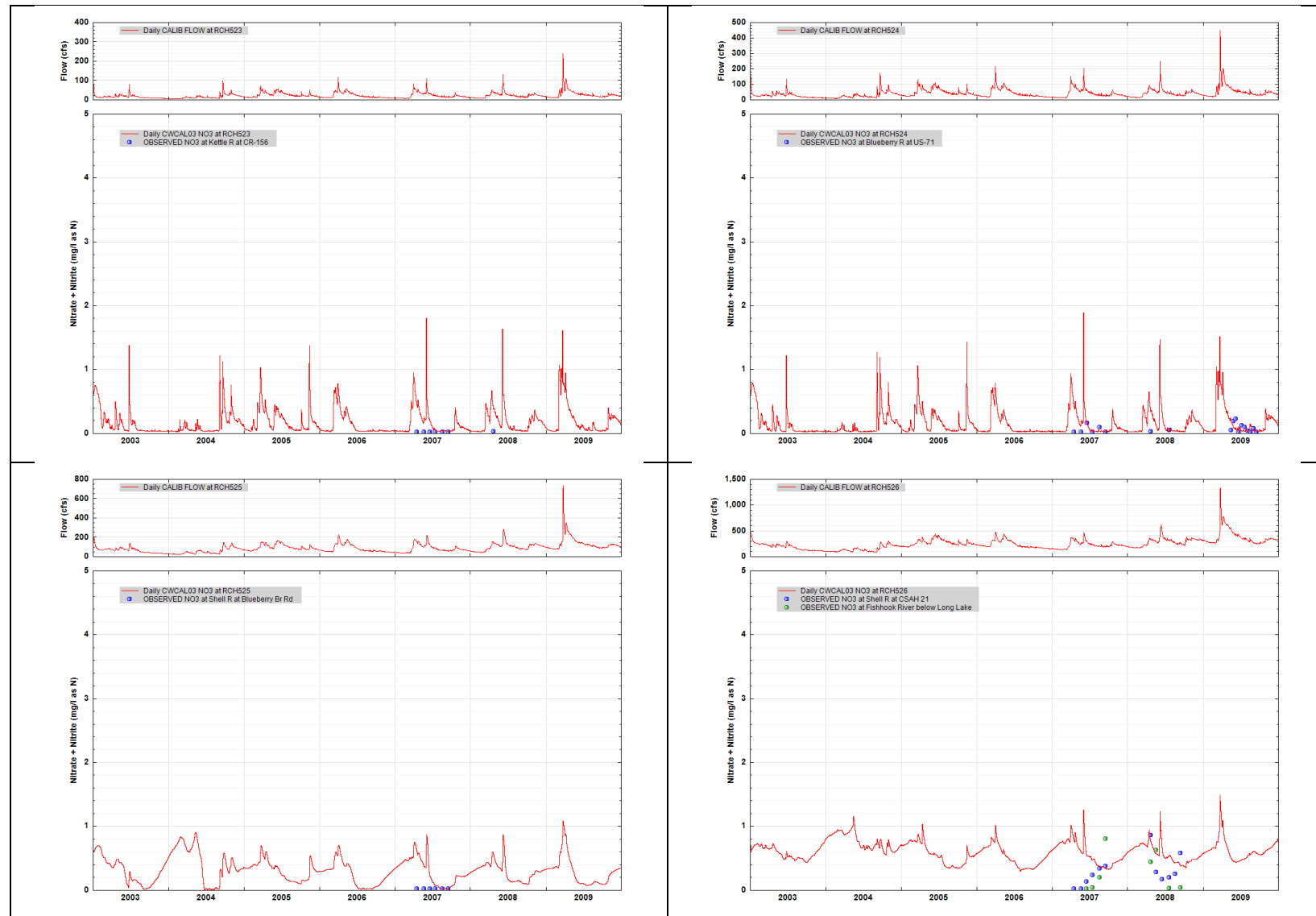


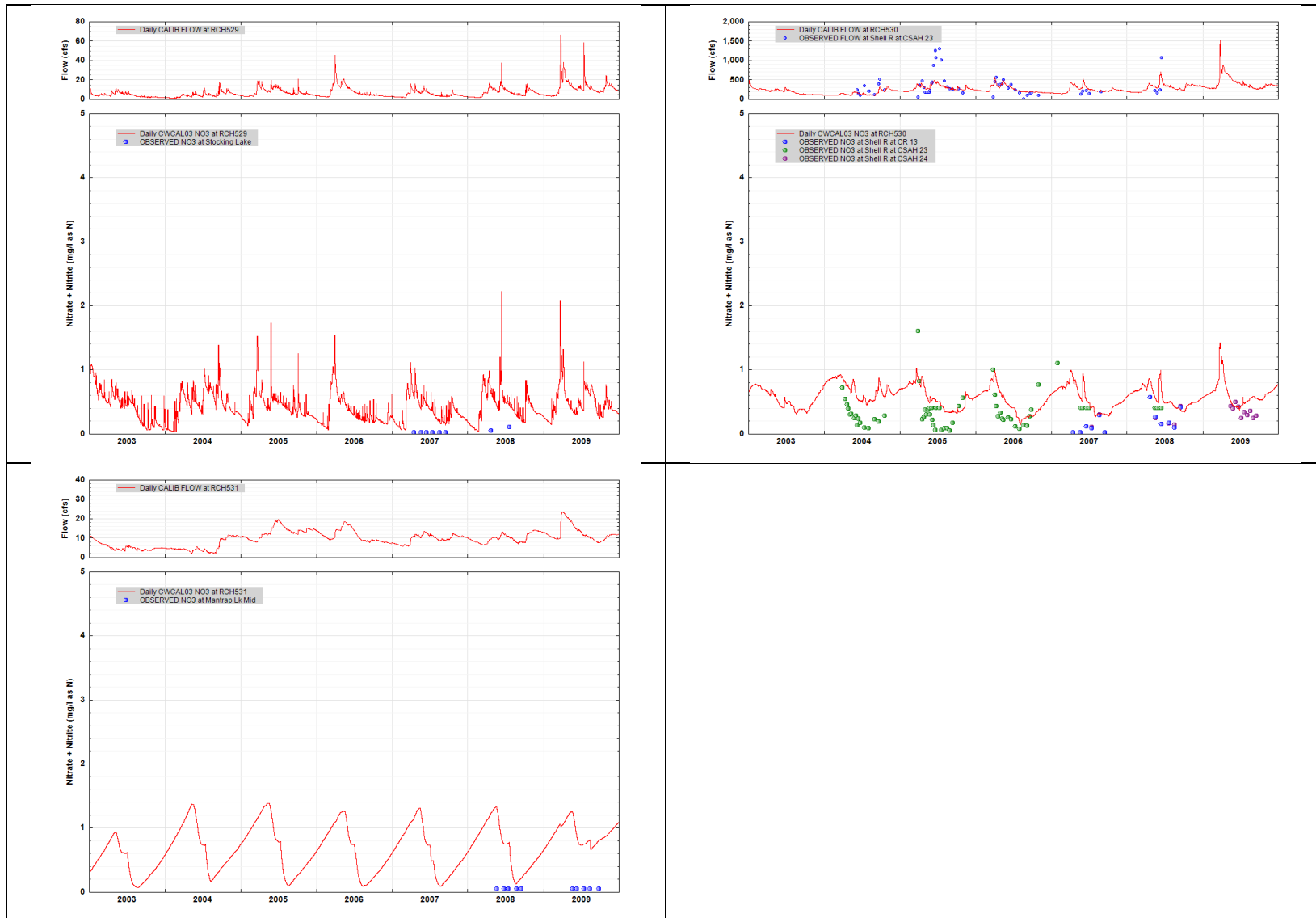


K.1.3 Crow Wing River Watershed



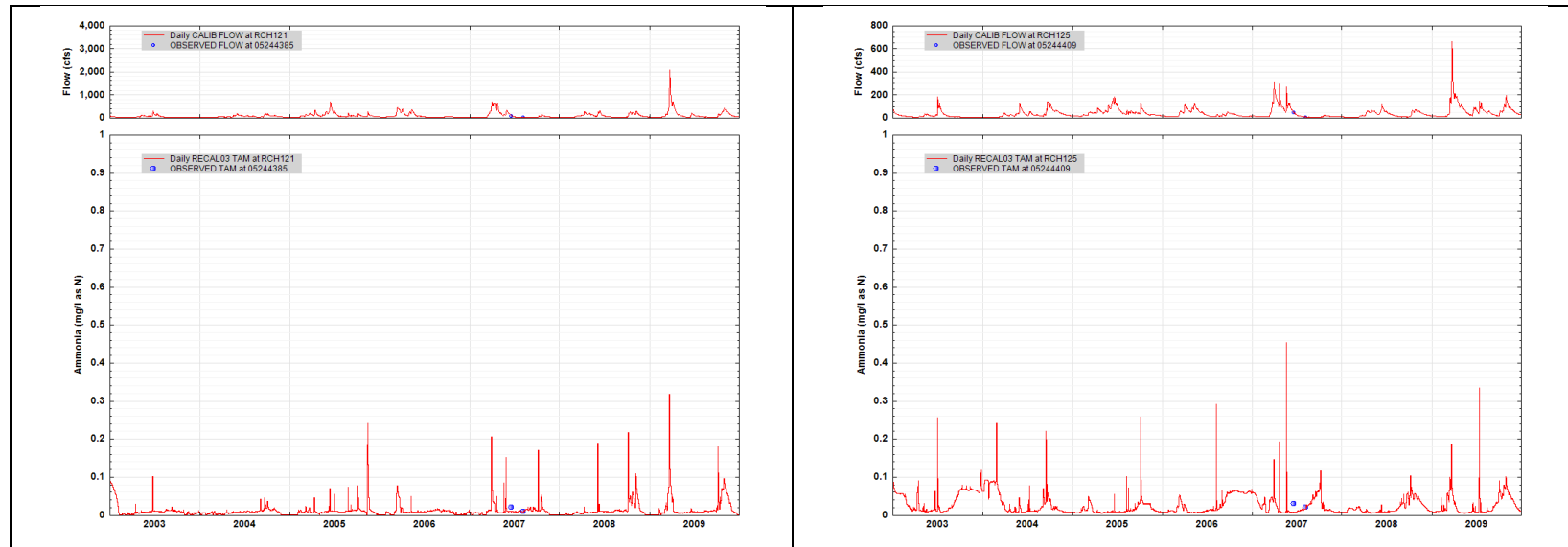




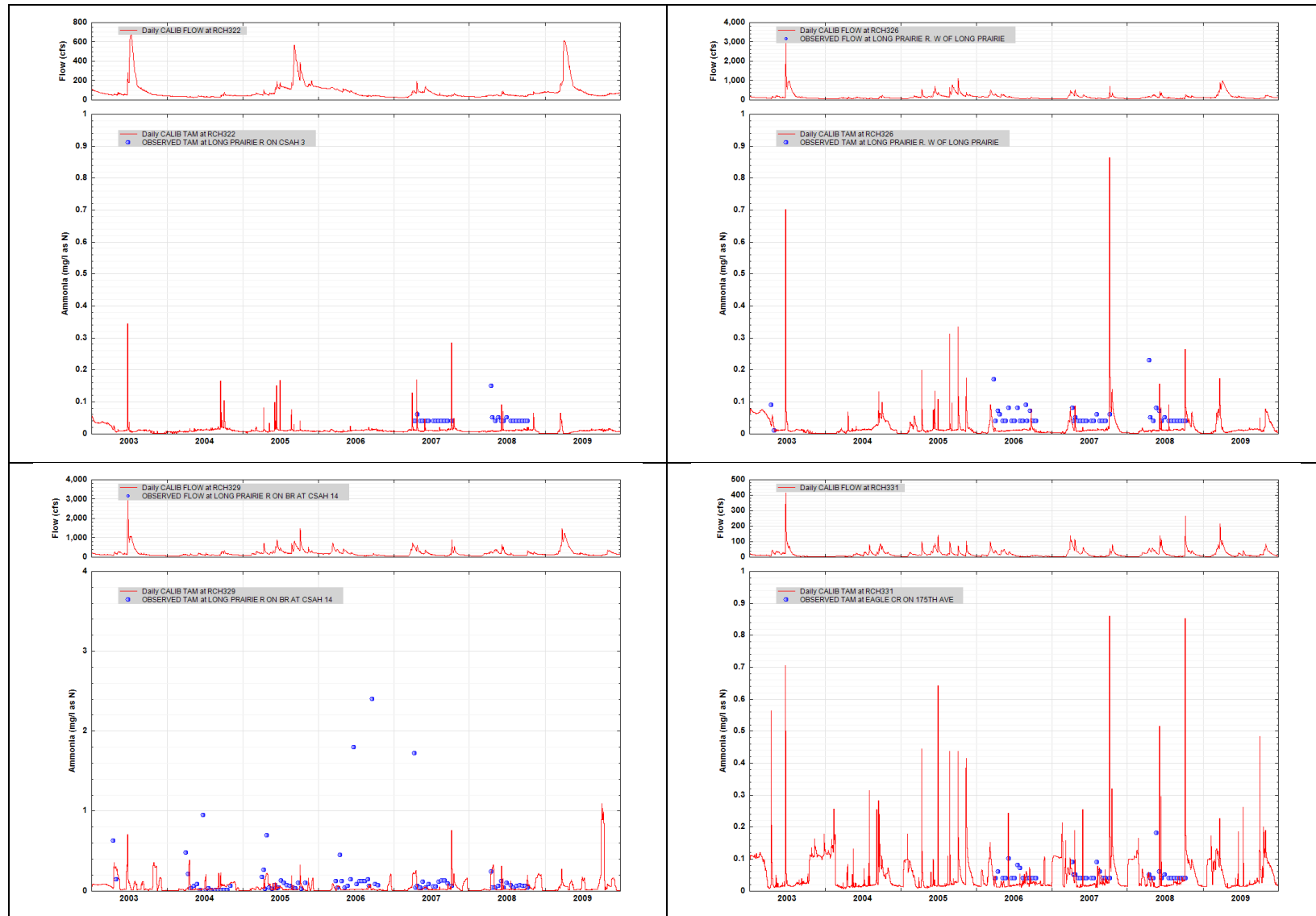


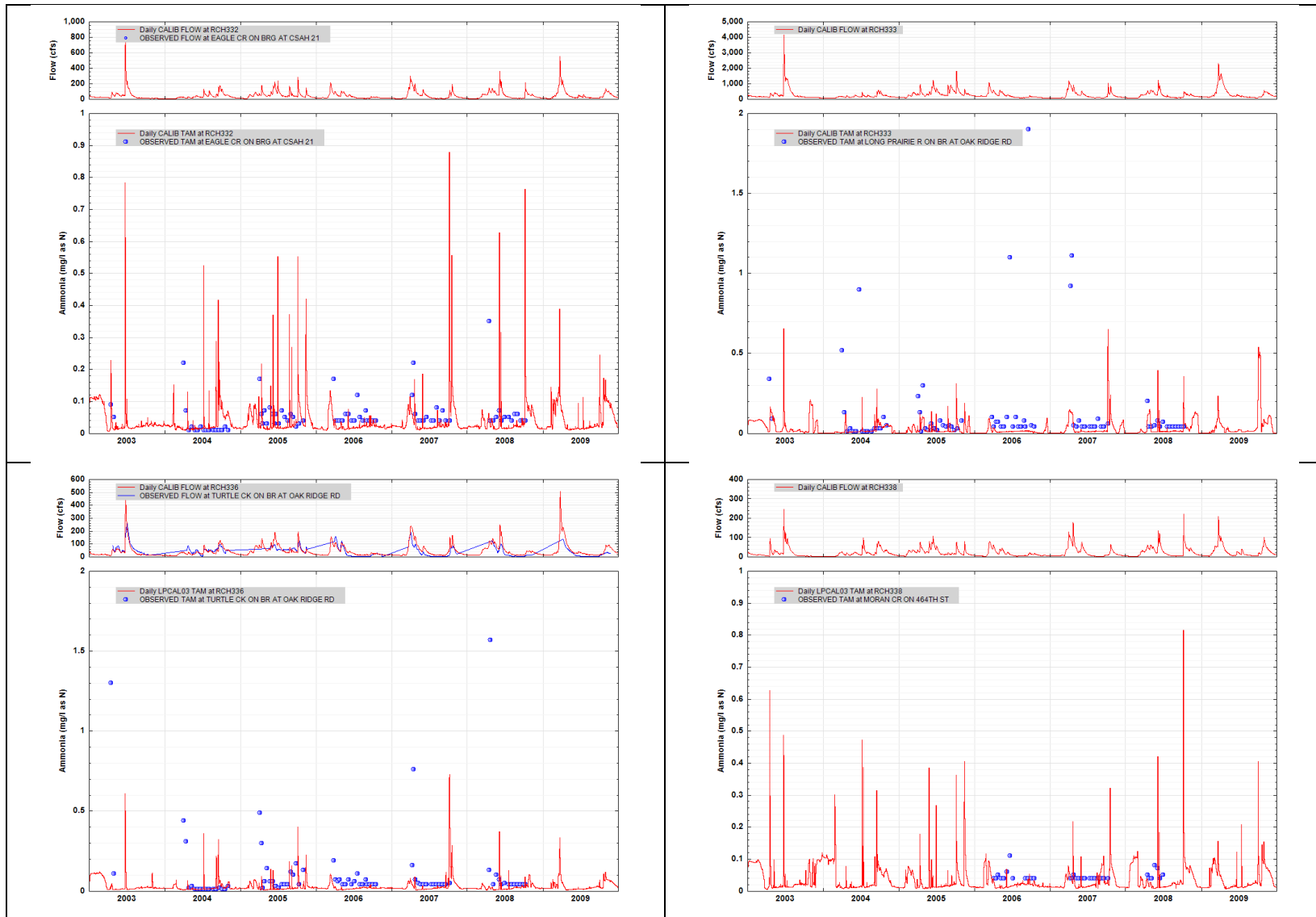
K.2 AMMONIA

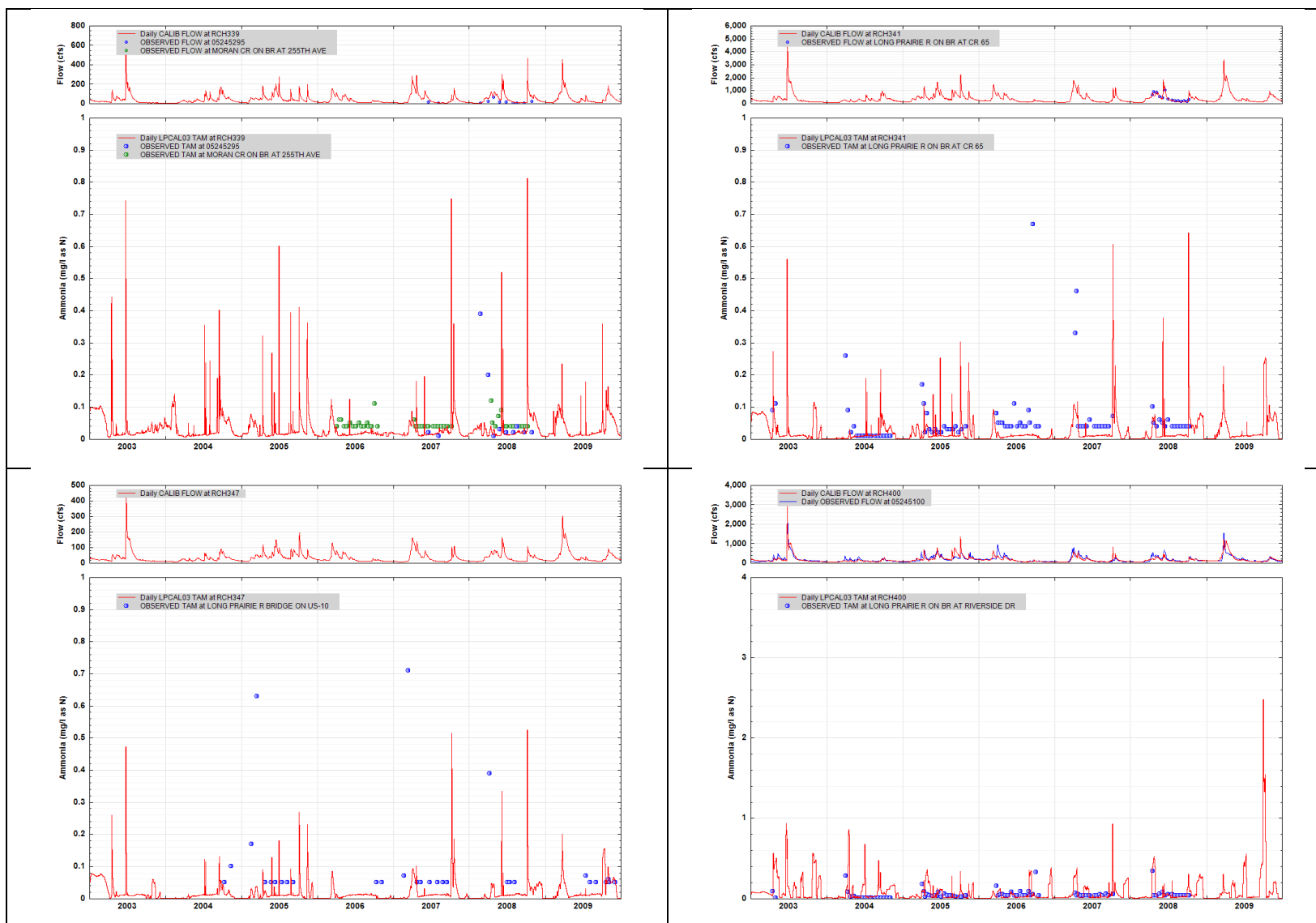
K.2.1 Redeye River Watershed



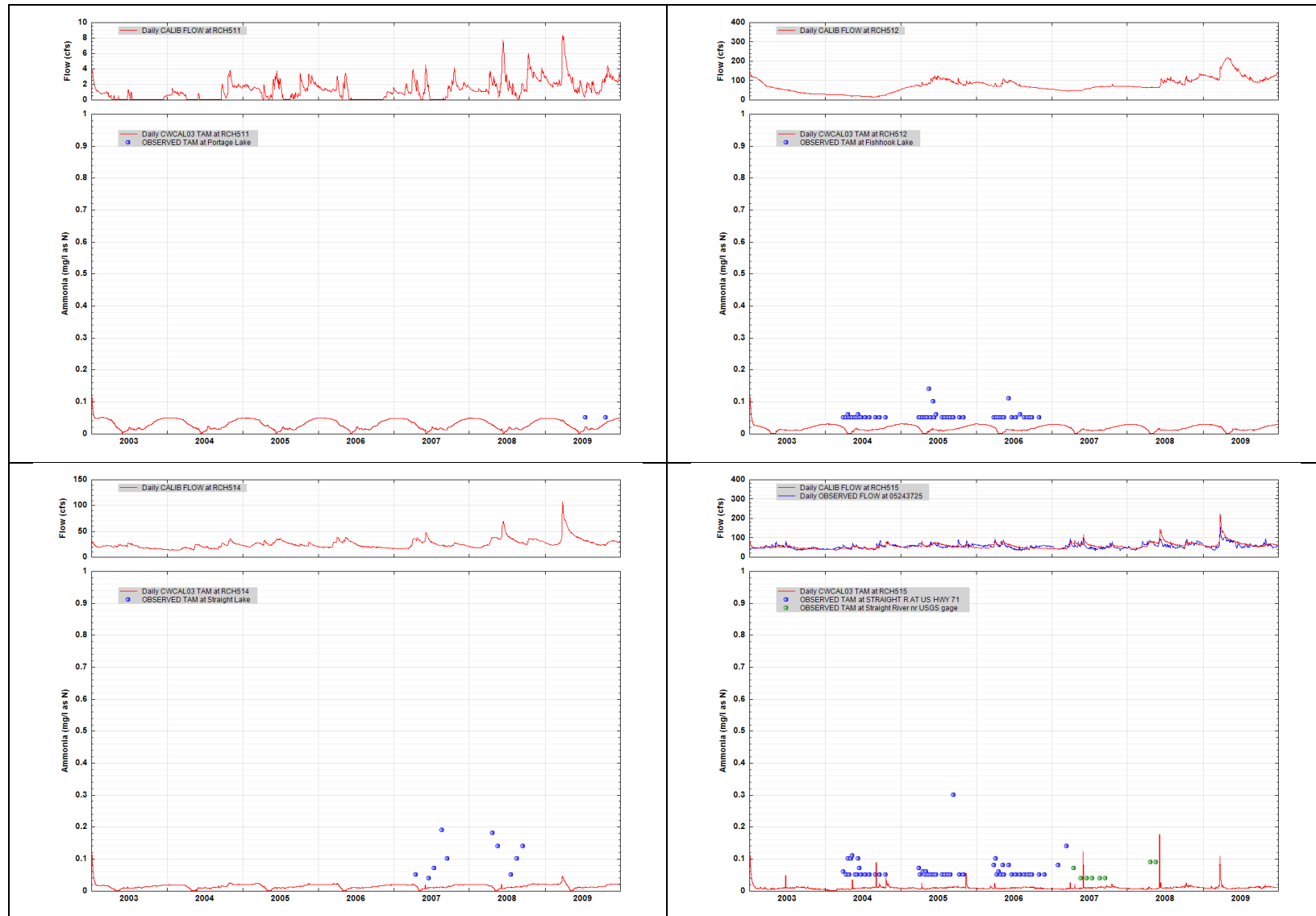
K.2.2 Long Prairie River Watershed



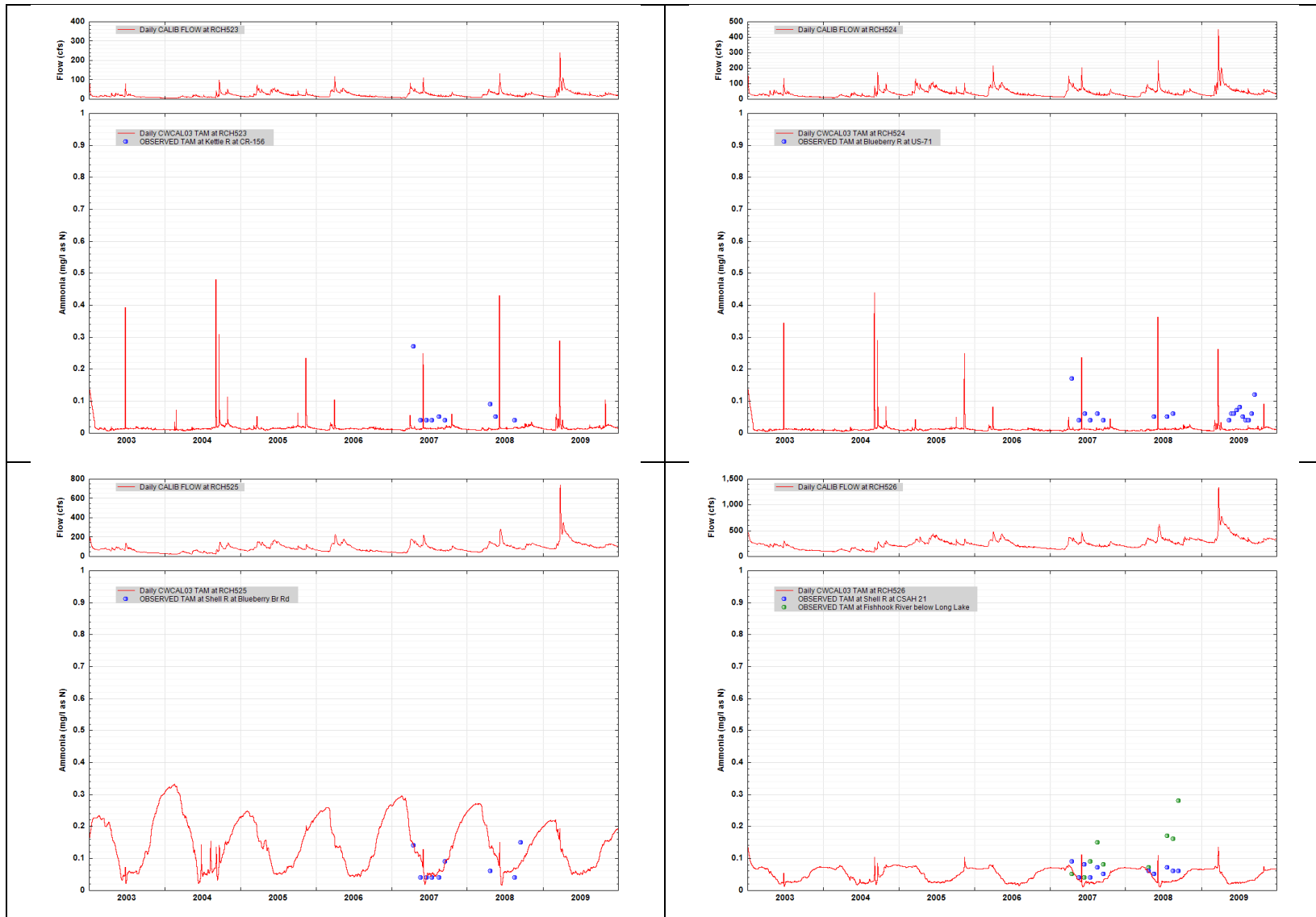


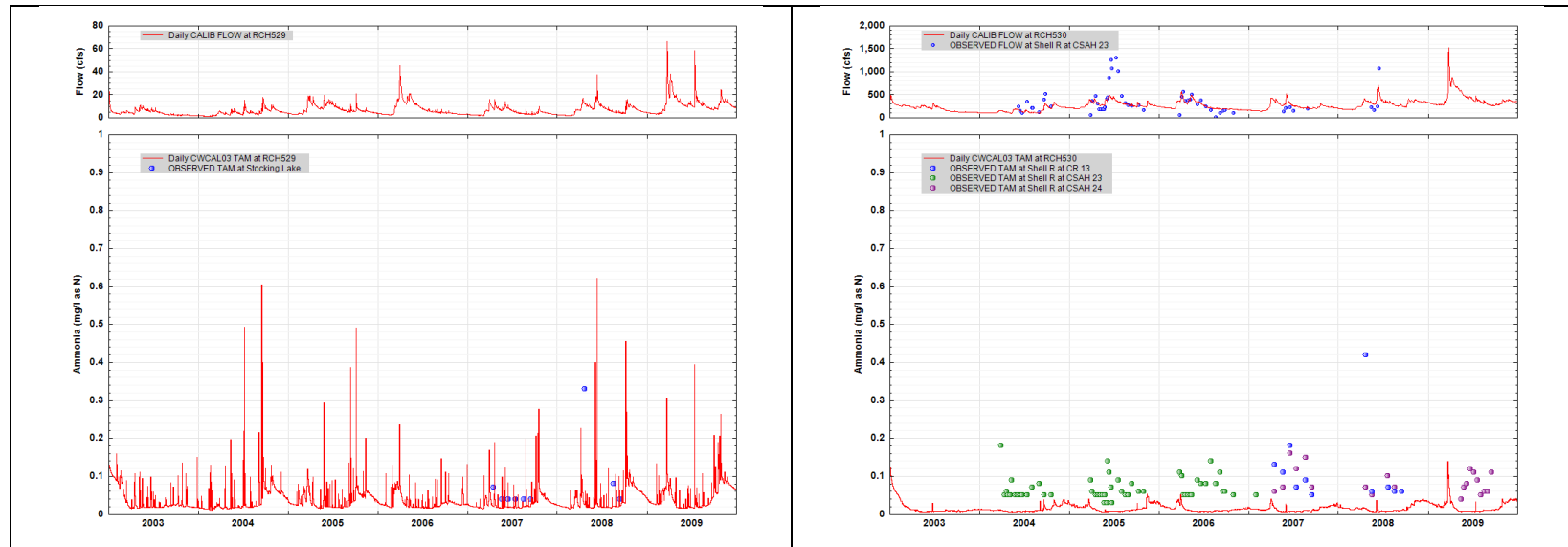


K.2.3 Crow Wing River Watershed

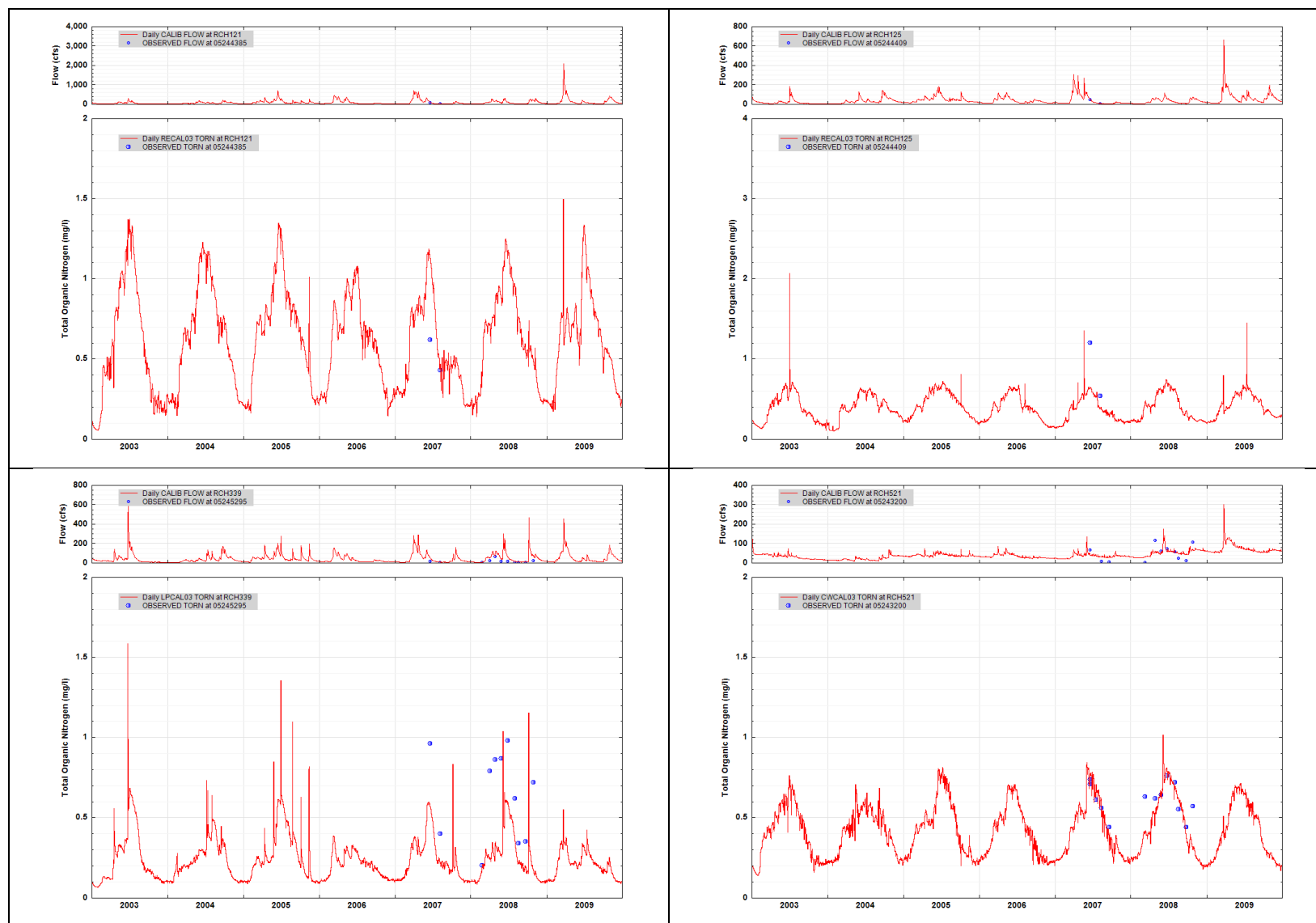








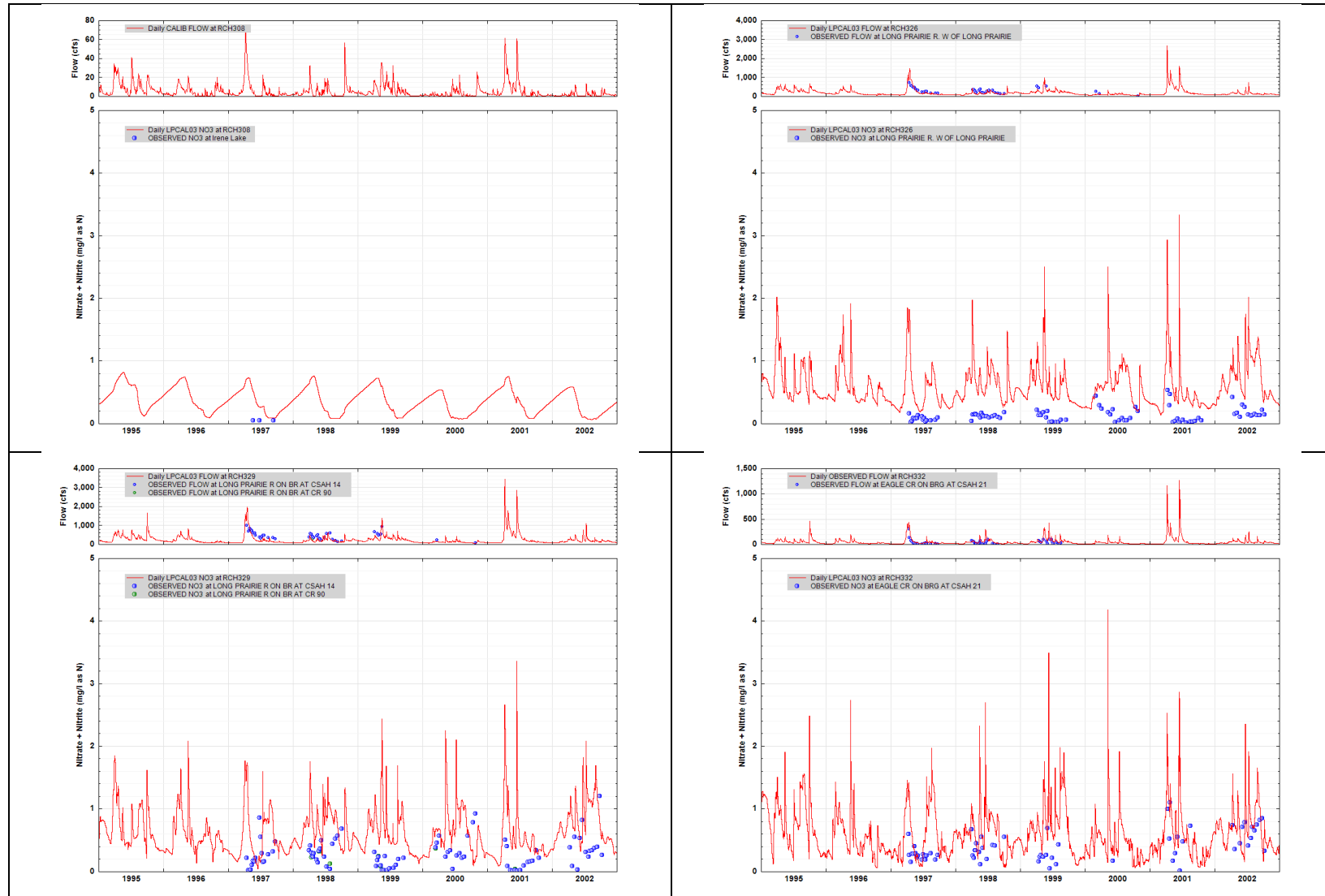
K.3 TOTAL ORGANIC NITROGEN

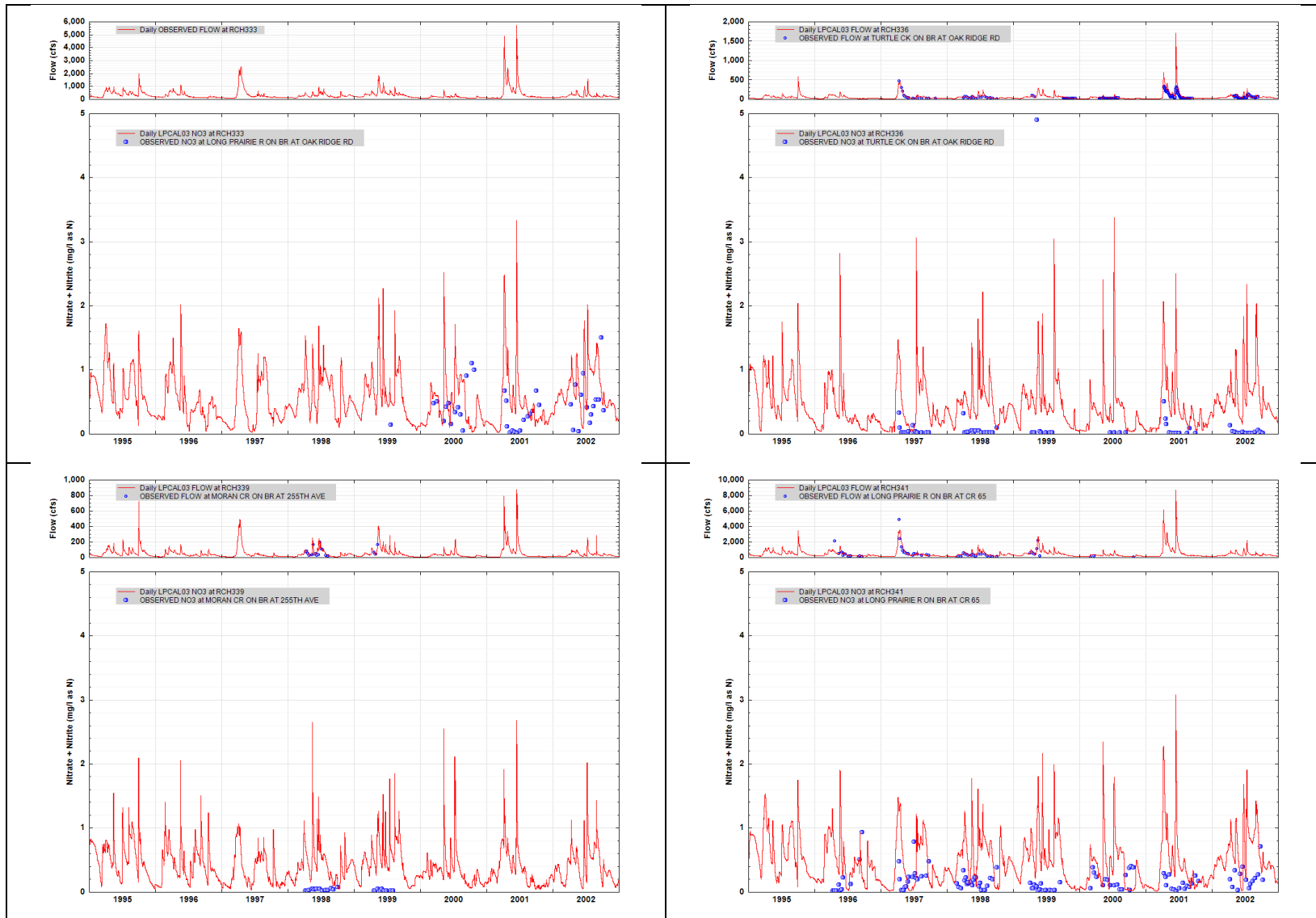


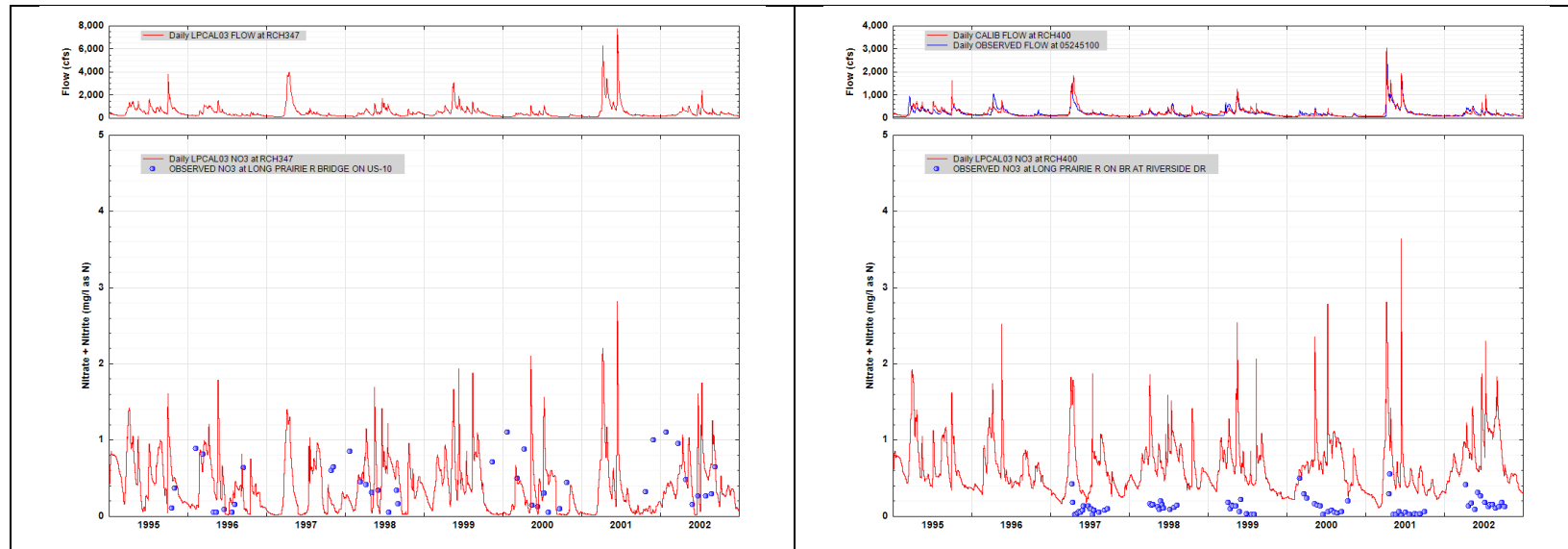
APPENDIX L OBSERVED AND SIMULATED NITROGEN CONSTITUENTS FOR THE VALIDATION PERIOD

