


Wenatchee Watershed Planning Area

Prediction of Gaged Streamflows By Modeling

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Cover photo: Department of Ecology flow measurement stations in the Wenatchee River basin.

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Prediction of Gaged Streamflows By Modeling

by

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Abstract

This study evaluates flow gaging stations in the Wenatchee River basin, Water Resource Inventory Area (WRIA) 45. The study addresses ten telemetry flow stations that the Washington State Department of Ecology (Ecology) currently operates, six of Ecology's historic manual staff gages that are no longer used, and five flow gaging stations operated by the United States Geological Survey (USGS).

This study developed regression-based models for the Ecology and USGS study gages based on other reference gages in the basin using power or linear relationships and a hydrograph separation method. The quality of these regressions was assessed using statistical methods. The quality of the regression-based models was very good (median percent relative standard deviation less than 5%) for some mainstem Wenatchee River stations, good (5-15%) to fair (15-30%) for tributary stations, and poor (>30%) for one tributary station.

Recommendations were made regarding the discontinuation or retention of the gages based on study results.

- Most Ecology gages that are regulatory control stations had fair or poor quality modeling results and should be retained.
- The model for the Ecology gage *Nason Creek near Mouth* had good quality results and could be considered for decommissioning or transfer.
- Ecology gages that are not regulatory control stations should be considered for decommissioning or transfer.
- Modeling results for USGS stations funded by Ecology were good for *Icicle Creek above Snow Creek near Leavenworth* and very good for the *Wenatchee River at Monitor*. Data needs and funding for these stations should be reviewed.

Regressions to predict streamflows at historical manual staff stations were developed.

The needs of Washington State and of local partners for this flow information should be evaluated and be compared to the quality of the regression-based models to determine whether direct flow measurements or the models are adequate to meet those needs.

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Introduction

Overview of the Watershed

The focus of this study is Water Resource Inventory Area 45 (WRIA 45 – see Figure 1), which is also referred to as the Wenatchee River basin and the Wenatchee Watershed Planning Area. The description of the Wenatchee River basin below is summarized from the Wenatchee Watershed Management Plan (WRIA 45 Planning Unit, 2006).

Geography

The Wenatchee River is a tributary of the Columbia River, with its mouth at the city of Wenatchee, Washington. The basin area is 1,330 square miles (344,500 hectares) and includes 230 miles of major rivers and streams. The headwaters of the Wenatchee River basin lie in the Cascade Mountains to the west. The Little Wenatchee and White Rivers flow into Lake Wenatchee, and the Wenatchee River mainstem begins at the outlet of the lake.

The Wenatchee River basin is diverse geographically and hydrologically. Elevations range from 600 feet (180 meters) at the mouth of the river to over 8,200 feet (2,500 meters) in the highest areas of the river's watershed. Its upper reaches are mountainous and forested, with alpine and glaciated areas at the highest elevations, while the downstream low-lying areas are semi-arid and mostly agricultural. There are several small towns in the basin, and the City of Wenatchee urban area lies at the mouth.

Climate

Winters are cold (averaging 15 to 30° F, or -9 to -1° C) with much of the precipitation as snow, especially in the mountains. Summers are hot (averaging 60 to 90° F, or 16 to 32° C) and dry.

The lower east end of the basin lies in the rain shadow of the Cascade Mountains with average precipitation of 8 inches (200 millimeters) per year. Precipitation increases towards the Cascade Mountain crest in the west end of the basin, where precipitation averages 130-150 inches (3,000 to 3,800 millimeters) per year. This precipitation falls mainly in winter (November through March), with thunderstorms occurring occasionally during the summer (typically seven or eight per year). In the lower parts of the basin, precipitation comes mainly as rain, while the uplands receive mostly snow. Snow depths during an average winter are typically less than a half foot on the lowlands, but the higher elevations receive, on average, between ten and twenty feet of snow.

Hydrology

Five major tributaries account for over 90% of the surface water in the Wenatchee River watershed:

- Little Wenatchee River
- White River
- Chiwawa River

- Nason Creek
- Icicle Creek

These tributaries combined are the “headwaters” of the Wenatchee River and drain the highest elevations at the crest of the Cascades.

Other important tributaries to the Wenatchee River include:
- Chiwaukum Creek
- Chumstick Creek
- Peshastin Creek
- Mission Creek

Flows in the higher elevations and main tributaries are dominated by snowmelt during the late spring and early summer. Low flows in summer and early fall are generally produced by groundwater inflows and irrigation return flows. Rainfall events can increase flows in the lower elevations in the fall, winter, and spring.

Groundwater resources are located primarily in bedrock or overlying sediment deposits. Productive aquifers can be found in alluvial and glacial outwash sediments. The geologic composition of aquifers is varied and not continuous across the watershed. Little is known about the total amount of groundwater available.

Land Ownership, Land Use, and Water Use

Political jurisdictions in the Wenatchee River basin include Chelan County, the City of Wenatchee, and the smaller cities of Cashmere and Leavenworth. The Wenatchee River basin is within the Usual and Accustomed fishing areas for the Yakama Nation established by treaty. Other local jurisdictions include the Chelan County Conservation District, Wenatchee Reclamation District, Chelan Public Utility District, and several Irrigation Districts. Less than 20% of the basin is privately owned, and much of the basin is U.S. Forest Service land.

The primary land uses in the Wenatchee River basin are forest management and production, orchard production, residential and lodging, agricultural support, and home-based industry. The population was approximately 23,850 in 2005, and is expected to increase by 2.4% per year from 2000 to 2025.

Municipal and domestic water use has been estimated at about 5,400 acre-feet of water per year in 2002 and is expected to grow to 7,950 acre-feet per year in 2025. These water uses tend to have a steady base consumption rate throughout the year, with a seasonal increase during hot weather due to irrigation of landscape, lawn, and home gardens. Residential, commercial, and industrial water use is expected to increase with population growth.

Agriculture dominates water use in the Wenatchee River basin. Total water right applications, claims, permits, and certificates total over 1,000 cubic feet per second (cfs) of instantaneous use. However, there is certainly overlap in some of the claims, permits, and certificates; actual irrigation use is less than that amount. However, this volume of use compares to a maximum

daily demand of less than 20 cfs for municipal and domestic use and another 4.4 cfs for commercial and industrial use. Fish propagation uses about 124 cfs.

Watershed Planning Process

The key group for watershed planning in WRIA 45 is the Wenatchee Watershed Planning Unit. Chelan County is the Lead Agency, and a variety of organizations participated in the Planning Unit.

The Wenatchee Watershed Planning Unit is described on its website:

> *The Wenatchee Watershed Planning Unit is made up of a diverse group of stakeholders representing a wide range of interests throughout the watershed. These interests include local governments, tribes, state and federal agencies, irrigation, agriculture, forestry, community groups, conservation groups, economic development, recreation, and individual citizens. In addition to the required water quantity component, the Planning Unit decided to address the instream flow, water quality, and habitat components as well. The efforts of the Wenatchee Watershed Planning Unit have led to the development of the final Wenatchee Watershed Management Plan which was completed in April 2006. Since then, a detailed implementation plan (completed in 2008) prioritizes projects for implementation.* (www.co.chelan.wa.us/nr/planning/watershed_planning/default.htm)

The Wenatchee Watershed Planning Unit is the primary forum for stakeholder input for this study.

Flow Monitoring

Department of Ecology Stations

The Washington State Department of Ecology (Ecology) has historically operated twenty-seven flow monitoring stations (www.ecy.wa.gov/programs/eap/flow/shu_main.html, and Figure 1) in the Wenatchee River basin. These stations consist of:

- Ten active *telemetry* gages providing real-time data.
- Eight historical staff gages where *manual stage height* readings were collected infrequently (at least once per month) over several years and converted to instantaneous flow values. Most of these stations were used for Total Maximum Daily Load (TMDL) studies. (Two of these stations are now active telemetry gages.)
- Six historical seasonal gages with less than one year of *continuous* data.
- Six historical staff gages with less than one year of *manual stage height* readings.

At all stations, direct measurements of streamflow discharge were taken on a regular basis. These measurements and direct stage height readings were used to develop rating curves for determining flow from stage height data.

The Ecology stations analyzed in this study are shown in Table 1. The ten active gages have sufficient data and were included, although the Icicle Creek station was a staff gage only until recently. The stations with manual staff gage data over multiple years were also analyzed. The other stations with less than one year of data were not included in this study.

USGS Stations

The U.S. Geological Survey (USGS) has gaged streamflow throughout the Wenatchee River basin at a variety of sites historically and currently (USGS, 2009):

- Five active stations in the Wenatchee River basin. These are listed in Table 2. Four of the five stations are partially funded by Ecology (noted in Table 2).
- Nine historical stations in the Wenatchee River basin with continuous flow. The USGS historical stations have no data after 1983 and will not be used for this analysis.

Instream Flow Rule

In 2007, Ecology established minimum instream flows for WRIA 45 in Chapter 173-545 WAC of state regulations (State of Washington, 2007). These regulatory flows are set at specific *regulatory control stations* throughout the basin with seniority set by the date of rule adoption. When water volume at a control station drops below the rule's flow levels, water users with more junior rights or new water appropriations cannot diminish or negatively affect the regulated flow.

Regulatory flow control stations established by WAC 173-545 are shown in Table 3. All control stations correspond to active Ecology or USGS flow monitoring stations, except for the USGS Mission Creek station which is a historical site (Figure 1, Tables 1 and 2). The historic USGS station is about one mile upstream of the current Ecology gage on Mission Creek, and the USGS gage represents over 99% of the watershed above the Ecology gage. Therefore these two gages can be considered functionally equivalent.

Table 1. Ecology flow monitoring stations in the Wenatchee River basin addressed by this study.

ID	Station Name	Code	Status	Type[1]	Start	End	Number of days
45N060	Rock Creek near mouth	Rock	Active	T	20-Sep-02	7-Jun-11	2082
45K090	White River near Plain	White	Active	T	20-Sep-02	7-Jun-11	3044
45L110	Little Wenatchee River below Rainy Creek	LWen	Active	T	18-Sep-02	7-Jun-11	1987
45J070	Nason Creek near mouth	Nason	Active	T	16-May-02	7-Jun-11	3069
45A240	Wenatchee River below Lake Wenatchee	Wen-Lk	Active	T	14-May-02	6-Jun-11	3190
45G060	Chiwaukum Creek near mouth	Chwkm	Active	T	15-May-02	7-Jun-11	2458
45C060	Chumstick Creek near mouth	Chmstk	Active	T	10-Aug-03	7-Jun-11	2275
45B070	Icicle Creek near Leavenworth	Ici-EC	Active Historical	T M	23-Nov-10 3-May-07	7-Jun-11 1-Sep-10	197 173
45F070	Peshastin Creek at Green Bridge Road	Psh-GB	Active	T	21-Sep-02	7-Jun-11	2978
45E070	Mission Creek near Cashmere	Miss-EC	Active	T	21-Nov-02	7-Jun-11	2770
45M060	Rainy Creek near mouth	Rainy	Historical	M	9-Oct-02	29-Jun-09	131
45P050	White Pine Creek at mouth	WPine	Historical	M	9-Oct-02	29-Jun-09	118
45Q060	Eagle Creek near mouth	Eagle	Historical	M	18-Dec-02	26-Nov-07	26
45F110	Peshastin Creek above Ingalls	Psh-aIng	Historical	M	14-Jan-03	11-Dec-08	146
45F100	Peshastin Creek below Ingalls	Psh-bIng	Historical	M	25-Jun-03	15-Jun-09	188
45D070	Brender Creek near Cashmere	Bren	Historical	M	3-Oct-96	15-Jun-09	243

[1] T = Telemetry; M = Manual Stage height

Table 2. USGS active flow monitoring stations in the Wenatchee River basin used in this study.

ID	Station Name	Code	Status	Type[1]	Start	End	Number of days
12456500	Chiwawa River near Plain	Chww	Active[2]	RT	15-May-1991	7-Jun-2011	7228
12457000	Wenatchee River at Plain	Wen-Pln	Active[2]	RT	1-Oct-1966	7-Jun-2011	12,679
12458000	Icicle Creek above Snow Creek near Leavenworth	Ici-GS	Active[2]	NRT	1-Oct-1966	10-Apr-2011	8,234
12459000	Wenatchee River at Peshastin	Wen-Psh	Active	RT	1-Oct-1966	7-Jun-2011	16,322
12462500	Wenatchee River at Monitor	Wen-Mon	Active[2]	RT	1-Oct-1962	7-Jun-2011	17,783

[1]RT = Real-time (Telemetry); NRT = Non-real-time
[2]Funded by Ecology

Table 3. Regulatory flow control stations in WRIA 45.

Stream Management Unit Name	Control Station Gage No.	River Mile (RM)	Township	Range	Section	Latitude (N) Deg	Min	Sec	Longitude (W) Deg	Min	Sec	Stream Management Reach Description	Comment
Chiwawa River near Plain	USGS 12456500	6.2	27 N	17 E	13	47	50	16	120	39	40	From the confluence of the Chiwawa River and the Wenatchee River upstream to the headwaters of the Chiwawa River	
Nason Creek near mouth	ECY 45J070	0.2	27 N	17 E	33	47	48	2	120	43	1	From the confluence of Nason Creek and the Wenatchee River upstream to the Nason Creek headwaters	
Wenatchee River at Plain	USGS 12457000	46.2	26 N	17 E	12	47	45	47	120	39	59	From Beaver Valley Hwy, RM 46.2, to the headwaters	
Icicle Cr. near Leavenworth	USGS 12458000	5.8	24 N	17 E	28	47	32	28	120	43	11	Headwaters of Icicle Creek to its mouth	Former Control Station, still in rule
Icicle Cr. near Leavenworth	ECY 45B070	2.2	24 N	17 E	24	47	33	49	120	40	4	Headwaters of Icicle Creek to its mouth	New Control Station, not yet in rule
Chumstick Cr. at North Road	ECY 45C060	0.3	24 N	18 E	6	47	36	18	120	38	55		Flow to be determined
Wenatchee R. at Peshastin	USGS 12459000	21.5	24 N	18 E	8	47	34	60	120	37	10	From the confluence of Derby Creek to Beaver Valley Hwy, RM 46.2, excluding Derby Creek and Icicle Creek	
Peshastin Cr. at Green Bridge Rd.	ECY 45F070	1.4	24 N	18 E	28	47	33	9	120	36	11	From the confluence of Peshastin Creek and the Wenatchee River upstream to the Peshastin Creek headwaters	
Mission Creek near Cashmere	ECY 45E070	0.2	23 N	19 E	5	47	31	16	120	28	33	From mouth to the headwaters	For 1983 Instream flows (WAC 173-545-050)
Mission Creek at Cashmere	USGS 12462000	1.5	23 N	19 E	9	47	30	35	120	28	24	From mouth to the headwaters	For 2001 Instream flows (WAC 173-545-060)
Wenatchee R. at Monitor	USGS 12462500	7.0	23 N	19 E	11	47	29	58	120	25	28	From mouth to confluence of Derby Creek, including Derby Creek and excluding Mission Creek	

Study Goals and Objectives

The goals of this project are to:

1. Develop computer models that can estimate streamflows in the Wenatchee River basin for Ecology flow monitoring stations and USGS flow monitoring stations funded by Ecology.

2. Assess the ability of computer models to support Ecology and the Wenatchee Watershed Planning Unit in their water management activities in the basin.

3. Support Ecology in making decisions about use of its flow gaging resources statewide.

To meet these goals, this project has the following objectives:

1. Develop statistical and simple hydrologic models that can predict streamflow at Ecology or Ecology-funded flow monitoring stations in the Wenatchee River basin, based on relationships with active long-term USGS flow stations or other Ecology flow stations.

2. Assess the quality of the results of the models developed for objective 1.

3. Provide support in determining a long-term approach to flow discharge assessment that combines direct monitoring of stage height with modeling approaches, thus allowing the total number of flow monitoring stations using continuous stream gage measurements to be reduced.

4. Identify any data gaps found in the modeling analysis and, if warranted, recommend more complex modeling approaches that might reasonably improve the use of models for flow discharge assessment.

5. Provide Ecology staff and local partners with training and technology transfer of project products.

Methods

The methods used in this study were described in the Quality Assurance Project Plan (Pickett, 2011). The implementation of that plan is described in this section.