L.1 NITRATE

L.1.1 Long Prairie River Watershed





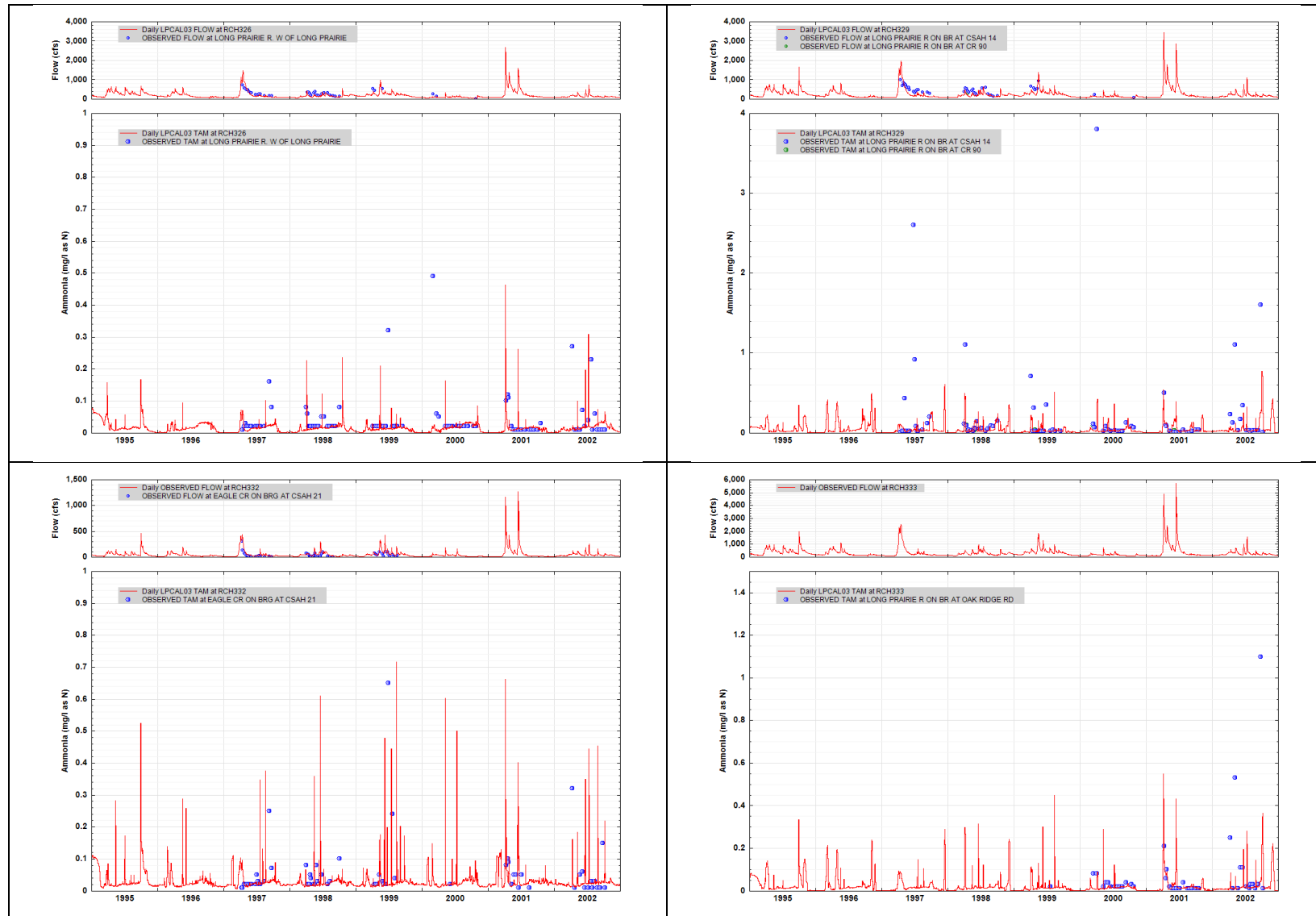


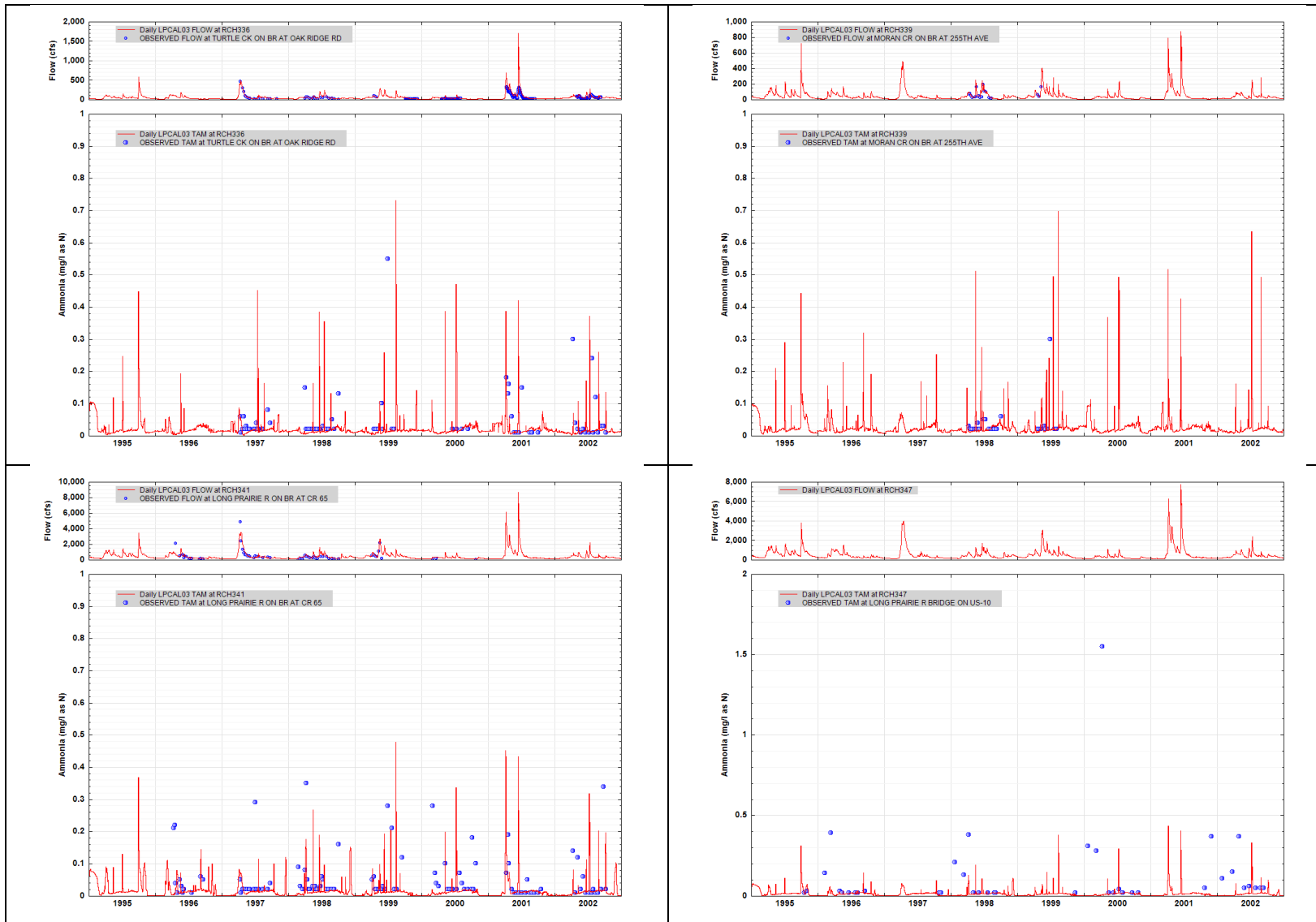
L.1.2 Crow Wing River Watershed

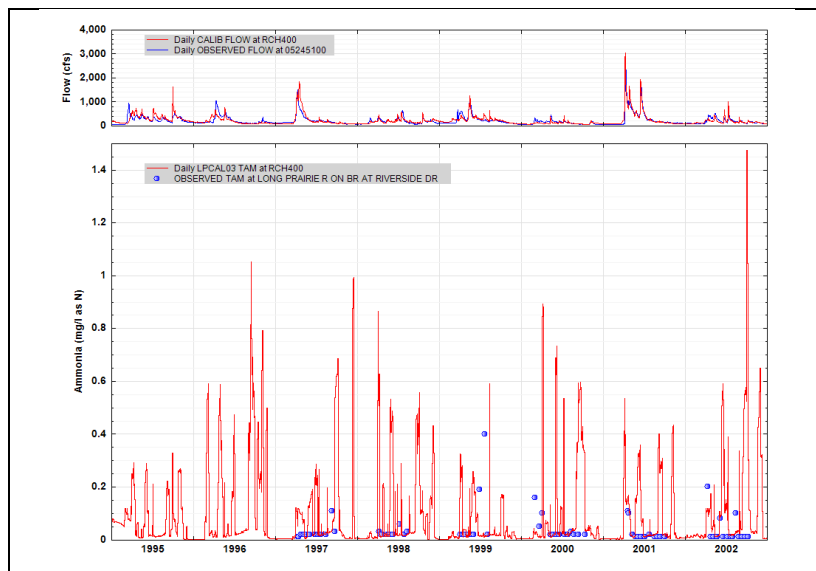


L.2 AMMONIA

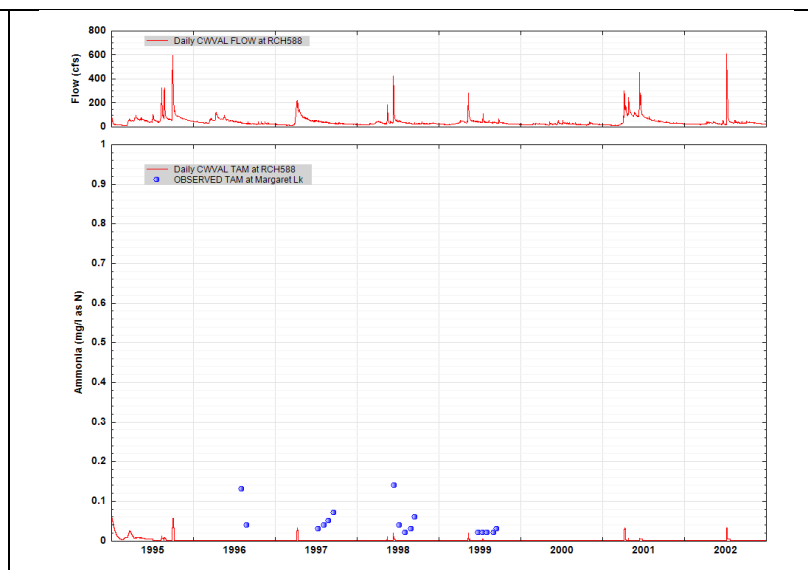
L.2.1 Long Prairie River Watershed







L.2.2 Crow Wing River Watershed

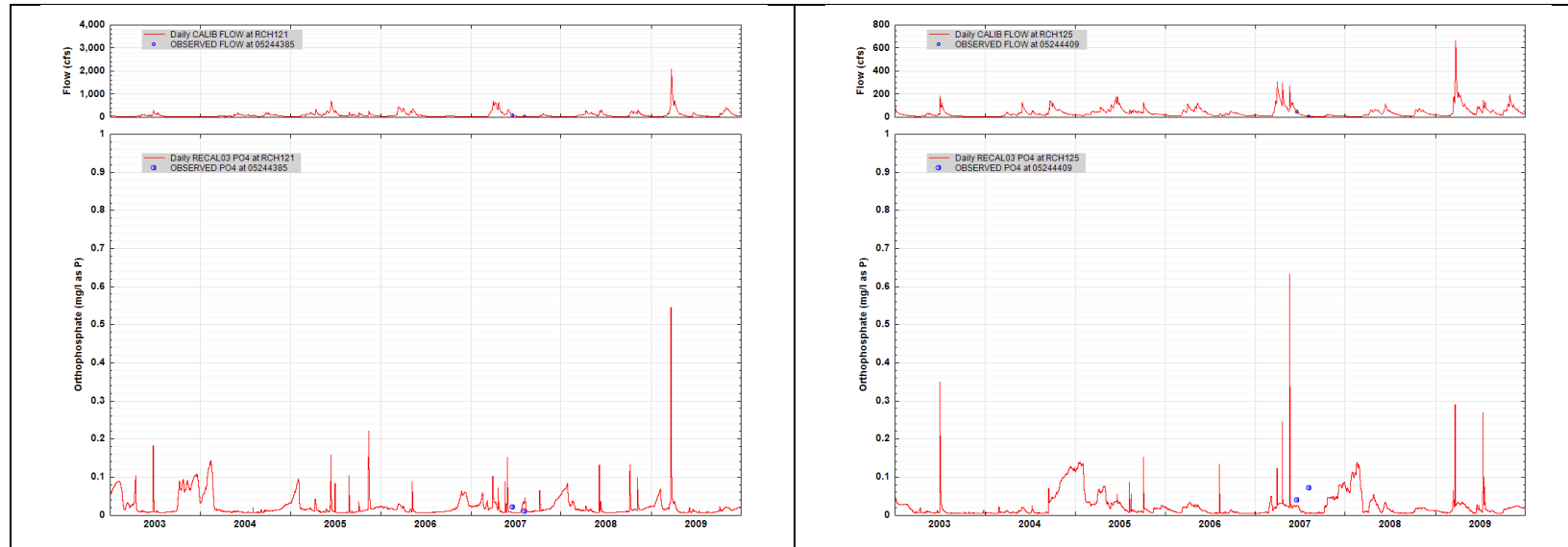


APPENDIX M

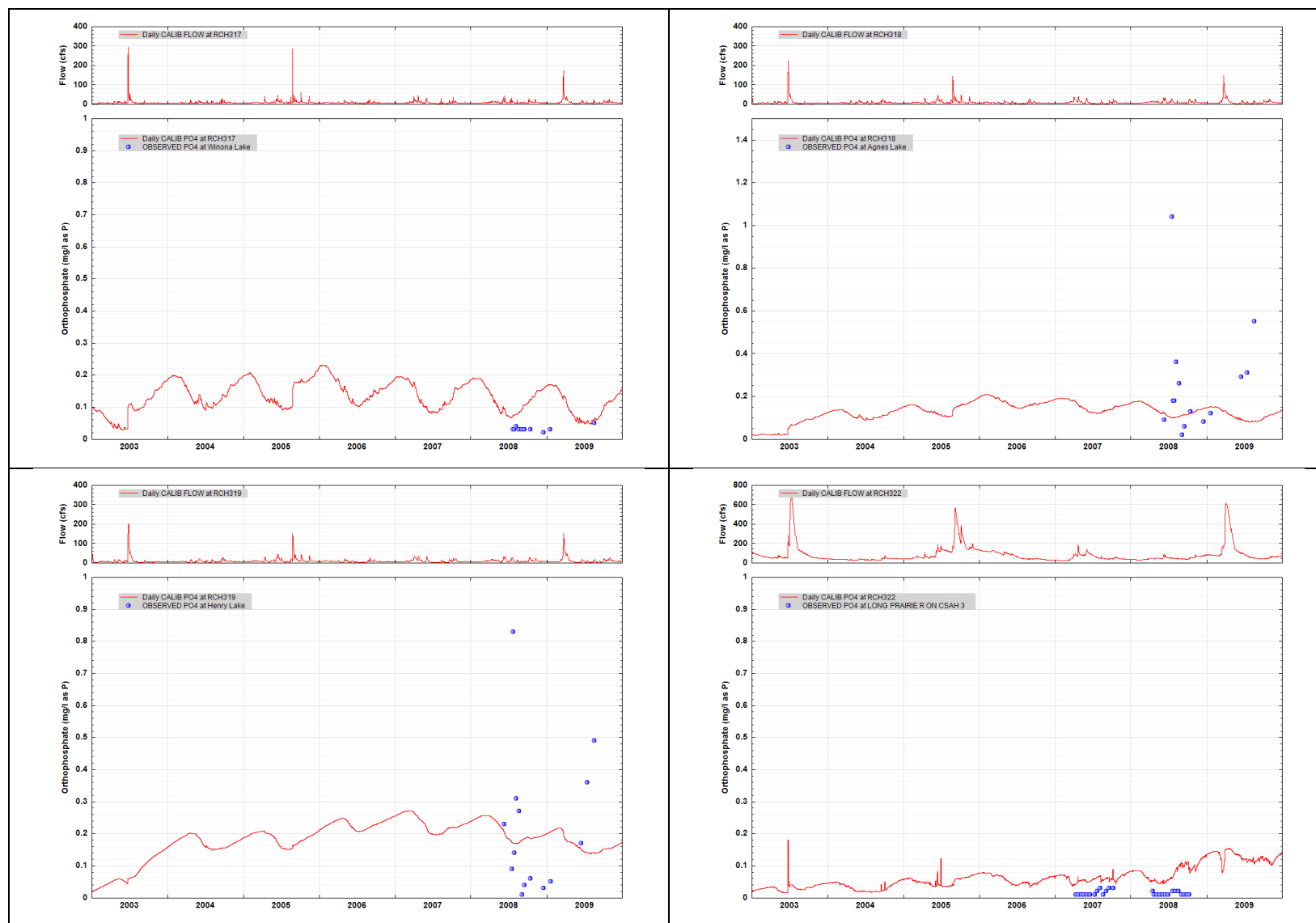
OBSERVED AND SIMULATED PHOSPHORUS CONSTITUENTS FOR THE CALIBRATION PERIOD

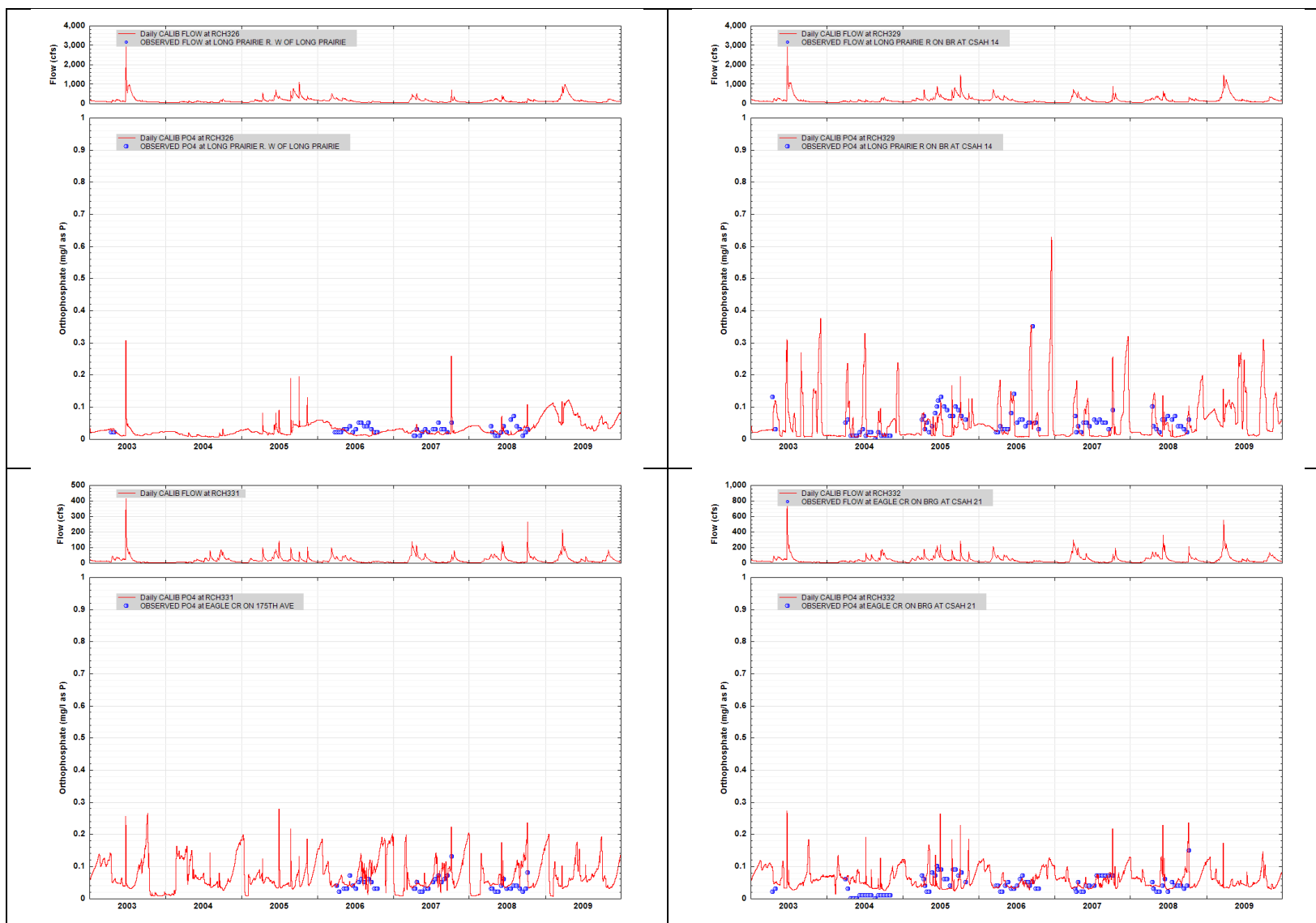
M.1 ORTHOPHOSPHATE

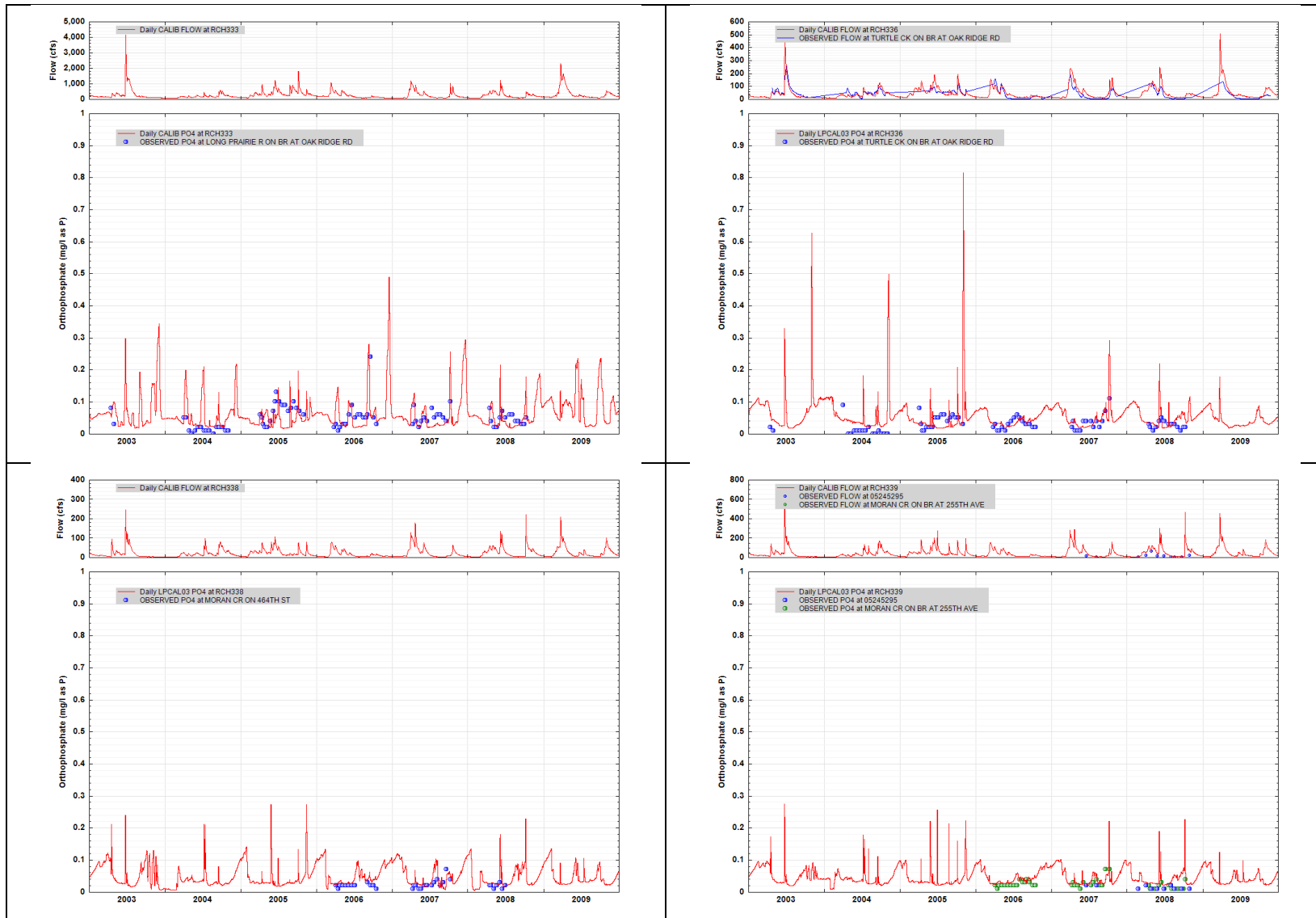
M.1.1 Redeye River Watershed

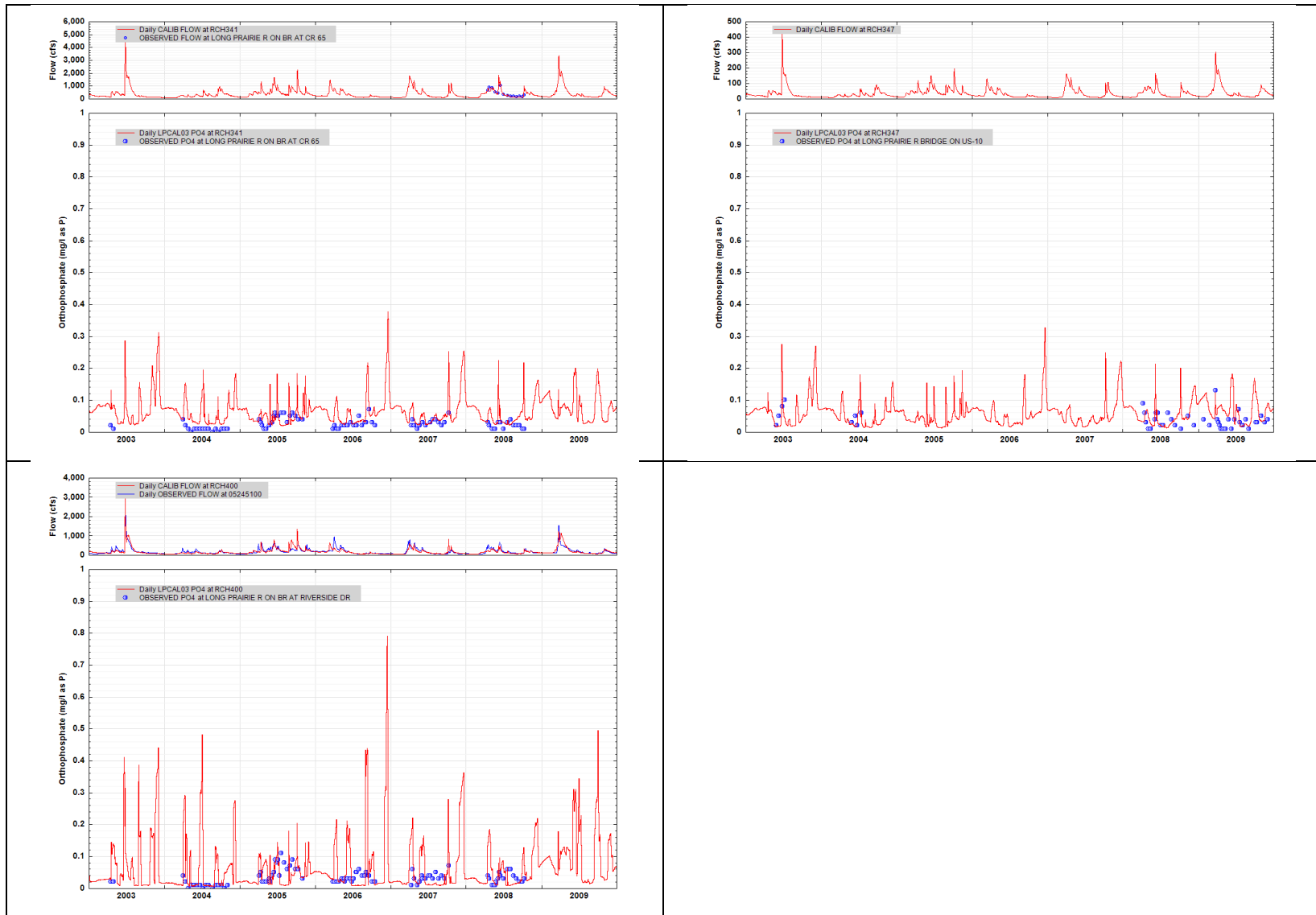


M.1.2 Long Prairie River Watershed



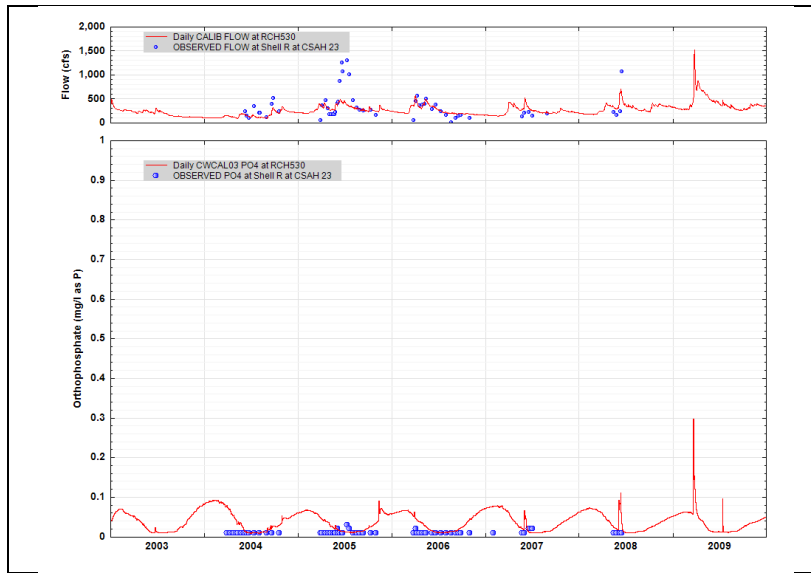






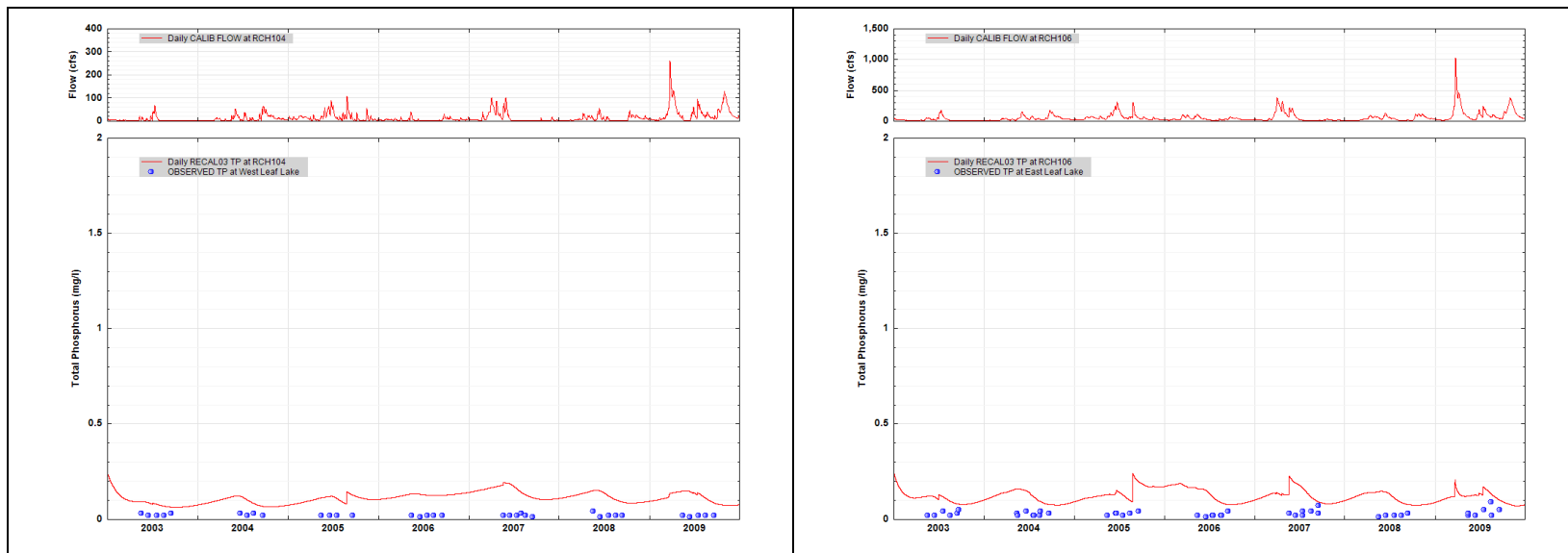
M.1.3 Crow Wing River Watershed

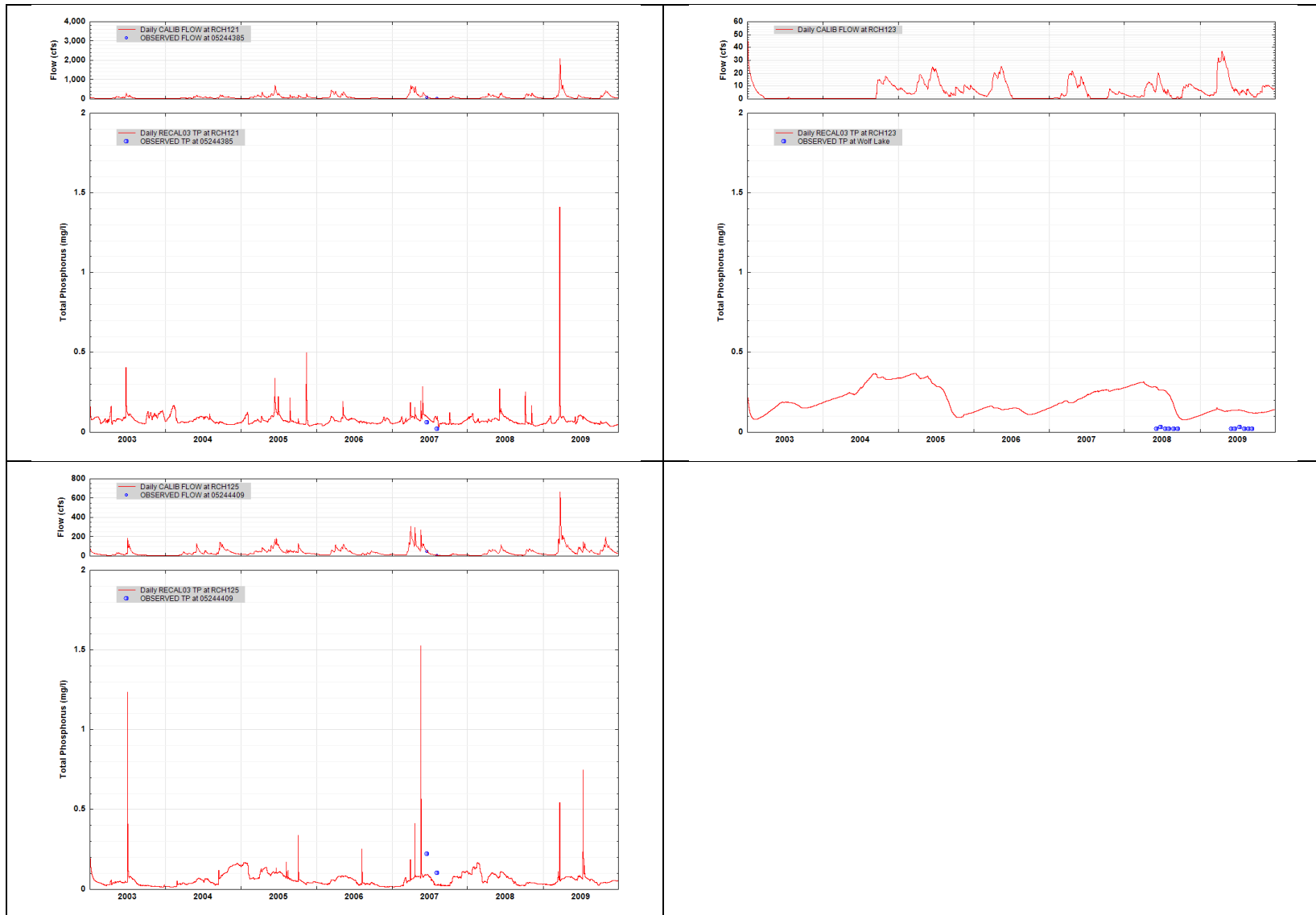




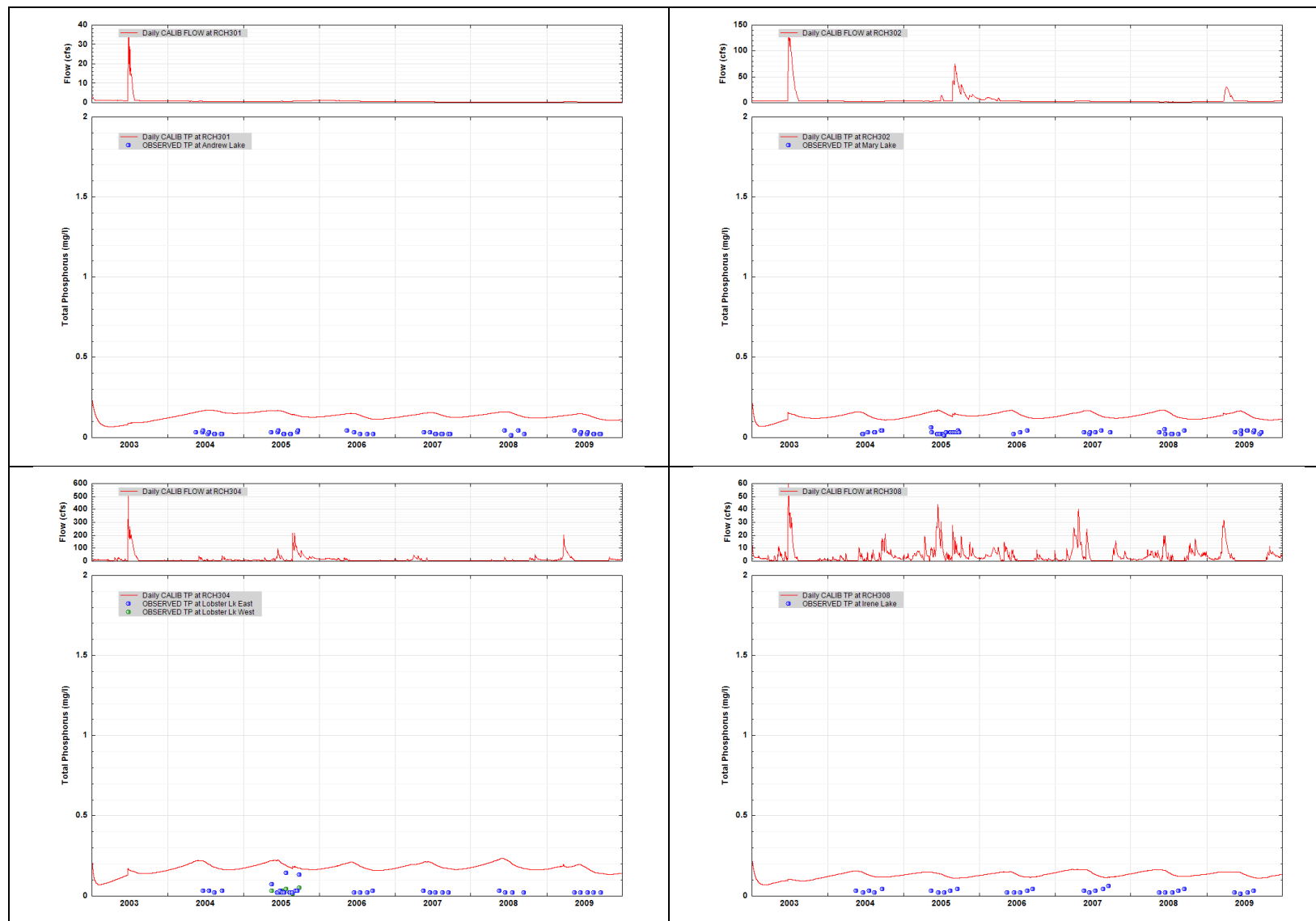
M.2 TOTAL PHOSPHORUS

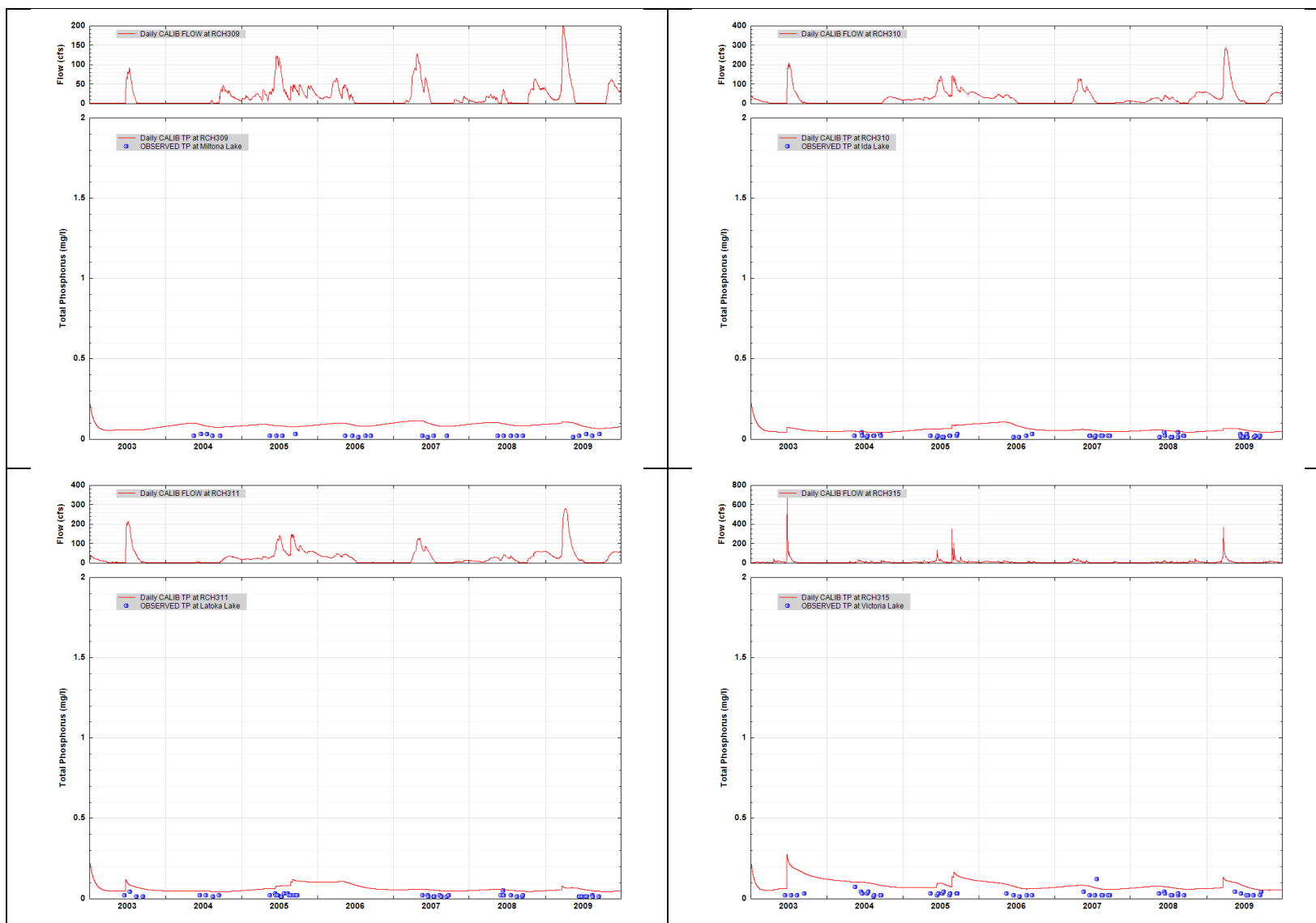
M.2.1 Redeye River Watershed

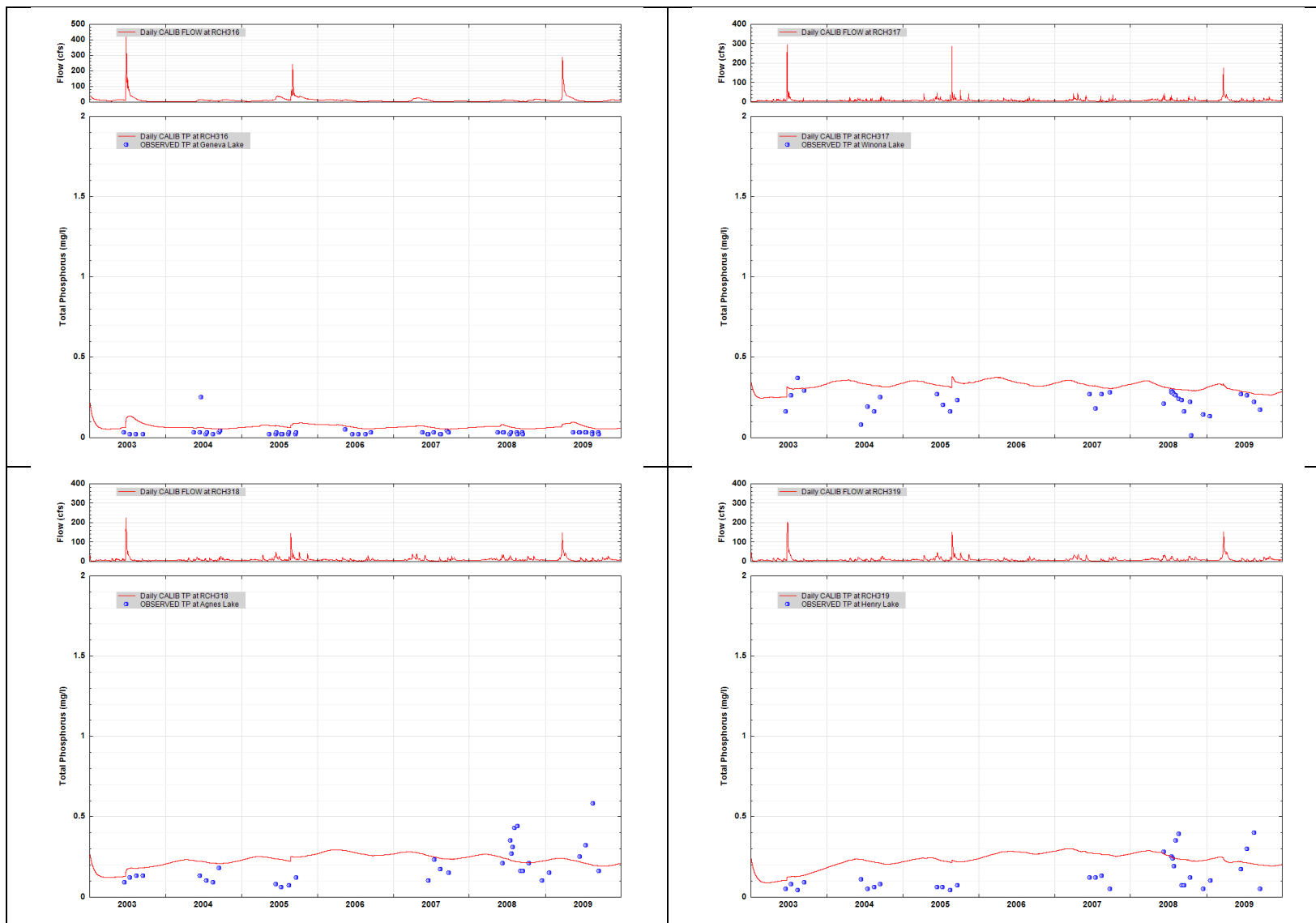


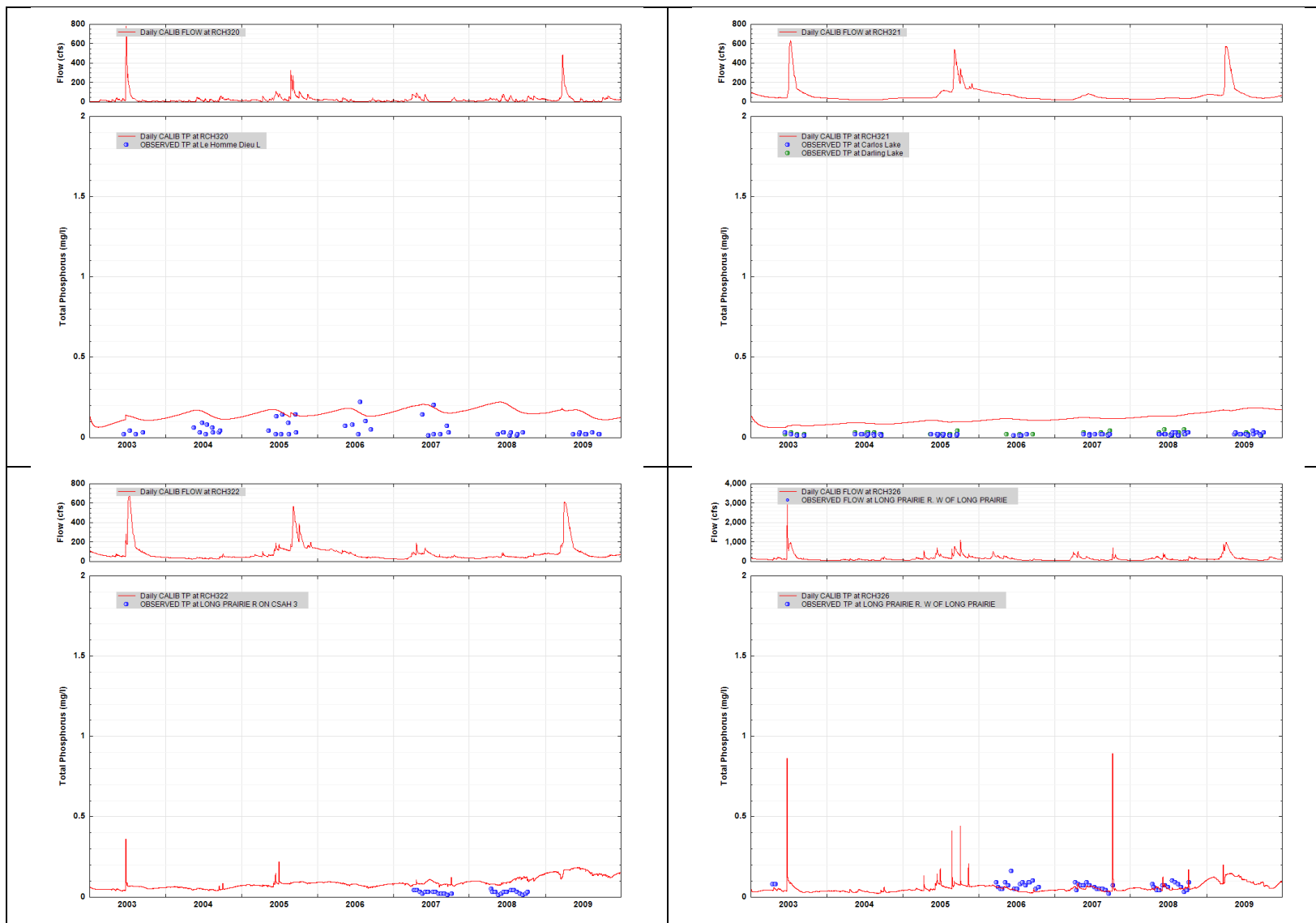


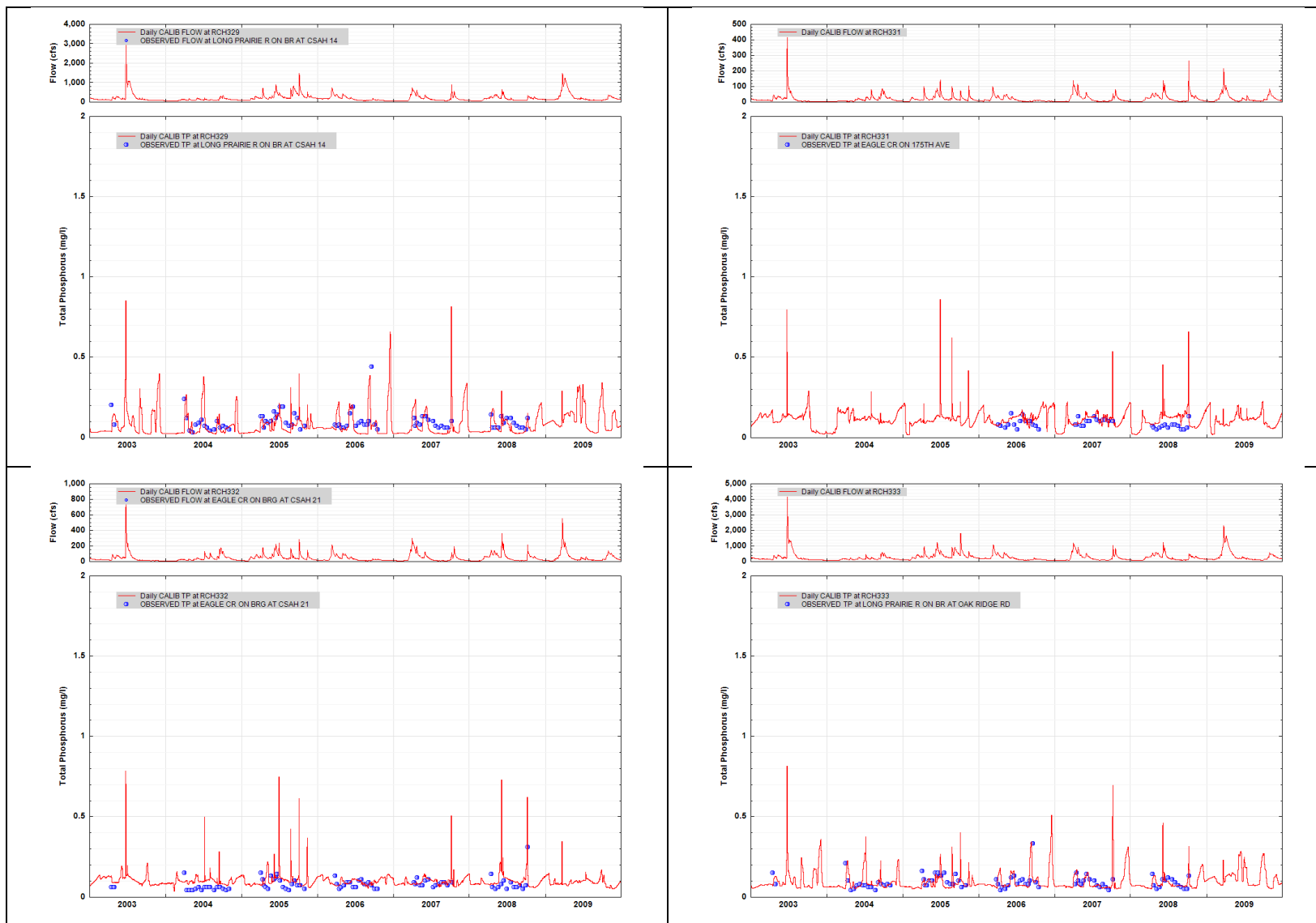
M.2.2 Long Prairie River Watershed

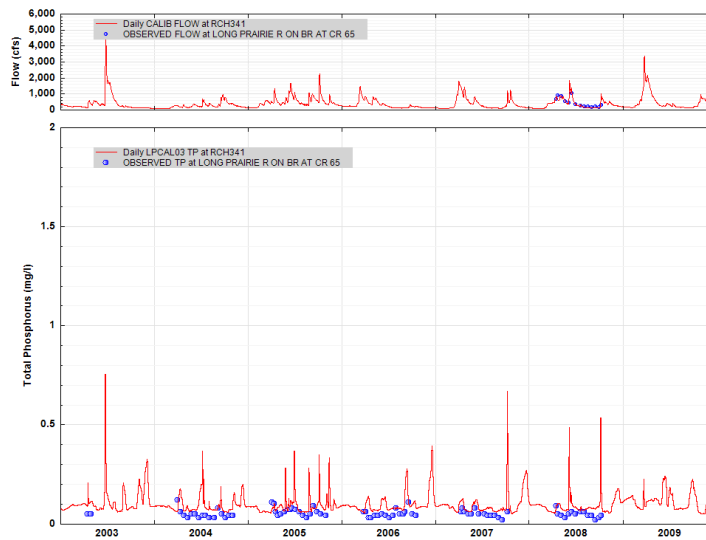
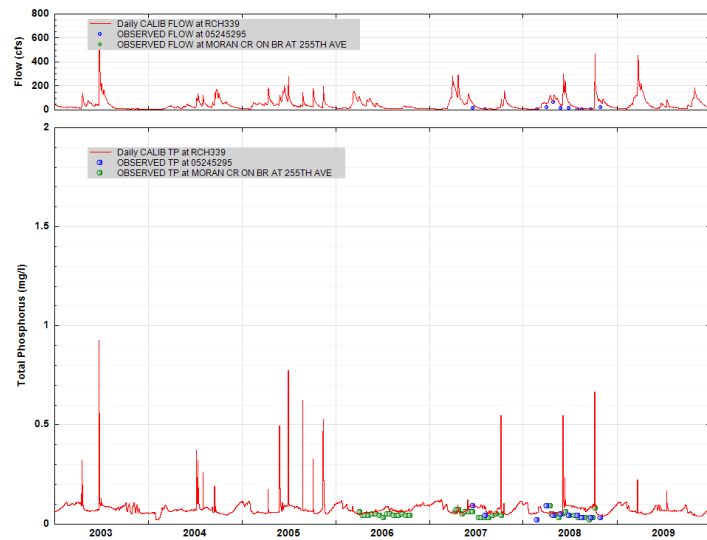
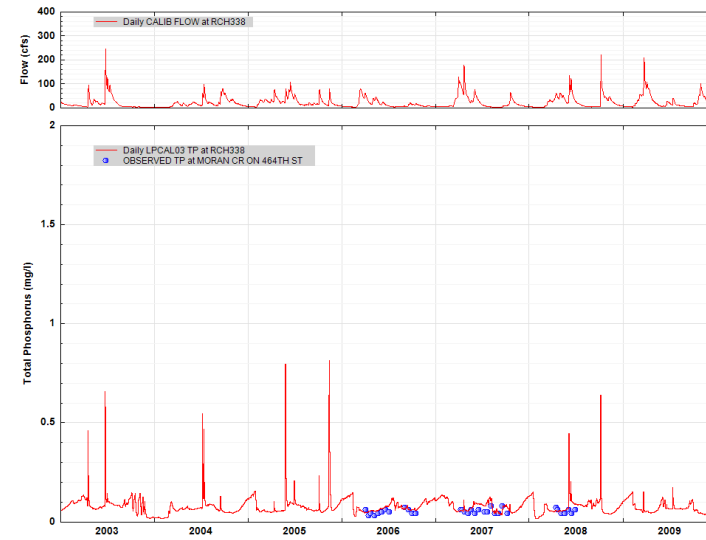
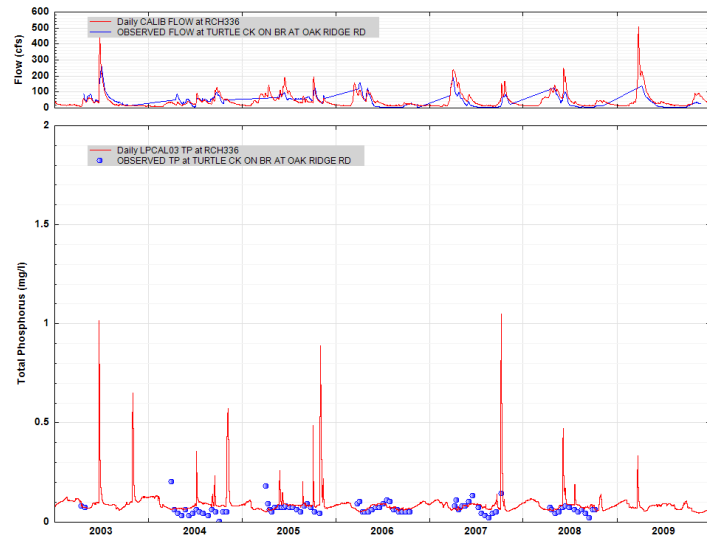


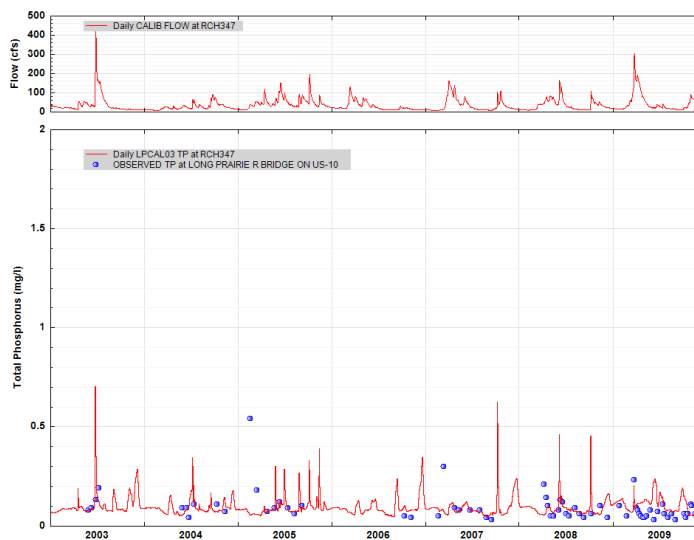
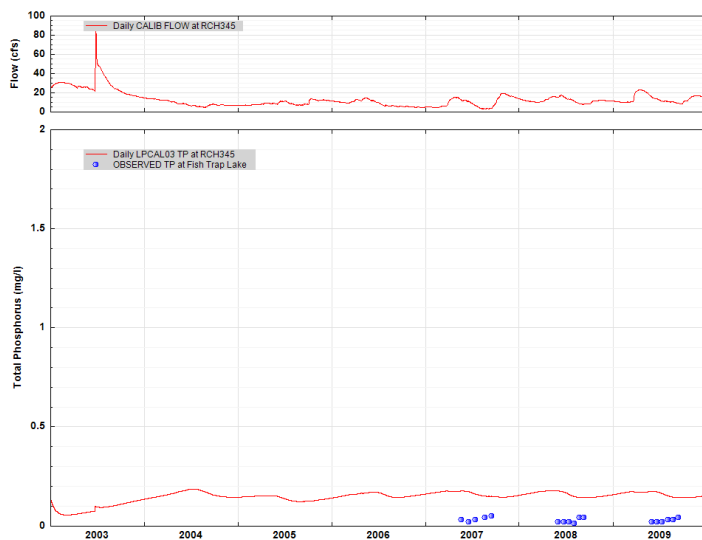
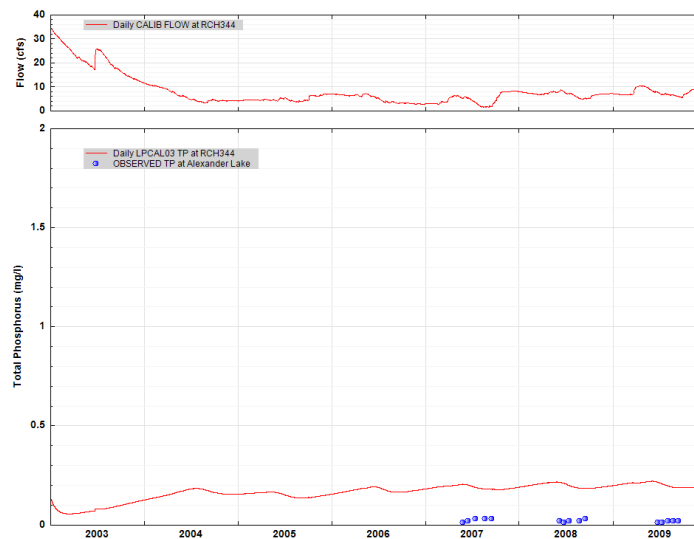
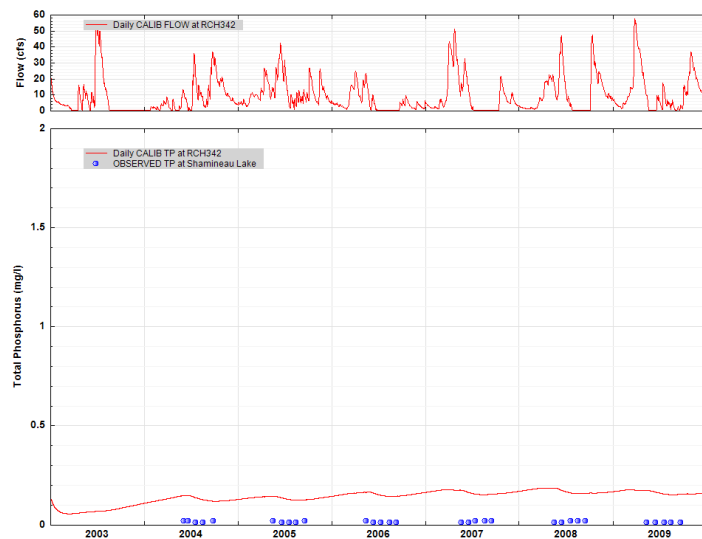