Data Sources and Characteristics

Flow Data

Daily average flow data were compiled for ten Ecology stations and five USGS stations with continuous data, and instantaneous flows were compiled for the eight Ecology stations with manual staff gage readings (Tables 1 and 2). Flows at Ecology stations were analyzed from the beginning of the data sets through February 17, 2011[1]. Flow data were withheld from the analysis when derived using interpolations or correlations.

Data sets for these stations were obtained from the Ecology River and Stream Flow Monitoring website (www.ecy.wa.gov/programs/eap/flow/shu_main.html) and from the USGS National Water Information System website (http://waterdata.usgs.gov/wa/nwis/sw).

Some of the flow data have been labeled as *provisional*, meaning that final data quality checks had not been completed. Ecology and USGS flow data are constantly under review and are updated as the review is completed. Provisional data were used for the development of the regressions with the understanding that the regressions would likely be updated in the future using the finalized flow information. This is reasonable since the provisional data are likely to be similar to the final values, and because the regressions will likely also be updated with additional data collected after February 2011.

Figures 2 through 22 show the streamflows for each of the Ecology stations as compared to flows from other selected gaging stations. Flows are presented using a logarithmic scale to more clearly illustrate patterns over time and allow comparison of flows of varying discharge amounts from different stations.

Flow patterns vary widely between stations at different locations in the basin. Notable characteristics of the flow patterns are:

- Wenatchee River flows are highly variable. Flows are close to or above 10,000 cfs in the winter and spring, while summer low flows drop to a few hundred cfs.
- Headwater rivers and creeks (White River, Little Wenatchee River, Chiwawa River, Nason Creek, and Icicle Creek) range from several thousand cfs at high flows to less than 100 cfs at low flows.
- Smaller high elevation creeks (Rock Creek, Chiwaukum Creek) show flows ranging from a several hundred cfs to 10 cfs or less.

[1] The data available at the beginning of the analysis in February 2011. Analysis will be updated to the most recent data available for the final report.

- Stations lower in the basin (Chumstick, Peshastin, and Mission Creeks) show very low summer flows, approaching 1 cfs or less.
- At most stations, low flows are occasionally seen in the late fall and winter due to dry spells or cold periods.
- Summer low flows show more variability at downstream stations than at upstream stations, likely reflecting more intensive irrigation withdrawals and return flows in the lower basin.
- Rock Creek shows signs of data quality problems, with data that can be "flat-lined" or disproportionately high. This is the highest elevation station, and Ecology staff report that the station does not function during hard freeze conditions.

Areal Flows

To get a better understanding of the hydrologic response of the watershed to precipitation and snowmelt, flows were standardized to *areal flows* (sometimes called *unit flows* in hydrology literature) by dividing the streamflow by watershed area and converting the values to units of inches per day. This allows comparison to precipitation and snowmelt in the same units.

Two stations were selected to illustrate meteorological conditions in the basin for comparison to areal flows:

1. Stevens Pass SNOTEL station (Station Code "SPST") www.wcc.nrcs.usda.gov/nwcc/site?sitenum=791&state=wa
2. Wenatchee/Pangborn Airport National Weather Service station (Station Codes "WPAP" and "KEAT") www.wunderground.com/history/airport/KEAT/2010/12/28/CustomHistory.html

Areal flows from the Ecology telemetry and stand-alone stations are shown in Figures 23 through 43. Also shown are precipitation data from the Wenatchee Airport; and non-snow precipitation, snowmelt, and average daily air temperatures from the Stevens Pass SNOTEL station.

Snowmelt was calculated from the daily change in snow water equivalent (SWE), with negative changes in SWE representing snowmelt. Losses in SWE can also occur from evaporation or sublimation, but this method provides an estimate of the potential contribution of snow pack loss to river flows.

Some characteristics in the data patterns shown in Figures 23 through 43 are of interest:

- The Wenatchee River (Figures 27, 33, 35, and 36) shows peak flows that correspond mostly to snowmelt but also to large rain events. Areal flows are high at the most upstream stations (over 1.0 inch per day at times) but decrease at downstream stations (less than 1.0 inch per day at Monitor).
- Headwater rivers and creeks (White, Little Wenatchee, and Chiwawa Rivers; Nason, Icicle, and Peshastin Creeks; Figures 24-26, 30, 32, and 34) show a similar pattern to the mainstem Wenatchee River: mostly snowmelt-dominated but with some response to large rain events. Areal flows are high, with values exceeding 1.0 inch per day at times.

- Smaller high-elevation streams – Rock and Chiwaukum Creeks (Figures 23 and 28) – have a largely snowmelt-dominated flow regime. Areal flows are lower (less than 0.5 inches per day).
- Streams at relatively low elevations (Chumstick and Mission Creeks; Figures 29 and 31) also show a strong snowmelt response, but with much lower watershed flow delivery rates (areal flows less than 0.1 inches per day).
- Patterns of areal flow generally follow precipitation rates, with the highest values at the highest elevation tributaries, and decreasing with elevation in the downstream direction.

Regressions and Other Analysis Methods

Flow data were first evaluated by comparing daily average flows from each study station for the entire record (May 14, 2002 through June 7, 2011) with flows from several USGS and Ecology reference stations using either linear or power regressions. A linear regression is in the form $y=mx+b$, while a power regression takes the form of $y=cx^d$. The regression between paired values of x and y determines either the coefficient m and the intercept b, or the coefficient c and the exponent d. A power regression is arithmetically identical to the linear regression of two log-transformed data sets.

A hydrograph separation technique was used to improve regression relationships. Hydrologic baseflows are the groundwater inflow component of a stream hydrograph. In reality, baseflows vary seasonally and from year to year. As a simplifying assumption for this analysis, baseflow was defined as all flows below a threshold level on either an annual or seasonal basis for all years considered in the analysis. The term *baseflow* will be used in this sense for the rest of this report.

Flow data were first reviewed, and values not derived from direct stage measurements (derived from interpolations or regressions from neighboring dates or stations) were removed. Data were also reviewed for periods of spurious values, and data clearly of poor quality were removed.

Reference stations were selected by evaluating correlations between the stations (Table 4). Reference stations were chosen from the best correlations in the following order:

1. At least one station with the best correlation at a stable, long-term USGS gage.
2. At least one station with the best correlation at a USGS gage or Ecology gage most likely to be retained, such as critical control stations.
3. Two more correlations at any gage with a long data record.

Table 4. Correlations between Wenatchee flow monitoring stations.

Coefficient colors emphasize strongest correlations: blue/bold = greater than 0.9, green/bold italic = between 0.8 and 0.9, red/italic = between 0.7 and 0.8, grey = less than 0.8. Station colors are explained in legend (upper right). Station IDs are defined in Tables 1 through 3.

ECY-Telemetry
USGS
ECY-Manual Staff
Control Station

	Rock	White	LWen	Nason	Wen-Lk	Chwkm	Chmstk	Ici-EC	Psh-GB	Miss-EC	Chww	Wen-Pln	Ici-GS	Wen-Psh	Wen-Mon	Rainy	WPine	Eagle	Psh-AIn	Psh-BIn
White	0.66																			
LWen	0.61	***0.89***																		
Nason	0.64	***0.86***	**0.92**																	
Wen-Lk	0.60	**0.94**	**0.91**	**0.91**																
Chwkm	0.61	***0.90***	***0.82***	***0.81***	**0.91**															
Chmstk	0.23	0.15	0.29	0.34	0.23	0.14														
Ici-EC	***0.77***	**0.93**	***0.89***	**0.97**	**0.95**	0.64	0.06													
Psh-GB	0.51	***0.75***	***0.81***	***0.84***	***0.80***	***0.71***	0.49	***0.85***												
Miss-EC	0.32	0.33	0.42	0.51	0.44	0.30	***0.79***	0.47	***0.71***											
Chww	***0.82***	**0.94**	***0.86***	***0.87***	**0.96**	**0.95**	0.21	**0.92**	***0.76***	0.33										
Wen-Pln	0.69	**0.94**	***0.89***	**0.91**	**0.99**	**0.91**	0.26	**0.95**	***0.79***	0.42	**0.98**									
Ici-GS	0.51	**0.95**	**0.91**	**0.92**	**0.96**	**0.92**	0.20	**0.99**	***0.84***	0.40	**0.94**	**0.96**								
Wen-Psh	0.67	**0.94**	***0.89***	**0.91**	**0.99**	**0.92**	0.27	**0.96**	***0.81***	0.44	**0.97**	**1.00**	**0.97**							
Wen-Mon	0.66	**0.93**	***0.89***	**0.92**	**0.99**	**0.91**	0.29	**0.96**	***0.82***	0.47	**0.97**	**1.00**	**0.97**	**1.00**						
Rainy	0.60	**0.91**	***0.90***	***0.89***	**0.93**	***0.86***	***0.79***	**0.97**	***0.80***	0.61	***0.89***	**0.92**	**0.91**	**0.91**	**0.91**					
WPine	0.52	**0.90**	**0.94**	**0.93**	**0.95**	**0.92**	0.66	**0.97**	**0.91**	0.46	**0.94**	**0.95**	**0.97**	**0.96**	**0.96**	**0.90**				
Eagle	-0.04	-0.12	-0.16	0.05	-0.06	-0.07	***0.81***	0.30	0.31	***0.84***	-0.15	-0.07	-0.08	-0.04	-0.03					
Psh-AIn	0.07	0.52	0.70	0.69	0.62	0.51	0.61	0.68	***0.86***	***0.74***	0.58	0.61	0.62	0.63	0.64	***0.77***	**0.94**	**0.96**		
Psh-BIn	0.34	0.69	***0.84***	***0.87***	***0.79***	***0.71***	0.60	***0.80***	**0.93**	***0.73***	***0.76***	***0.80***	***0.81***	***0.82***	***0.83***	***0.86***	**0.94**	0.10	***0.75***	
Bren	0.26	0.36	0.37	0.40	0.34	0.47	0.32	0.28	0.45	0.44	0.42	0.40	0.40	0.41	0.41	0.34	0.27	0.22	0.25	0.35

Regressions were then developed using the following process:

1. Simple regressions were developed between the study stations and the reference stations, and quality metrics were calculated. For these and all other regressions, linear and power regressions were evaluated, and the one that produced a better fit with data was chosen.
2. Areal flows were calculated for the study and reference stations.
3. Where the time-of-travel in the streams differ, offsetting or lagging flow information in time can sometimes improve the relationship between gages. To evaluate whether time-of-travel differences existed, flow time series were compared to determine whether transient flow peaks coincided or were offset by one or two days.
4. The baseflow threshold at each study gage was determined by comparison of the flow time series to precipitation and snowmelt. The threshold was selected to capture the majority of flows unaffected by precipitation events from early summer through mid-autumn. At some stations, flows below the baseflow threshold were also observed during cold spells in the winter.
5. For each reference gage (the independent variable in the regression), a baseflow threshold was then selected that produced baseflow periods most similar to the study gage. (Specifically, this was the median of the flows from the reference gage on the dates at the beginning and ending of a baseflow period for the evaluation gage.)
6. The "summer" season was separated from the "winter" season by determining the month when spring freshet flows ended and baseflows began, and the month when baseflows ended. Different choices of beginning and ending months were evaluated to determine the split that produced the best quality regressions.
7. For each reference station, the flow record for paired study and reference station flows were split into two categories, four categories, or three categories for analysis:
   a. Two categories
      - *Baseflows* – less than the baseflow threshold occurring all year.
      - *Non-baseflows (Freshet and storm flows)* – greater than the baseflow threshold occurring all year.
   b. Four categories
      - *Summer baseflows* – less than the baseflow threshold occurring from mid-summer through early autumn.
      - *Winter baseflows* – less than the baseflow threshold occurring from late autumn through early summer.
      - *Winter non-baseflows* – greater than the baseflow threshold occurring from late autumn through early summer.
      - *Summer non-baseflows* – greater than the baseflow threshold occurring from mid-summer through early autumn.
   c. Three categories, either:
      - *Summer baseflows* – less than the baseflow threshold occurring from mid-summer through early autumn.

- *Summer non-baseflows* – greater than the baseflow threshold occurring from mid-summer through early autumn.
- *Winter flows* – flows occurring from November through June.

or:

- *Summer baseflows* – less than the baseflow threshold occurring from mid-summer through early autumn.
- *Winter baseflows* – less than the baseflow threshold occurring from late autumn through early summer.
- *Non-baseflows (Freshet and storm flows)* – greater than the baseflow threshold occurring all year.

Quality metrics were evaluated for all combinations.

Quality Analysis

As described in the project plan (Pickett, 2011), model accuracy was assessed by comparison of paired daily flow values from the measured and modeled time series. Bias was assessed by calculating the relative percent difference (RPD) for all predicted and observed pairs individually, and then evaluating the median of RPD values for all predicted and observed pairs.

$RPD_i = [100 * (P_i - O_i)] / [(O_i + P_i) / 2]$, where
$P_i = i^{th}$ prediction
$O_i = i^{th}$ observation
RPD_i = relative percent difference of the i^{th} predicted and observed pair

Precision was assessed with the percent relative standard deviation (%RSD) for predicted and observed pairs individually and using the median of values for all pairs of results. The %RSD presents variation in terms of the standard deviation divided by the mean of predicted and observed values.

$\%RSD_i = (SD_i * 100) / [(P_i + O_i) / 2]$, where
SD_i = standard deviation of the i^{th} predicted and observed pair
$\%RSD_i$ = percent relative standard deviation of the i^{th} predicted and observed pair

The uncertainty of the flows determined by each regression equation was evaluated using the %RSD for all flow conditions and for baseflows. For evaluating the regression for baseflows, observed and modeled data from the study gage were stratified using the baseflow threshold for that station.

The following terminology will be used to describe model results:

Median %RSD for annual streamflow or summer baseflow	Characterization
Less than 5%	Very Good
Greater than 5% and less than 15%	Good
Greater than 15% and less than 30%	Fair
Greater than 30%	Poor

Results

Time-Lagging of Data

For all pairs of stations evaluated, peak flows occurred most often on the same date, with the following exceptions:

- Peak flows in Rock and Chiwaukum Creeks and in the White River tended to precede flows in the Wenatchee River by one day.
- Peak flows in Nason Creek tended to precede flows in the Wenatchee River at Peshastin by one day.
- Peak flows in Icicle, Peshastin, and Mission Creeks tended to precede flows in the Wenatchee River at Monitor by one day.

The improvement in the regression with time-lagged data was very small. Also, using data from a reference station lagged one day later would not have practical value since predictions from that station would be a day late. In other words, using a regression with a one-day lag, one would have to use today's flows at the downstream station to predict yesterday's flows. This would not be useful for real-time forecasting.

For these reasons, time-lagging of data was not used in this study where the reference station is downstream of the study station. The only exceptions where time-lagging was used were for the USGS Wenatchee River stations at Monitor and at Peshastin. For these study stations, a composite reference station was developed for the Monitor station from the sum of flows from:

- The Wenatchee River at Peshastin on the same day, plus
  - The Peshastin Creek at Green Bridge Road station on the previous day, plus
  - The Mission Creek near Cashmere station on the previous day.

For the Peshastin station, a composite reference station was developed from the difference of flows:

- The Wenatchee River at Monitor on the same day, minus
  - The Peshastin Creek at Green Bridge Road station on the previous day, minus
  - The Mission Creek near Cashmere station on the previous day.

Regression-Based Model Parameters

Table 5 presents the results of the regression modeling analysis. For each study gage, regressions from a primary and a secondary reference station are presented. Alternative regression options are presented because of the possibility that some the gages could be discontinued or data might not be available for other reasons.

For each study station, the following is shown:

- The reference flow monitoring station (see Tables 1 and 2 for station codes and full station information).
- The reference station baseflow threshold used for hydrograph separation.
- The season and flow category for separating flow for each regression.
- Whether the regression is a linear or a power regression.
- The coefficient and y-intercept of the linear regression, or the coefficient and exponent of the power regression.
- The r^2 of the regression (a measure of the goodness-of-fit for each individual regression).
- The number of values (n) that each regression is based on.

Regression-Based Model Quality

Table 6 shows the quality of each regression. Goodness-of-fit is indicated by the median %RSD values for all flows and for the summer baseflows.