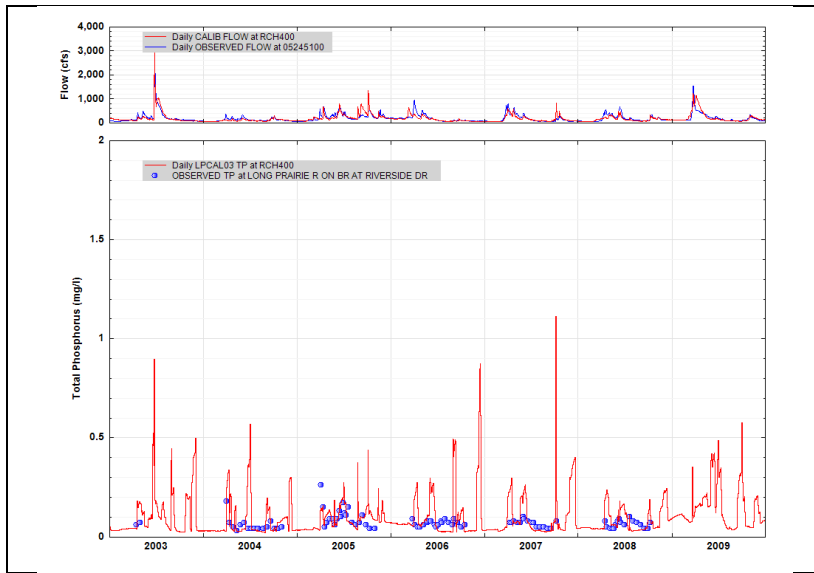




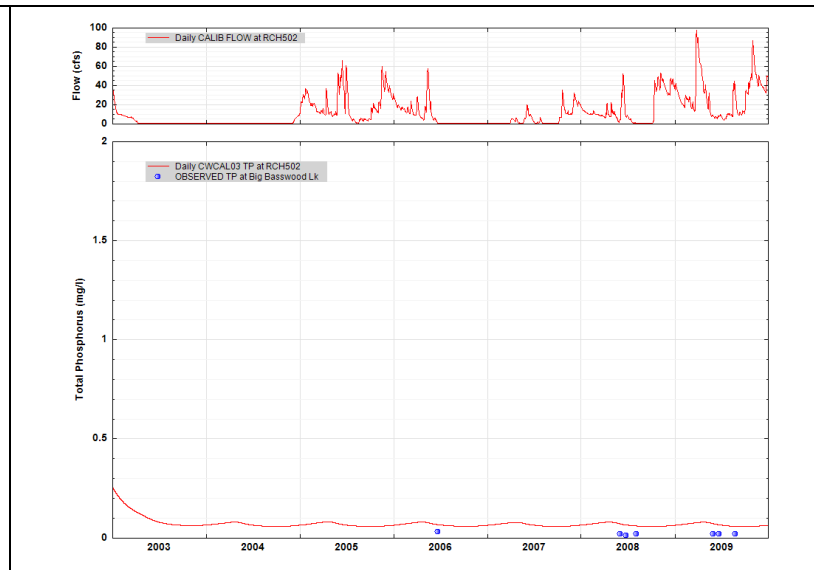
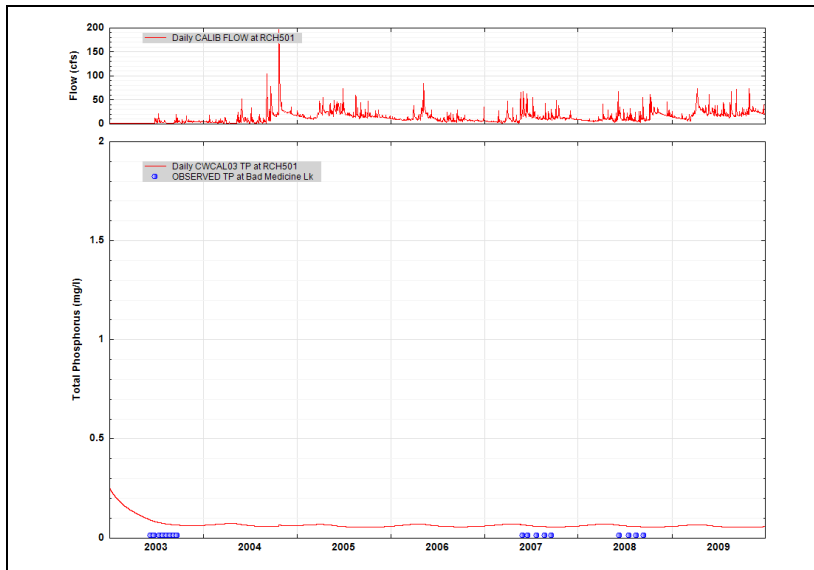


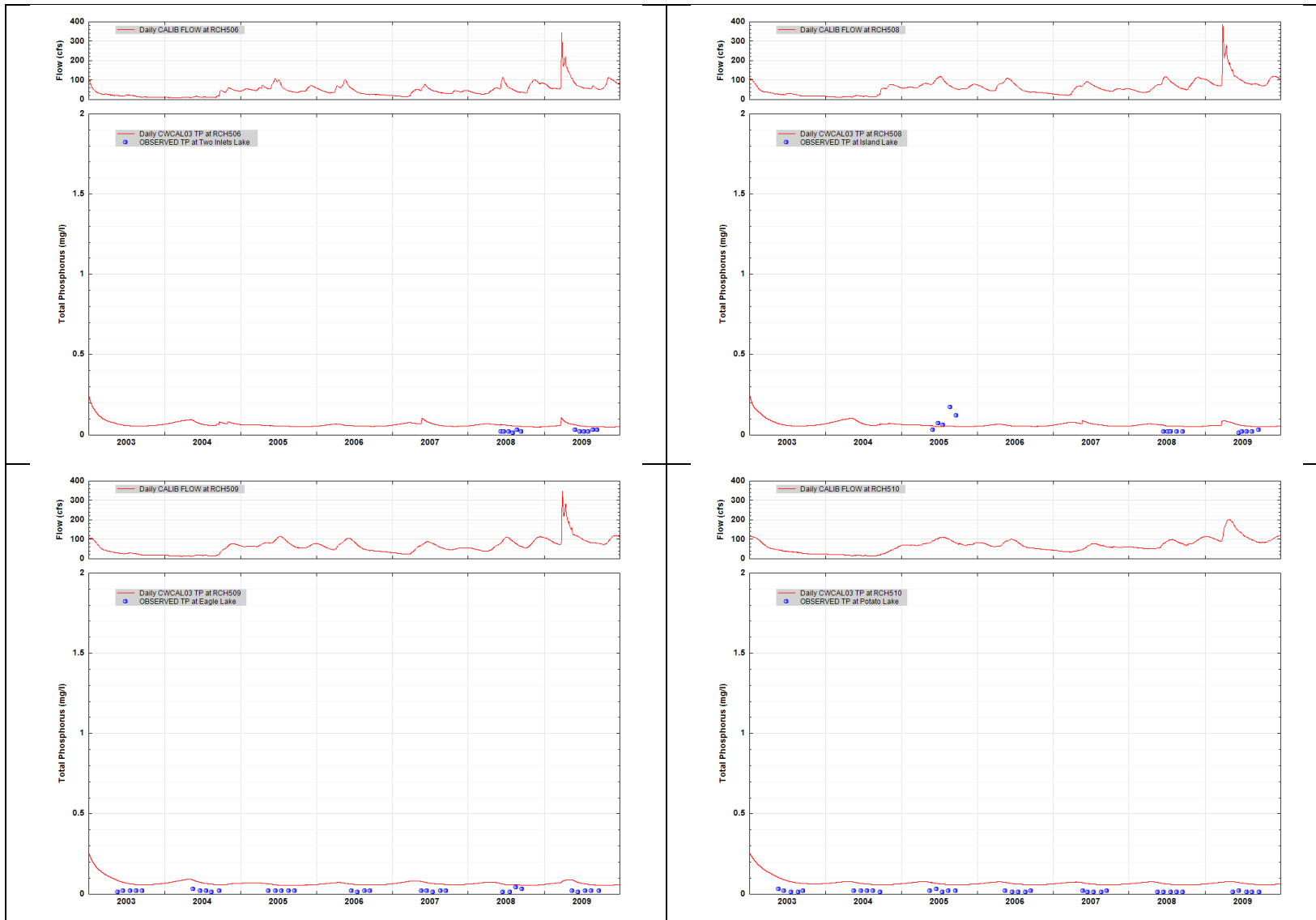


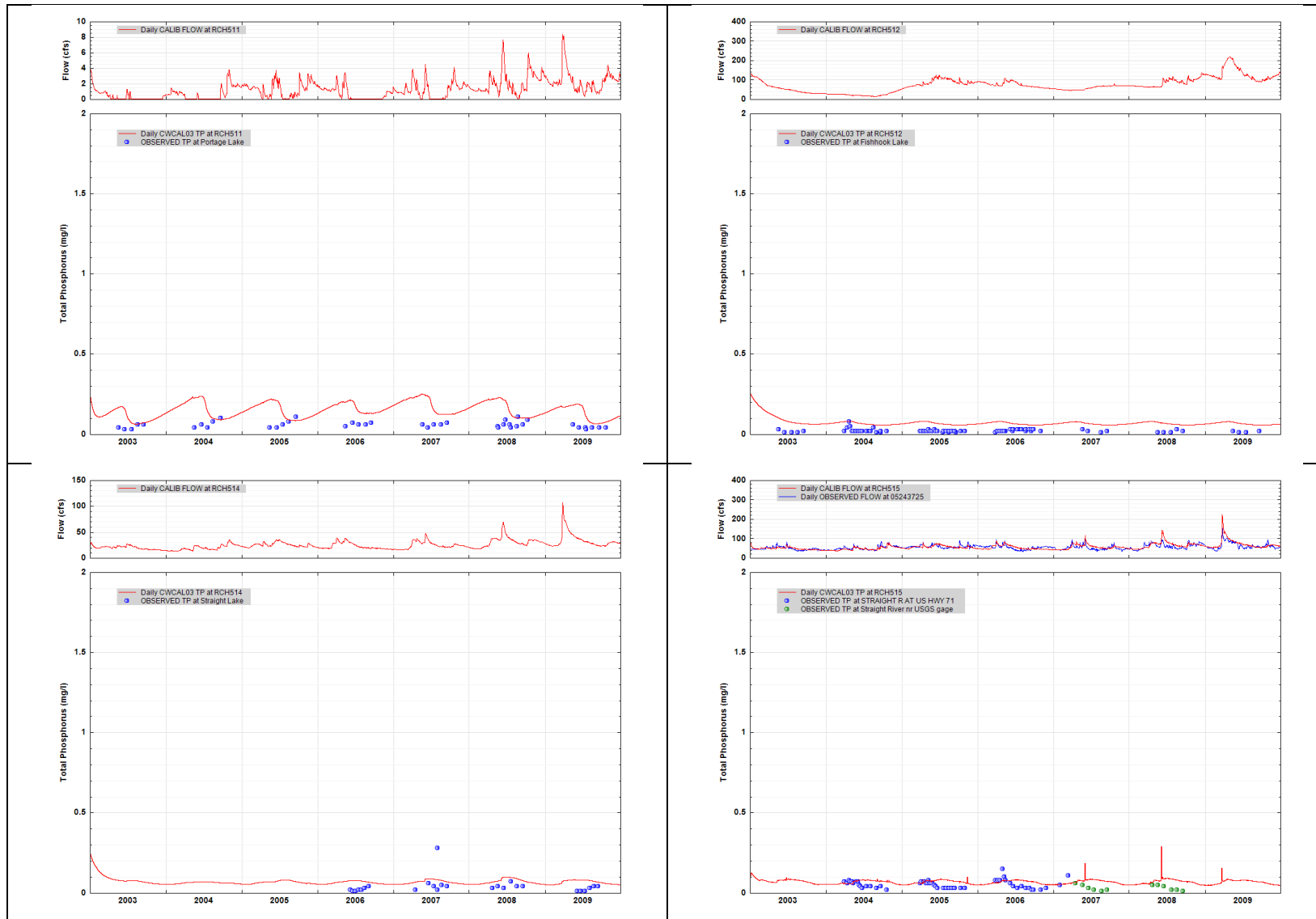




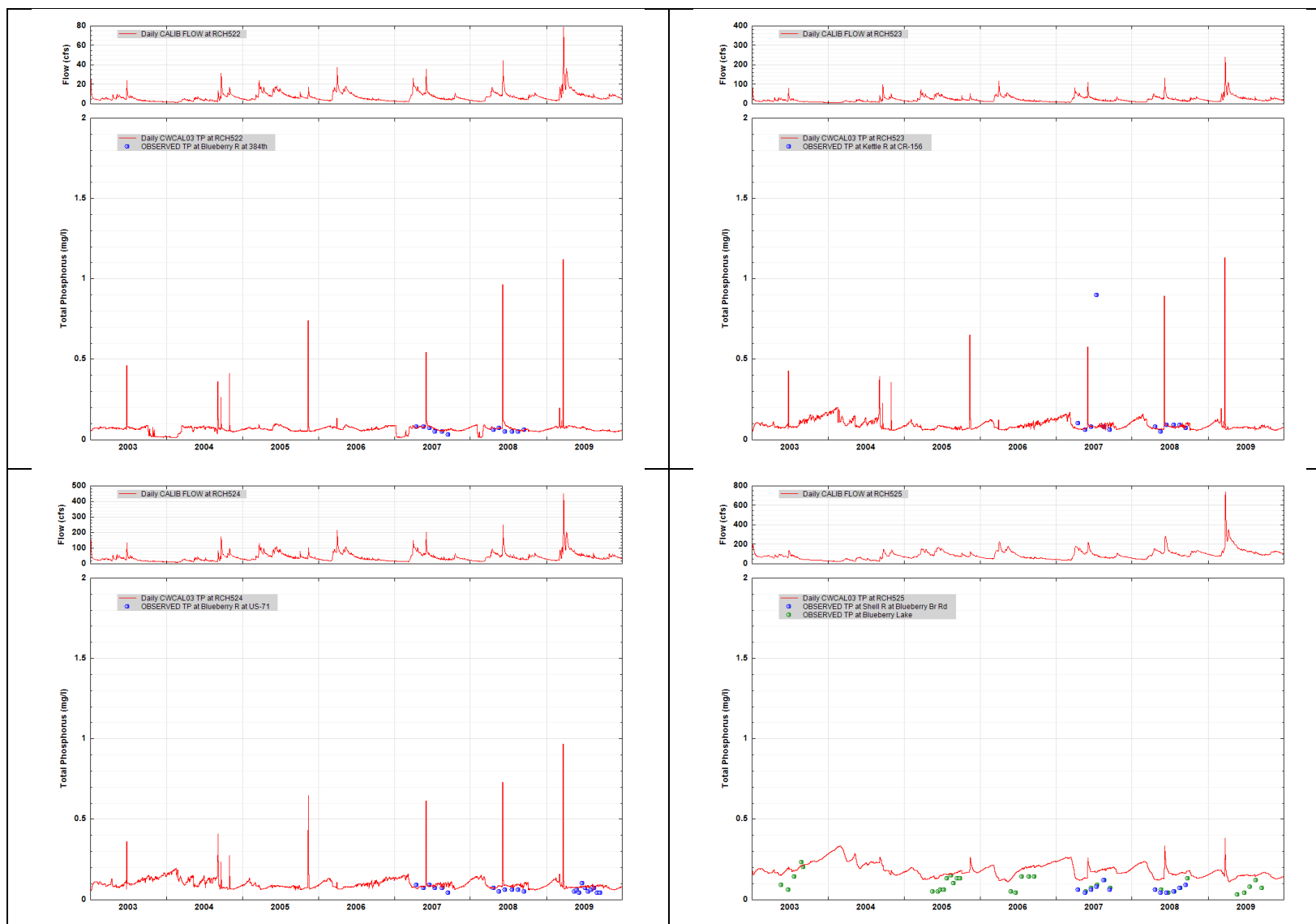
M.2.3 Crow Wing River Watershed

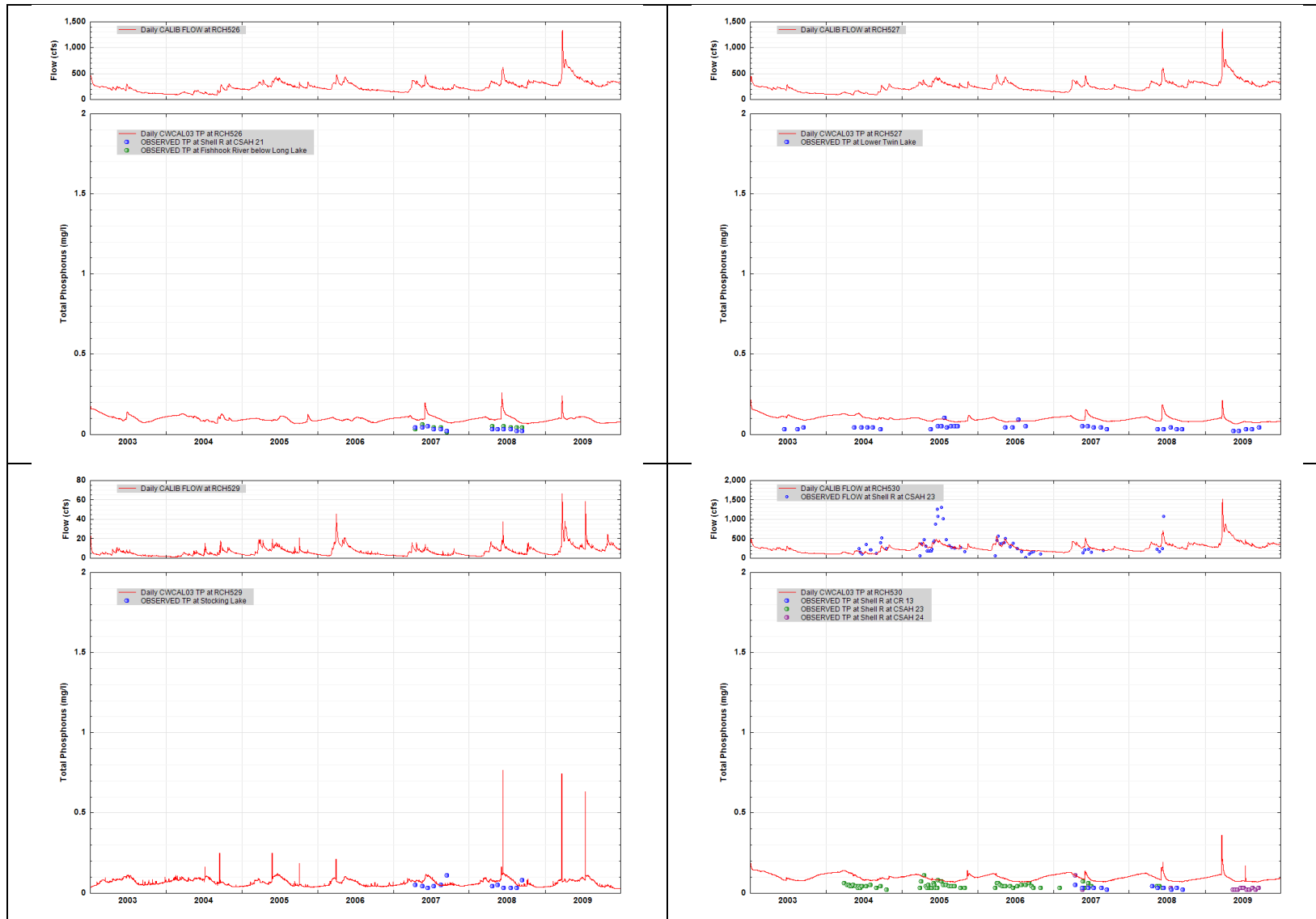




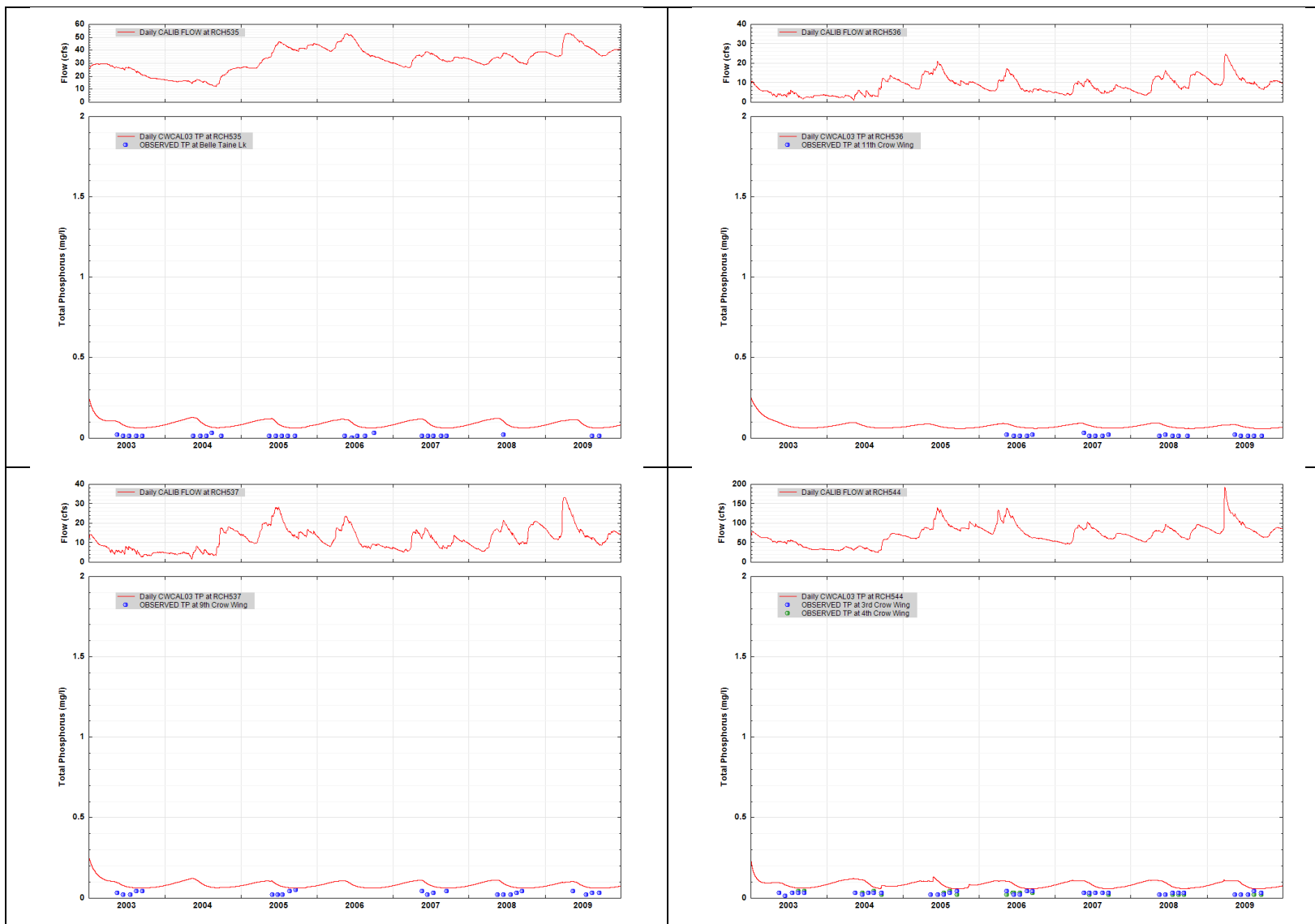


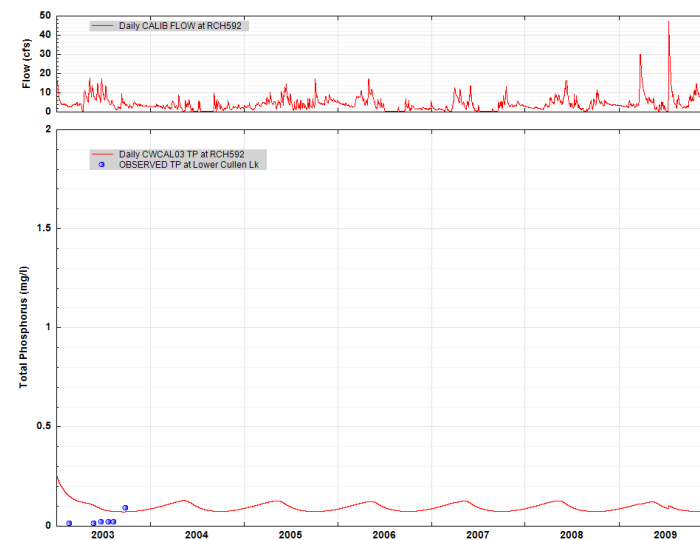
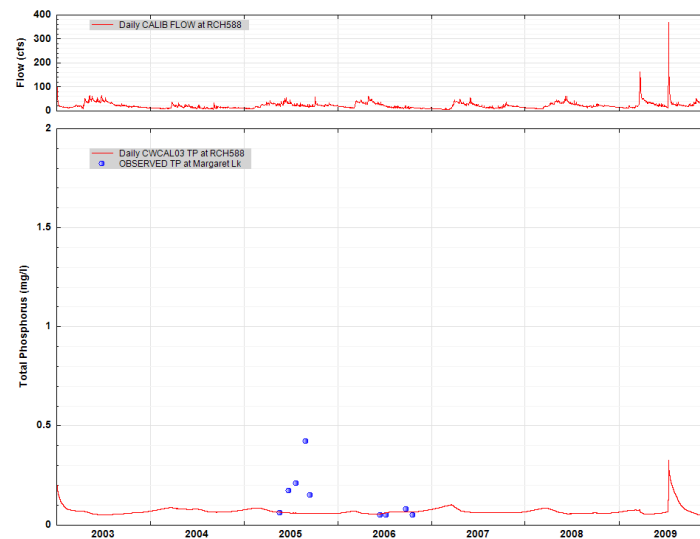
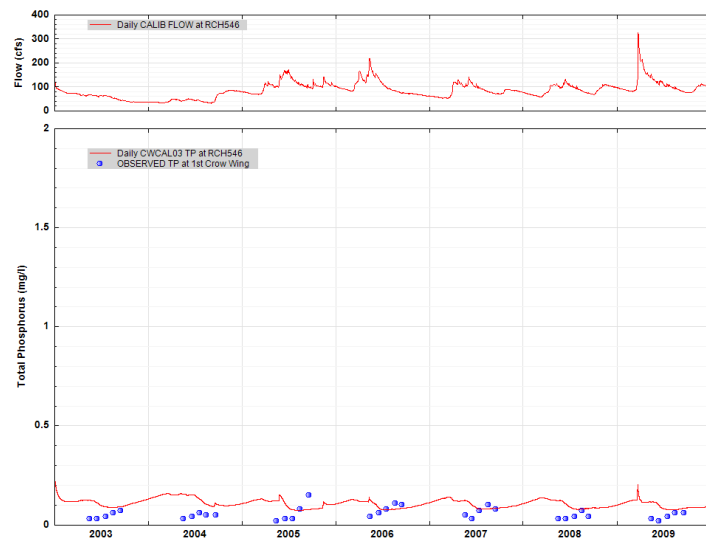