- Primary regression-based models had very good fits, with %RSD values below 5% for both baseflows and all flows, at these continuous flow stations:
  - Wenatchee River below Lake Wenatchee
  - Wenatchee River at Plain
  - Wenatchee River at Peshastin
  - Wenatchee River at Monitor
- The primary regression-based model had a very good fit for summer baseflows and a good fit for all flows at:
  - Chiwawa River near Plain
- Five stations had good quality primary regression-based models for both all flows and summer baseflows:
  - White River near Plain
  - Little Wenatchee River below Rainy Creek
  - Nason Creek near Mouth
  - Chiwaukum Creek near Mouth
  - Icicle Creek above Snow Creek near Leavenworth
- The primary regression-based models had a good fit for summer baseflows and a fair fit for all flows at the Chumstick Creek near Mouth station.
- The primary regression-based models had a fair fit for summer baseflows and for all flows at these stations:
  - Rock Creek near Mouth
  - Peshastin Creek at Green Bridge Road

Table 5. Regressions for study gages using the hydrograph separation method.

Ecology Telemetry Gages										
Station ID	Station Name	Reference Station Code	Baseflow Threshold (cfs)	Hydrograph Separation		Linear or Power?	Coefficient	Intercept or Exponent	r^2	n
				Season	Flow level					
45N060	Rock Creek near Mouth	Chww (Primary)	none	All year	All flows	Linear	0.105	-2.319	0.6669	1344
45N060	Rock Creek near Mouth	White (Secondary)	24.9	Sep-Oct	Baseflow	Power	0.131	0.944	0.1448	310
				Sep-Oct	Non-baseflow	Power	1.15	0.433	0.2591	204
				Nov-Aug	All flows	Power	0.093	0.898	0.45	1556
45K090	White River near Plain	Wen-Pln (Primary)	603	Sep-Oct	Baseflow	Power	0.105	1.22	0.688	361
				Sep-Oct	Non-baseflow	Power	0.404	1.00	0.742	169
				Nov-Aug	Baseflow	Power	0.104	1.21	0.50	219
				Nov-Aug	Non-baseflow	Power	0.293	1.02	0.92	2295
45K090	White River near Plain	Wen-Lk (Secondary)	463	Aug-Oct	Baseflow	Power	0.210	0.96	0.63	474
				Aug-Oct	Non-baseflow	Power	0.710	0.960	0.63	316
				Nov-Jul	All flows	Power	0.227	1.09	0.93	2400
45L110	Little Wenatchee River below Rainy Creek	Nason (Primary)	70	Aug-Sep	Baseflow	Power	3.67	0.679	0.40	238
				Oct-Jul	Baseflow	Power	0.486	1.26	0.323	100
				All year	Non-baseflow	Power	2.12	0.916	0.82	2731
45L110	Little Wenatchee River below Rainy Creek	Wen-Pln (Secondary)	601	Jul-Sep	Baseflow	Power	0.600	0.696	0.322	173
				Jul-Sep	Non-baseflow	Linear	0.139	-21.3	0.732	287
				Oct-Jun	Baseflow	Power	0.0046	1.60	0.42	117
				Oct-Jun	Non-baseflow	Power	0.371	0.933	0.81	1410
45J070	Nason Creek near Mouth	Wen-Psh (Primary)	797	Jul-Sep	Baseflow	Power	0.043	1.07	0.615	318
				Jul-Sep	Non-baseflow	Power	0.033	1.09	0.914	509
				Oct-Jun	All flows	Power	0.070	1.07	0.91	2242
45J070	Nason Creek near Mouth	Ici-GS (Secondary)	167	Aug-Sep	Baseflow	Power	0.255	1.05	0.572	303
				Aug-Sep	Non-baseflow	Linear	0.390	-16.5	0.745	246
				Oct-Jul	Baseflow	Power	0.222	0.189	0.584	265
				Oct-Jul	Non-baseflow	Linear	0.579	18.5	0.83	2201
45A240	Wenatchee River below Lake Wenatchee	Wen-Chww[1] (Primary)	463	All year	Baseflow	Power	1.51	0.935	0.965	620
				All year	Non-baseflow	Power	0.974	1.01	0.99	2468
45A240	Wenatchee River below Lake Wenatchee	Wen-Pln (Secondary)	631	Aug-Nov	Baseflow	Power	0.520	1.06	0.98	512
				Aug-Nov	Non-baseflow	Linear	0.877	-76.6	0.99	536
				Dec-Jul	All flows	Power	1.07	0.959	0.99	2142

[1]Difference of Wen-Pln minus Chww (no lag)

Table 5, continued. Regressions for study gages using the hydrograph separation method.

Ecology Telemetry Gages										
Station ID	Station Name	Reference Station Code	Baseflow Threshold (cfs)	Hydrograph Separation		Linear or Power?	Coefficient	Intercept or Exponent	r^2	N
				Season	Flow level					
45G060	Chiwaukum Creek near Mouth	Wen-Pln (Primary)	603	Sep-Oct	Baseflow	Power	0.0186	1.14	0.77	281
				Nov-Aug	Baseflow	Linear	0.0382	2.13	0.30	173
				Nov-Aug	Non-baseflow	Power	0.032	1.05	0.84	2004
45G060	Chiwaukum Creek near Mouth	Wen-Psh (Secondary)	824	Aug-Nov	Baseflow	Power	0.0147	1.11	0.64	416
				Aug-Nov	Non-baseflow	Power	0.0565	0.926	0.63	492
				Dec-Jul	All flows	Power	0.0158	1.10	0.85	1550
45C060	Chumstick Creek near Mouth	Miss-EC (Primary)	2.9	Aug-Oct	Baseflow	Power	3.57	0.0397	0.04	375
				Nov-Jul	Baseflow	Linear	0.934	1.82	0.32	135
				All year	Non-baseflow	Power	1.46	0.795	0.67	1510
45C060	Chumstick Creek near Mouth	Psh-GB (Secondary)	30.6	Aug-Sep	Baseflow	Power	2.29	0.199	0.12	287
				Oct-Jul	Baseflow	Power	1.79	0.133	0.05	164
				All year	Non-baseflow	Power	0.299	0.728	0.41	1692
45F070	Peshastin Creek at Green Bridge Road	Wen-Mon (Primary)	897	Aug-Sep	Baseflow	Power	0.0205	0.999	0.26	364
				Aug-Sep	Non-baseflow	Power	0.0014	1.39	0.42	134
				Oct-Jul	Baseflow	Linear	0.0393	1.27	0.15	266
				Oct-Jul	Non-baseflow	Linear	0.0572	16.6	0.62	2214
45F070	Peshastin Creek at Green Bridge Road	Nason (Secondary)	78.0	Jul-Sep	Baseflow	Power	0.272	1.02	0.37	412
				Jul-Sep	Non-baseflow	Power	0.543	0.923	0.76	415
				Oct-Jun	Baseflow	Linear	0.217	11.2	0.08	164
				Oct-Jun	Non-baseflow	Power	1.12	0.871	0.68	2078
45E070	Mission Creek near Cashmere	Chmstk (Primary)	3.4	Aug-Sep	Baseflow	Power	1.25E-06	11.0	0.21	80
				Aug-Sep	Non-baseflow	Power	0.0370	2.13	0.06	210
				Oct-Jul	All flows	Power	0.727	1.14	0.67	1730
45E070	Mission Creek near Cashmere	Psh-GB (Secondary)	23.6	Aug-Oct	Baseflow	Power	0.0253	1.17	0.13	412
				Aug-Oct	Non-baseflow	Power	0.146	0.696	0.18	239
				Nov-Jul	All flows	Power	0.0740	1.04	0.53	2115

Table 5, continued. Regressions for study gages using the hydrograph separation method.

USGS Gages										
Station ID	Station Name	Reference Station Code	Baseflow Threshold (cfs)	Hydrograph Separation		Linear or Power?	Coefficient	Intercept or Exponent	r^2	n
				Season	Flow level					
12456500	Chiwawa River near Plain	Wen-Pln (Primary)	495	Aug-Oct	Baseflow	Power	1.62	0.713	0.787	341
				Aug-Oct	Non-baseflow	Linear	0.225	30.8	0.861	487
				Nov-Jul	Baseflow	Linear	0.0522	63.4	0.173	89
				Nov-Jul	Non-baseflow	Linear	0.278	-77.4	0.94	2293
12456500	Chiwawa River near Plain	Wen-Psh (Secondary)	697.4	Aug-Oct	Baseflow	Power	0.574	0.842	0.762	364
				Aug-Oct	Non-baseflow	Linear	0.183	15.6	0.787	464
				Nov-Jul	Baseflow	Power	9.44	0.351	0.21	82
				Nov-Jul	Non-baseflow	Linear	0.209	-102.8	0.94	2300
12457000	Wenatchee River at Plain	Chww+Wen[2] (Primary)	591.2	Aug-Nov	Baseflow	Power	0.845	1.02	0.979	447
				Aug-Nov	Non-baseflow	Linear	0.966	9.23	0.994	594
				Dec-Jul	All flows	Power	1.08	0.989	0.996	2047
12457000	Wenatchee River at Plain	Wen-Psh (Secondary)	783.8	Sep-Nov	Baseflow	Power	0.402	1.09	0.935	383
				Dec-Aug	Baseflow	Power	1.06	0.943	0.807	194
				All year	Non-baseflow	Linear	0.751	-73.3	0.996	2735
12458000	Icicle Creek above Snow Creek near Leavenworth	Wen-Psh (Primary)	969	Aug-Nov	Baseflow	Power	0.209	0.998	0.813	645
				Aug-Nov	Non-baseflow	Power	0.167	1.03	0.854	453
				Dec-Jul	Baseflow	Linear	0.285	-74.2	0.80	204
				Dec-Jul	Non-baseflow	Power	0.115	1.03	0.97	1952
12458000	Icicle Creek above Snow Creek near Leavenworth	Wen-Lk (Secondary)	552	All year	Baseflow	Power	0.810	0.867	0.716	874
				All year	Non-baseflow	Power	0.285	1.03	0.95	2316
12459000	Wenatchee River at Peshastin	Wen-Sum[3] (Primary)	812	Aug-Oct	Baseflow	Linear	1.03	36.0	0.90	388
				Nov-Jul	Baseflow	Power	0.275	1.19	0.95	71
				All flows	Non-baseflow	Linear	0.976	45.0	0.998	2302
12459000	Wenatchee River at Peshastin	Wen-Lk (Secondary)	482	Jul-Oct	Baseflow	Power	4.85	0.836	0.929	511
				Jul-Oct	Non-baseflow	Power	2.02	0.979	0.985	557
				Nov-Jun	Baseflow	Power	3.14	0.907	0.827	158
				Nov-Jun	Non-baseflow	Power	1.78	1.00	0.99	1964

[2]Sum of Chww plus Wen-Lk (no lag)

[3]Differrence of Wen-Mon minus Psh-GB (lagged – previous day) minus Miss-EC (lagged – previous day)

Table 5, continued. Regressions for study gages using the hydrograph separation method.

USGS Gages										
Station ID	Station Name	Reference Station Code	Baseflow Threshold (cfs)	Hydrograph Separation		Linear or Power?	Coefficient	Intercept or Exponent	r^2	n
12462500	Wenatchee River at Monitor	Wen+Sum[4] (Primary)	913	Aug-Oct	Baseflow	Linear	0.948	-13.5	0.90	410
				Aug-Oct	Non-baseflow	Linear	1.02	-61.3	0.995	241
				Nov-Jul	Baseflow	Power	2.53	0.871	0.964	103
				Nov-Jul	Non-baseflow	Linear	1.02	-38.5	0.998	2000
12462500	Wenatchee River at Monitor	Wen-Psh (Secondary)	859	Aug-Oct	Baseflow	Power	1.01	0.992	0.828	521
				Aug-Oct	Non-baseflow	Linear	1.04	-33.0	0.993	307
				Nov-Jul	Baseflow	Power	3.11	0.846	0.905	173
				Nov-Jul	Non-baseflow	Linear	1.09	-18.5	0.996	2311

[4]Sum of Wen-Psh plus Psh-GB (lagged – previous day) plus Miss-EC (lagged – previous day)

Ecology Manual Staff or Recent Telemetry Gages									
Station ID	Station Name	Reference Station Code	Baseflow Threshold (cfs)	Hydrograph Separation	Linear or Power?	Coefficient	Intercept or Exponent	r^2	n
45B070	Icicle Creek near Leavenworth	Ici-GS	(Primary)	None	Linear	0.962	46.2	0.97	255
		Wen-Psh	(Secondary)	None	Power	0.136	1.1	0.94	261
45M060	Rainy Creek near Mouth	Wen-Lk	(Primary)	None	Power	0.0962	0.866	0.89	107
		Wen-Pln	(Secondary)	None	Power	0.0918	0.837	0.88	100
45P050	White Pine Creek at Mouth	Wen-Mon	(Primary)	None	Linear	0.0295	-0.6	0.92	69
		Wen-Lk	(Secondary)	None	Linear	0.0424	-0.8	0.92	64
45Q060	Eagle Creek near Mouth	Chmstk	(Primary)	None	Power	0.0430	1.34	0.69	20
		Miss-EC	(Secondary)	None	Power	0.0916	1.05	0.74	26
45F110	Peshastin Creek above Ingalls	Nason	(Primary)	None	Power	0.269	0.830	0.71	96
		Miss-EC	(Secondary)	None	Linear	2.53	7.1	0.73	87
45F100	Peshastin Creek below Ingalls	Nason	(Primary)	None	Power	1.60	0.774	0.83	102
		Wen-Mon	(Secondary)	None	Power	0.0705	0.942	0.85	105
45D070	Brender Creek near Cashmere	Wen-Mon	(Primary)	None	Power	0.292	0.269	0.16	185
		Psh-GB	(Secondary)	None	Linear	0.0033	2.2	0.20	175

Table 6. Model quality results for regressions as median %RSD for study gaging stations.

Station ID	Station Name	Reference Station Code	Hydrograph Separation Unit	Median %RSD for regression-based model					
				<5%	5-10%	10 - 15%	15 - 20%	20 - 30%	30 - 40%
Ecology Telemetry Gages									
45N060	Rock Creek near Mouth	Chww	Summer baseflow All flows				X X		
45N060	Rock Creek near Mouth	White	Summer baseflow All flows				X	 X	
45K090	White River near Plain	Wen-Pln	Summer baseflow All flows		X	 X			
45K090	White River near Plain	Wen-Lk	Summer baseflow All flows			X X			
45L110	Little Wenatchee River below Rainy Creek	Nason	Summer baseflow All flows			X X			
45L110	Little Wenatchee River below Rainy Creek	Wen-Pln	Summer baseflow All flows			X X			
45J070	Nason Creek near Mouth	Wen-Psh	Summer baseflow All flows		X	 X			
45J070	Nason Creek near Mouth	Ici-GS	Summer baseflow All flows		X	 X			
45A240	Wenatchee River below Lake Wenatchee	Wen-Chww	Summer baseflow All flows	X X					
45A240	Wenatchee River below Lake Wenatchee	Wen-Pln	Summer baseflow All flows	X X					
45G060	Chiwaukum Creek near Mouth	Wen-Pln	Summer baseflow All flows		X X				
45G060	Chiwaukum Creek near Mouth	Wen-Psh	Summer baseflow All flows		X	 X			
45C060	Chumstick Creek near Mouth	Miss-EC	Summer baseflow All flows			X		 X	
45C060	Chumstick Creek near Mouth	Psh-GB	Summer baseflow All flows			X			 X
45F070	Peshastin Creek at Green Bridge Road	Wen-Mon	Summer baseflow All flows				X	 X	
45F070	Peshastin Creek at Green Bridge Road	Nason	Summer baseflow All flows					X X	

Table 6, continued. Model quality results for regressions as median %RSD for study gaging stations.

Station ID	Station Name	Reference Station Code	Hydrograph Separation Unit	Median %RSD for regression-based model					
				<5%	5-10%	10 - 15%	15 - 20%	20 - 30%	30 - 40%
45E070	Mission Creek near Cashmere	Chmstk	Summer baseflow All flows						X X
45E070	Mission Creek near Cashmere	Psh-GB	Summer baseflow All flows						X X
USGS Gages									
12456500	Chiwawa River near Plain	Wen-Pln	Summer baseflow All flows	X	 X				
12456500	Chiwawa River near Plain	Wen-Psh	Summer baseflow All flows	X	 X				
12457000	Wenatchee River at Plain	Chww+Wen	Summer baseflow All flows	X X					
12457000	Wenatchee River at Plain	Wen-Psh	Summer baseflow All flows	X X					
12458000	Icicle Creek above Snow Creek near Leavenworth	Wen-Psh	Summer baseflow All flows		X X				
12458000	Icicle Creek above Snow Creek near Leavenworth	Wen-Lk	Summer baseflow All flows		X X				
12459000	Wenatchee River at Peshastin	Wen-Sum	Summer baseflow All flows	X X					
12459000	Wenatchee River at Peshastin	Wen-Lk	Summer baseflow All flows	X X					
12462500	Wenatchee River at Monitor	Wen+Sum	Summer baseflow All flows	X X					
12462500	Wenatchee River at Monitor	Wen-Psh	Summer baseflow All flows	 X	X				

Table 6, continued. Model quality results for regressions as median %RSD for study gaging stations.

Ecology Manual Staff or Recent Telemetry Gages									
Station ID	Station Name	Reference Station Code	Hydrograph Separation Unit	Median %RSD for regression-based model					
				<5%	5-10%	10 - 15%	15 - 20%	20 - 30%	30 - 40%
45B070	Icicle Creek near Leavenworth	Ici-GS Wen-Psh	All flows All flows		X X				
45M060	Rainy Creek near Mouth	Wen-Pln Wen-Lk	All flows All flows			X X			
45P050	White Pine Creek at Mouth	Wen-Mon Wen-Lk	All flows All flows		X	 X			
45Q060	Eagle Creek near Mouth	Chmstk Miss-EC	All flows All flows					X	 X
45F110	Peshastin Creek above Ingalls	Miss-EC Nason	All flows All flows					X X	
45F100	Peshastin Creek below Ingalls	Nason Psh-GB	All flows All flows				X X		
45D070	Brender Creek near Cashmere	Wen-Mon Psh-GB	All flows All flows					X X	

- The primary regression-based models had a poor fit for summer baseflows and for all flows at the Mission Creek near Cashmere station.
- The quality of regression-based models was good for all flows at:
  - Icicle Creek near Leavenworth
  - Rainy Creek near Mouth
  - White Pine Creek at Mouth
- The quality of regression-based models was fair for all flows at:
  - Eagle Creek near Mouth
  - Peshastin Creek above Ingalls
  - Peshastin Creek below Ingalls
  - Brender Creek near Cashmere

Figures 44 through 64 show the measured and modeled values for each study station based on the primary reference station, along with the goodness-of-fit as RPD shown on the right axis. A few patterns should be noted:

- Small difference in very low flows can produce an RPD of high magnitude[2]. This is not representative of the goodness-of-fit for low flows and would tend to inflate the average RPD for the model.
- For higher flows, extreme RPD values highlight the differences in the hydrograph behavior between the study and reference station.
- Over all flows, the median RPD was good, with a range of +/- 7% for all stations, except for two manual staff stations that were 10% and -19%. For baseflows, the RPD values were within a similar range but biased high, and two stations had median values of 12% and 23%. This is consistent with the tendency of RPD at low flows to produce high values.
- The range of RPD values vary widely among the stations: from the narrowest range of -21% to 26% at the Wenatchee River at Plain station, to the widest range of -197% to 200% at the Mission Creek near Cashmere station. Note that the right-hand scale on the graph varies between figures so that the temporal patterns can be seen clearly.

Table 7 summarizes the reference stations analyzed for the Ecology study stations. The numbers in the grid indicate whether the active station is the primary (1^o) or secondary (2^o) preference. Totals for each station are shown at the bottom. Table 7 gives some sense of which gages were most useful as reference stations.

[2] For example, flows of 24.6 and 25.1 cfs produce an RPD of 1.9%, but flows of 0.2 and 0.7 cfs produce an RPD of 113.7%, even though the difference for both is 0.5 cfs.

Table 7. Summary of study and reference flow monitoring stations.

Reference stations → / Study Stations ↓	White	LWen	Nason	Wen-Lk	Chwkm	Chmstk	Psh-GB	Miss-EC	Chww	Wen-Pln	Ici-GS	Wen-Psh	Wen-Mon
Rock	2°								1°				
White				2°						1°			
LWen			1°							2°			
Nason											2°	1°	
Wen-Lk									1°	1°			
Chwkm										1°		2°	
Chmstk							2°	1°					
Psh-GB			2°										1°
Miss-EC						1°	2°						
Chww										1°		2°	
Wen-Pln				1°					1°			2°	
Ici-GS				2°								1°	
Wen-Psh		2°					1°	1°					1°
Wen-Mon							1°	1°				1°	
Ici-EC											1°	2°	
Rainy				2°						1°			
WPine				2°									1°
Eagle						1°		2°					
Psh-AIn			2°					1°					
Psh-BIn			1°				2°						
Bren							2°						1°
No. Primary	-	-	2	1	-	2	2	4	3	5	1	3	4
No. Secondary	1	1	2	4	-	-	4	1	-	1	1	4	-
TOTAL	1	1	4	5	-	2	6	5	3	6	2	7	4

Preferences: 1° = Primary; 2° = Secondary

Discussion

The gaged streams in the Wenatchee River basin can vary widely in their range of flows but are similar in their runoff patterns. The principal factors determining their flow patterns appear to be elevation and land use. Based on this analysis, some patterns emerge:

- The model for the Ecology *Rock Creek near Mouth* station has poor quality, but the station also has flow data quality problems and is not sited at a regulatory control station. Decommissioning or transfer of this station should be considered.

- Several Ecology stations have good quality regression-based models and are not located at a regulatory control station: *White River near Plain, Little Wenatchee River below Rainy Creek,* and *Chiwaukum Creek near Mouth*. These stations should be considered for decommissioning or transfer.

- The Ecology *Nason Creek near Mouth* station has good quality regression-based model results but is a regulatory control station. If the model is adequate to meet the needs for water management at this location, it could be considered for decommissioning or transfer.

- Very good quality results were found at the Ecology station *Wenatchee River below Lake Wenatchee* and at the USGS station *Wenatchee River at Plain*. The USGS *Chiwawa River near Plain* station had very good quality for summer low flows and good quality for all flows. Only two of these three stations are needed. Since the two USGS stations are regulatory control stations, the regression-based model for *Wenatchee River below Lake Wenatchee* should be adequate for most needs.

- The Ecology and USGS gages on Icicle Creek both have good quality model results. Ecology may not need to fund both stations. Reduction of funding for the USGS gage should be considered after a review of Ecology's needs for this station's data.

  The Ecology gage only recently was converted to a telemetry station producing continuous data. This is a regulatory control station, and the continuous data record is too short to develop reliable regressions, so decommissioning at this time is not recommended.

  However, after several years of data have been collected at the Ecology station, it should be reviewed again for redundancy with the USGS gage. If a regression-based model would meet water management needs at one of these locations, then only the other station would need to be funded.

- The quality of the model results for Ecology stations *Chumstick Creek near Mouth* and *Peshastin Creek at Green Bridge Road* is fair, and the quality of the results at Ecology station *Mission Creek near Cashmere* is poor. These three stations are regulatory control stations, and continued funding and operation of these stations is recommended.

- Ecology does not provide funding for the USGS gage *Wenatchee River at Peshastin*, but provides funding for the USGS gage *Wenatchee River at Monitor*. The quality of regression-based models for these gages (each gage based on the other, plus or minus the sum of the tributaries in-between) are very good. There appears to be redundancy between these

stations, since either one could be used to predict the other. However these are long-term stations where flows are used for a variety of needs including regulatory control stations. Ecology should work with local partners to review data needs at these stations and funding for the Monitor gage.

- None of the manual staff stations in the basin are in service. Models were developed for use at these stations for flow assessment, and the models are available should the need arise.

Conclusions and Recommendations

This study draws the following conclusions and recommendations:

- The hydrograph separation method can be used to develop regression-based computer models to estimate streamflow at Ecology gaging stations in the Wenatchee River basin (WRIA 45).

- The quality of the streamflow estimates from these regression-based models was evaluated, and based on the results of that evaluation, recommendations are provided for Ecology's support of flow gaging stations:

    - *Rock Creek near Mouth*: Decommissioning or transfer of this station should be considered.

    - *White River near Plain*, *Little Wenatchee River below Rainy Creek*, and *Chiwaukum Creek near mouth*: Decommissioning or transfer of these stations should be considered.

    - *Nason Creek near Mouth*: If the model is adequate to meet the needs for water management at this location, this station could be considered for decommissioning or transfer.

    - *Icicle Creek near Leavenworth*: Continued funding and operation of this station is recommended. However, after several years of data have been collected, this Ecology station should be reviewed again for redundancy with the USGS gage to determine if a regression-based model would meet water management needs at this location.

    - *Icicle Creek above Snow Creek near Leavenworth*: Reduction of funding to the USGS gage might be considered.

    - *Chumstick Creek near Mouth, Peshastin Creek at Green Bridge Road, and Mission Creek near Cashmere*: Continued funding and operation of these stations is recommended.

    - *Wenatchee River below Lake Wenatchee*: Decommissioning or transfer of this station should be considered.

    - *Wenatchee River at Plain* and *Chiwawa River near Plain*: Continued funding of these stations is recommended.

    - *Wenatchee River at Monitor* and *Wenatchee River at Peshastin*. Review data needs and funding for these gages.

- Regressions are available to predict flows for decommissioned staff gage stations.

- The accuracy of the regression-based models should be evaluated against flow monitoring needs for Ecology and the local community to determine whether the models provide an acceptable substitute for flow gaging. All regression-based models for study flow stations should be used for specific purposes with consideration as to whether their accuracy serves that purpose. Stations may be redundant in terms of the ability of the regression to predict

flows, but removal of a station may still lose other information or the ability to use that flow data for other analyses. Conceptually the regressions should be used as "screening tools" to trigger a direct evaluation of flow, or used for purposes where a rough estimate is acceptable.

- Regressions from provisional data should be of sufficient quality to be applied to the regression-based models. Updating of regression models with quality-checked data could slightly improve the quality of the regressions. Regression-based models should be updated when additional measured flow data are available and when flow data quality reviews are completed.

- Technology transfer of these regression-based models and training on the use and updating of the models should be provided as needed to staff from Ecology, local partners, or other agencies.

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Figures

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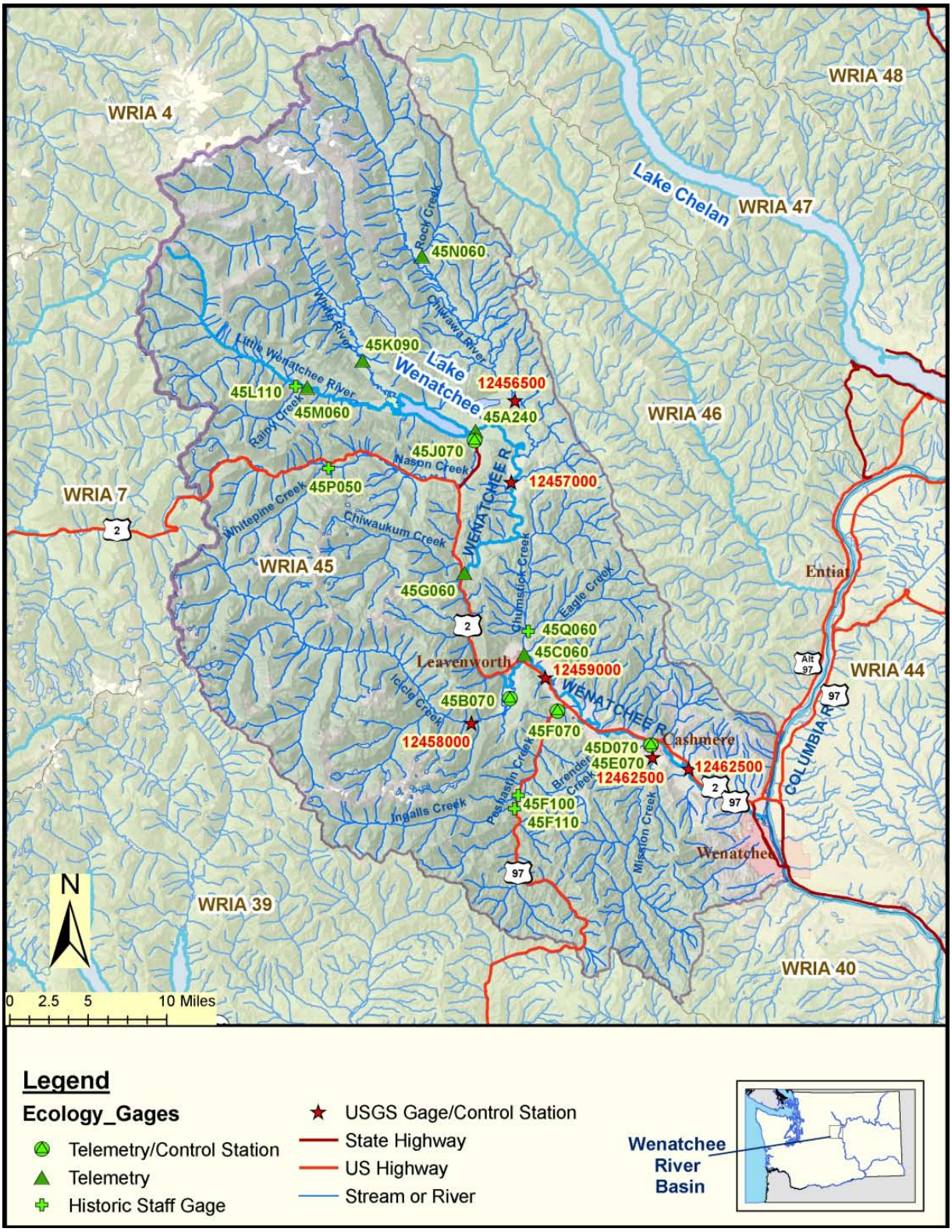

Figure 1. Wenatchee watershed and study area (Water Resource Inventory Area 45).

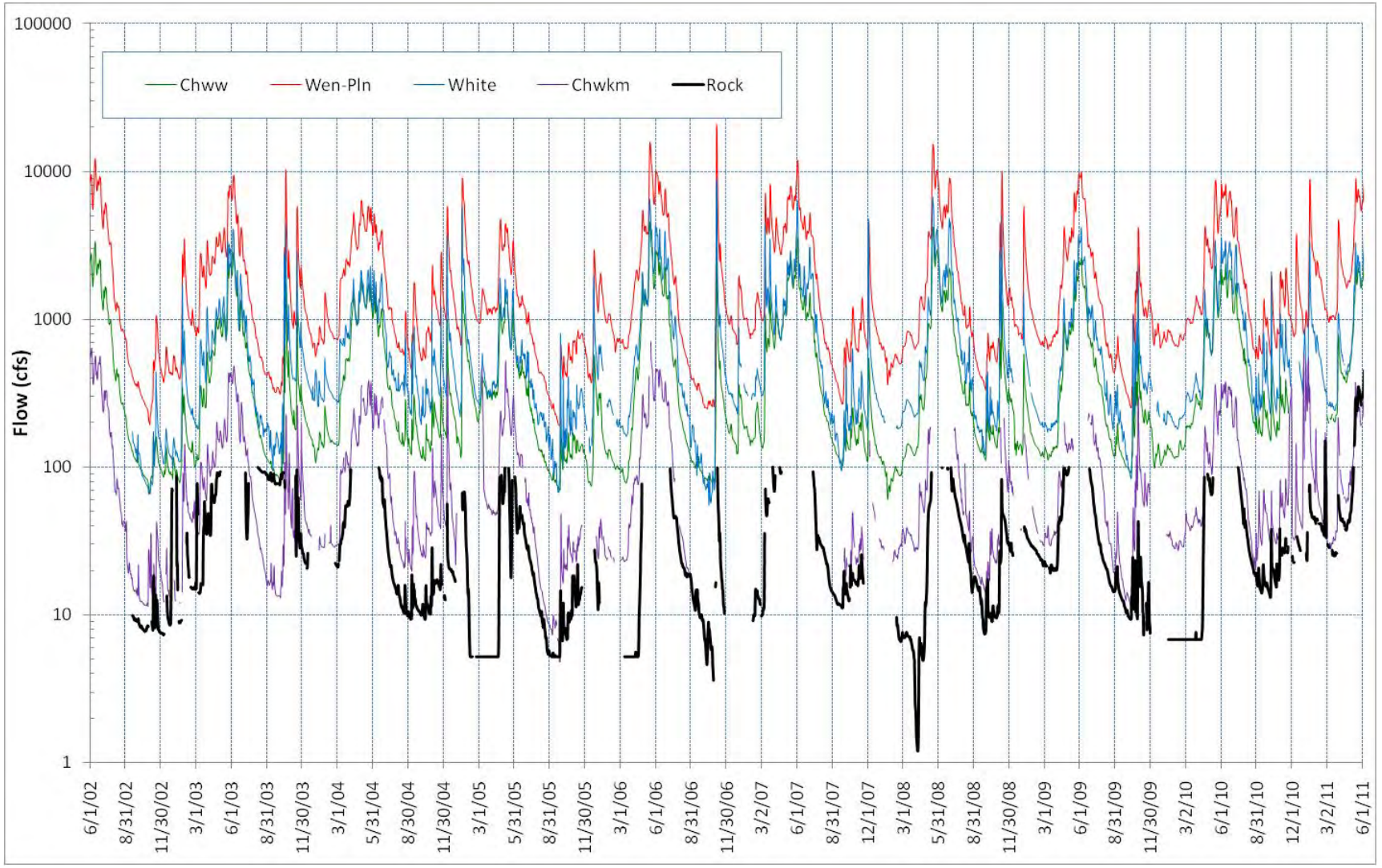

Figure 2. Measured flows at the Ecology “Rock Creek near Mouth” gaging station, with flows from other selected gages.