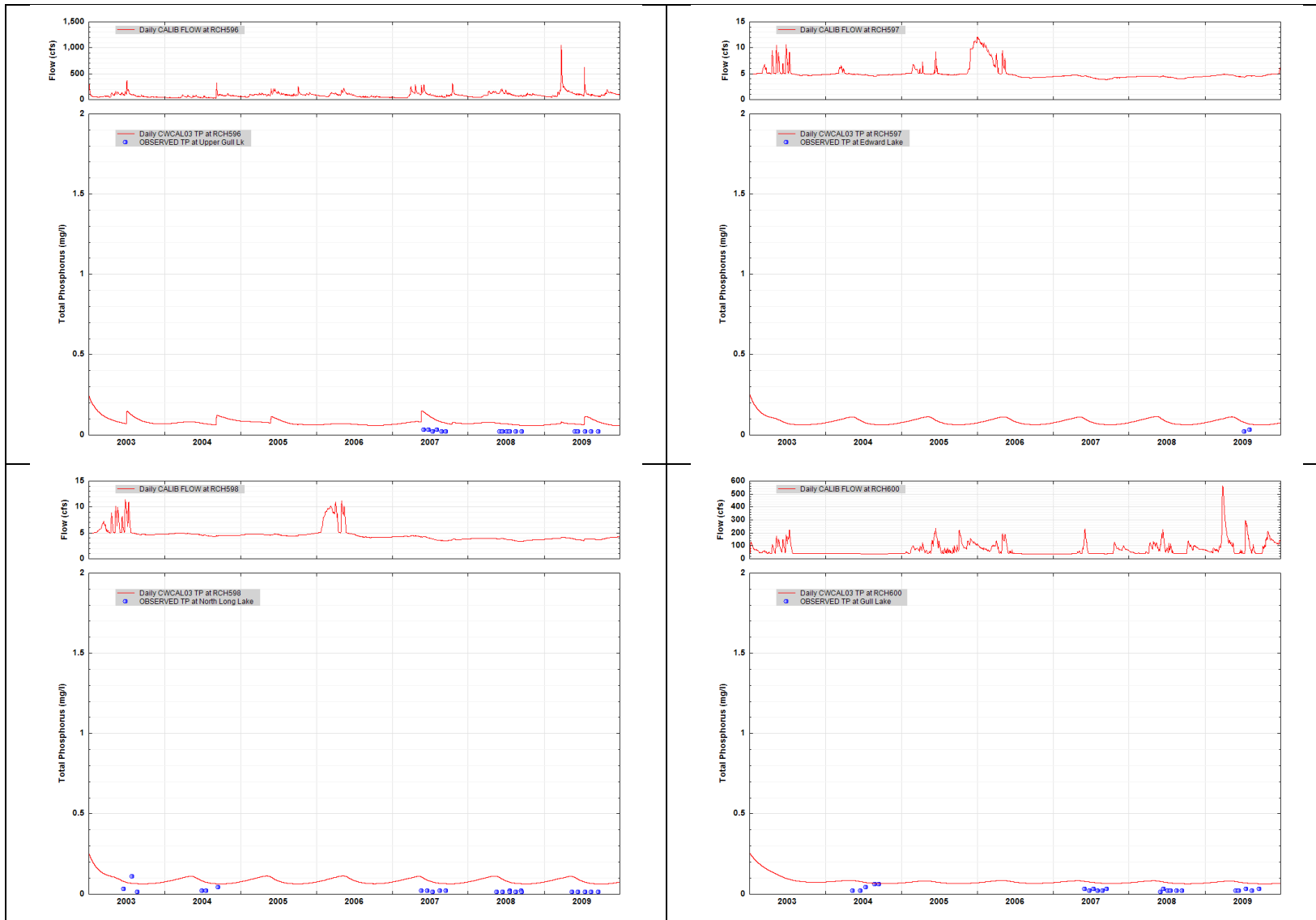










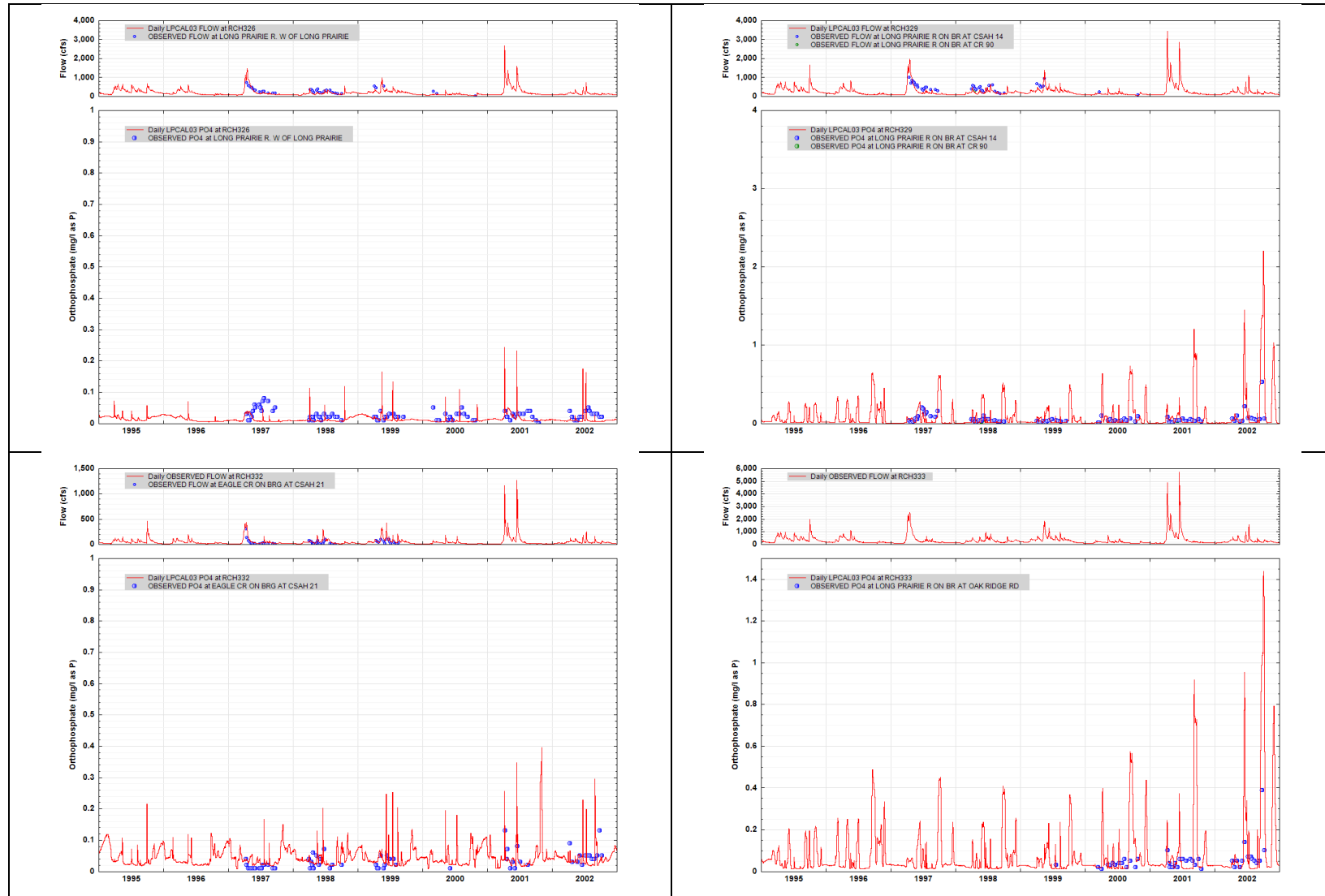


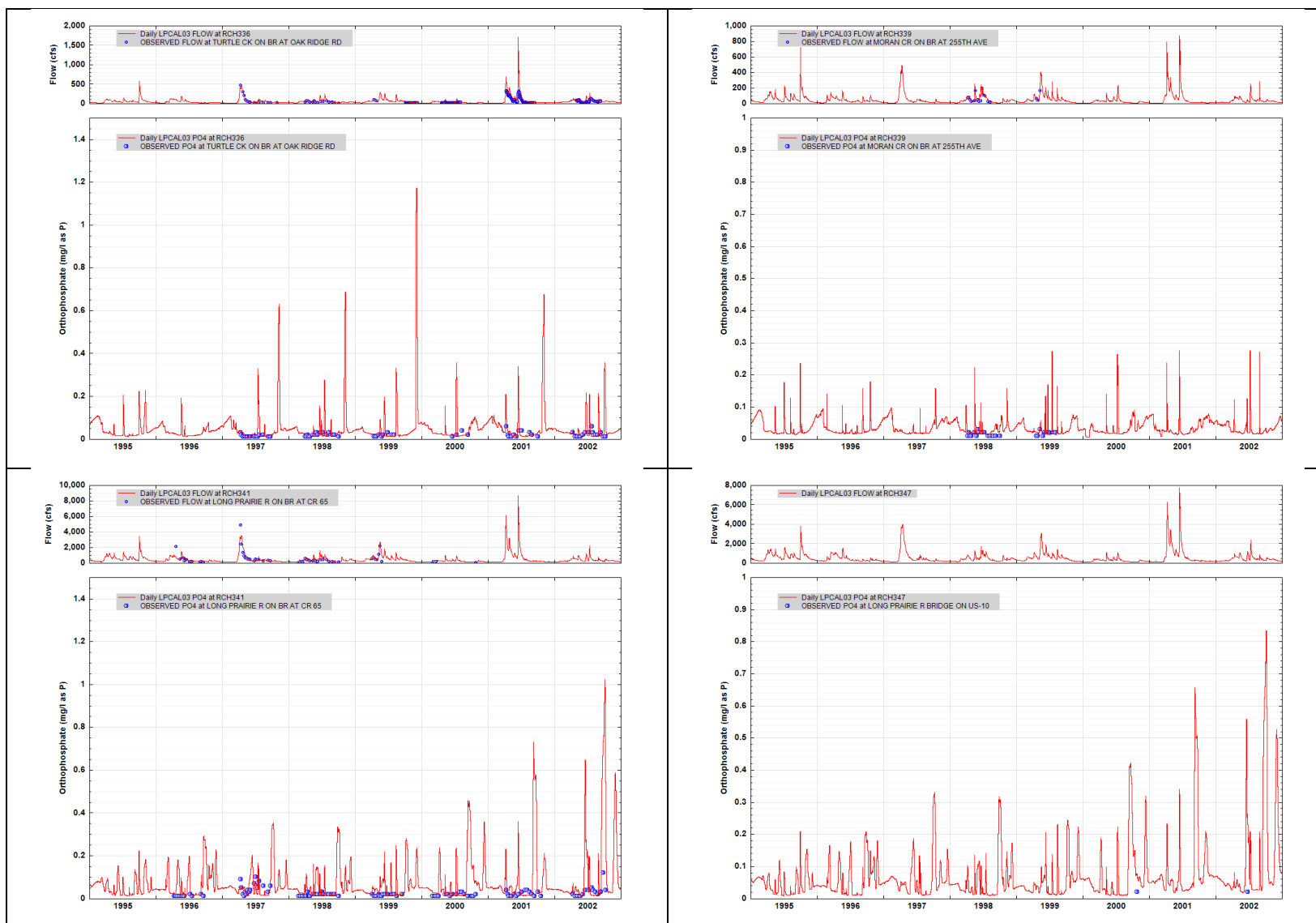
APPENDIX N

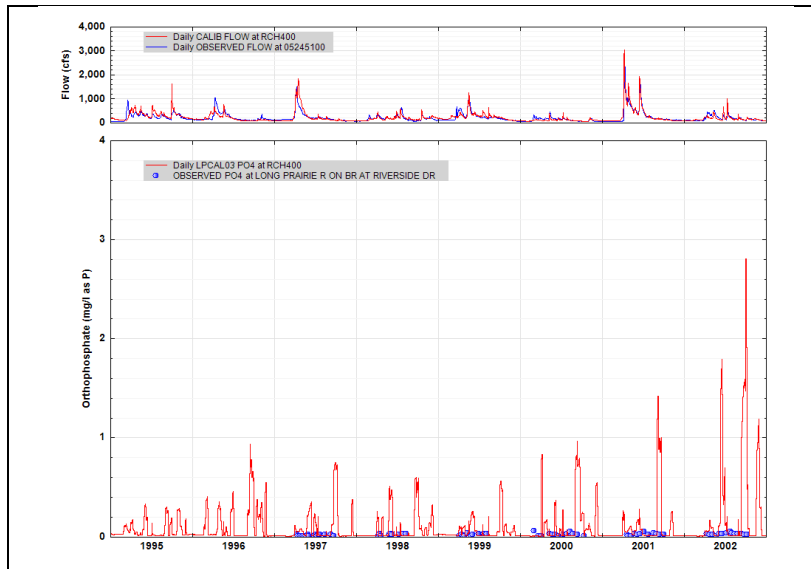
OBSERVED AND SIMULATED PHOSPHORUS CONSTITUENTS FOR THE VALIDATION PERIOD

N.1 ORTHOPHOSPHATE

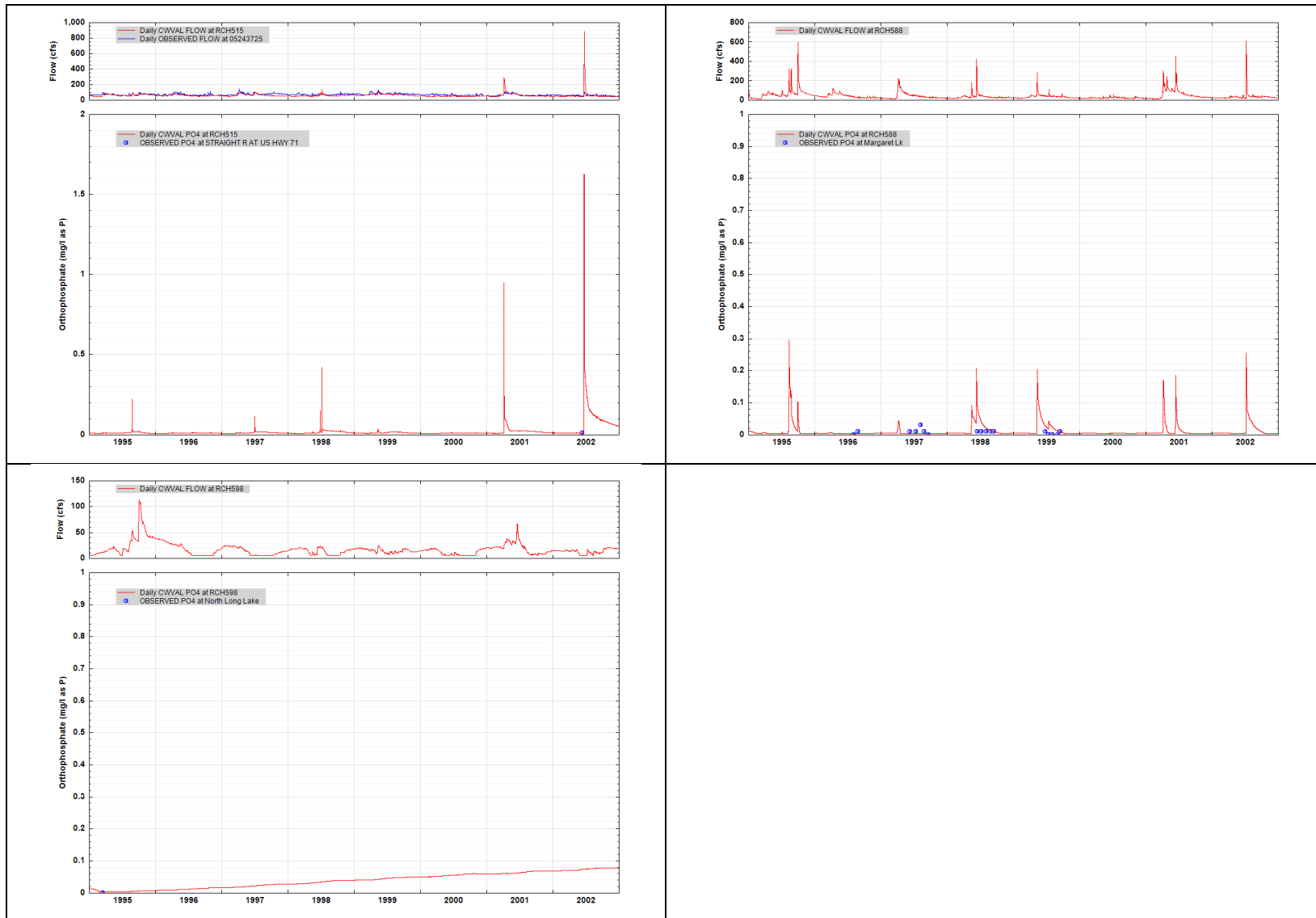
N.1.1 Long Prairie River Watershed







N.1.2 Crow Wing River Watershed

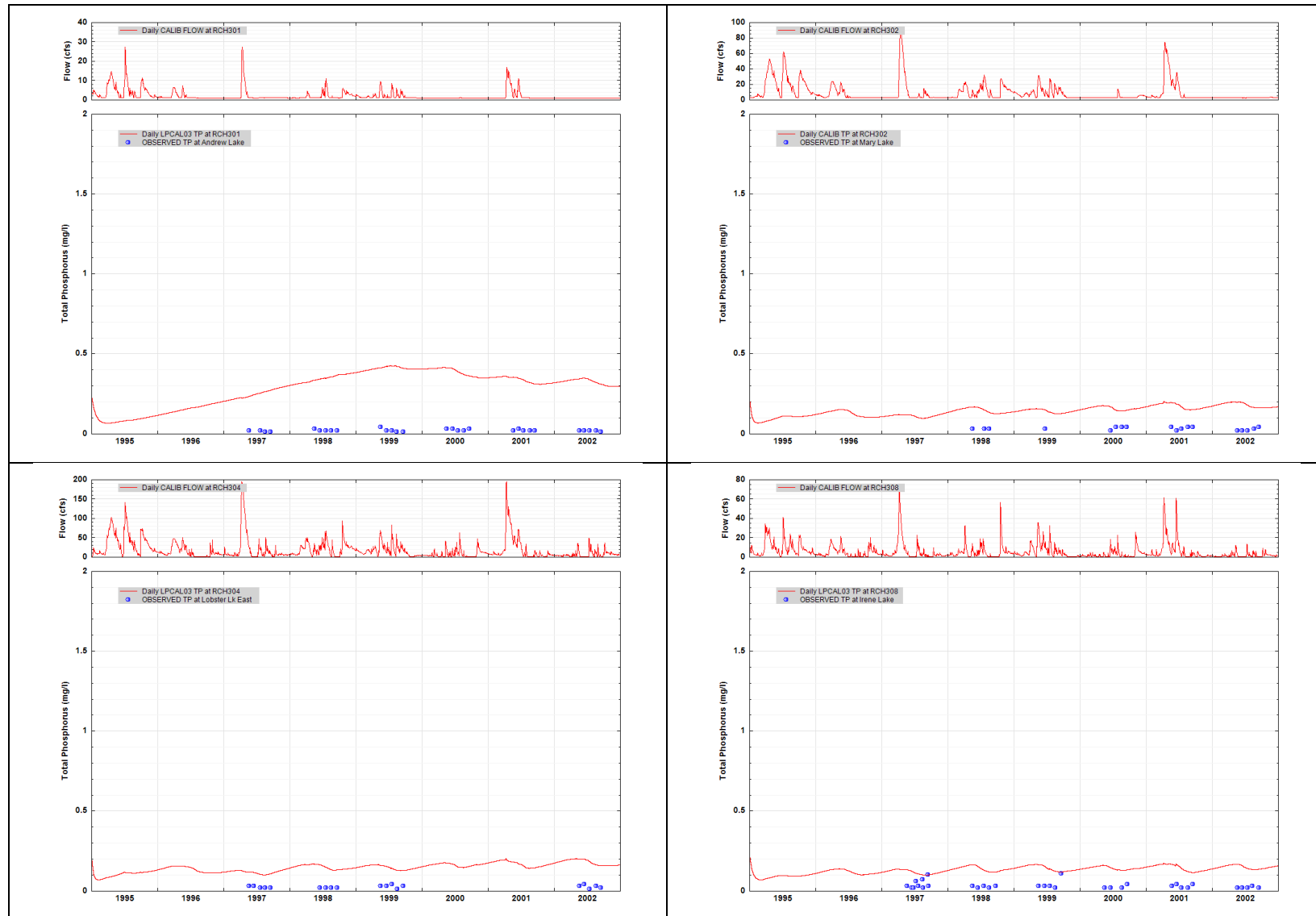


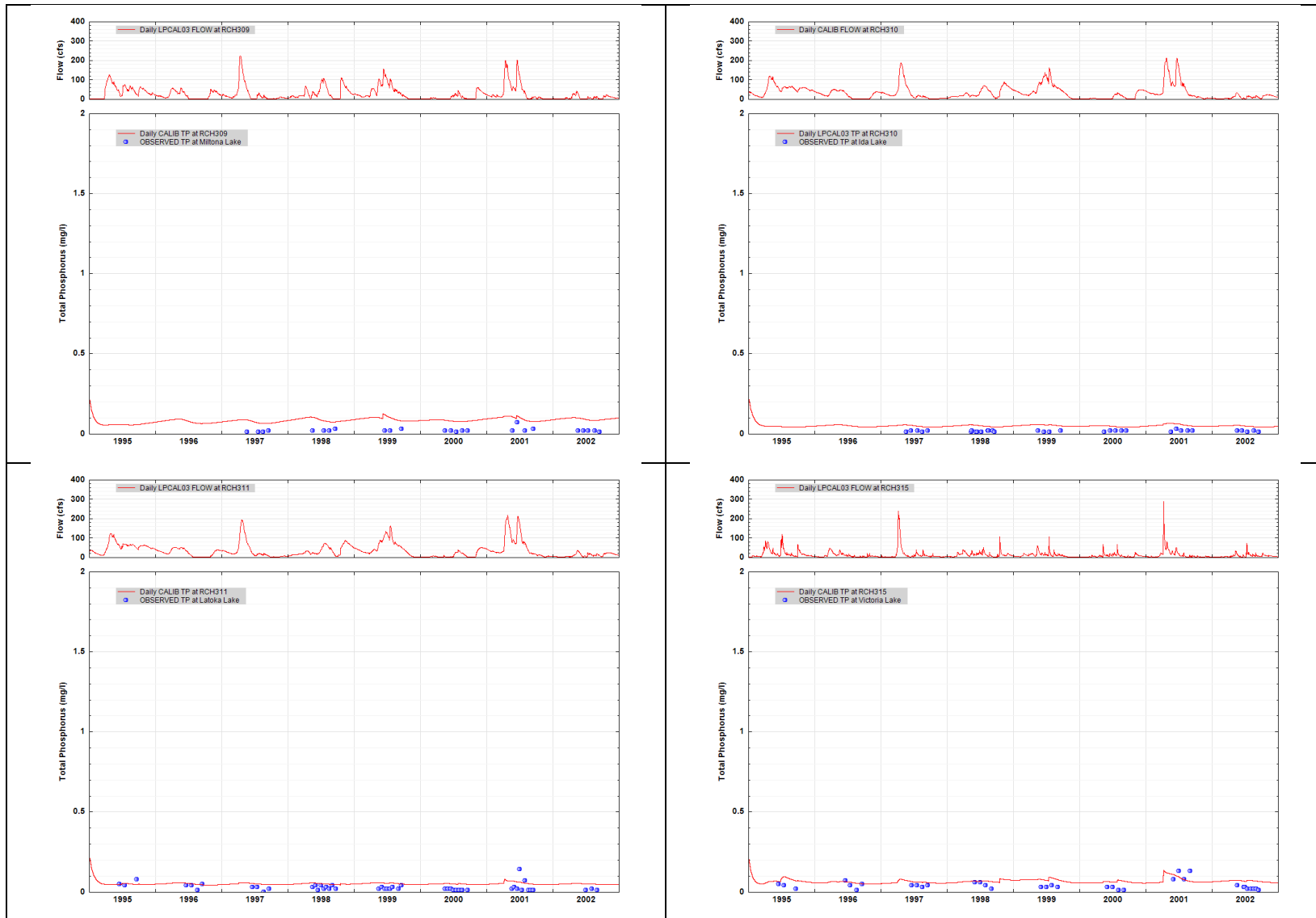
N.2 TOTAL PHOSPHORUS

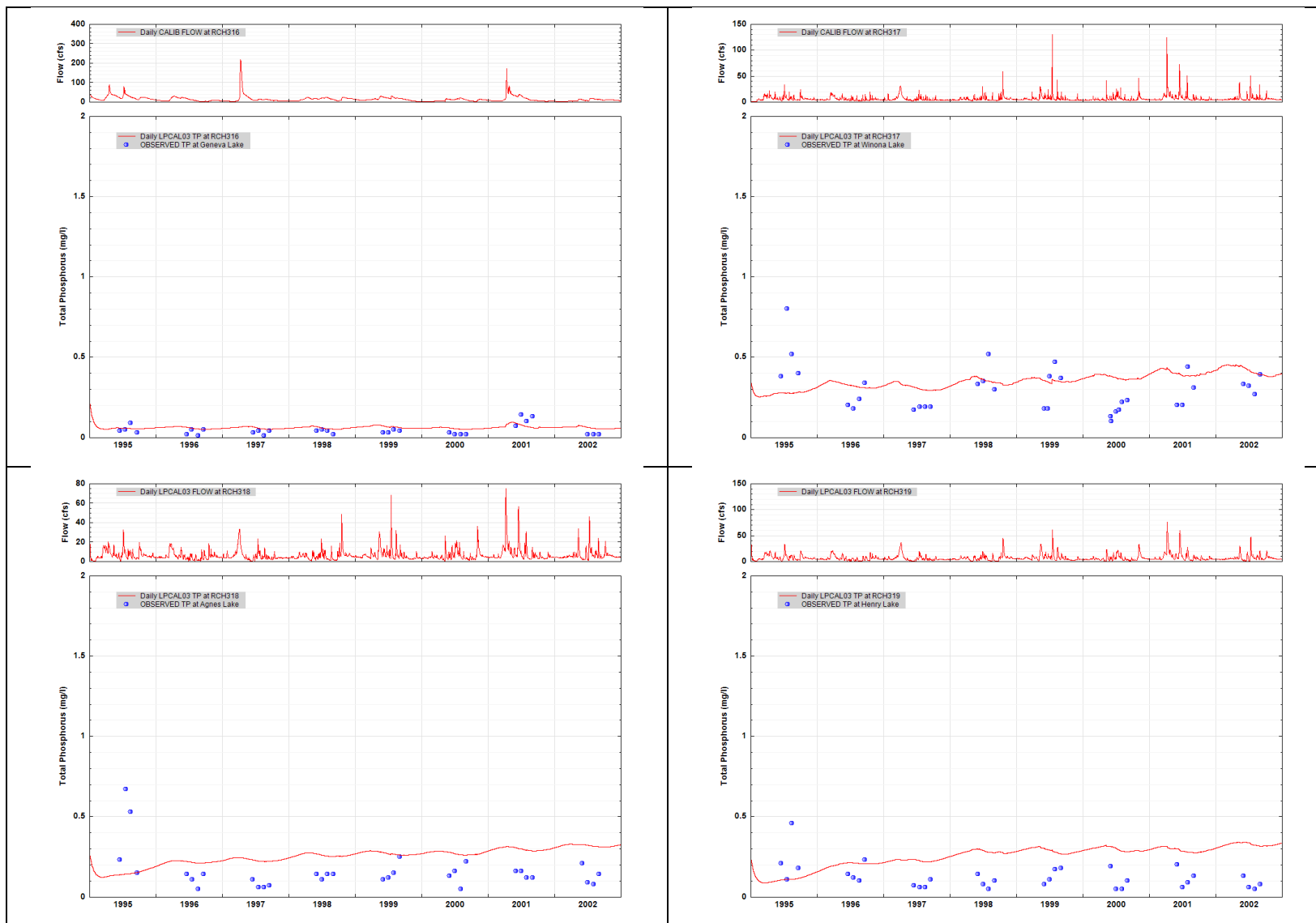
N.2.1 Redeye River Watershed

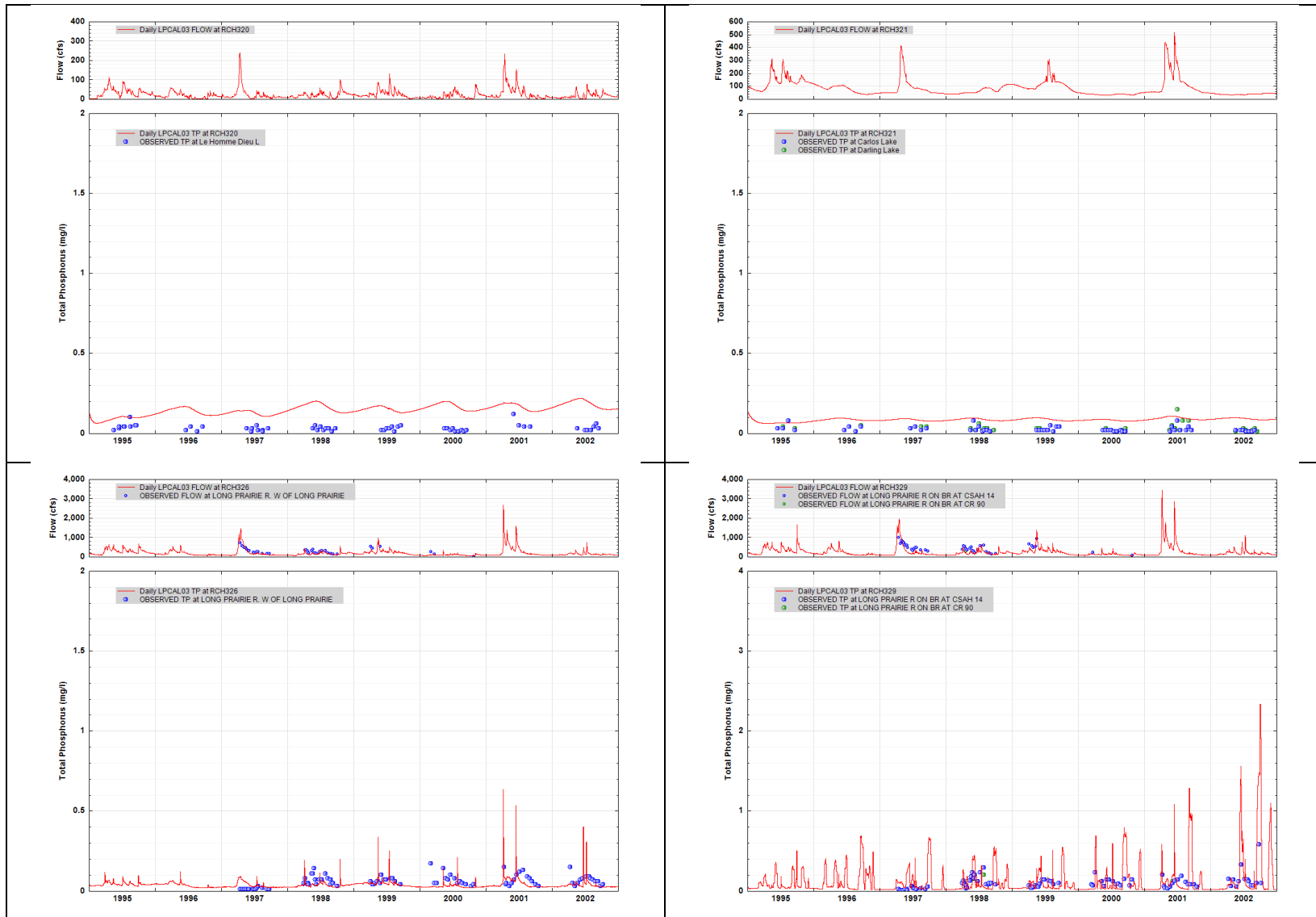


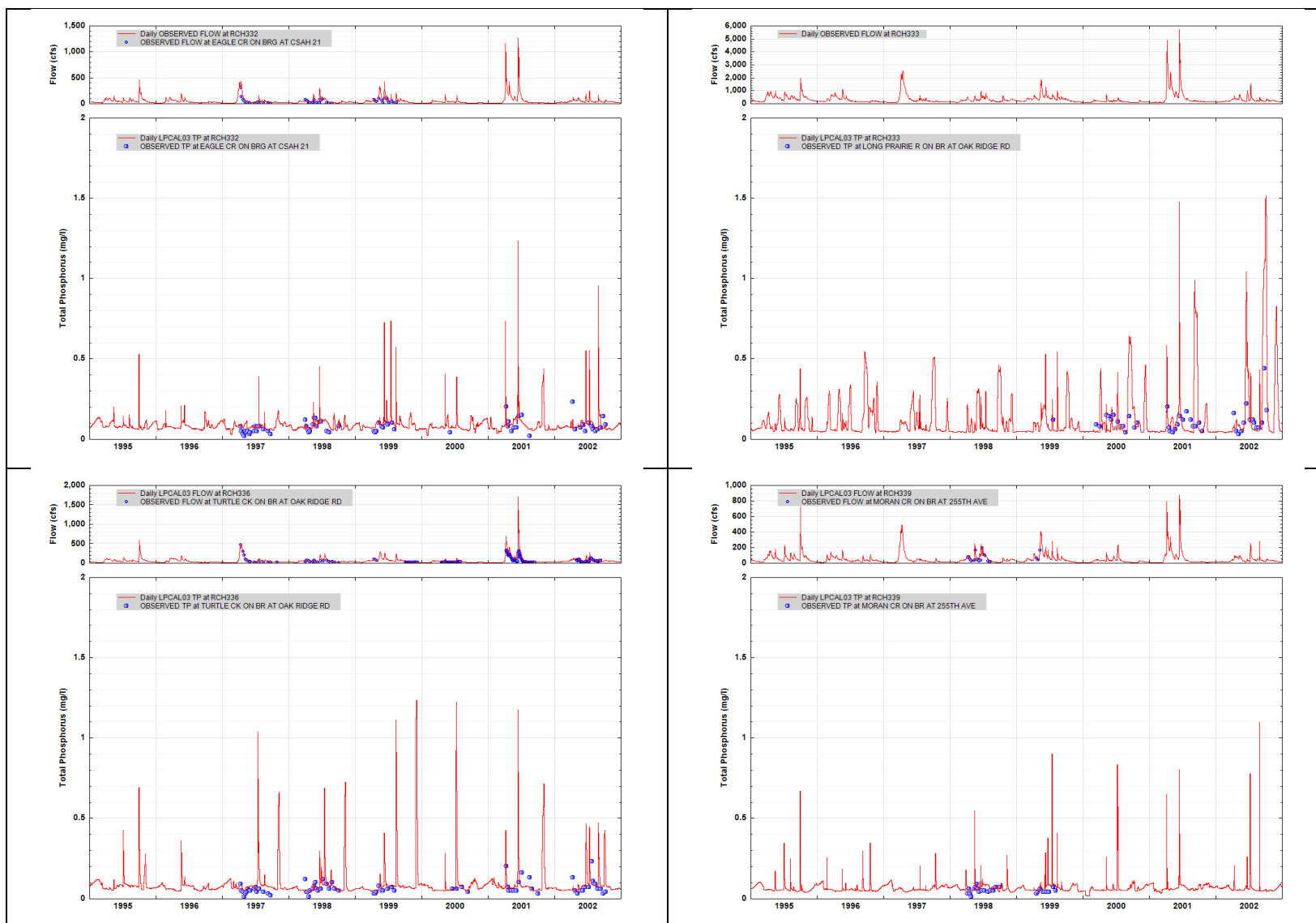
N.2.2 Long Prairie River Watershed





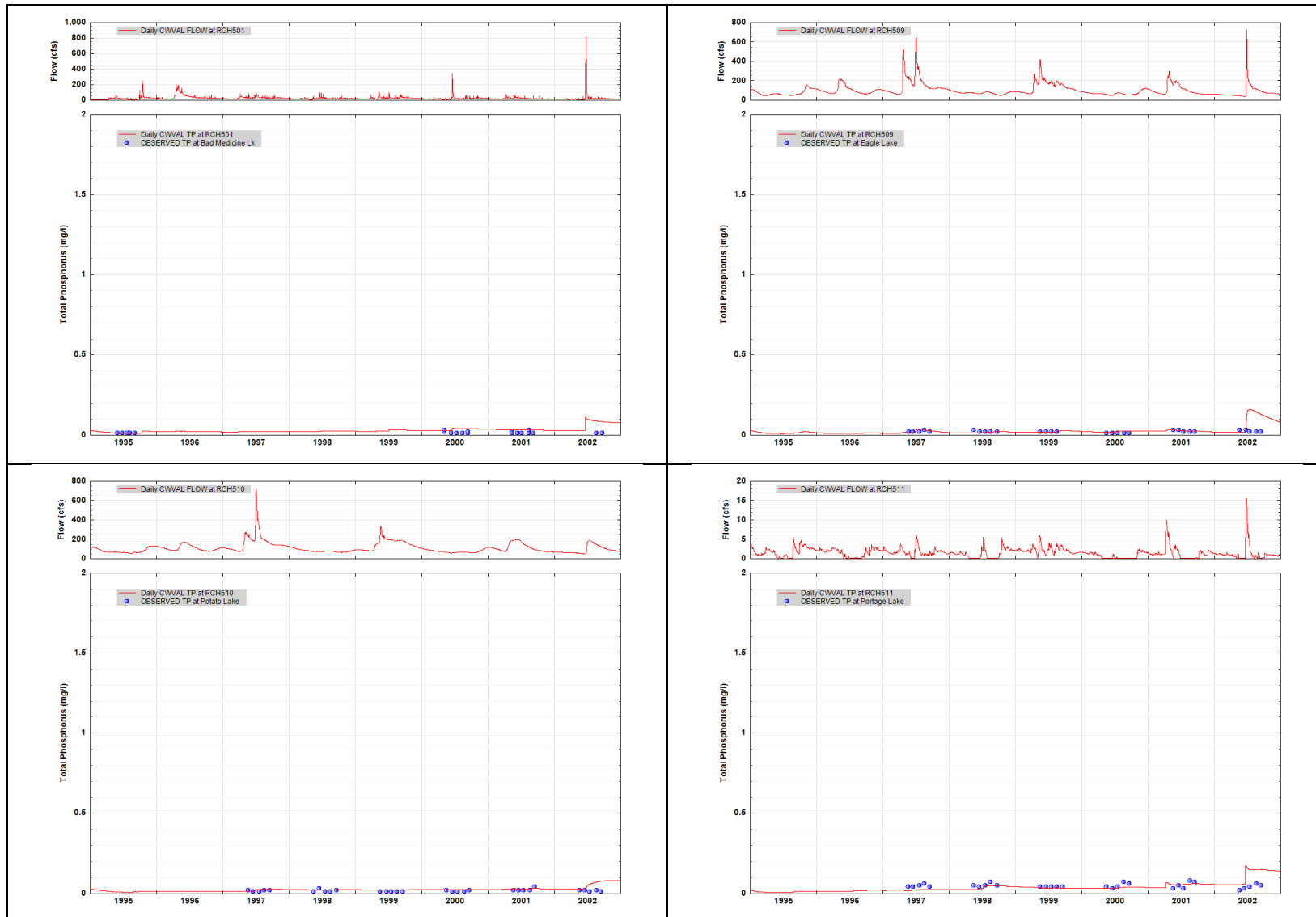