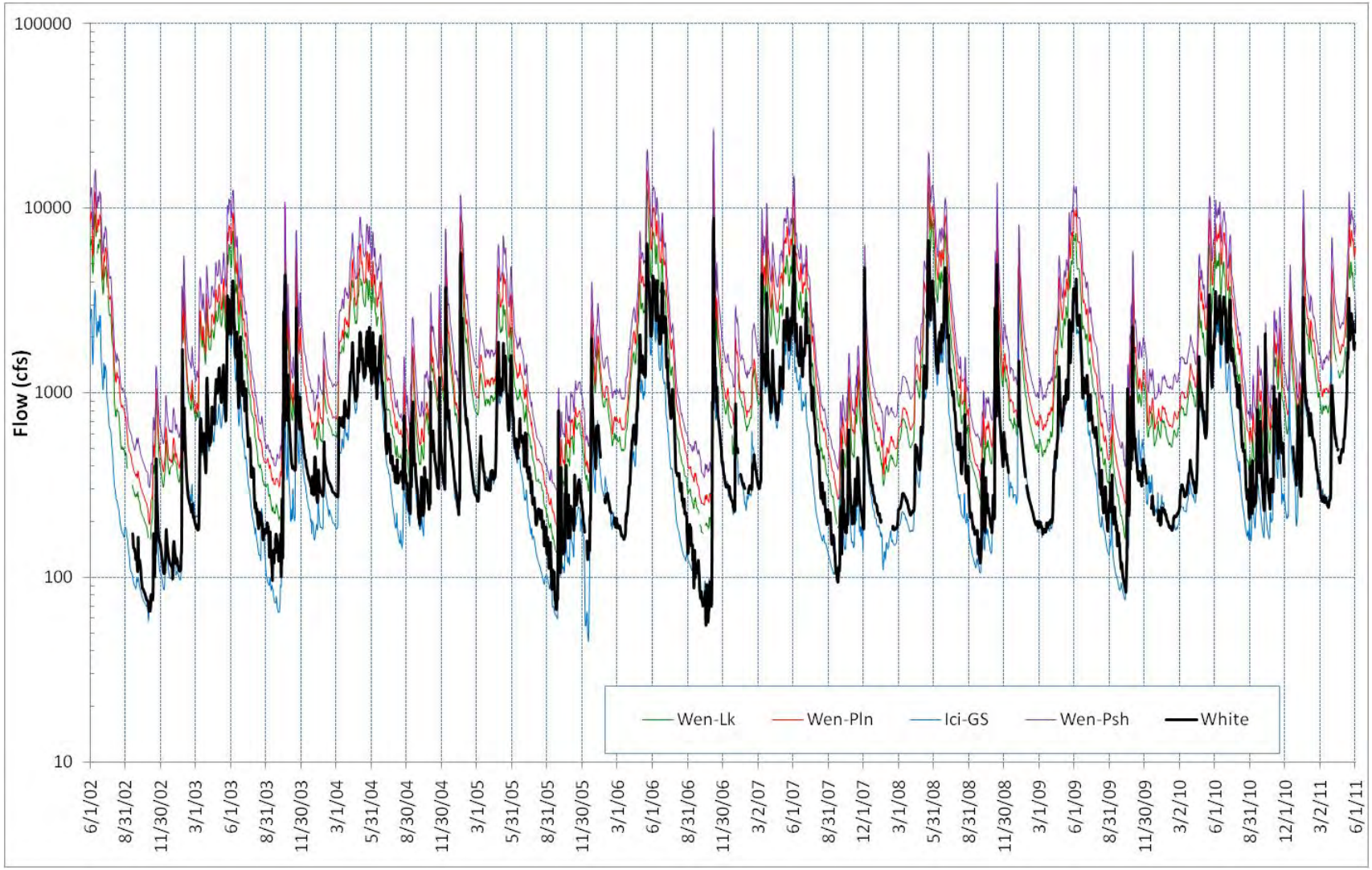

Figure 3. Measured flows at the Ecology "White River near Plain" gaging station, with flows from other selected gages.

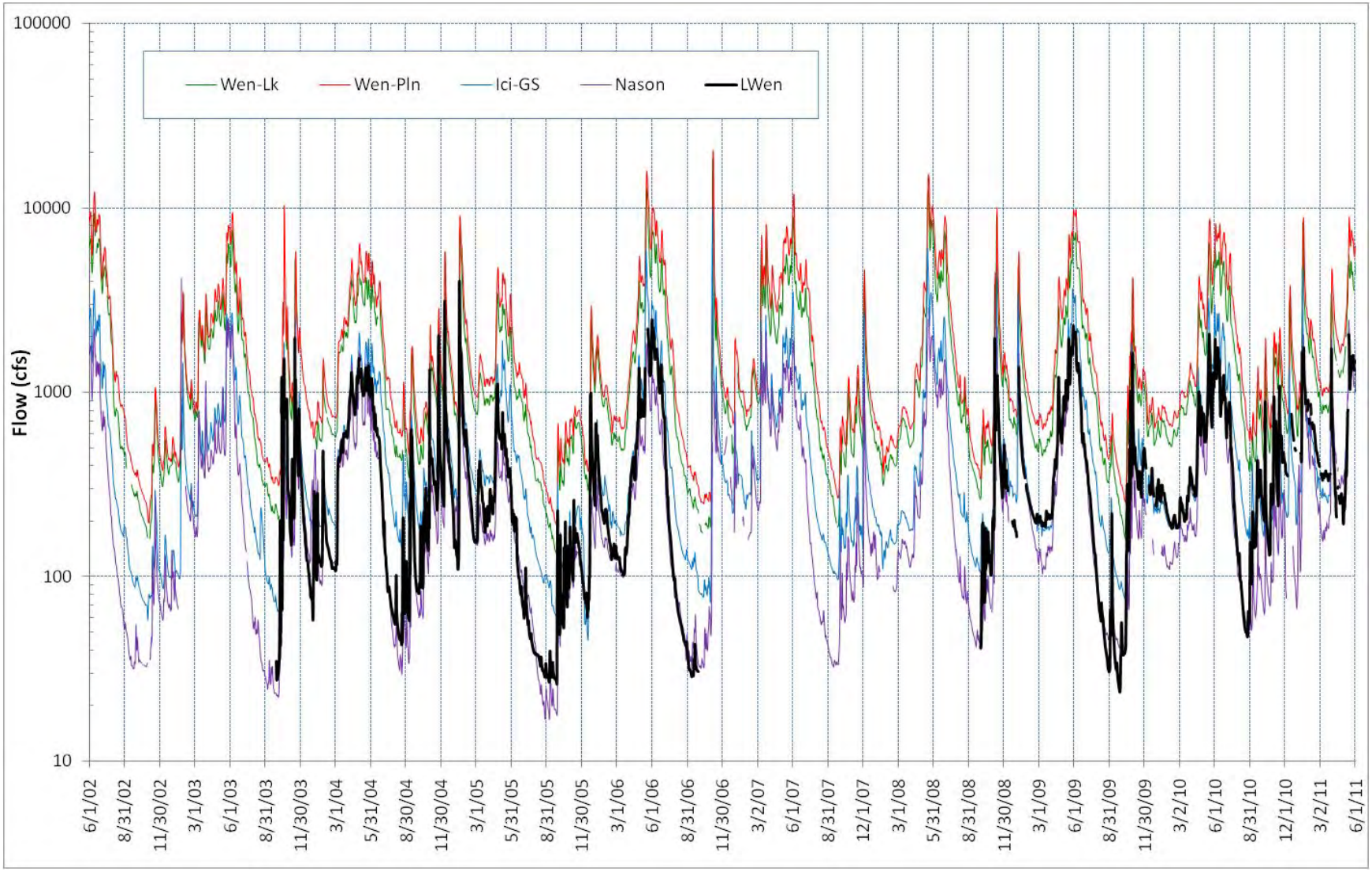

Figure 4. Measured flows at the Ecology "Little Wenatchee River below Rainy Creek" gaging station, with flows from other selected gages.

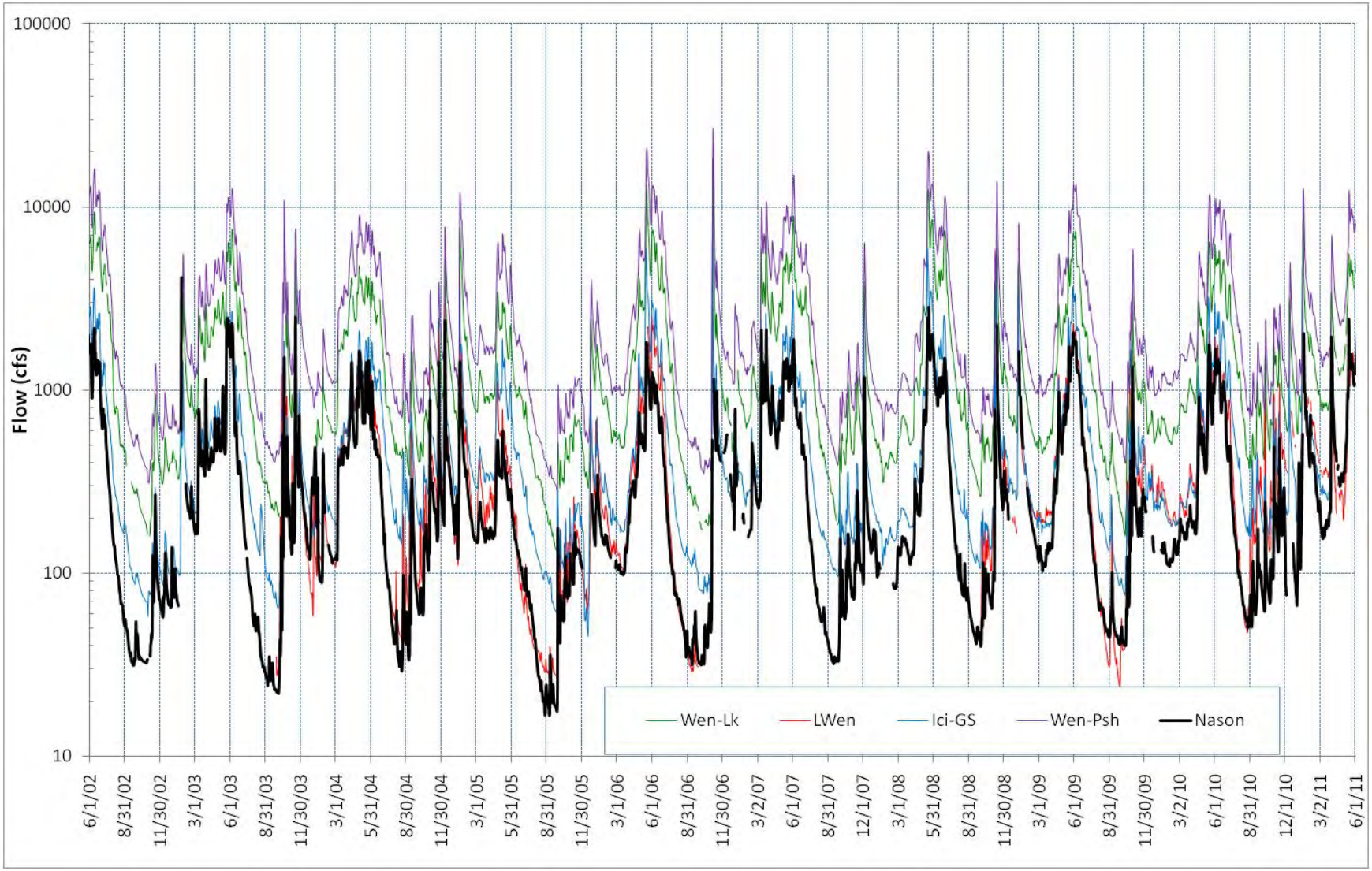

Figure 5. Measured flows at the Ecology "Nason Creek near mouth" gaging station, with flows from other selected gages.

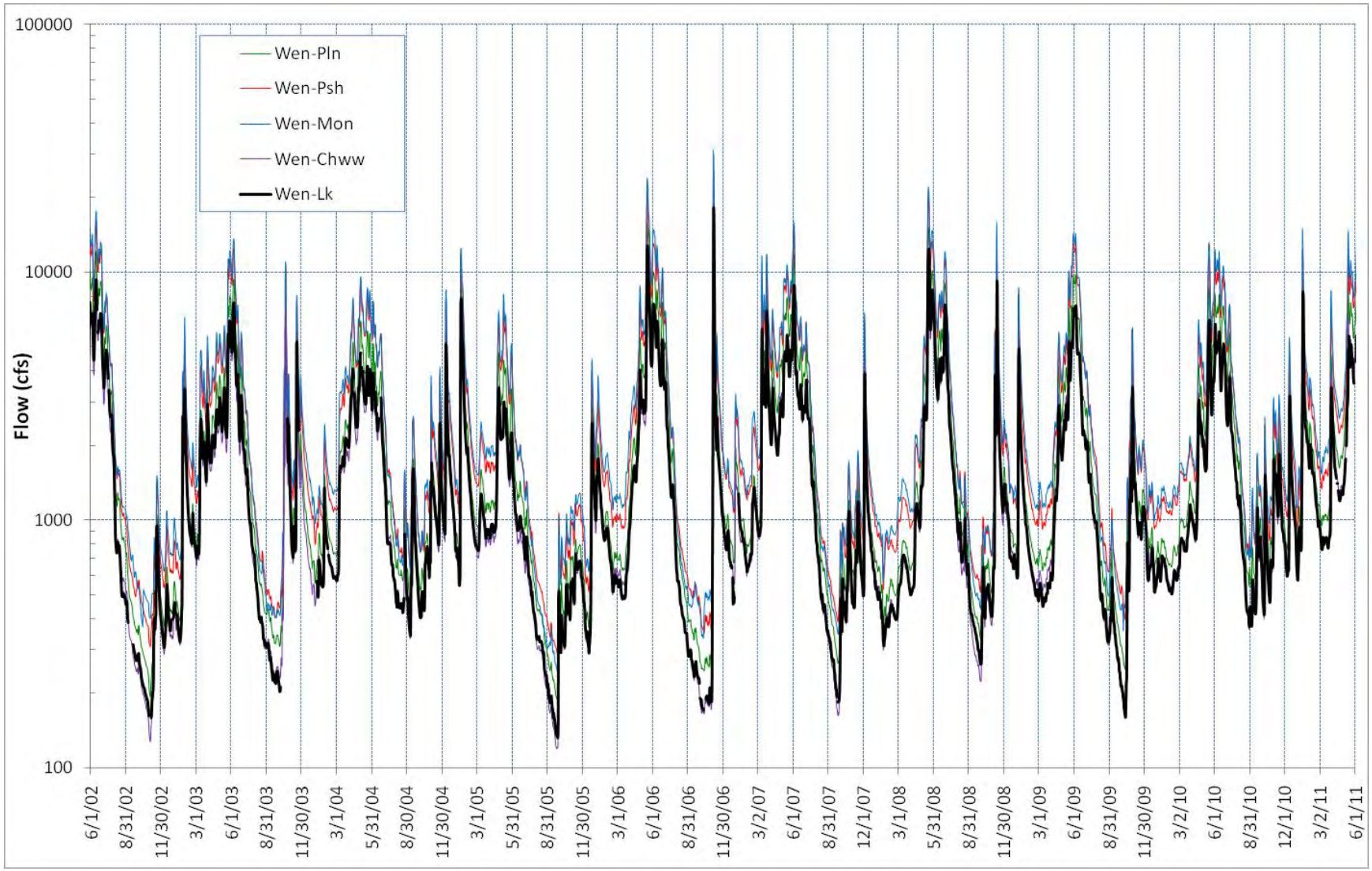

Figure 6. Measured flows at the Ecology "Wenatchee River below Lake Wenatchee" gaging station, with flows from other selected gages.