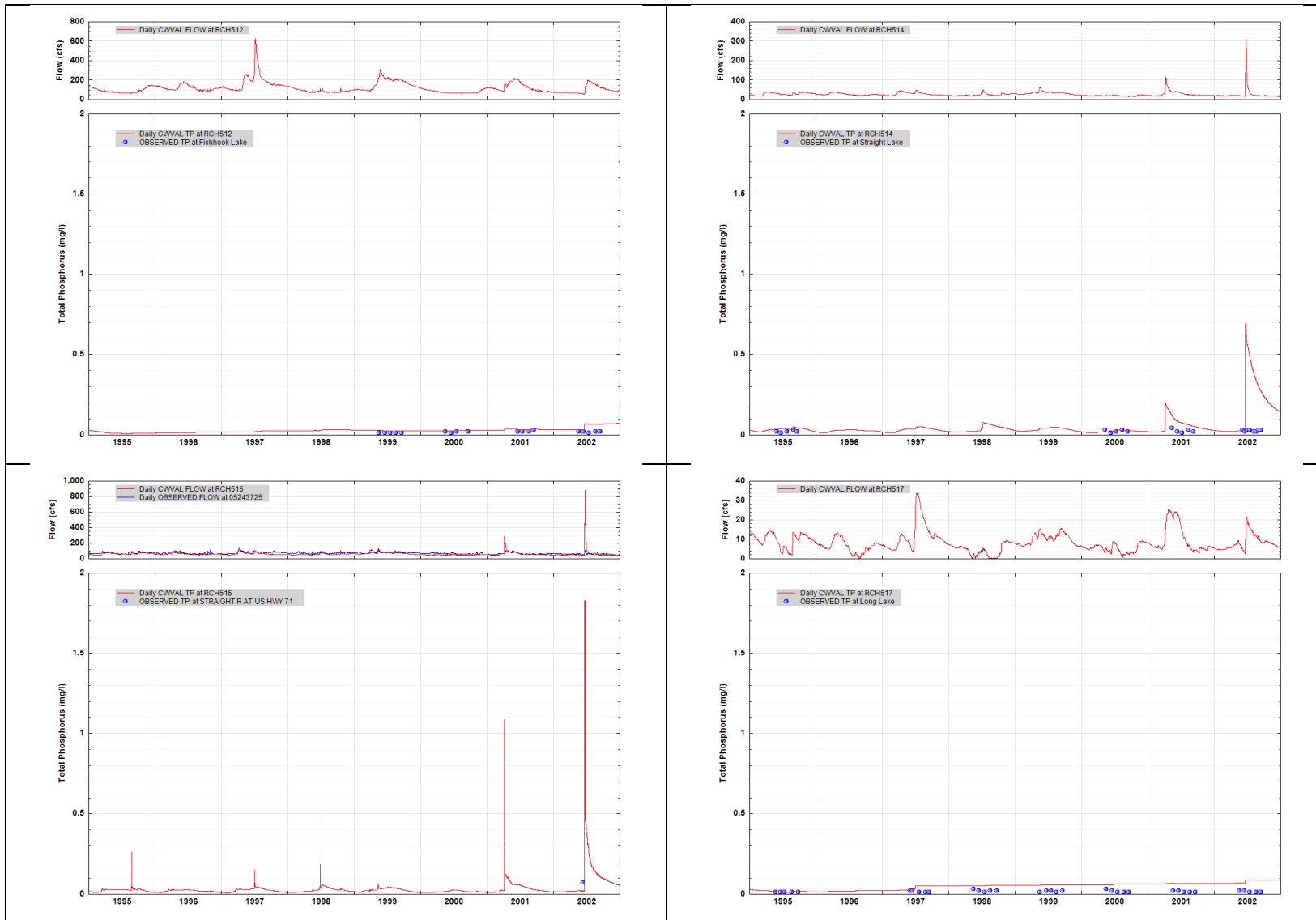


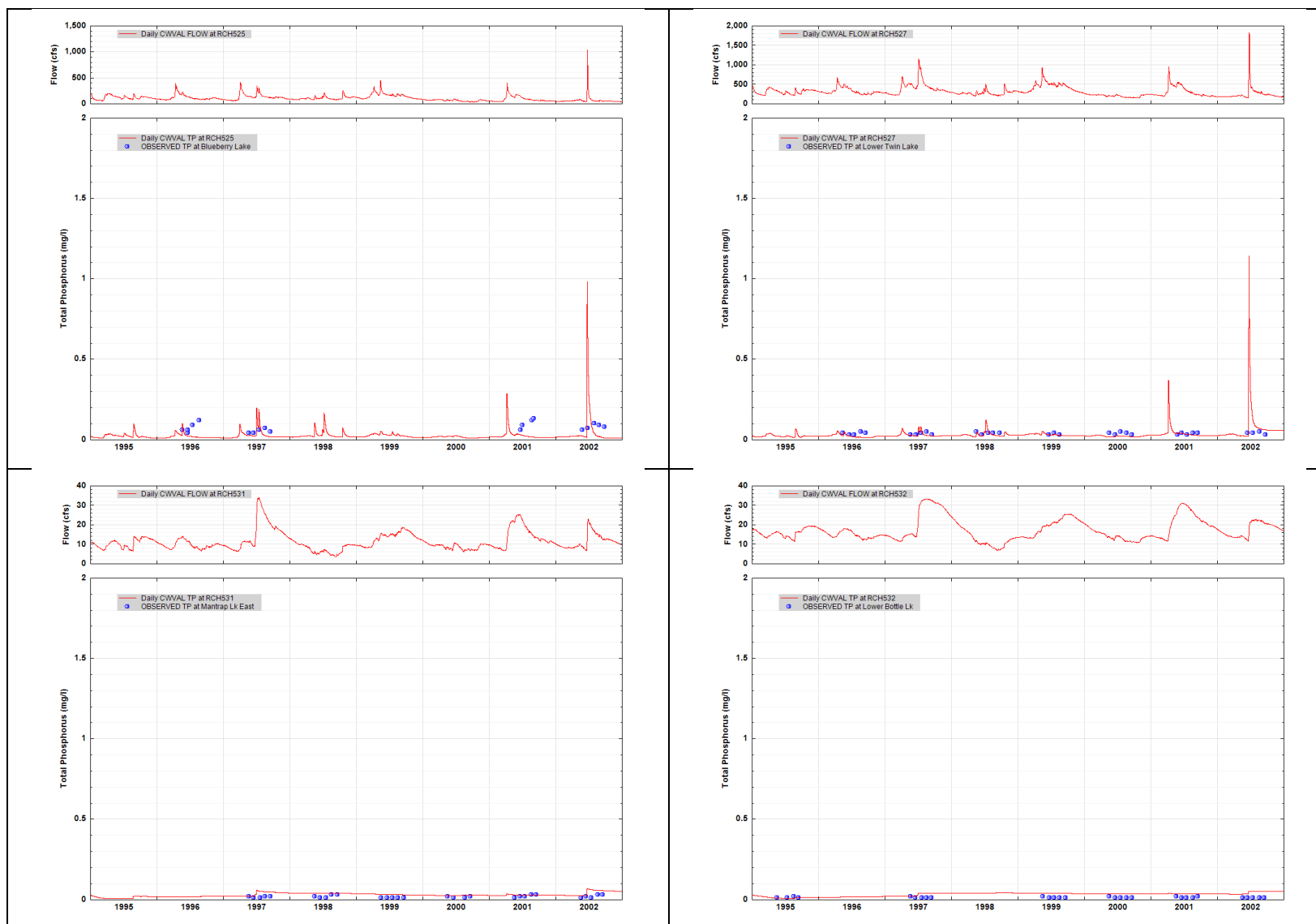


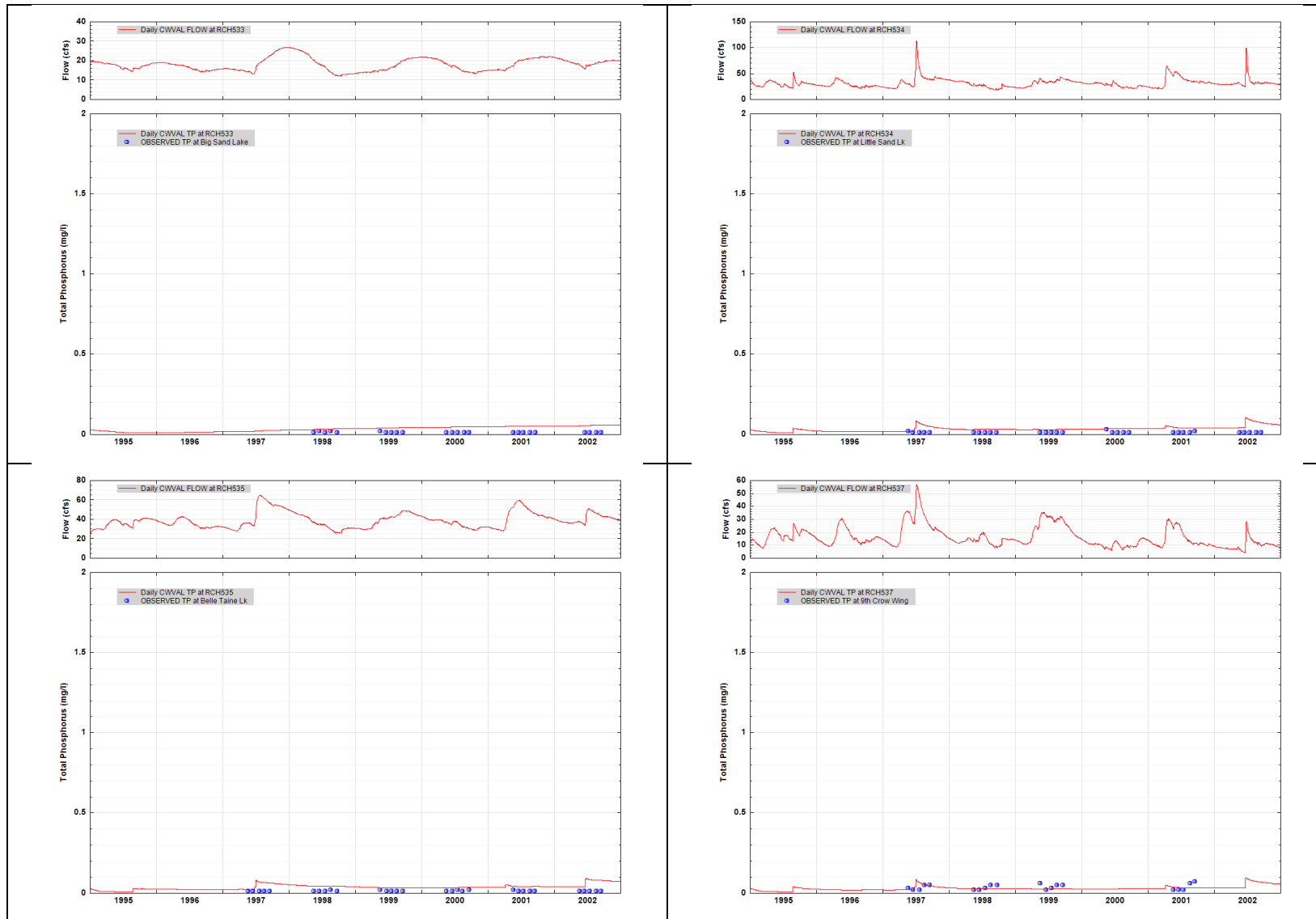


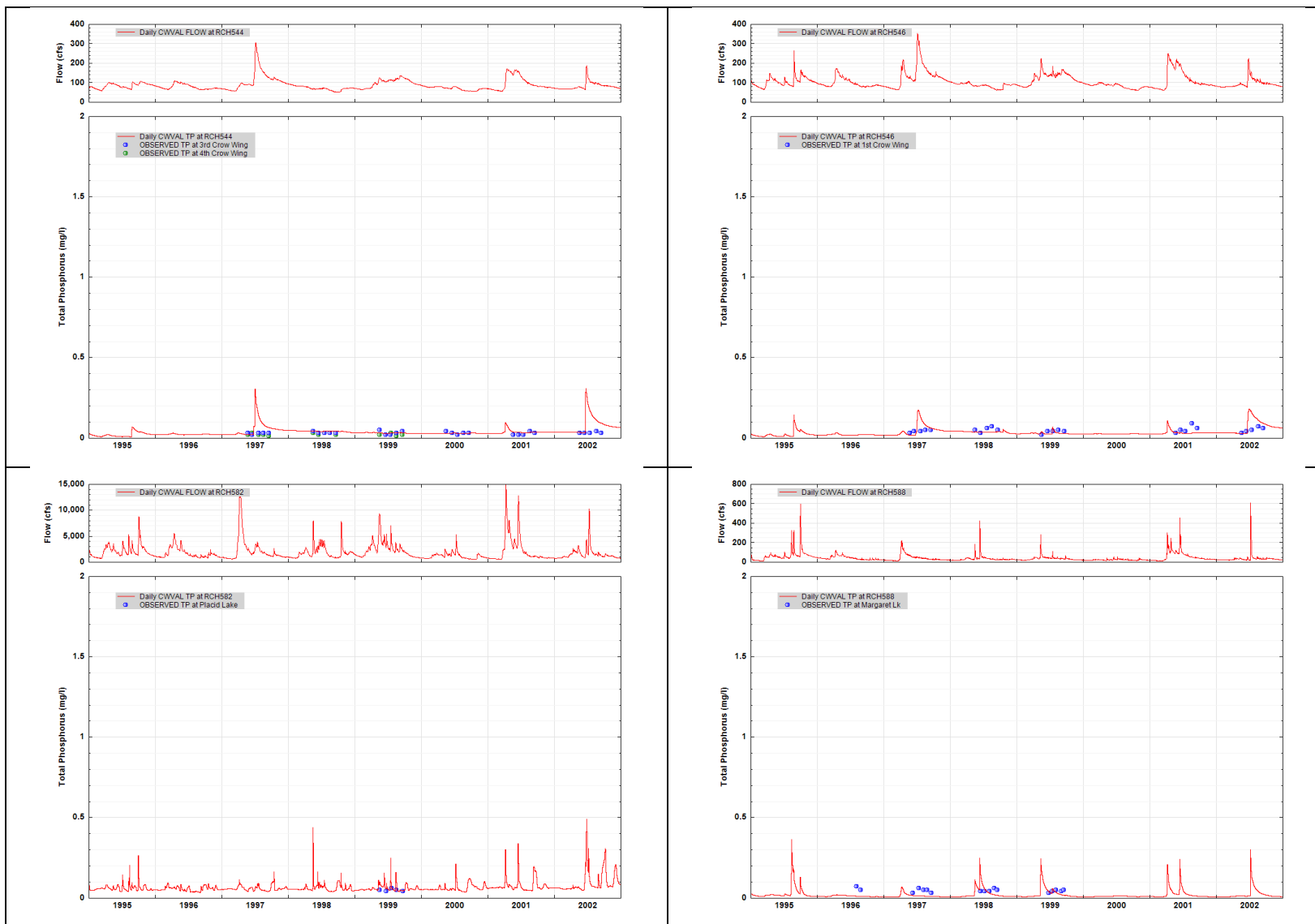
N.2.3 Crow Wing River Watershed

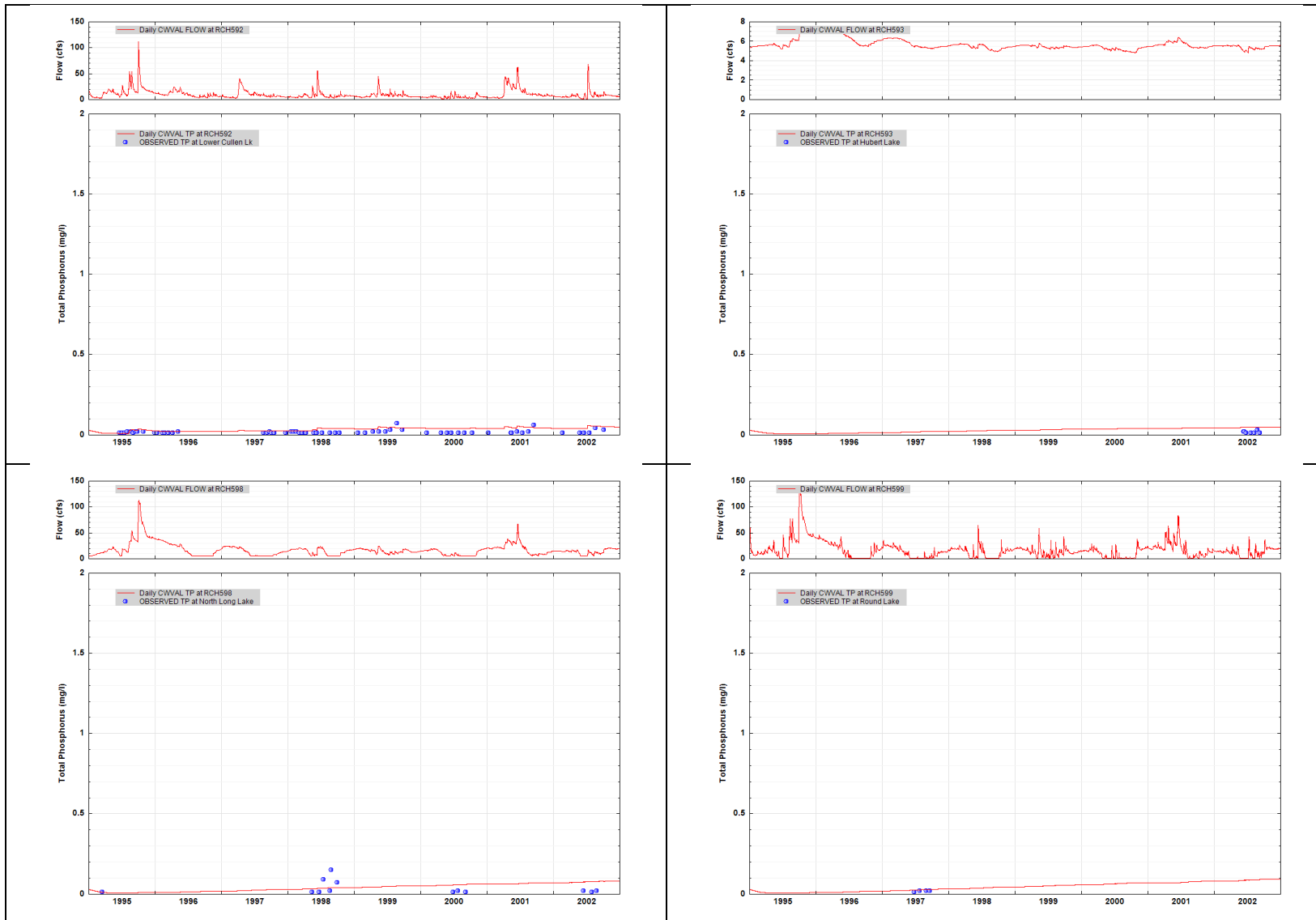






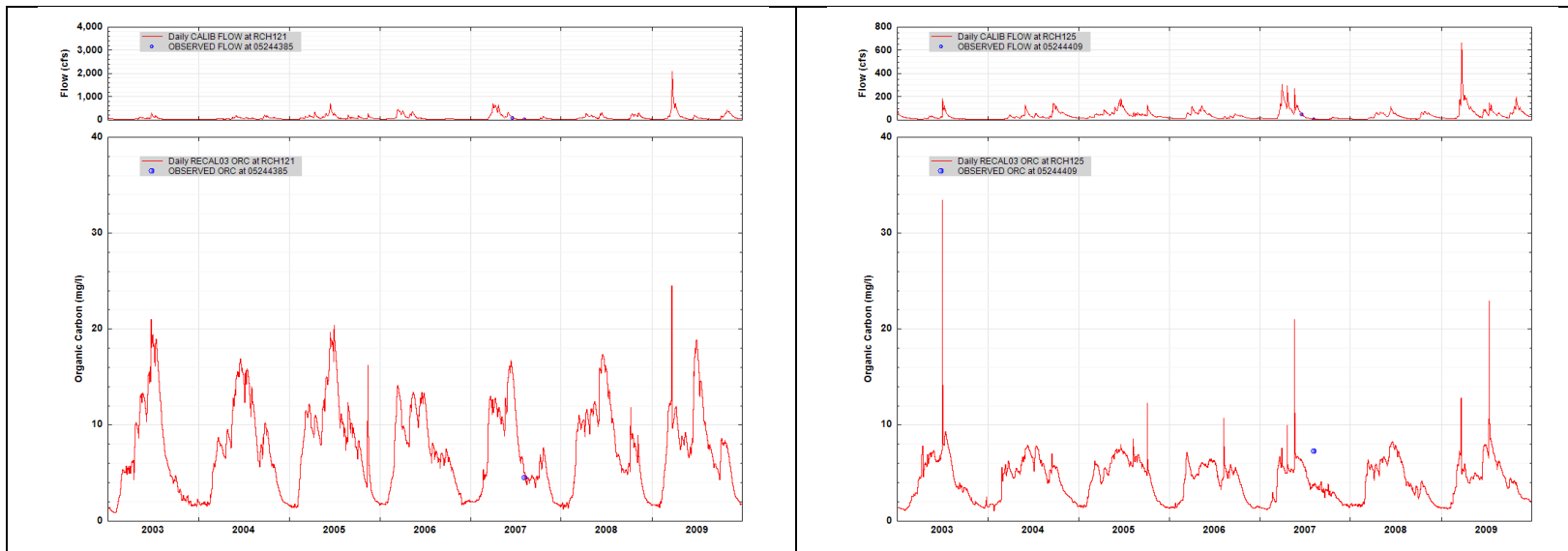


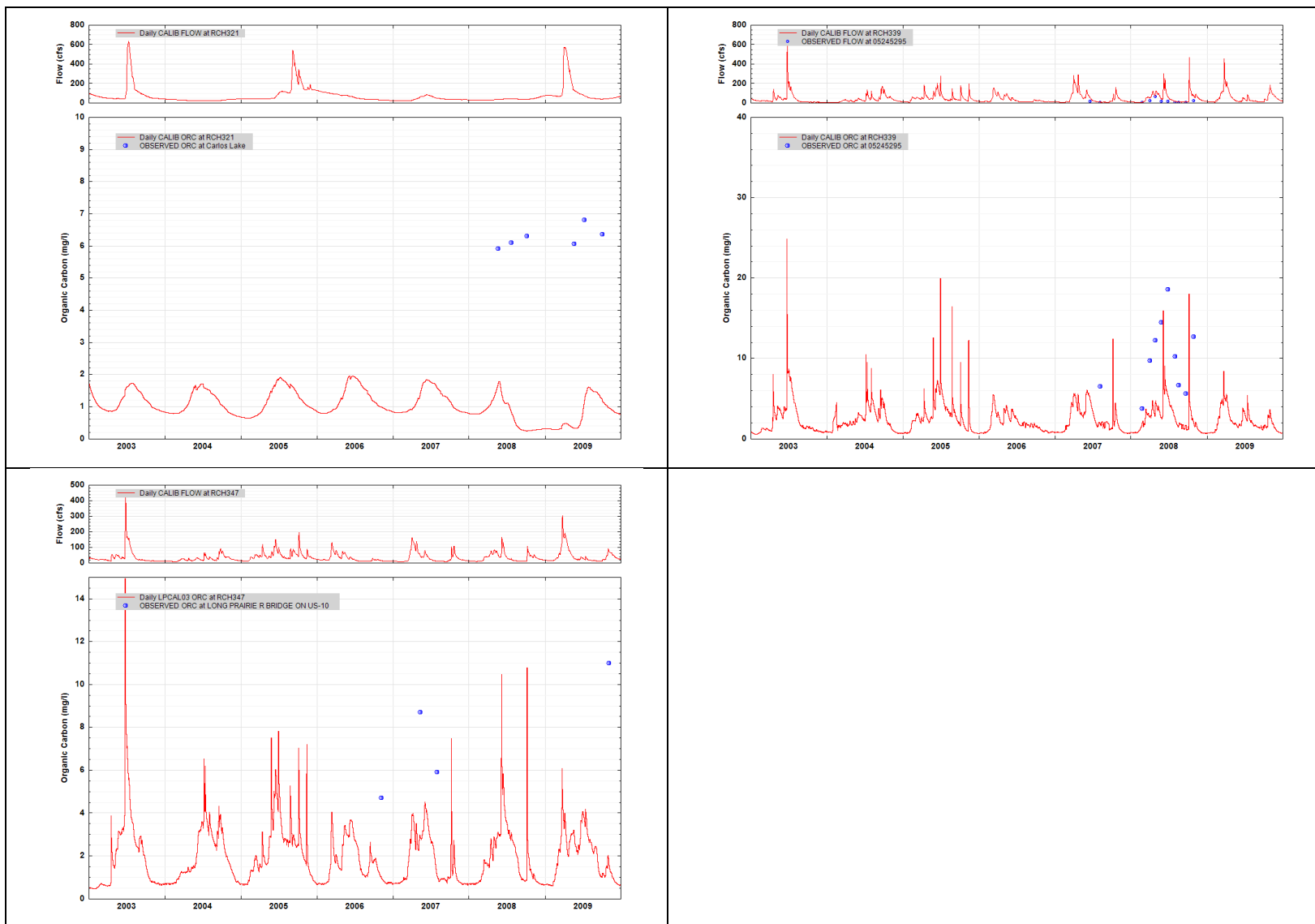


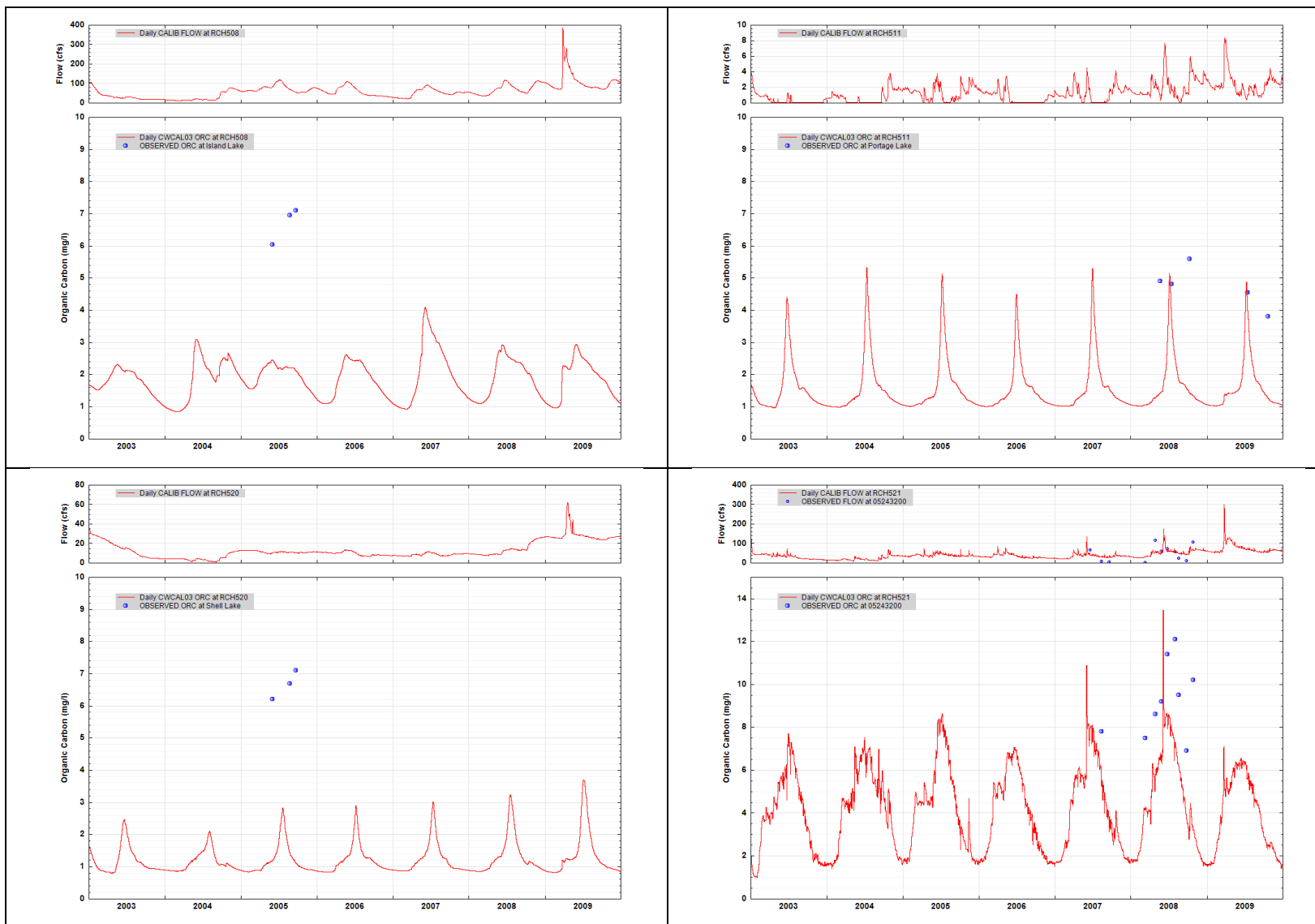


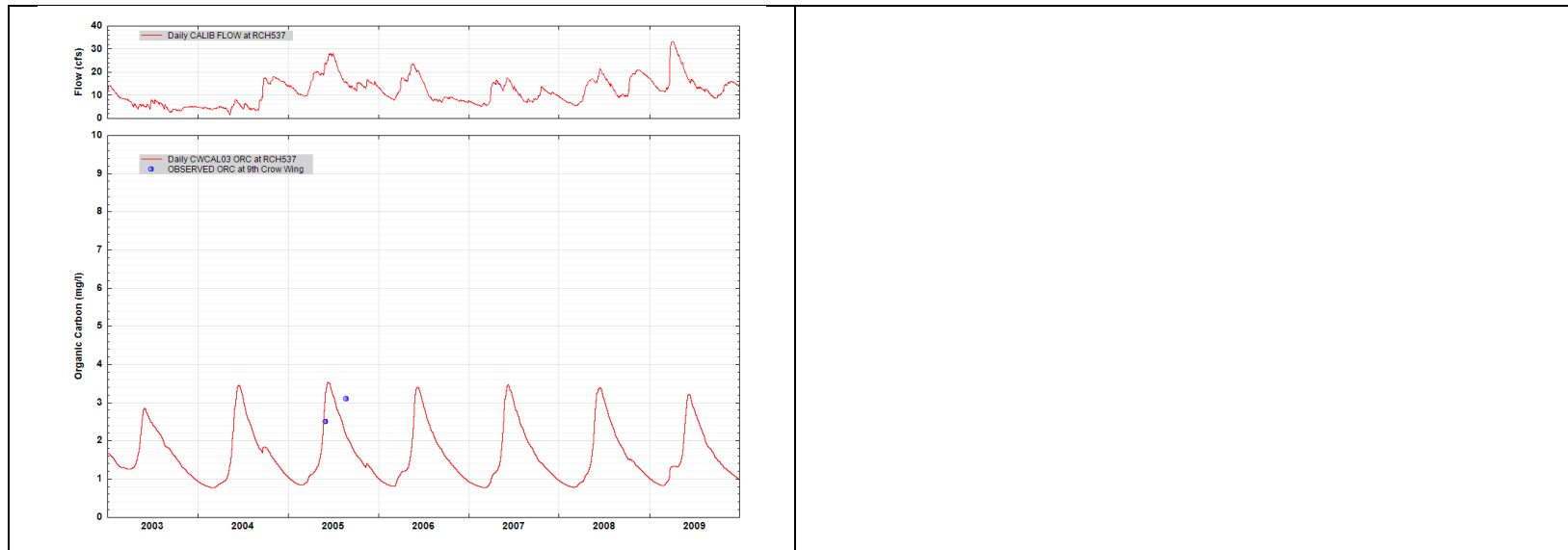
APPENDIX O OBSERVED AND SIMULATED ORGANIC CARBON FOR THE CALIBRATION PERIOD

O.1 REDEYE RIVER WATERSHED



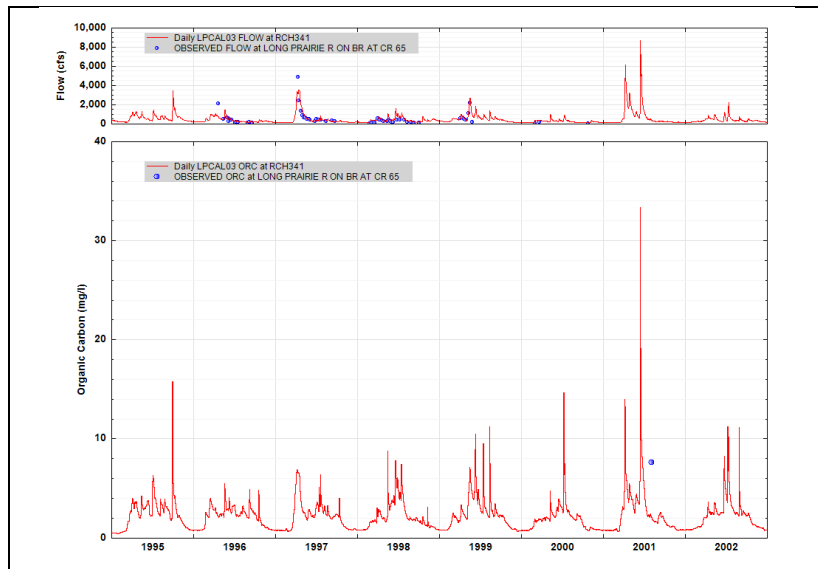
O.2 LONG PRAIRIE RIVER WATERSHED

O.3 CROW WING RIVER WATERSHED



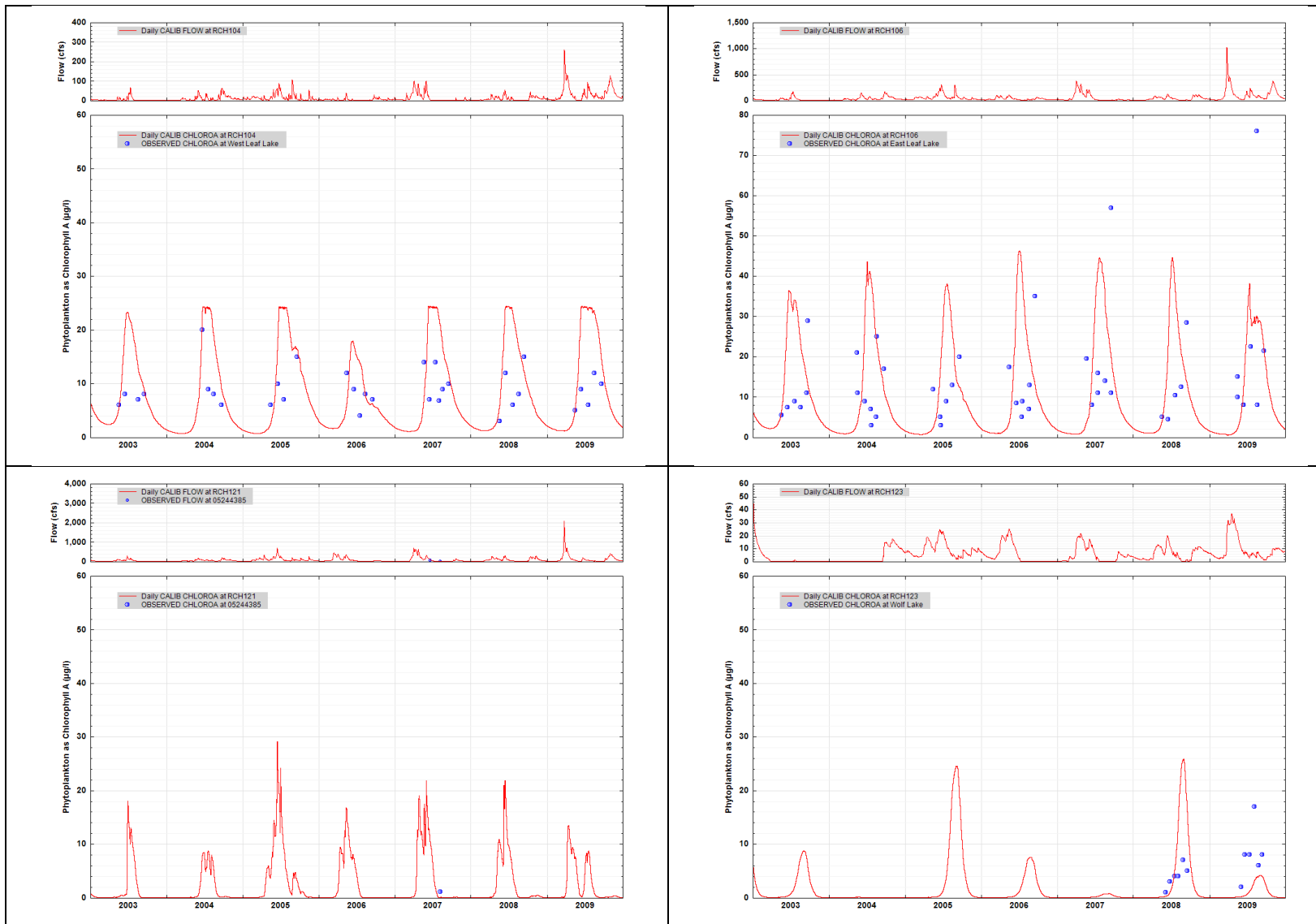
APPENDIX P OBSERVED AND SIMULATED ORGANIC CARBON FOR THE VALIDATION PERIOD