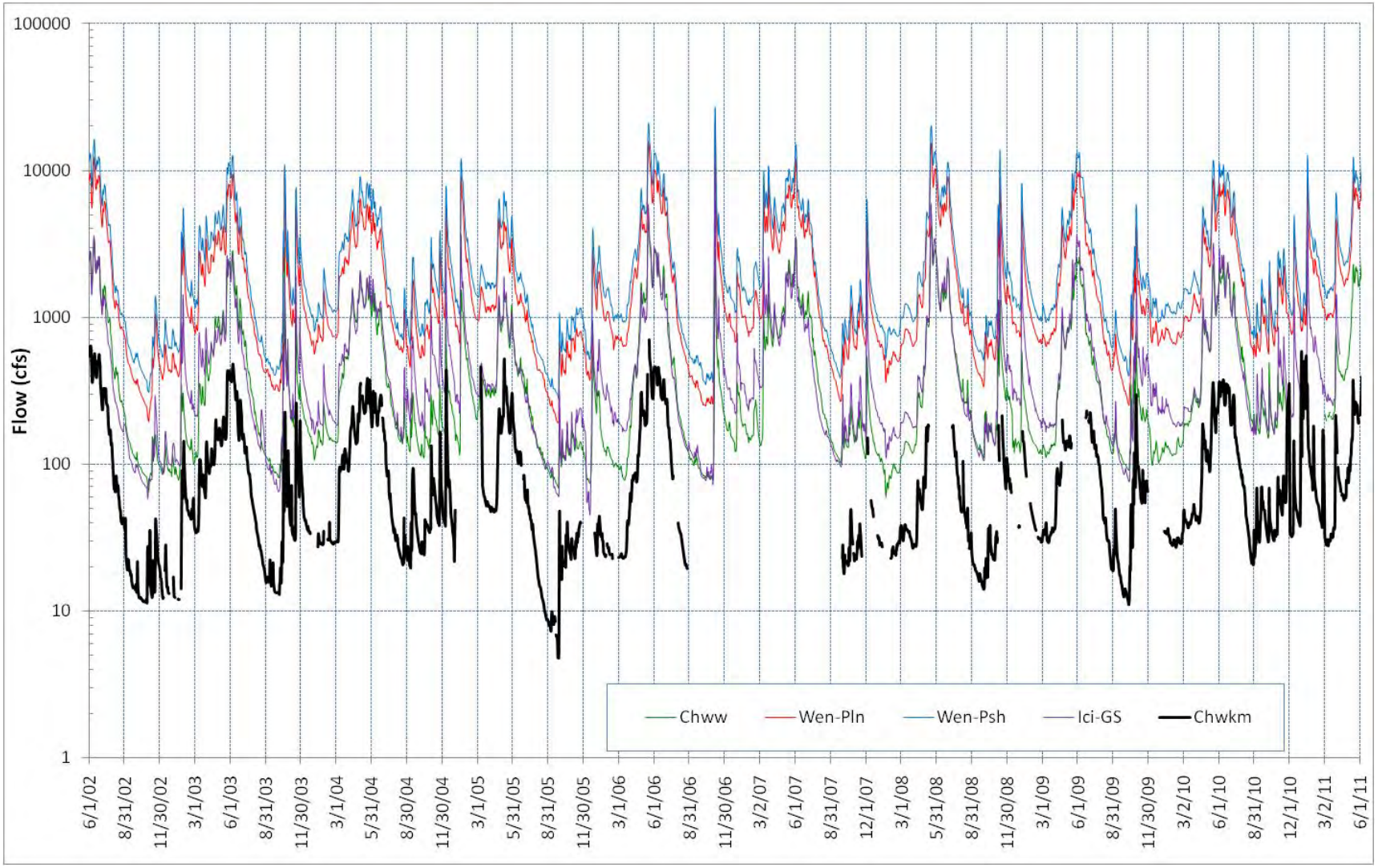

Figure 7. Measured flows at the Ecology "Chiwaukum Creek near mouth" gaging station, with flows from other selected gages.

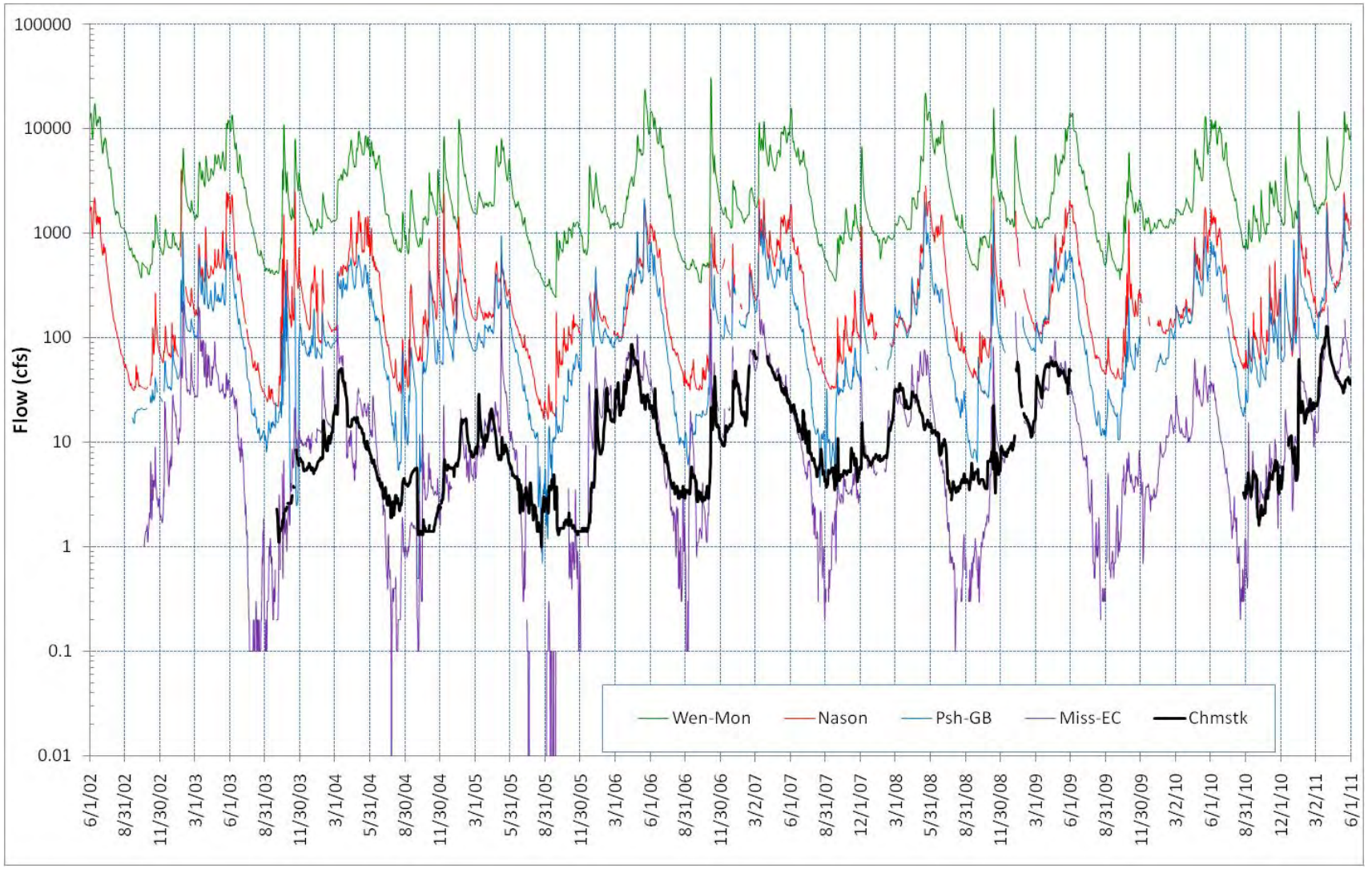

Figure 8. Measured flows at the Ecology “Chumstick Creek near mouth” gaging station, with flows from other selected gages.

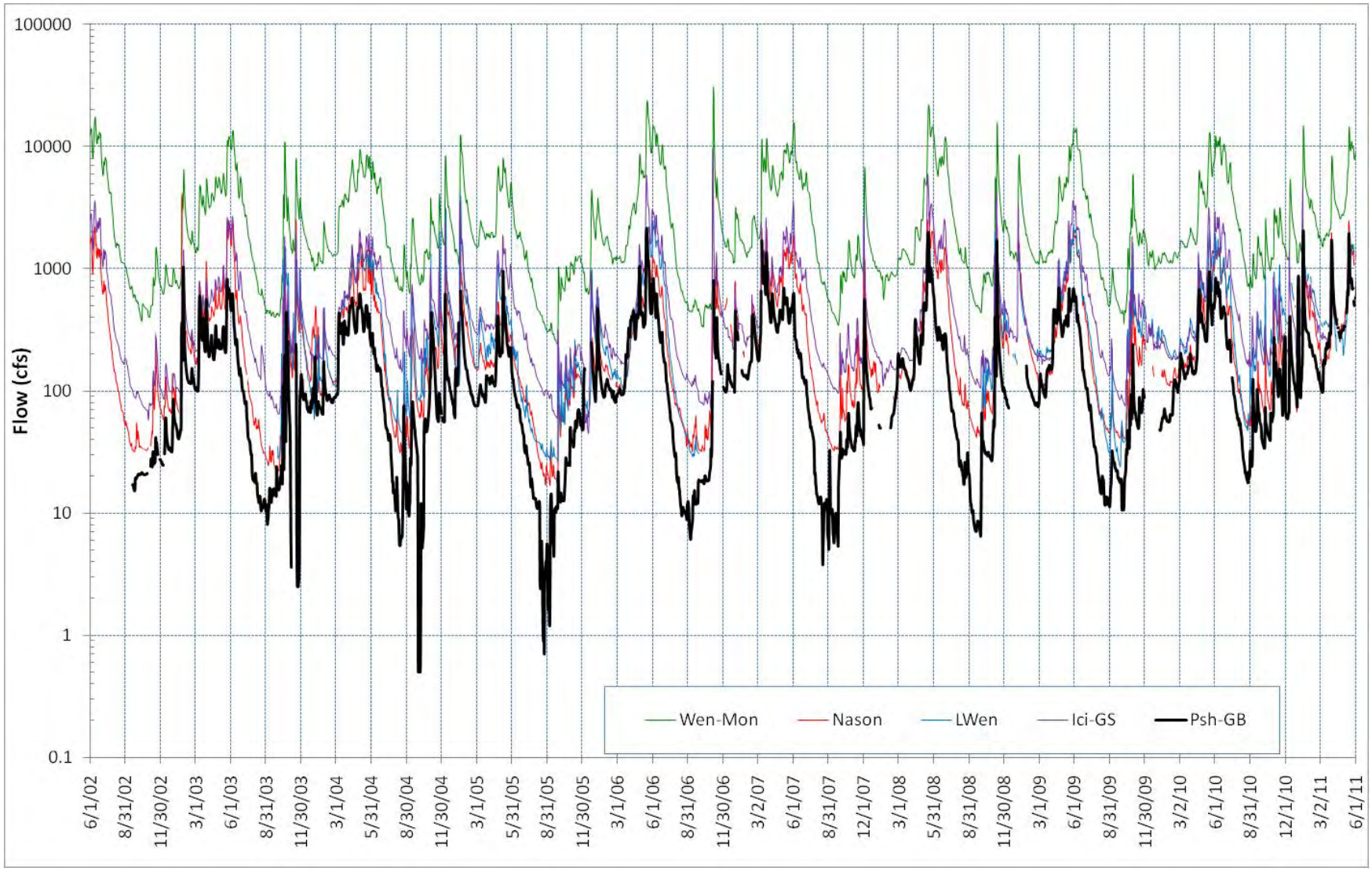

Figure 9. Measured flows at the Ecology "Peshastin Creek at Green Bridge Road" gaging station, with flows from other selected gages.

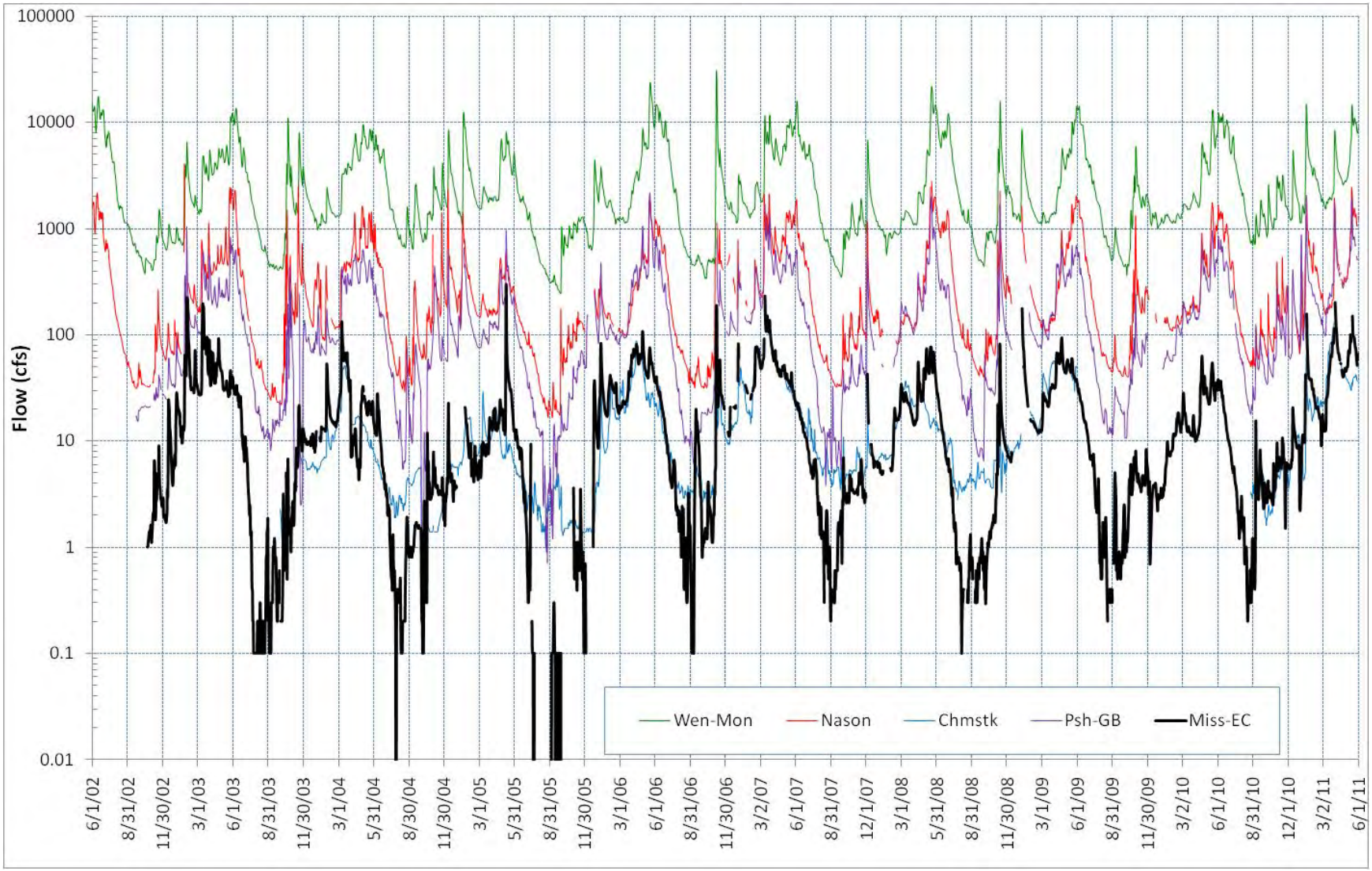

Figure 10. Measured flows at the Ecology “Mission Creek near Cashmere” gaging station, with flows from other selected gages.

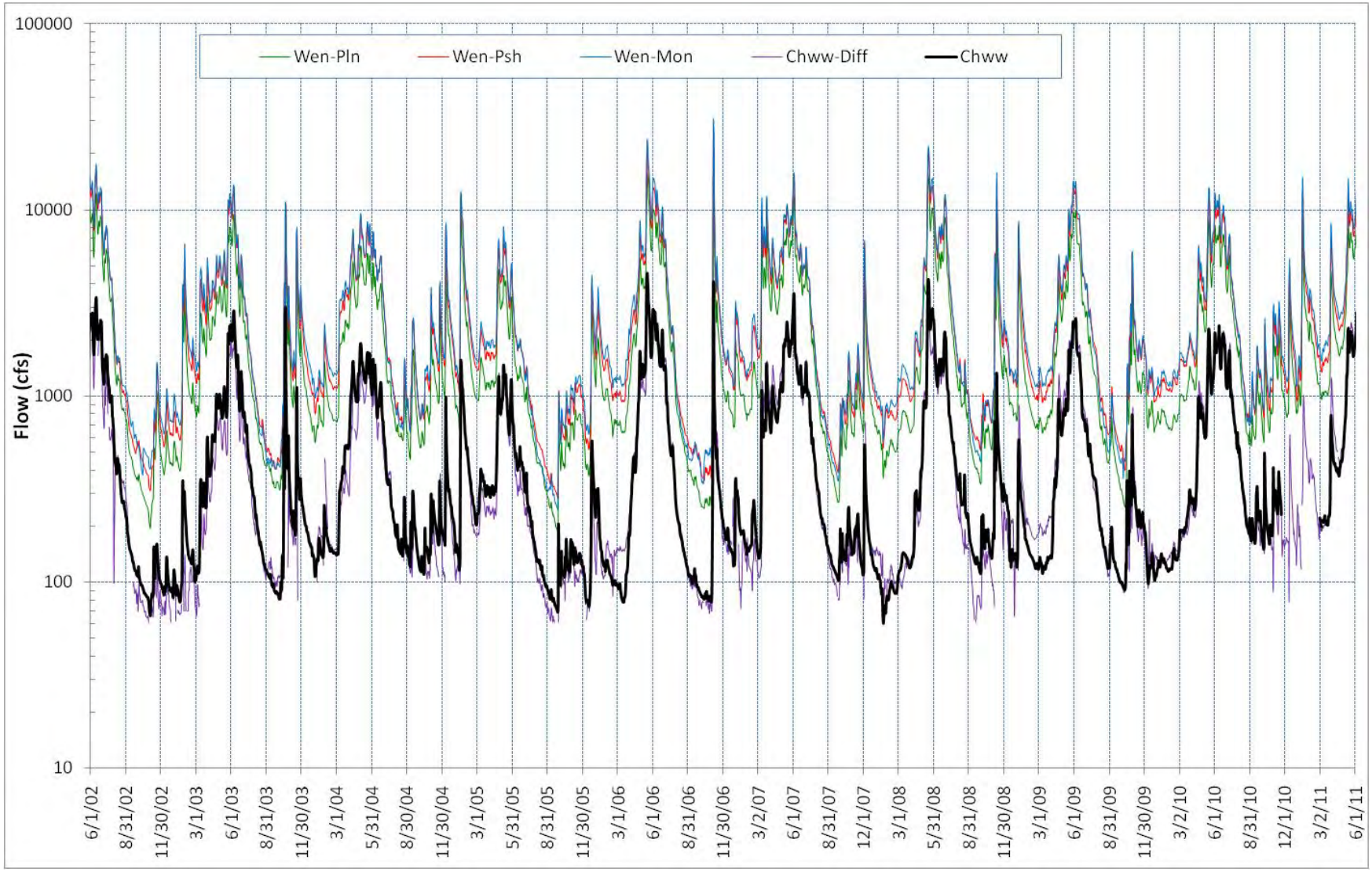

Figure 11. Measured flows at the USGS “Chiwawa River near Plain” gaging station, with flows from other selected gages.

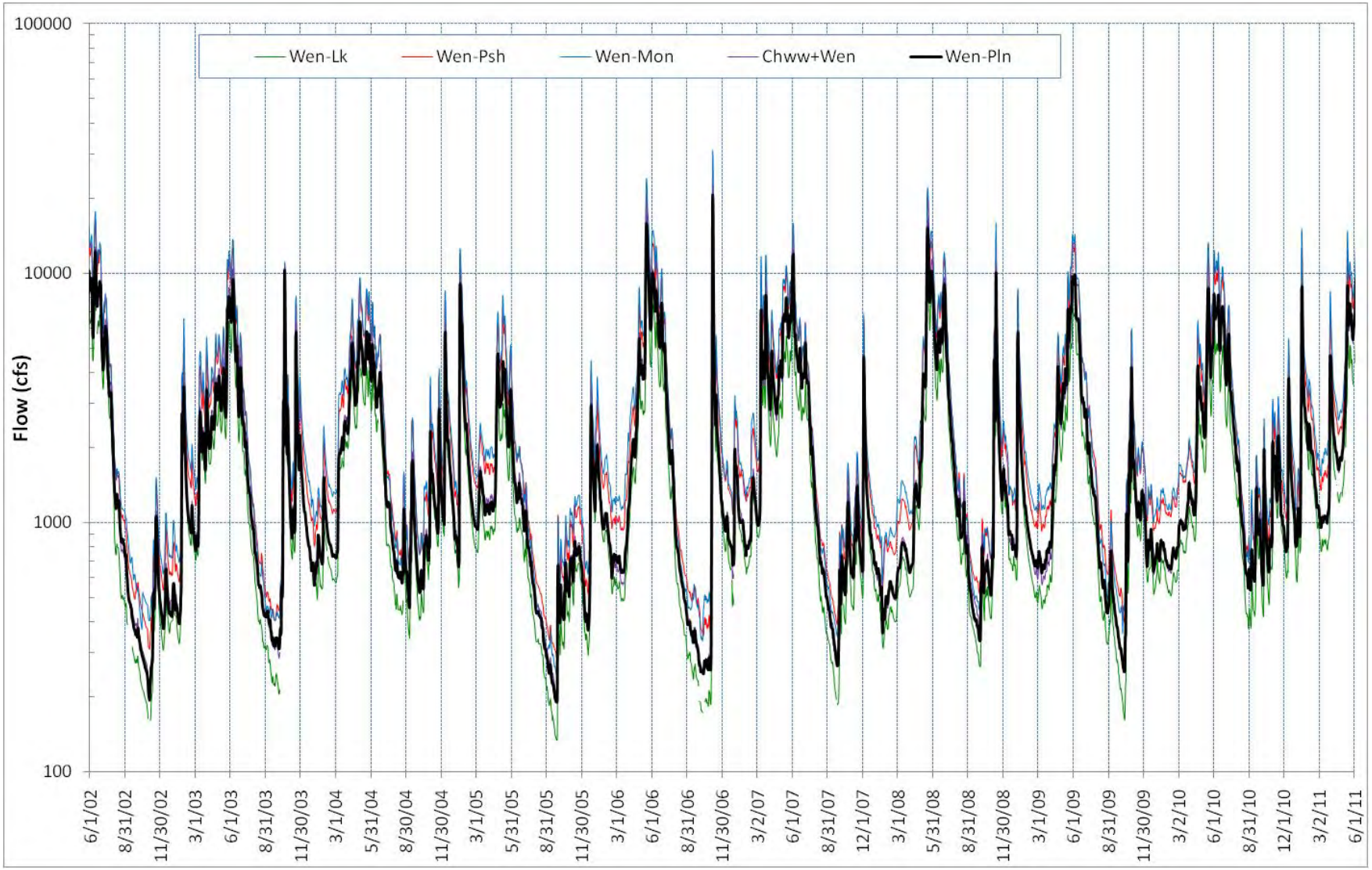

Figure 12. Measured flows at the USGS “Wenatchee River at Plain” gaging station, with flows from other selected gages.

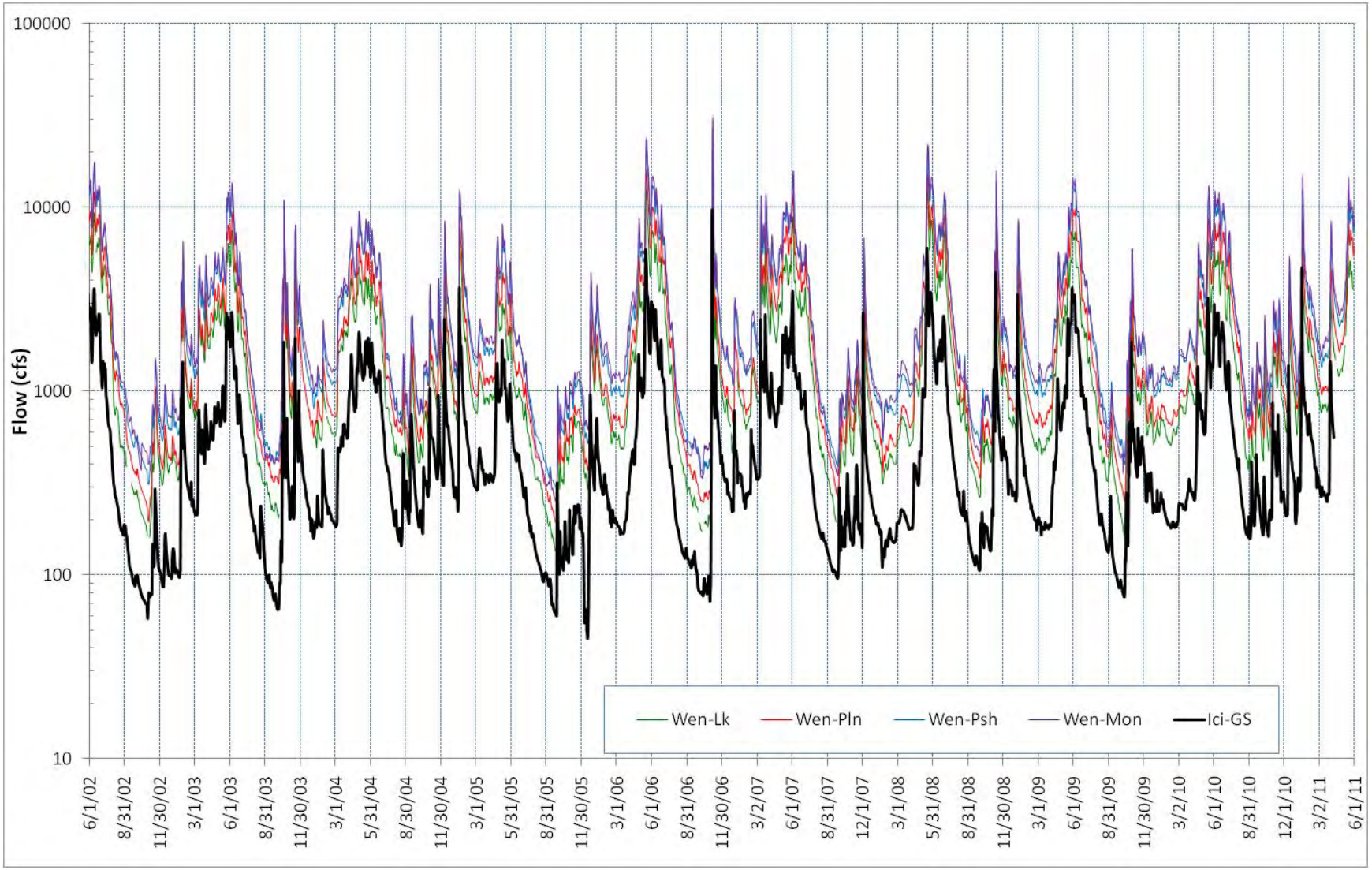

Figure 13. Measured flows at the USGS "Icicle Creek above Snow Creek near Leavenworth" gaging station, with flows from other selected gages.

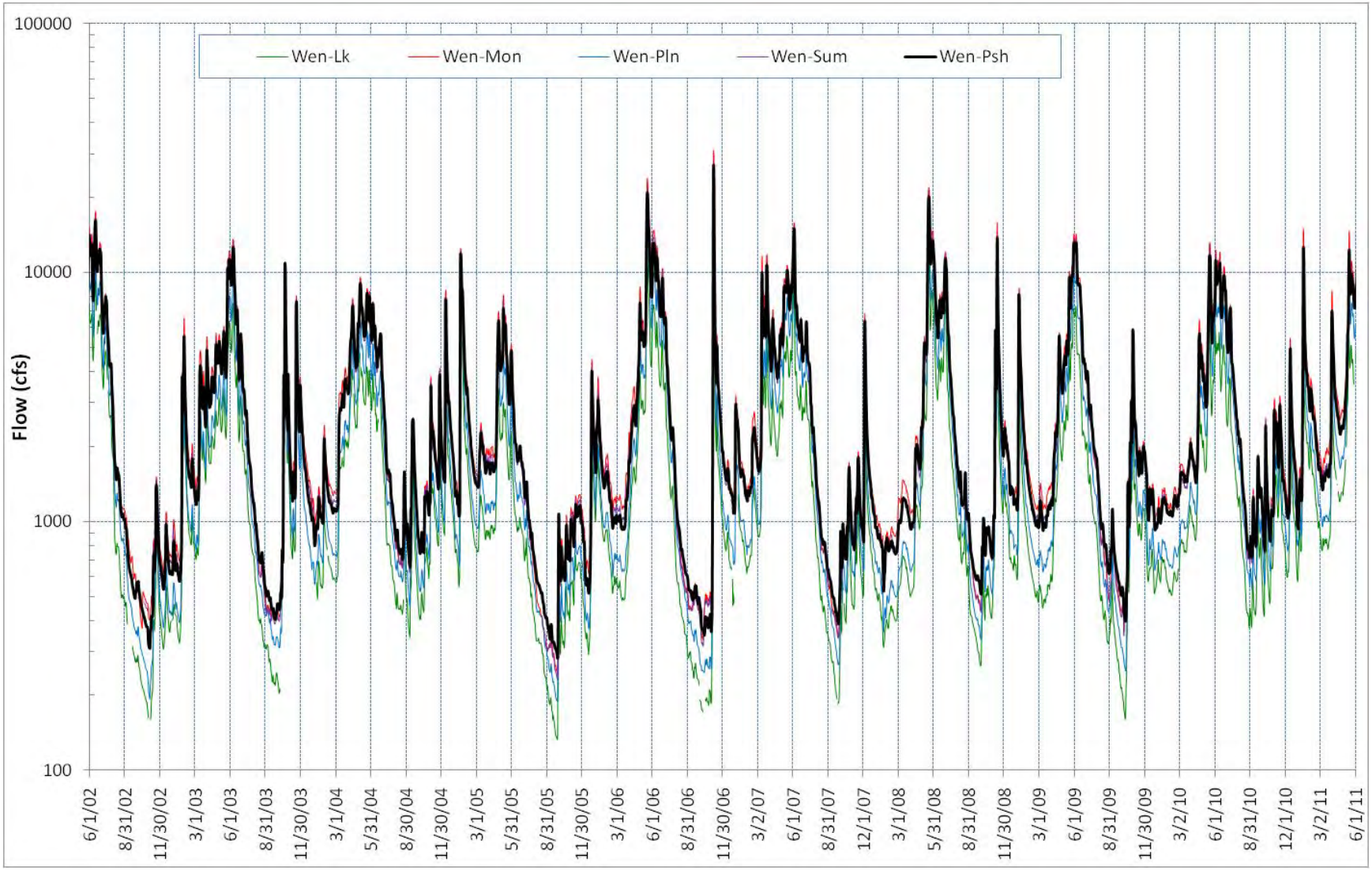

Figure 14. Measured flows at the USGS “Wenatchee River at Peshastin” gaging station, with flows from other selected gages.