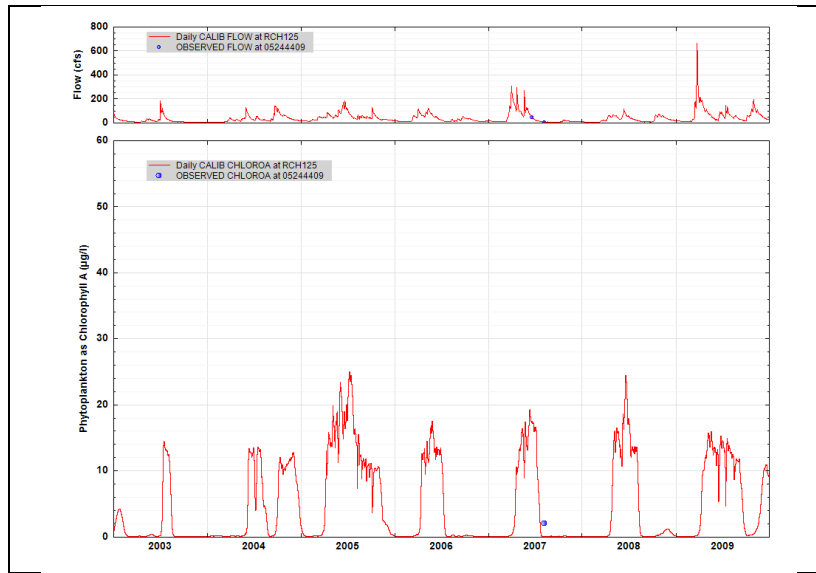
P.1 LONG PRAIRIE RIVER WATERSHED

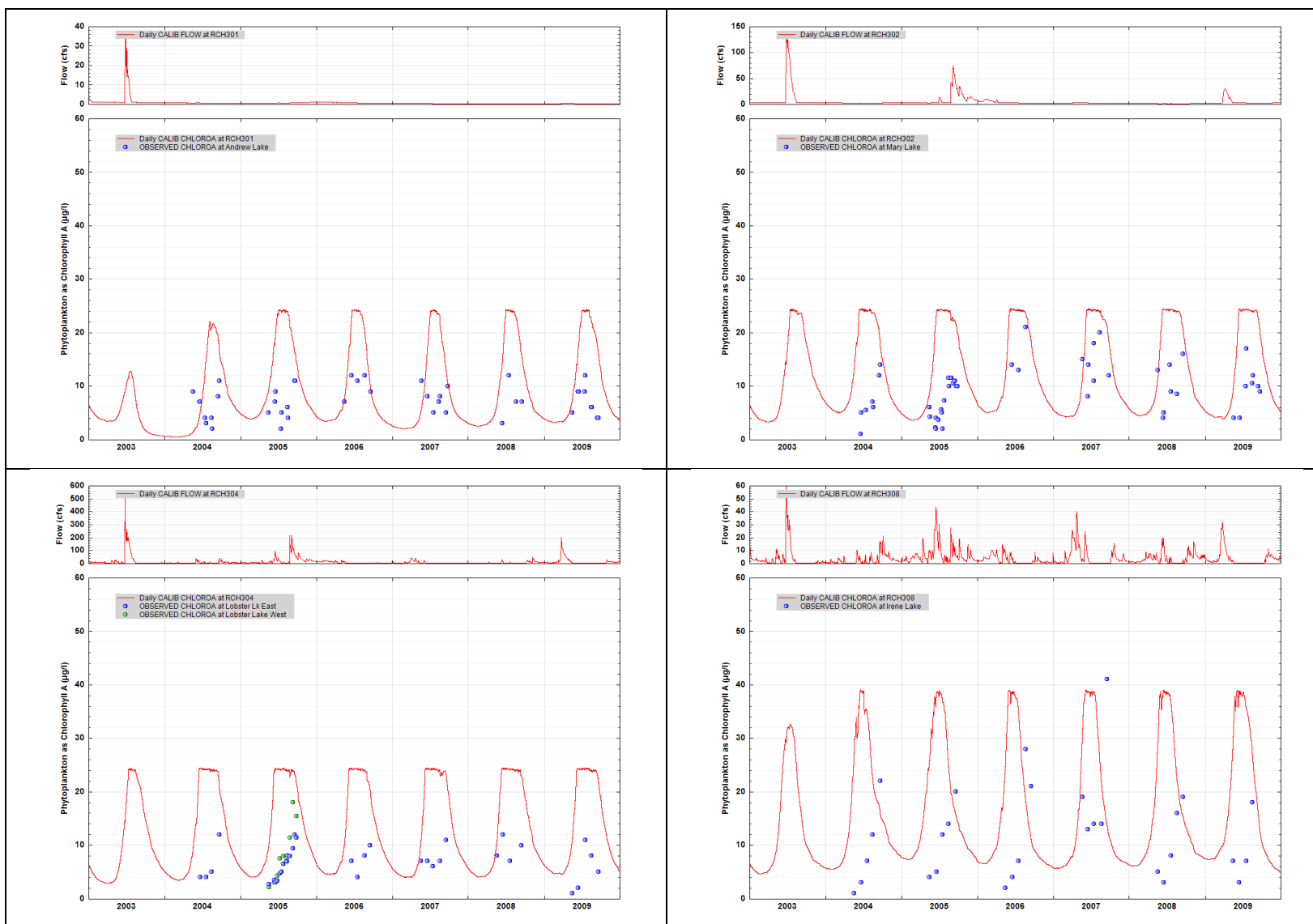


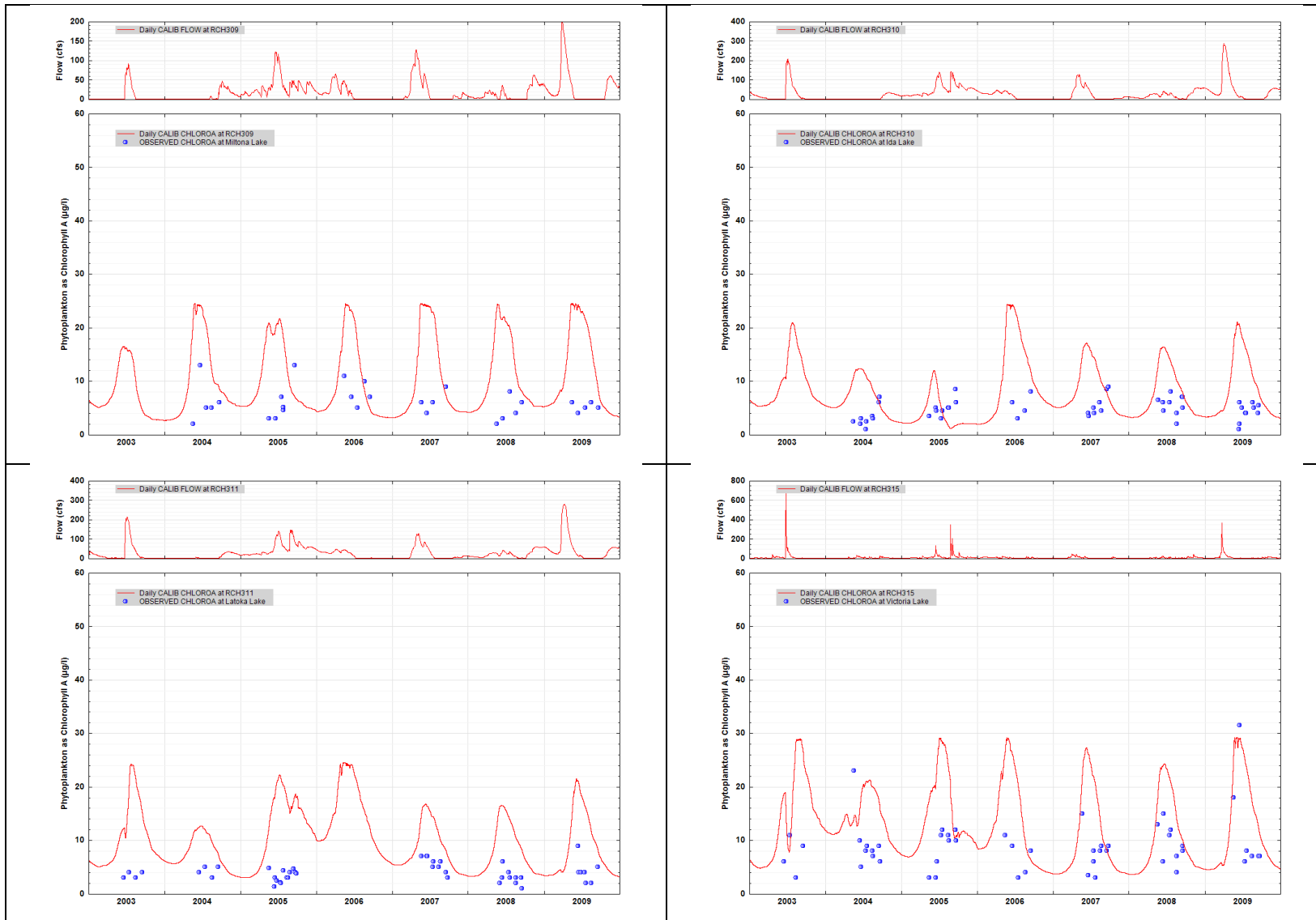
APPENDIX Q OBSERVED AND SIMULATED CHLOROPHYLL A FOR THE CALIBRATION PERIOD

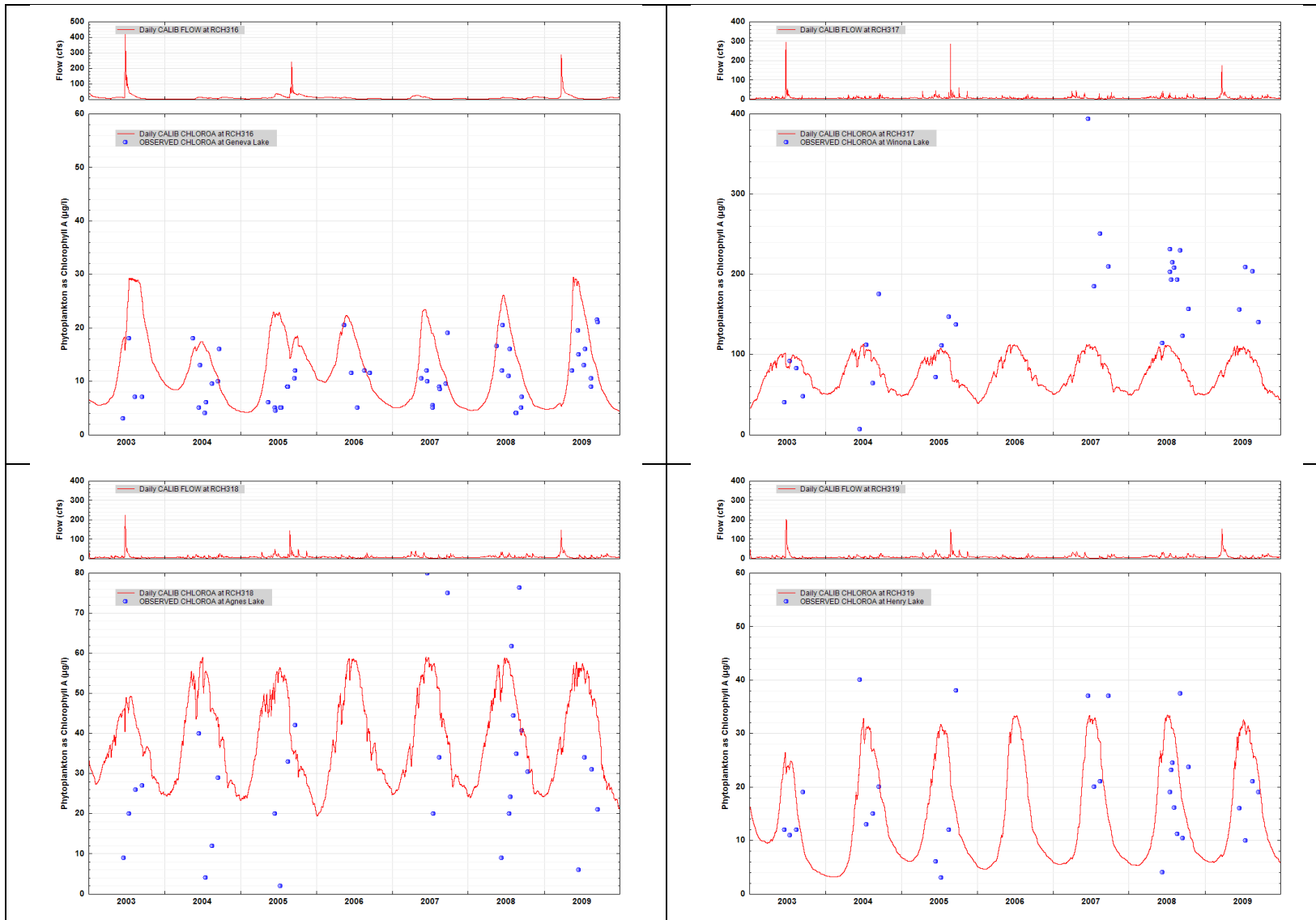
Q.1 REDEYE RIVER WATERSHED

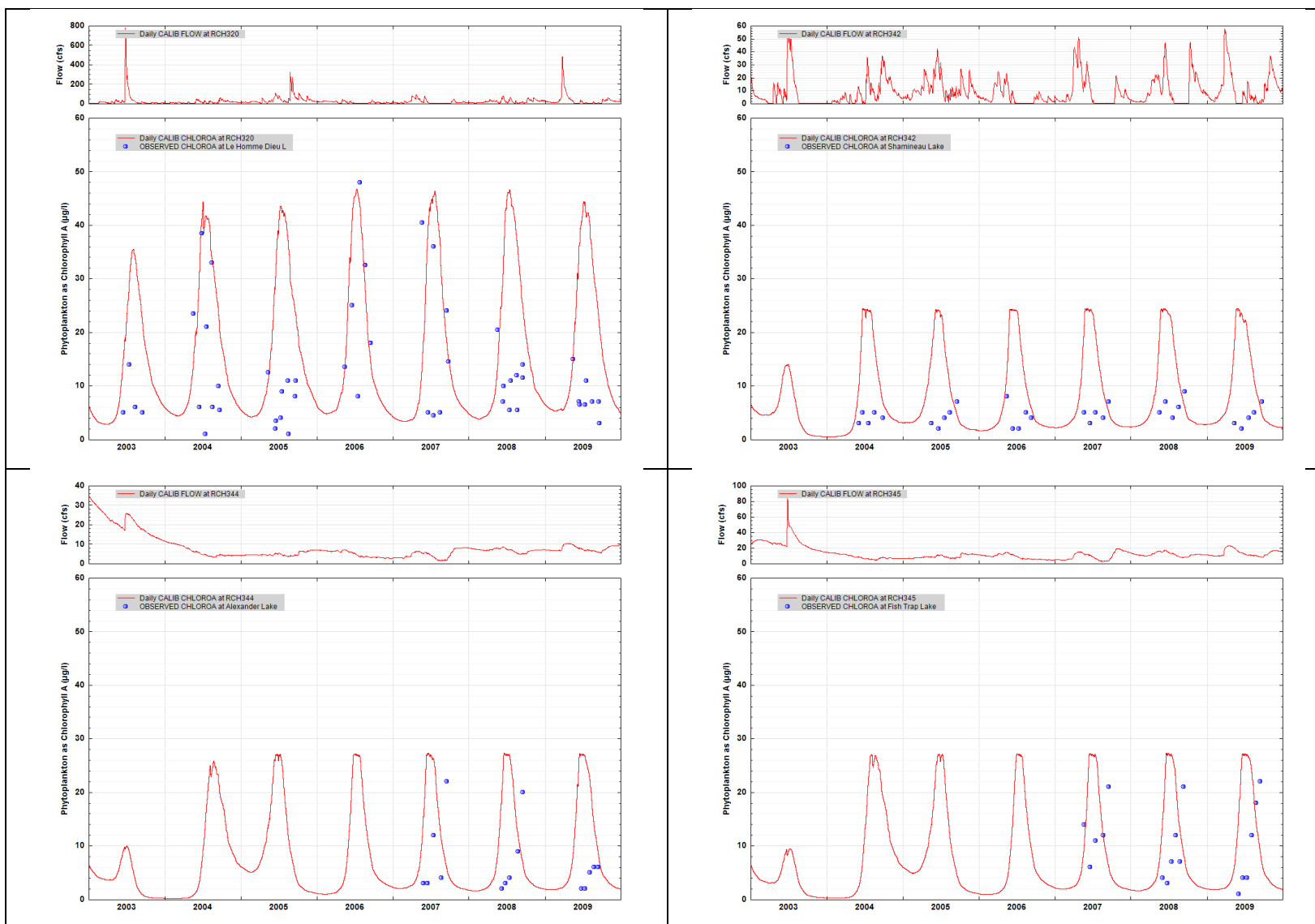


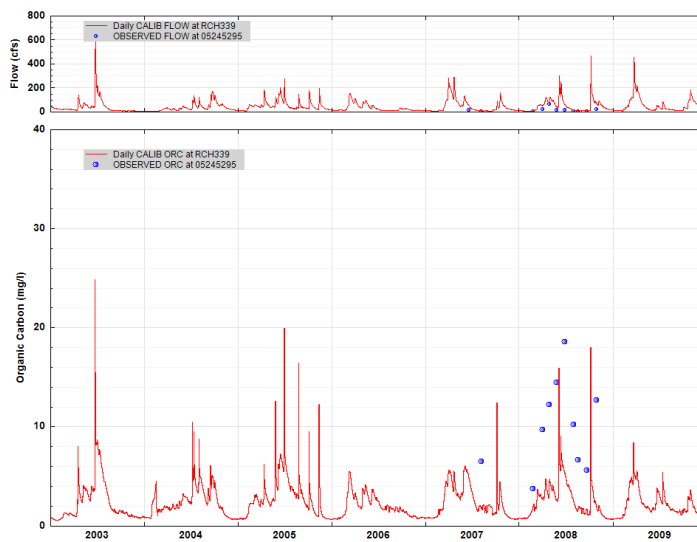
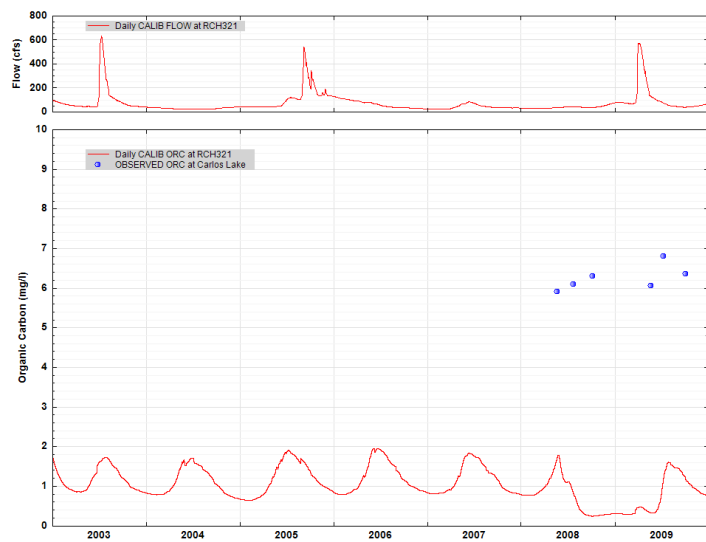
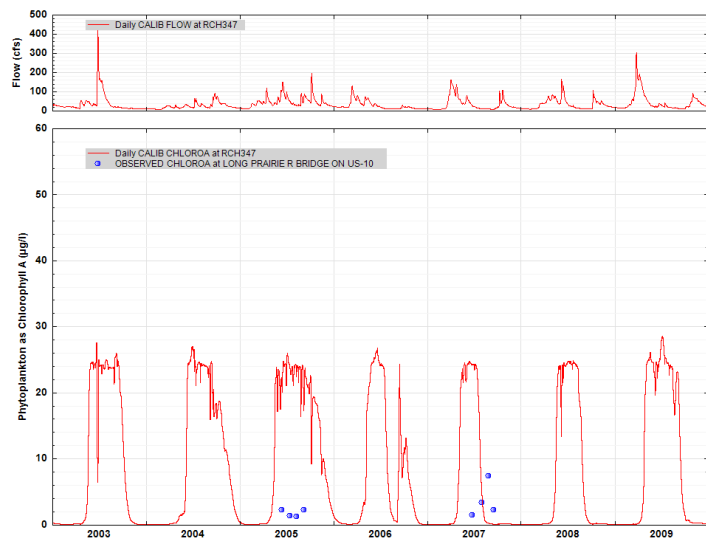


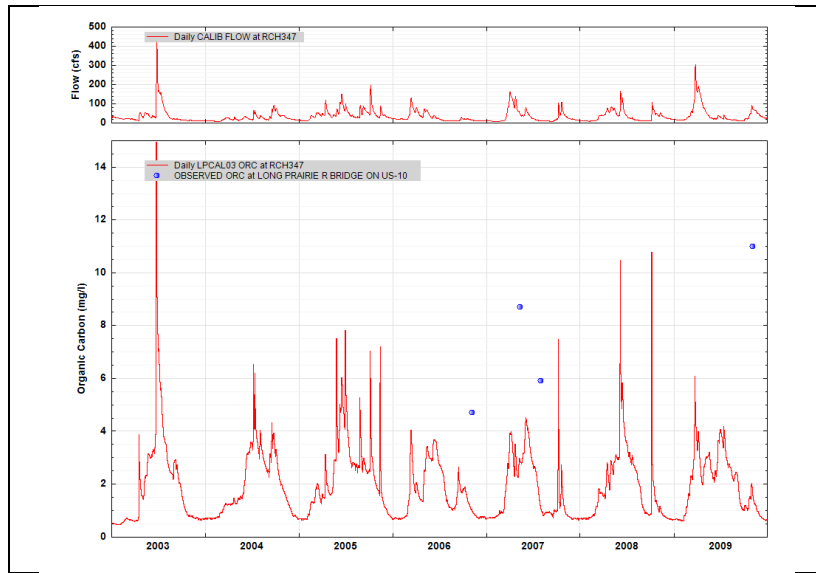
Q.2 LONG PRAIRIE RIVER WATERSHED

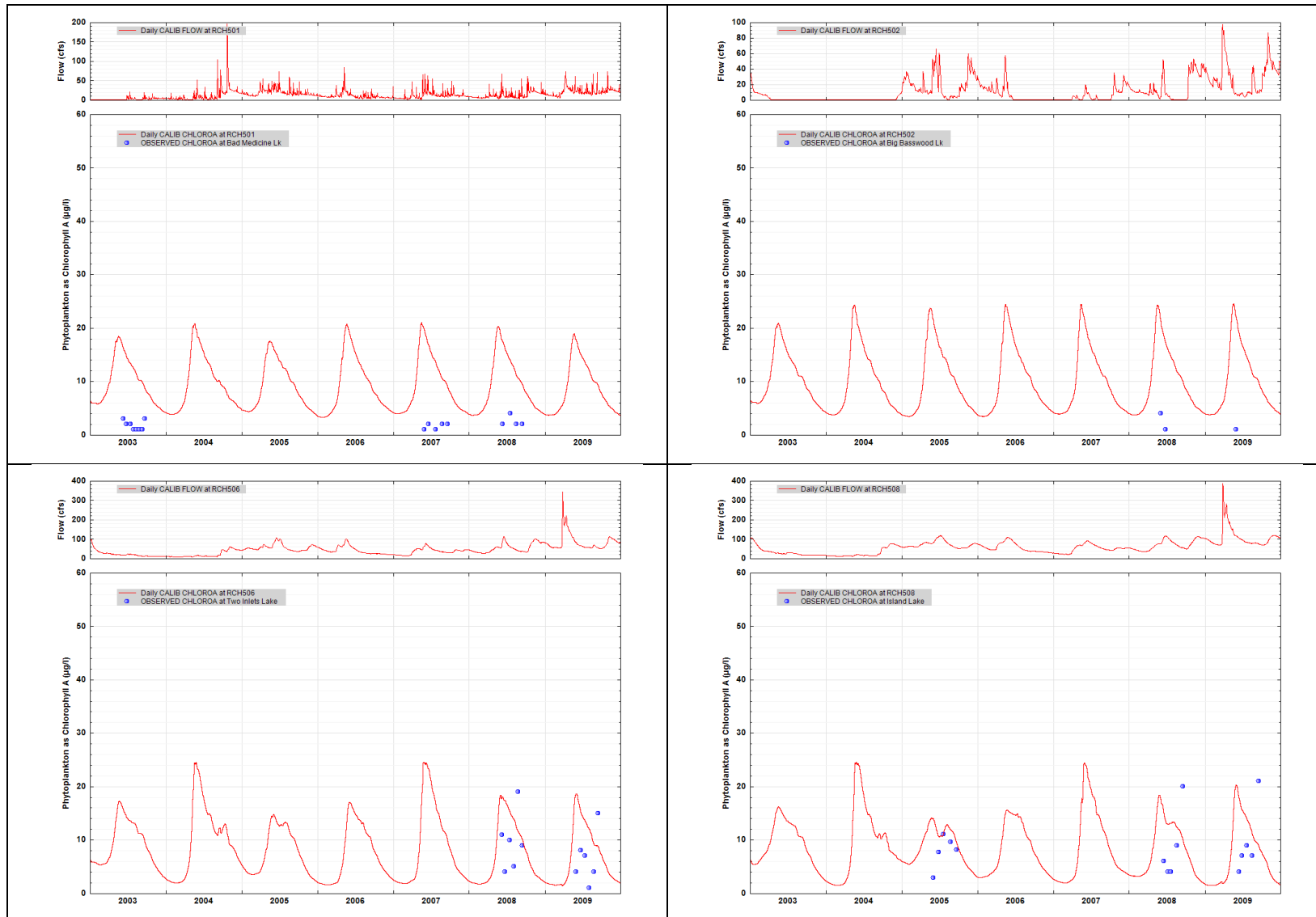


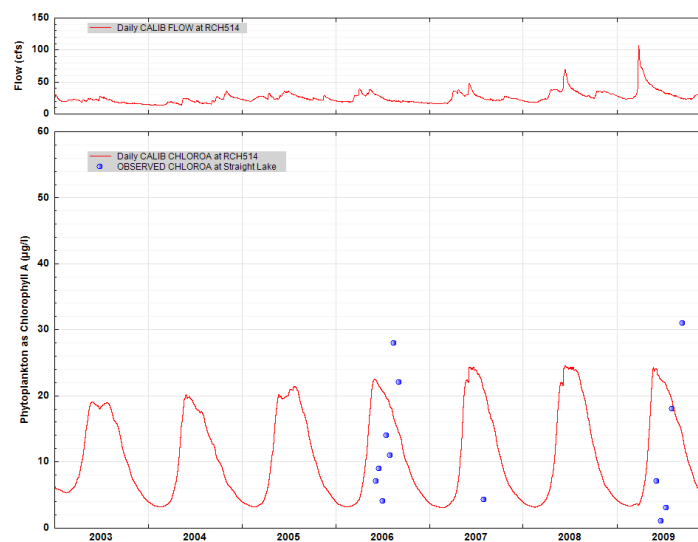
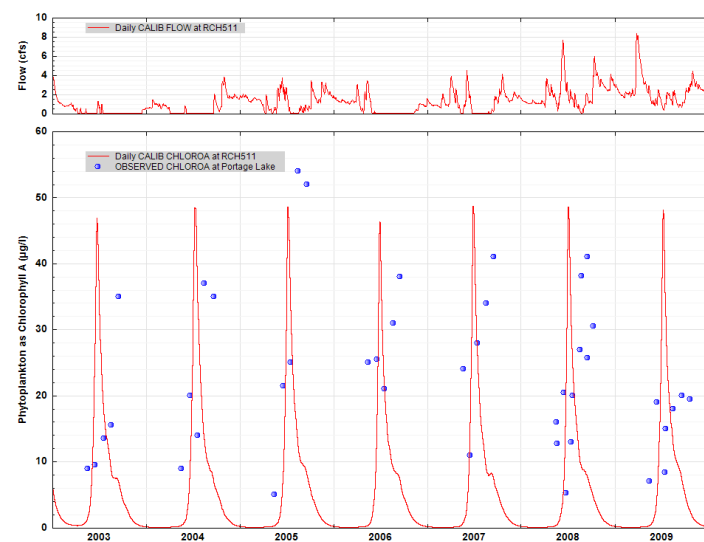
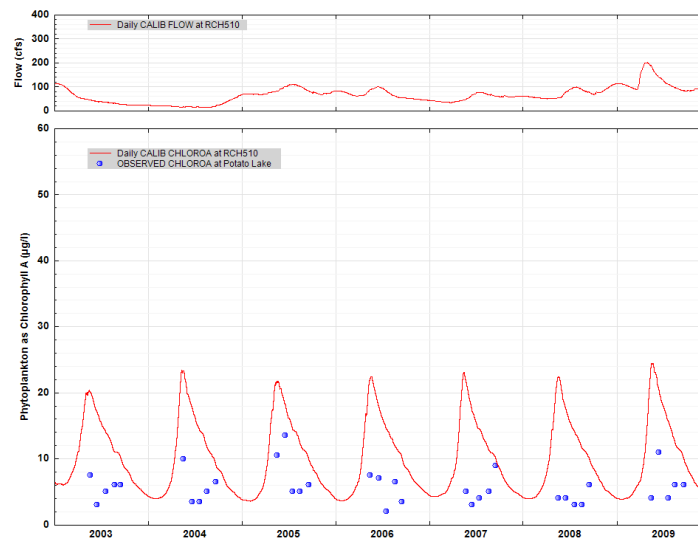
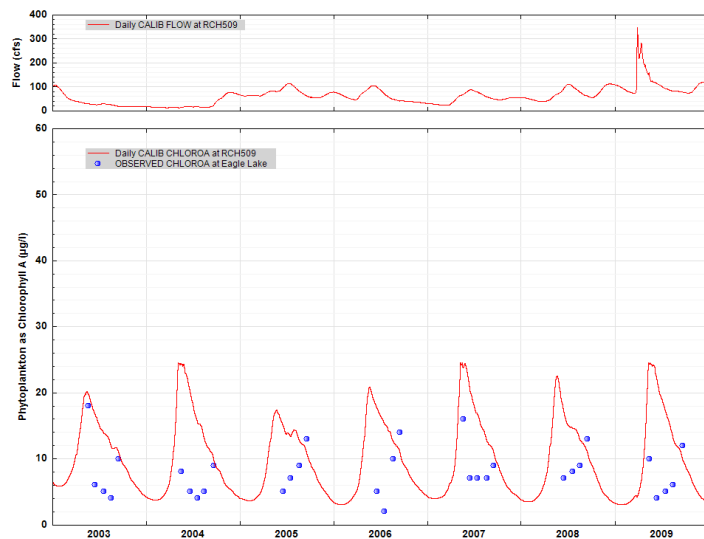


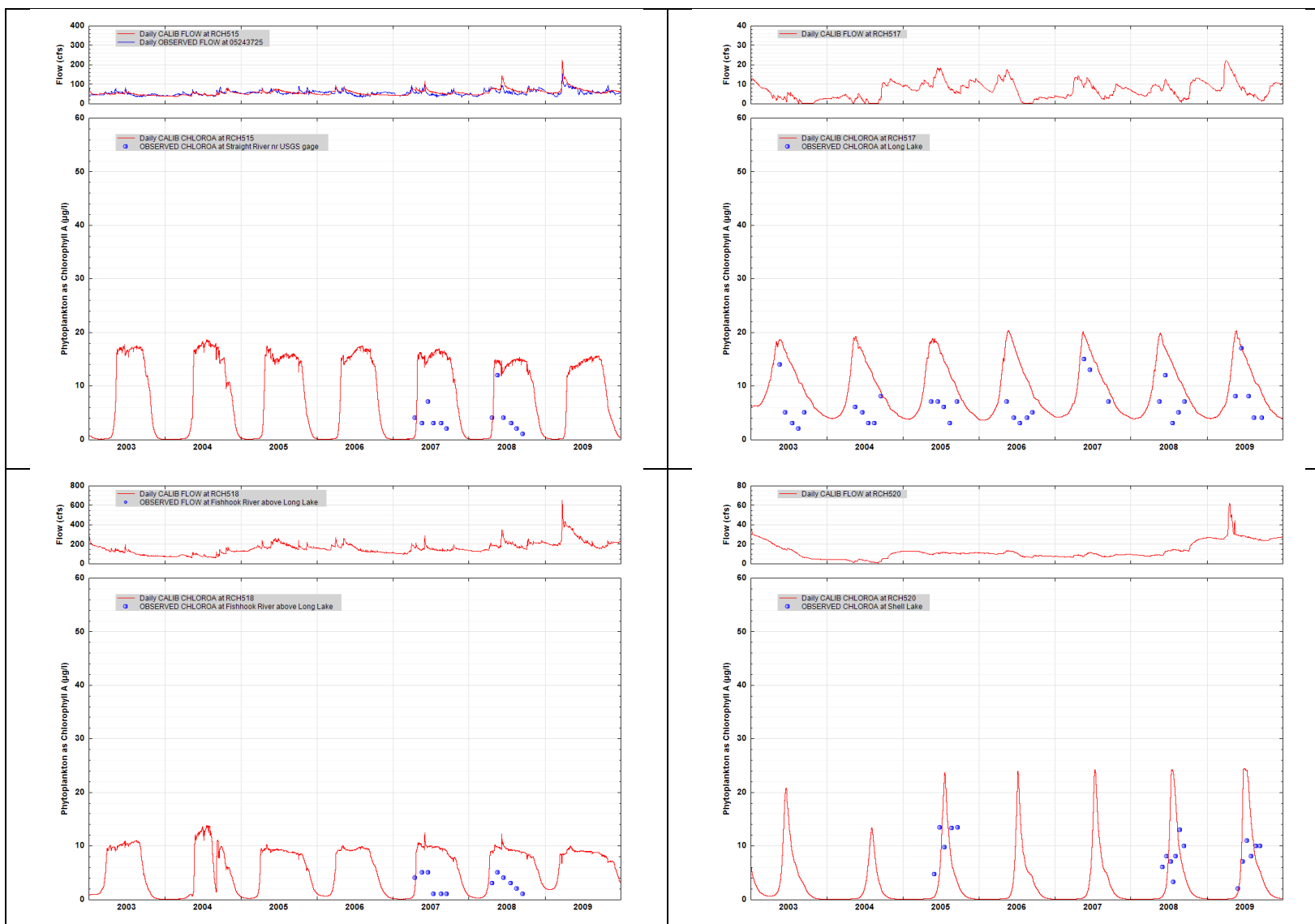


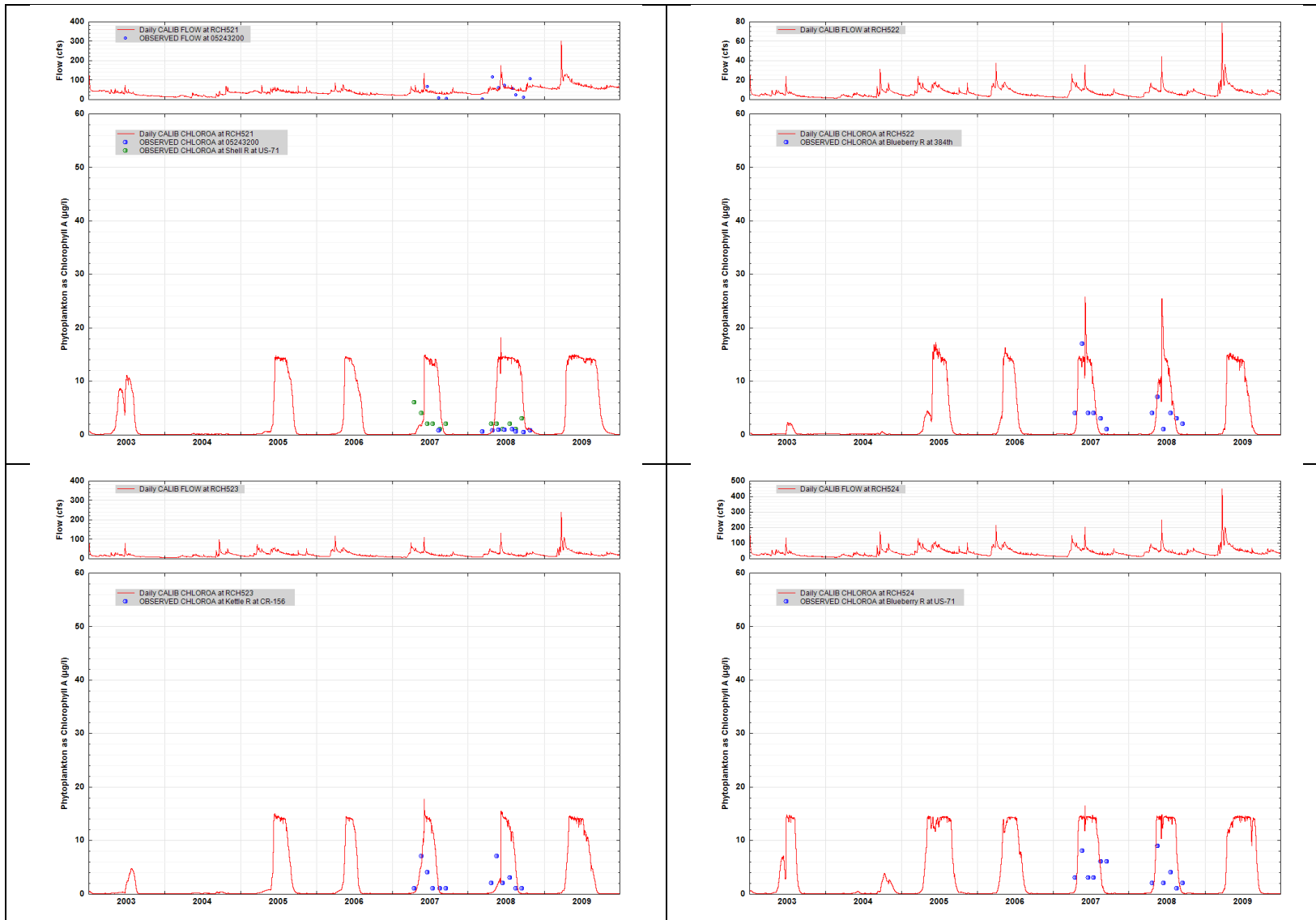


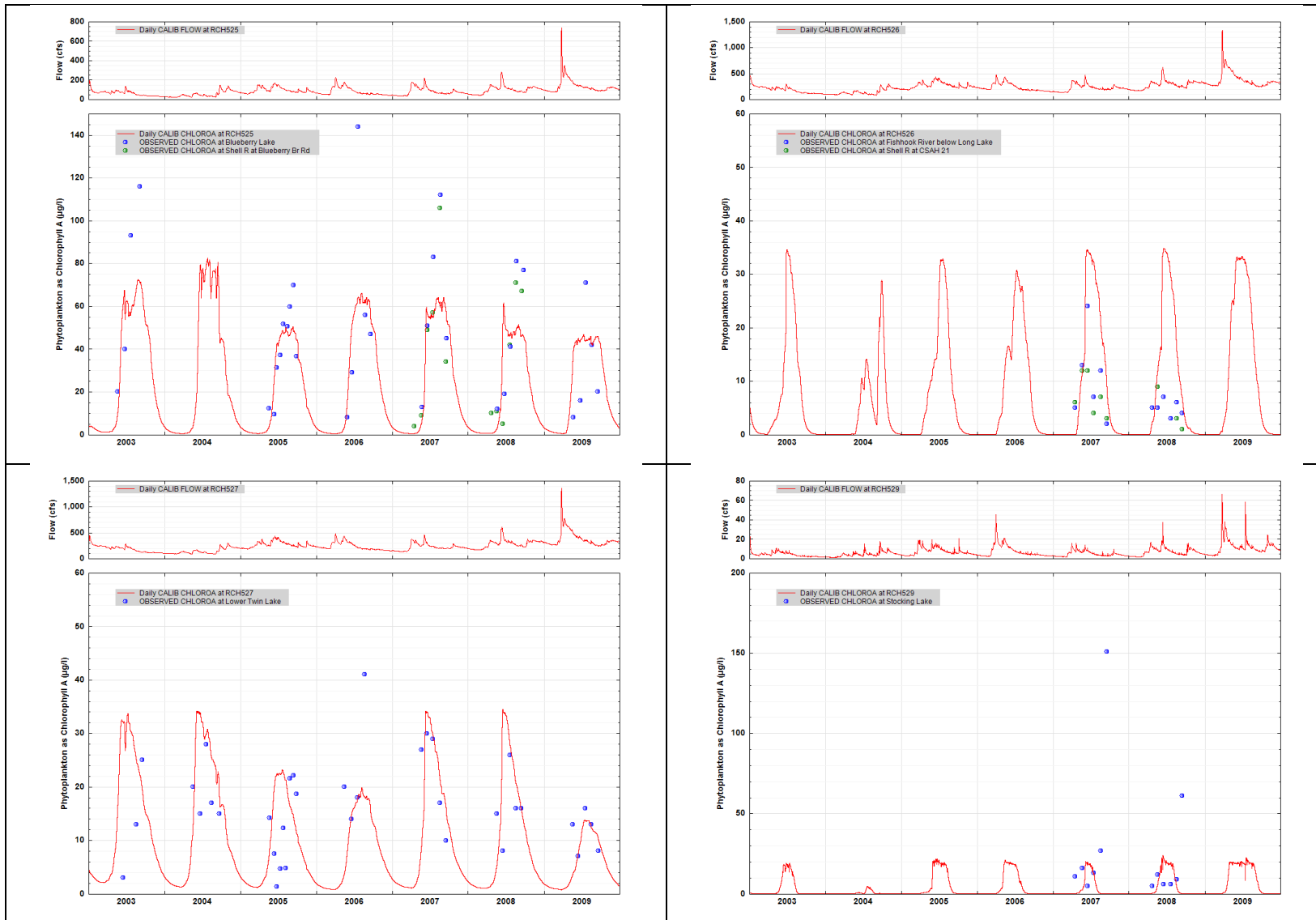


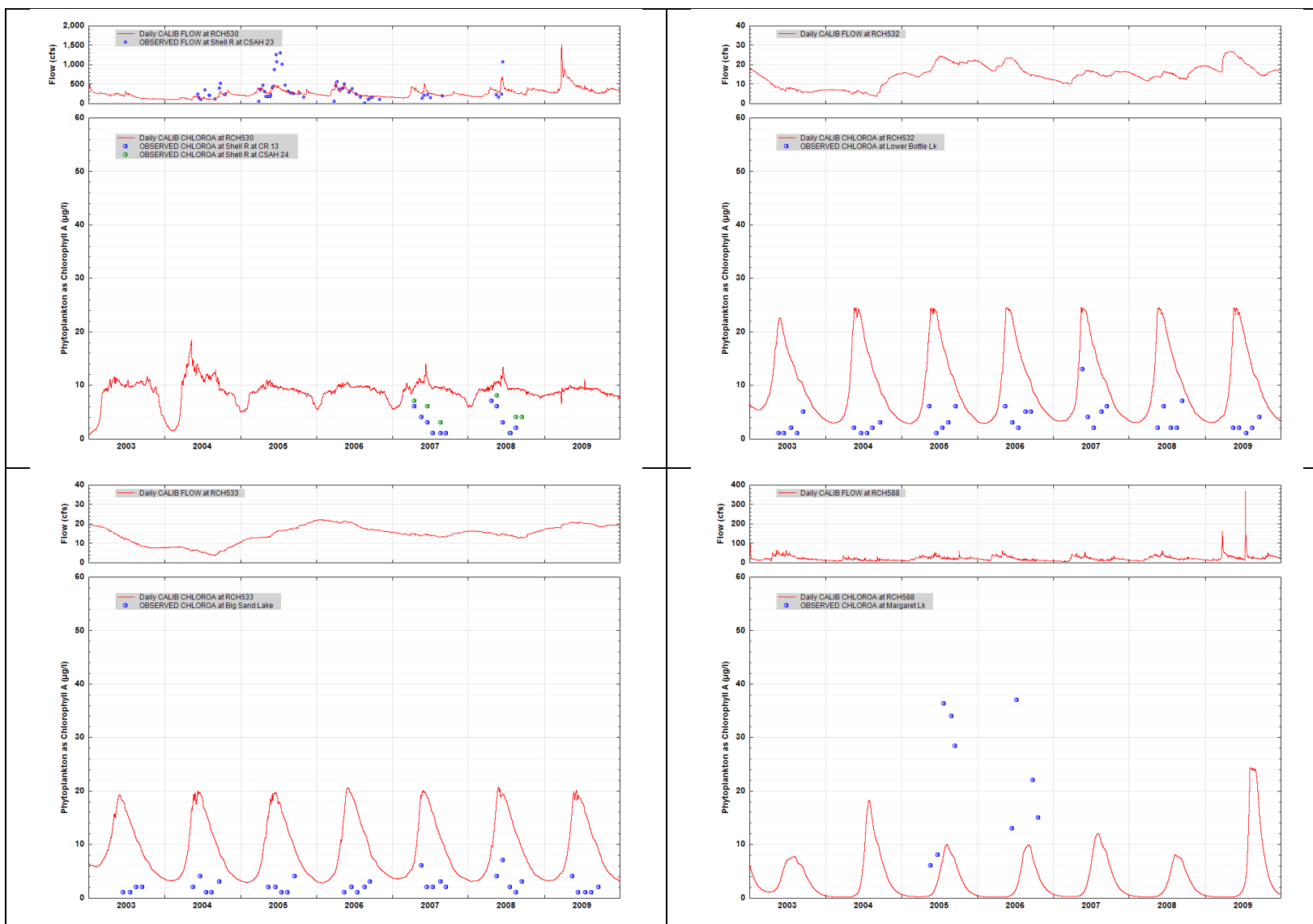
Q.3 CROW WING RIVER WATERSHED

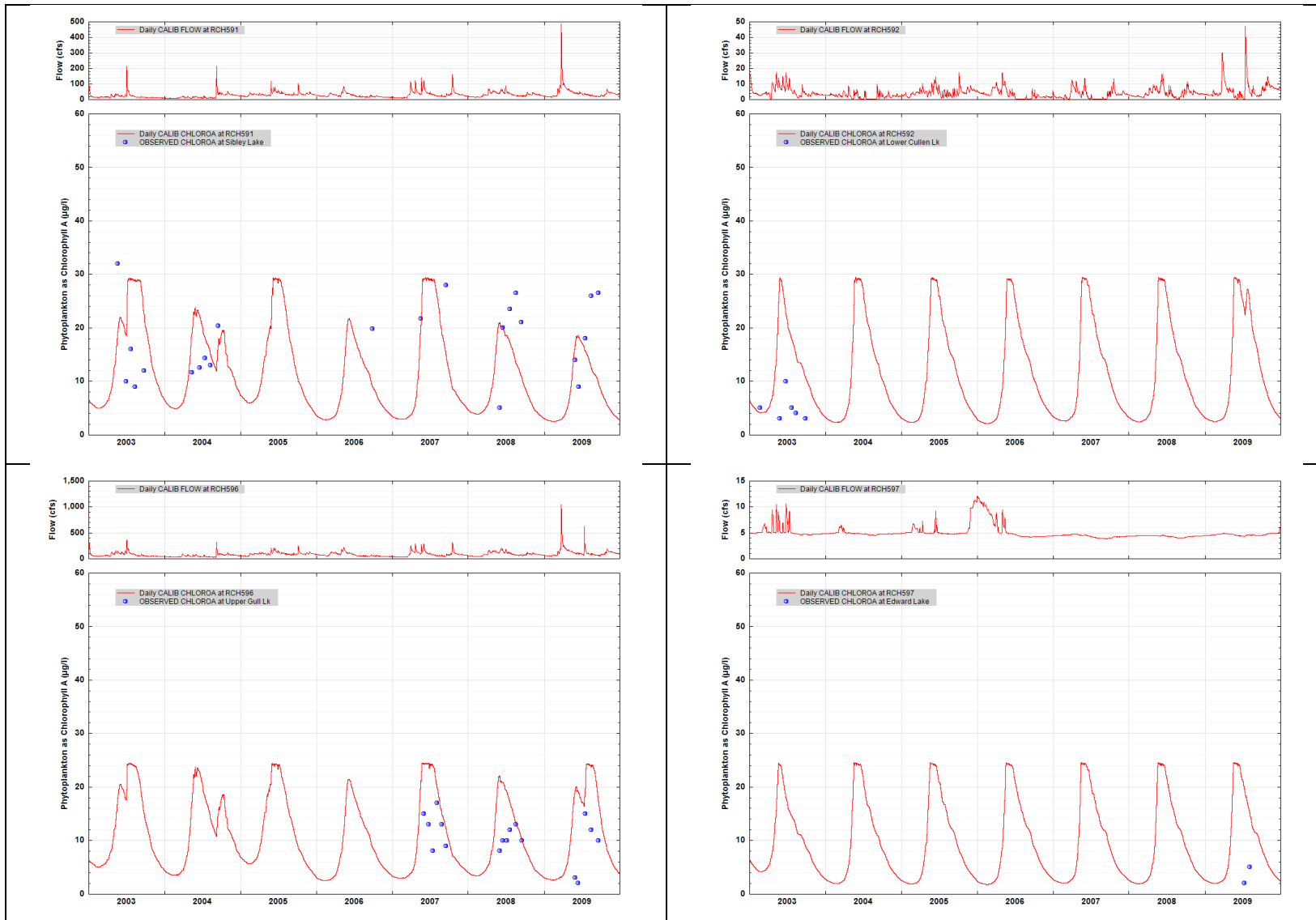


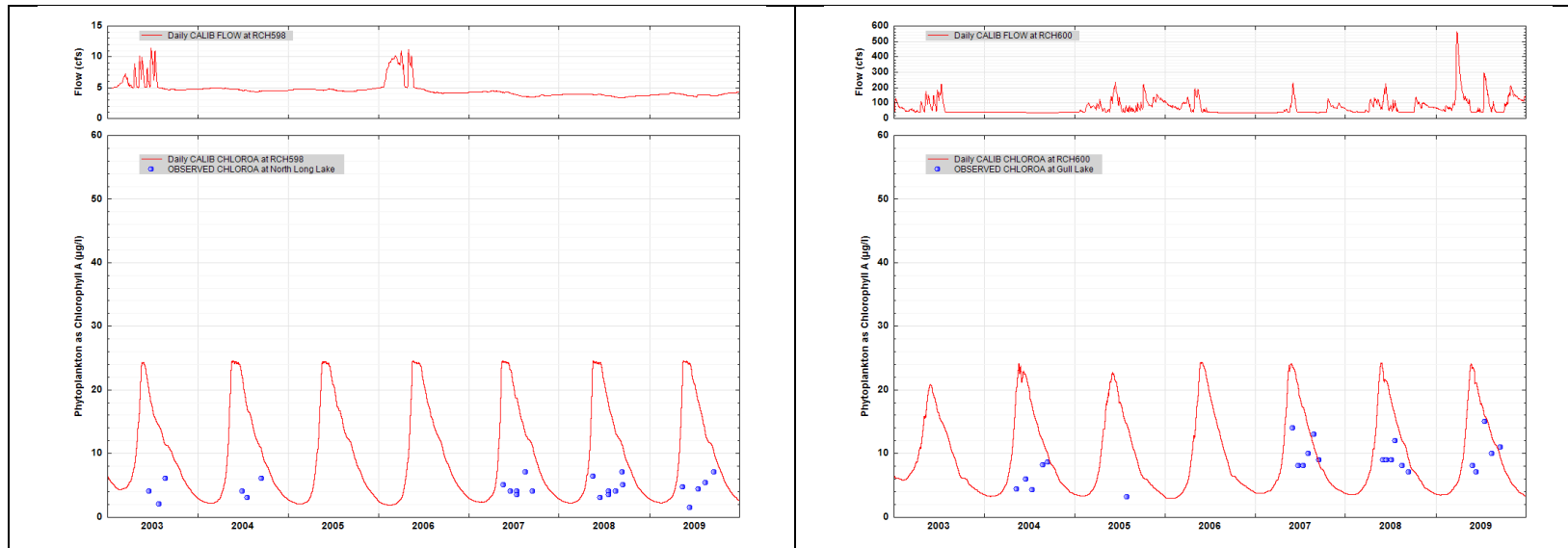






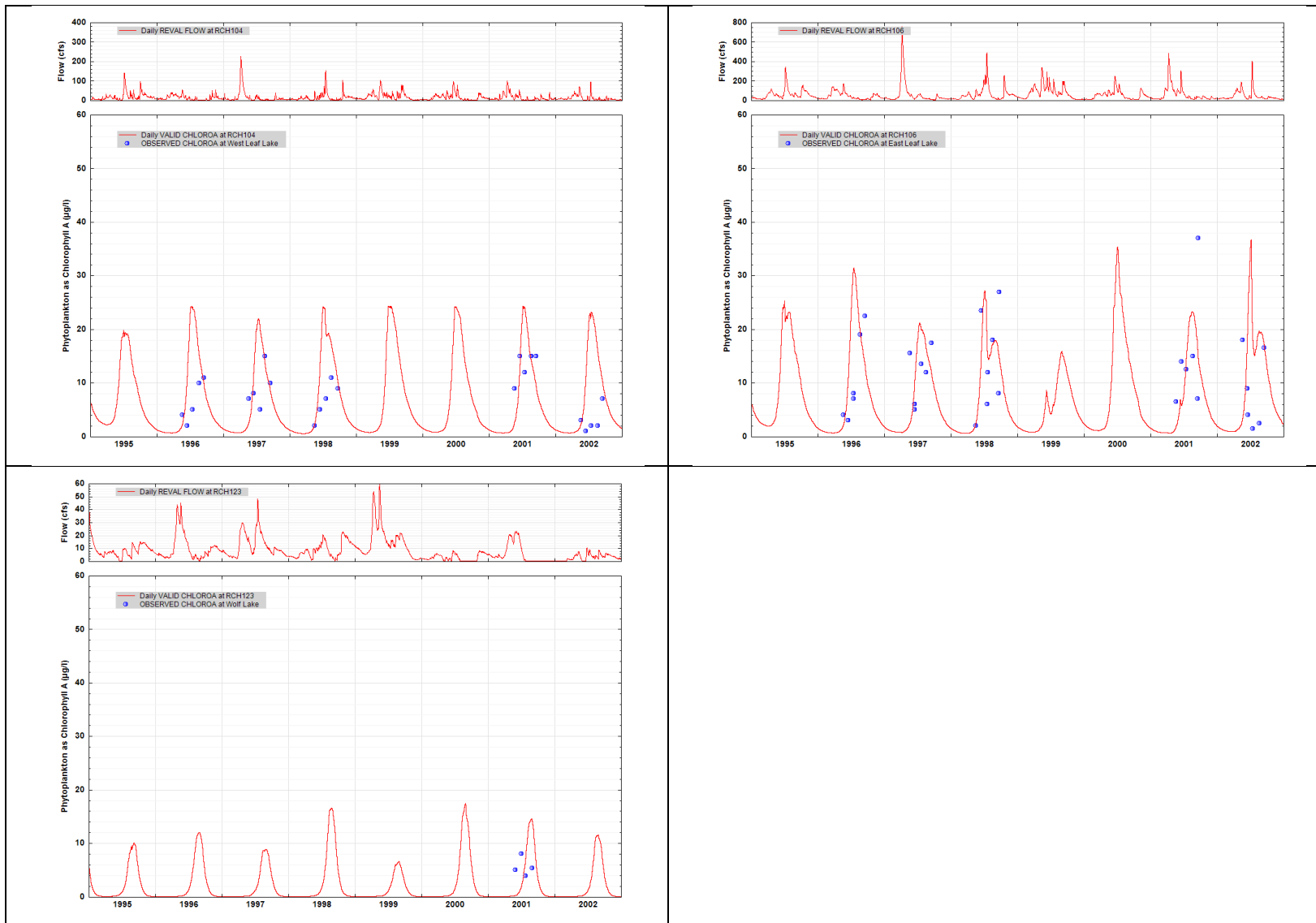


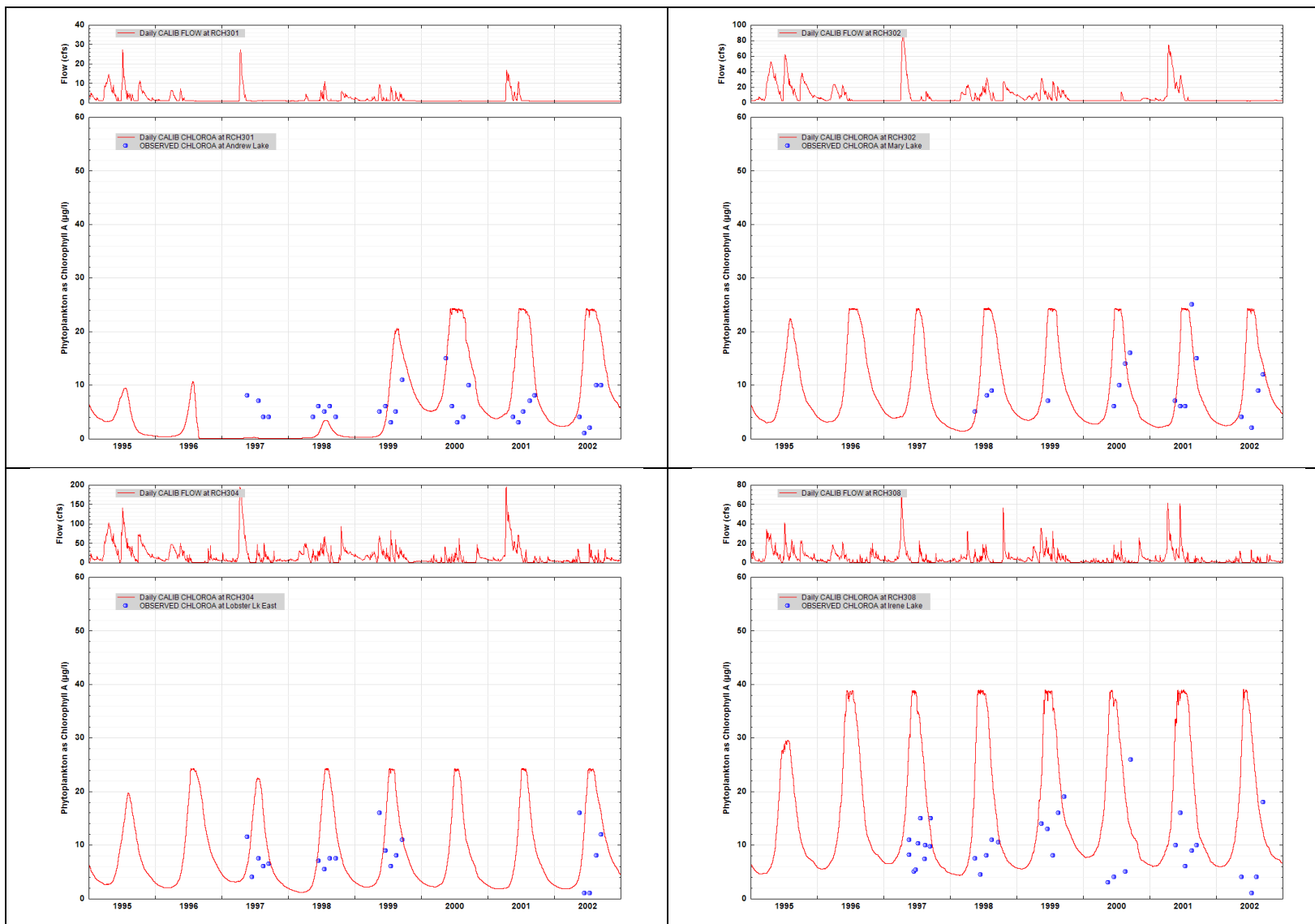


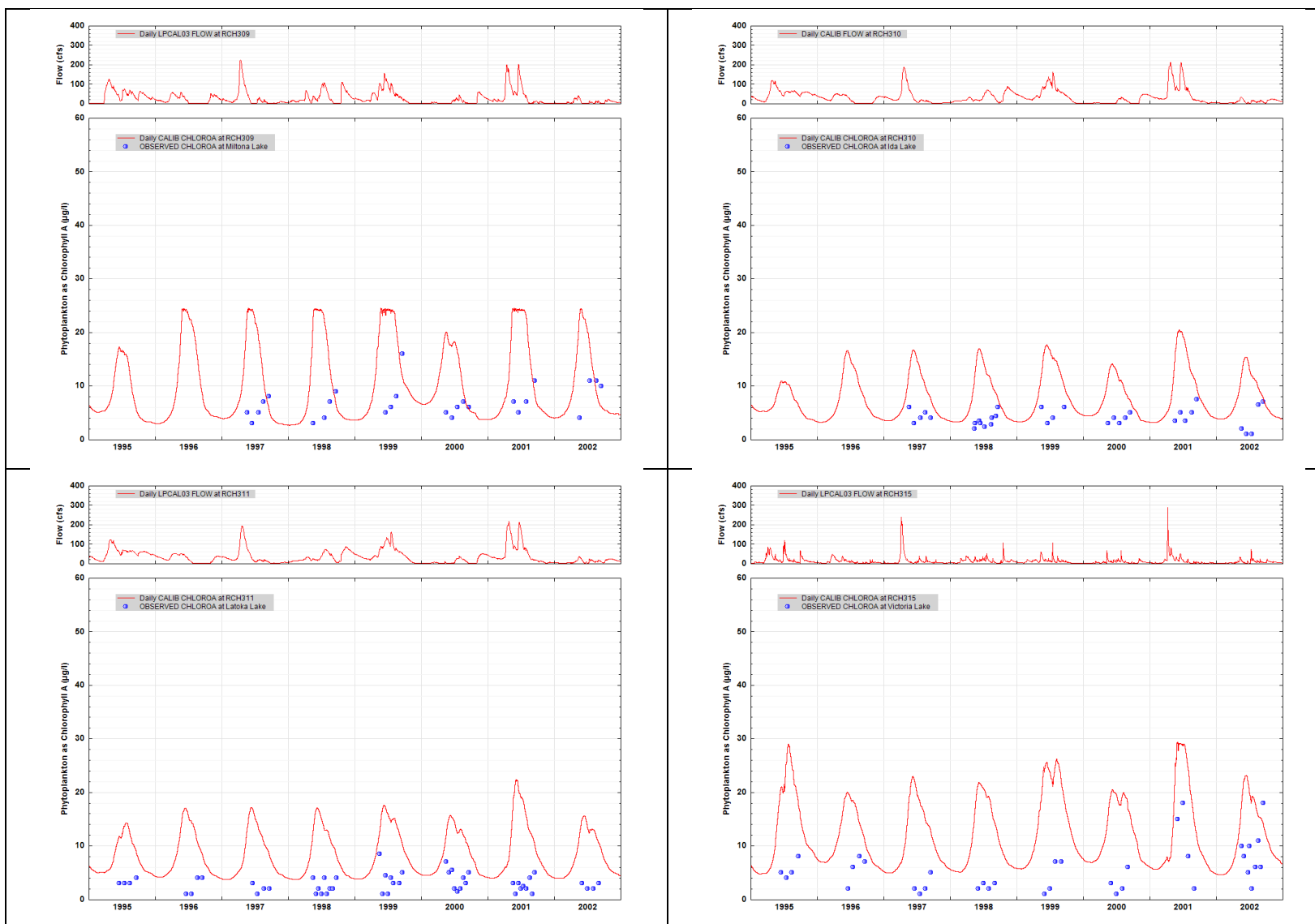


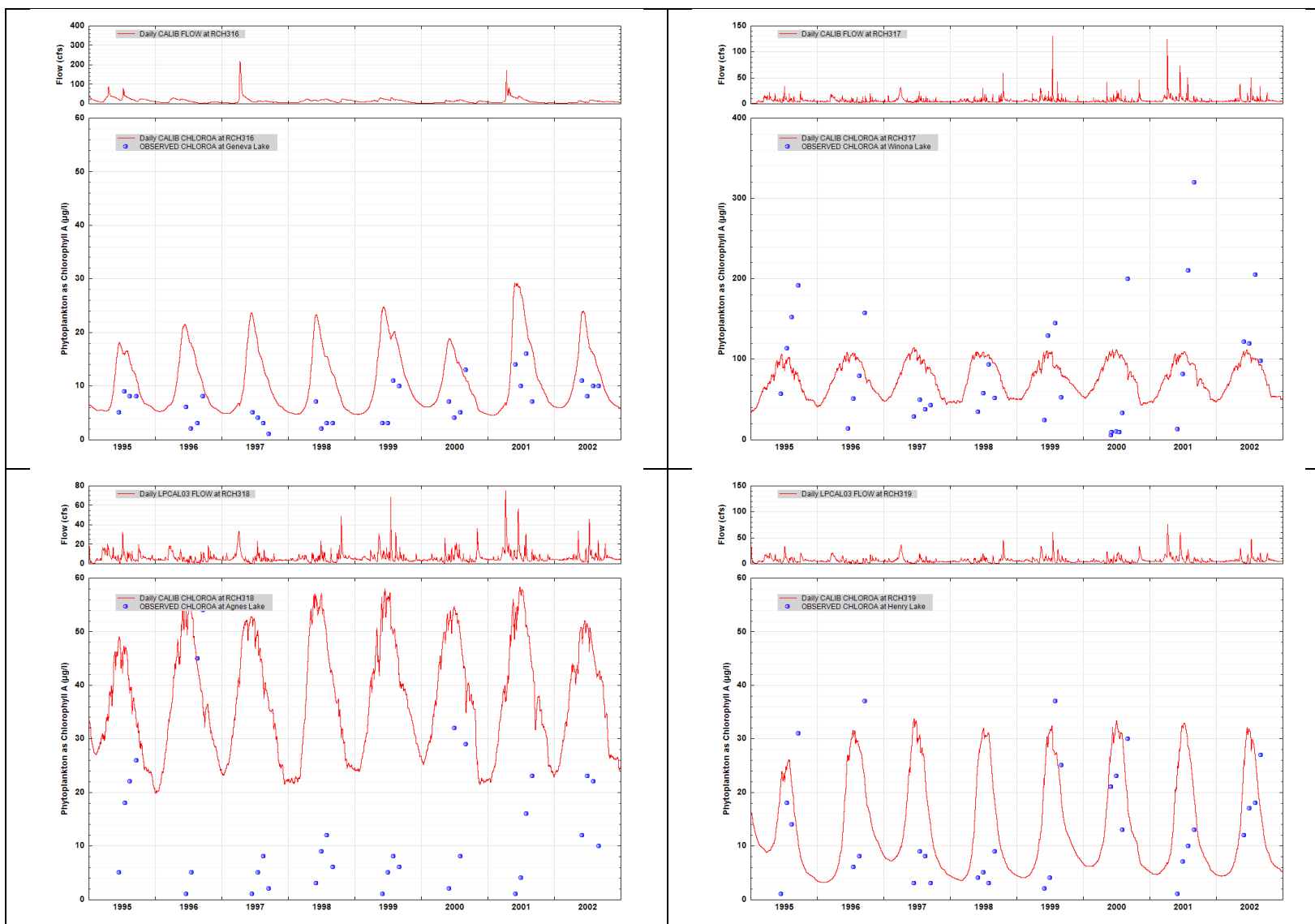
APPENDIX R OBSERVED AND SIMULATED CHLOROPHYLL A FOR THE VALIDATION PERIOD

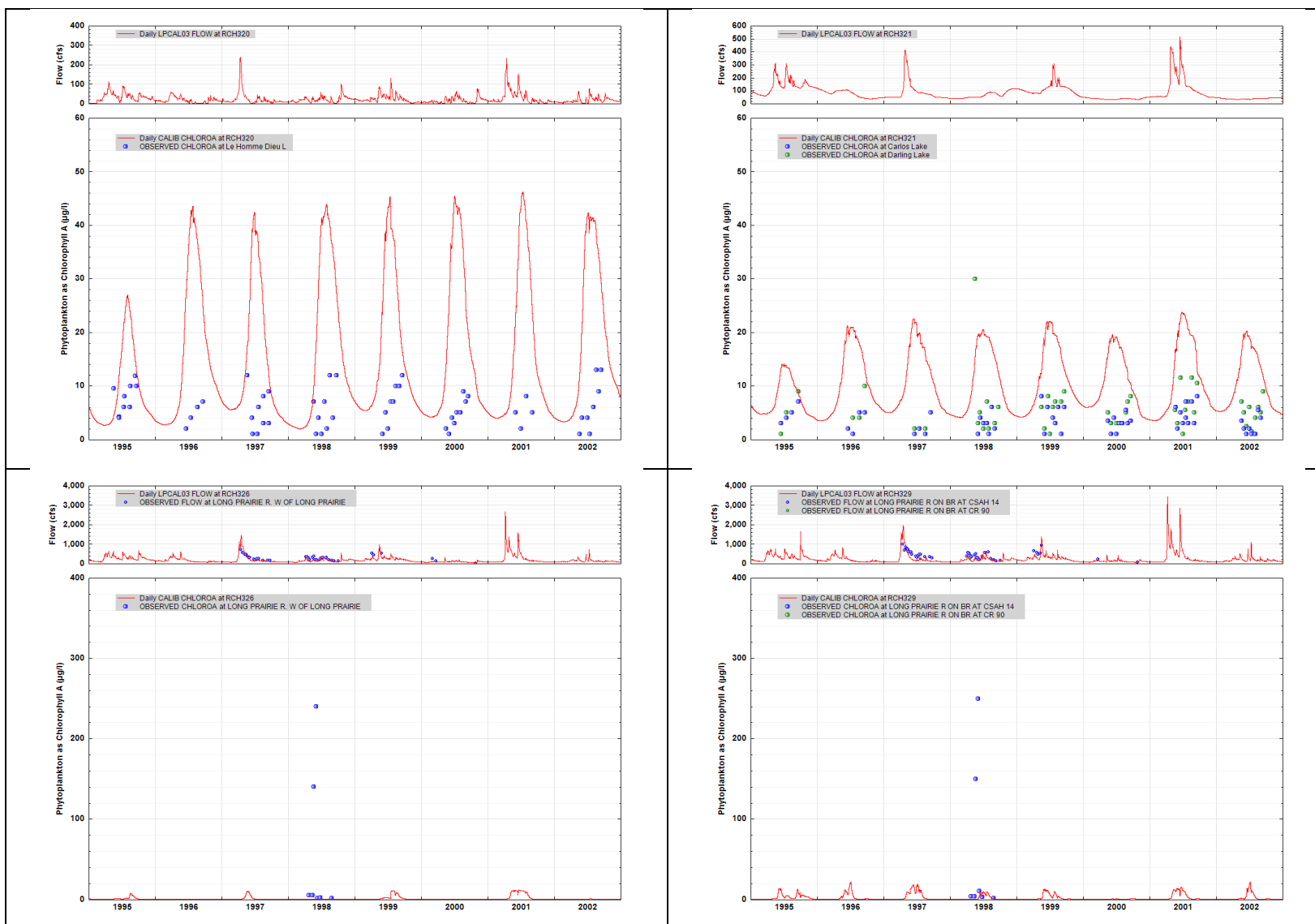
R.1 REDEYE RIVER WATERSHED

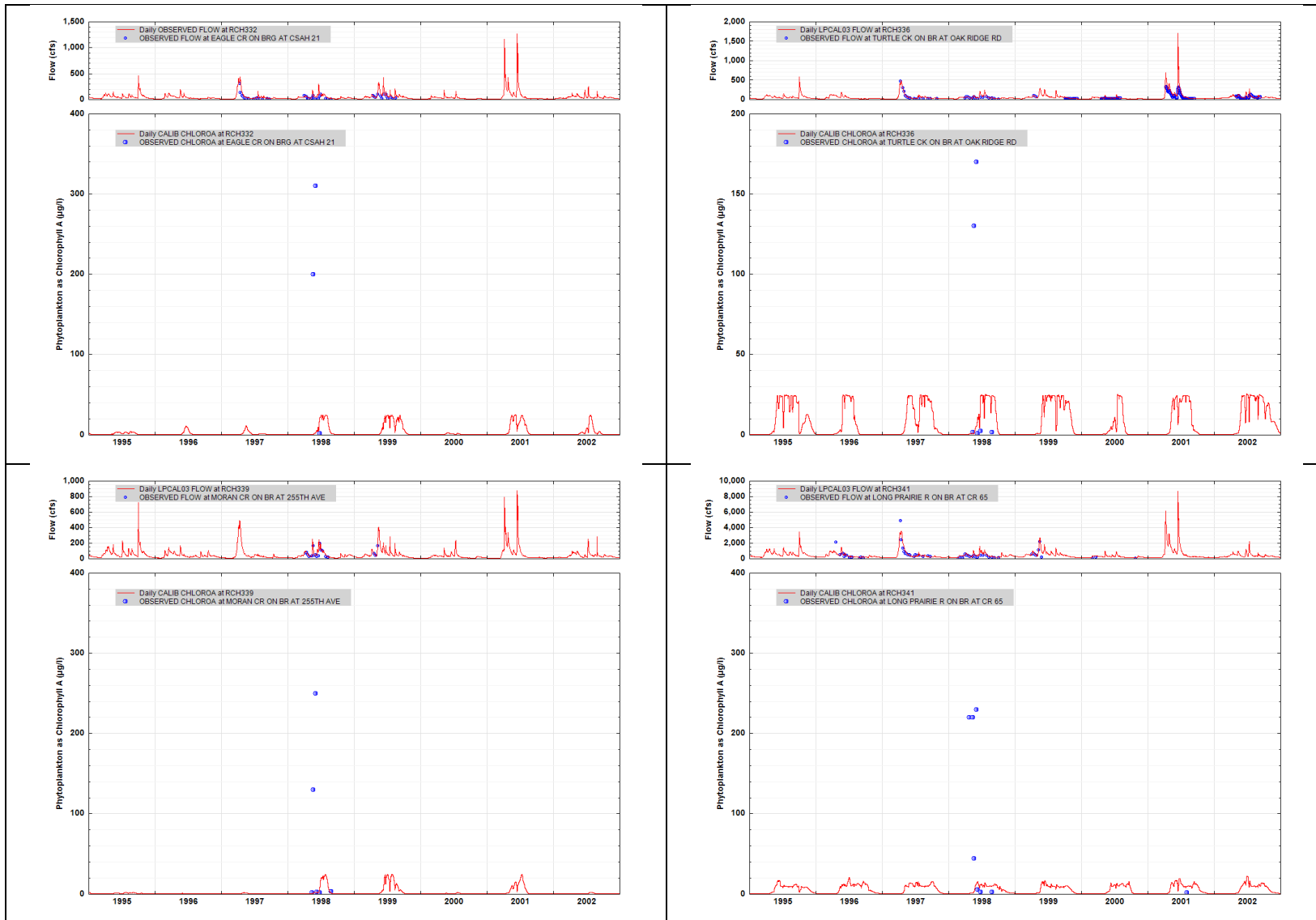


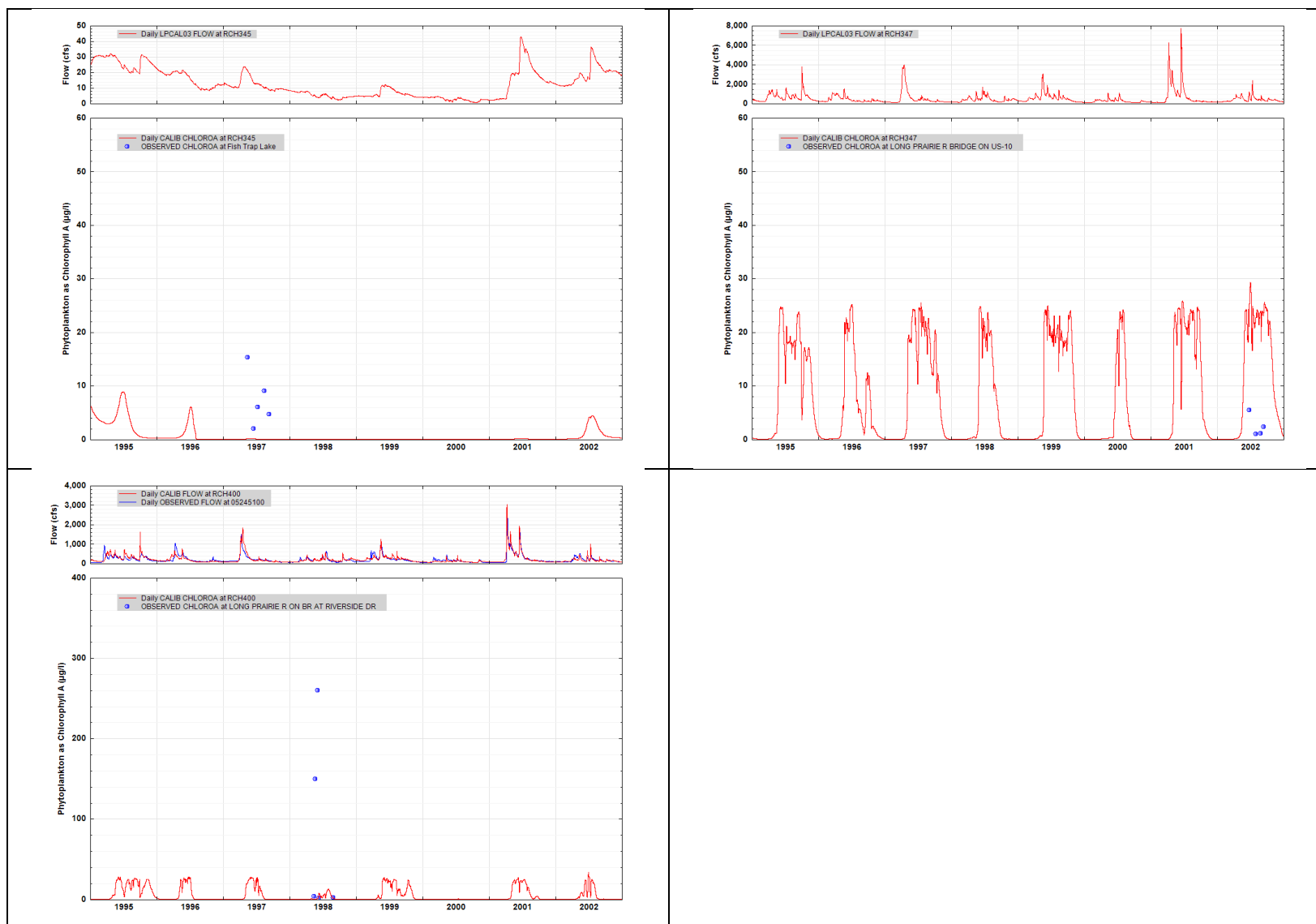
R.2 LONG PRAIRIE RIVER WATERSHED











R.3 CROW WING RIVER WATERSHED