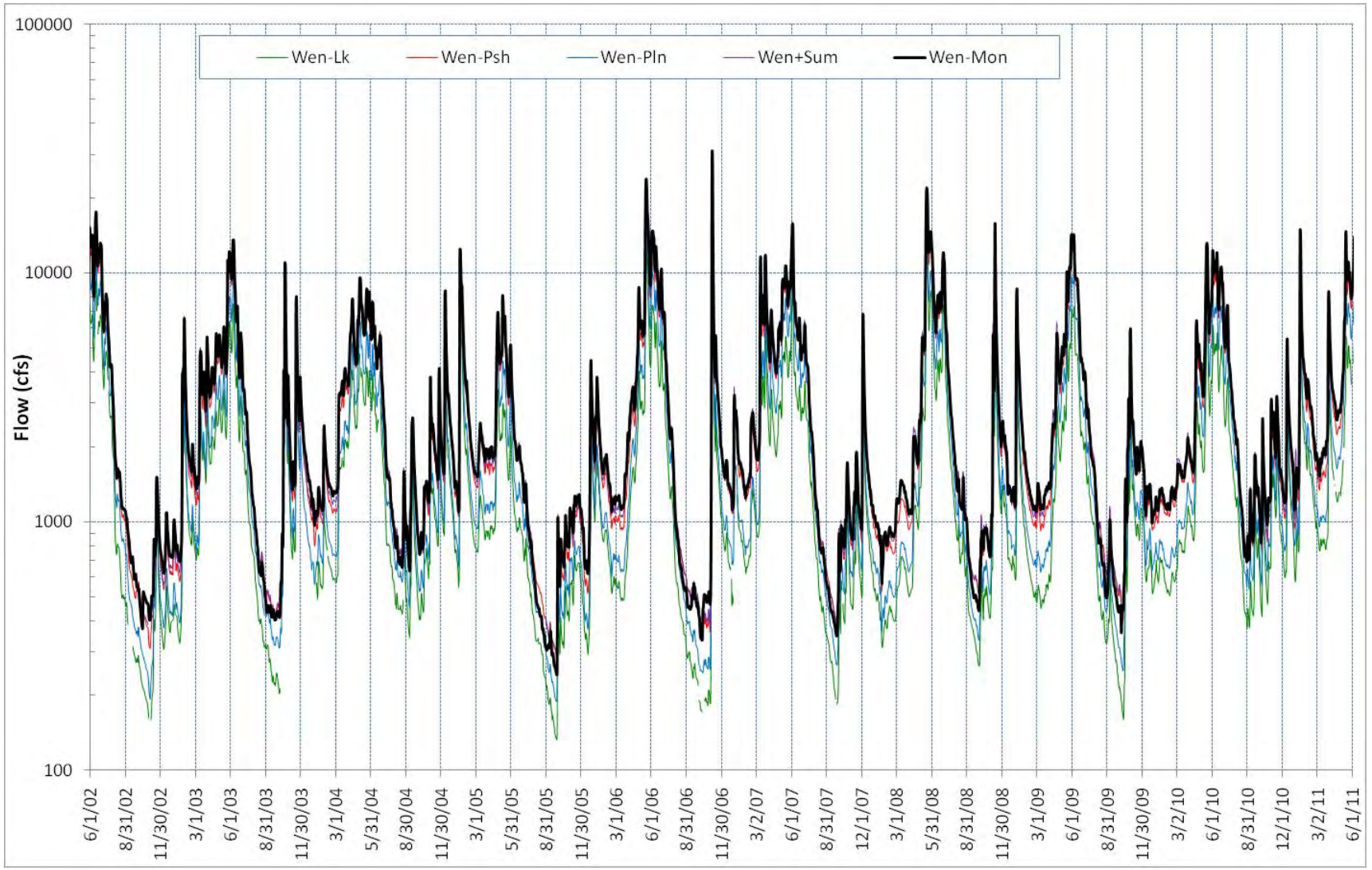

Figure 15. Measured flows at the USGS “Wenatchee River at Monitor” gaging station, with flows from other selected gages.

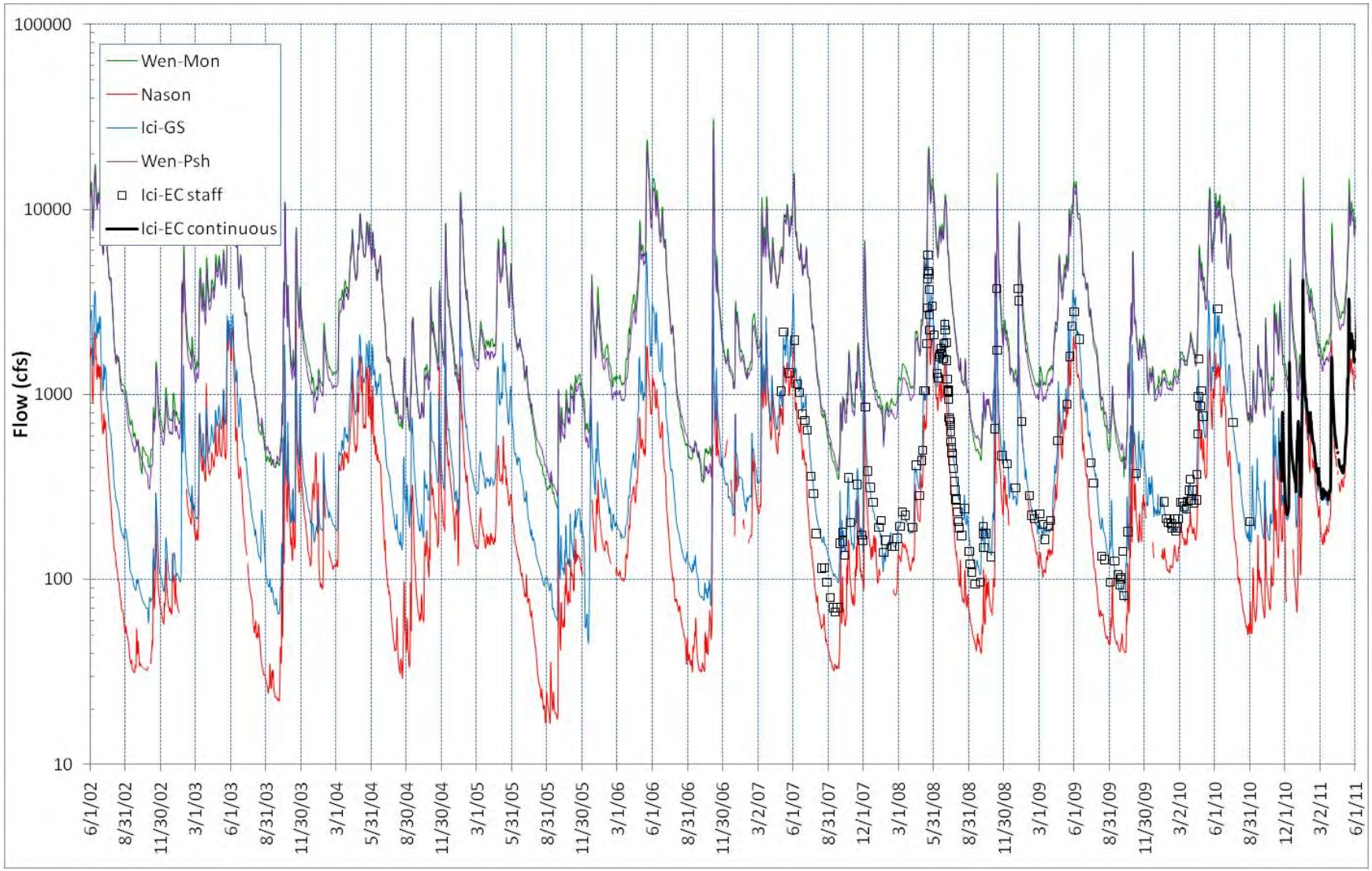

Figure 16. Measured flows at the Ecology “Icicle Creek near Leavenworth” gaging station, with flows from other selected gages.

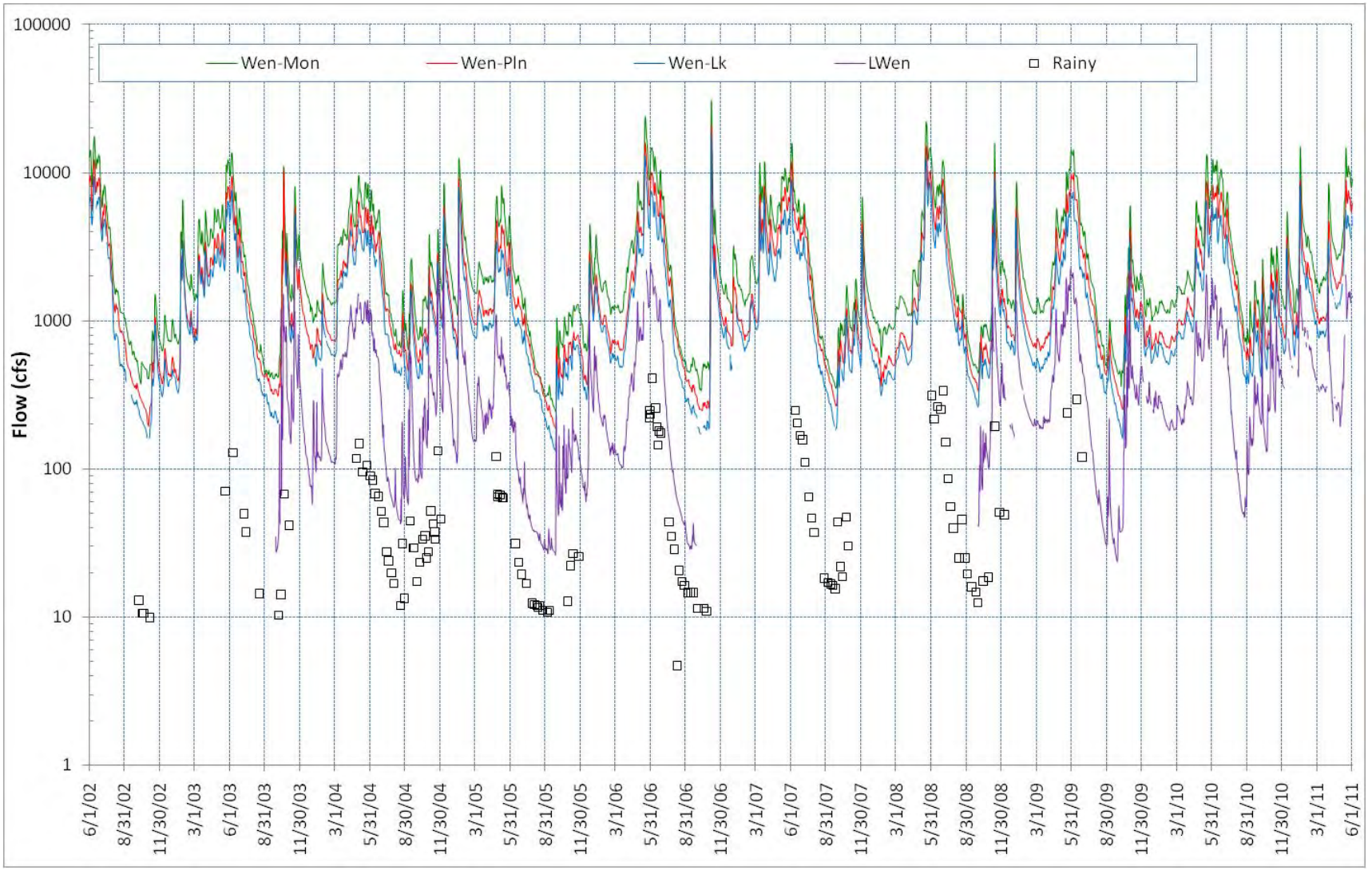

Figure 17. Measured flows at the Ecology “Rainy Creek near Mouth” gaging station, with flows from other selected gages.

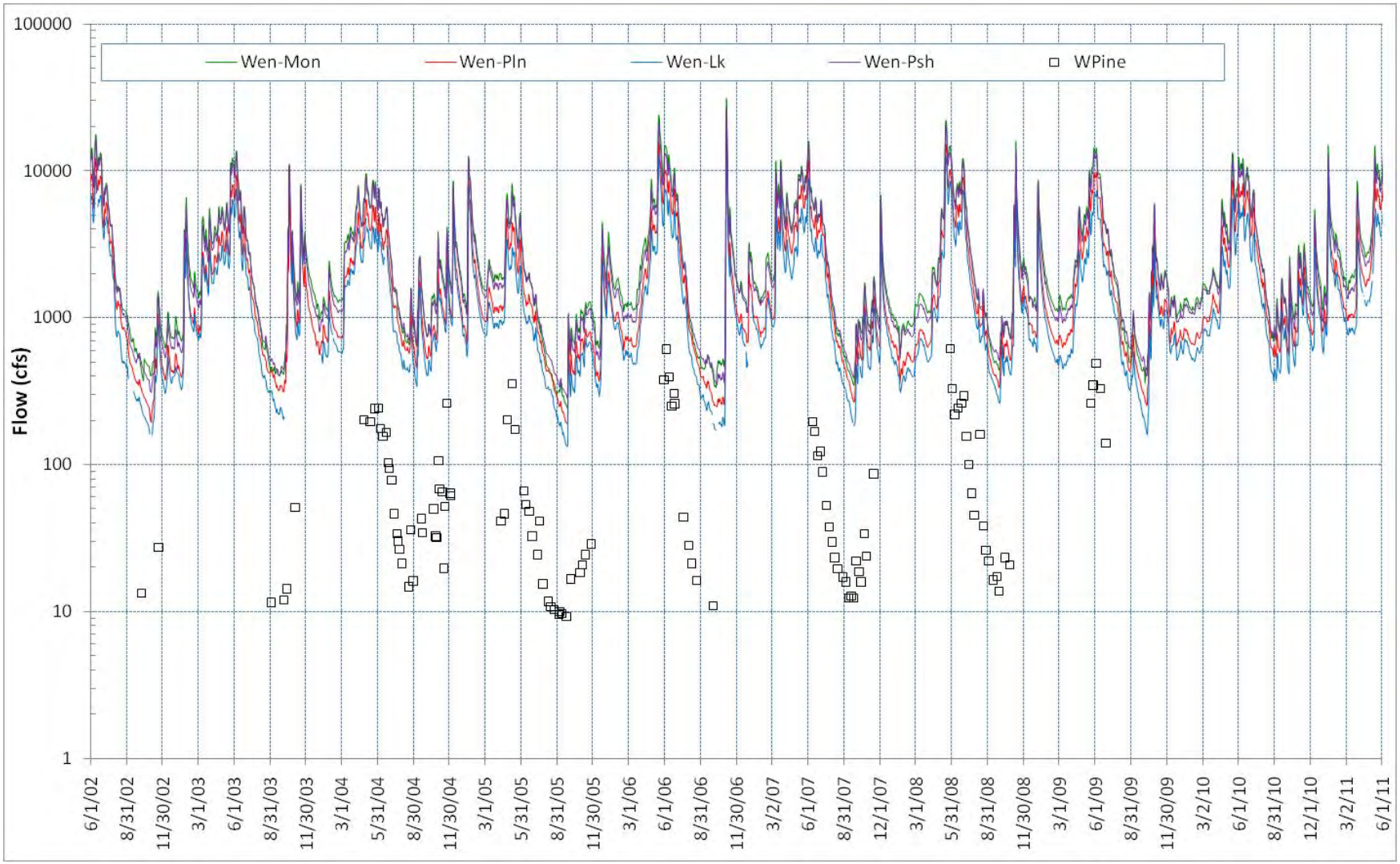

Figure 18. Measured flows at the Ecology "White Pine Creek at Mouth" gaging station, with flows from other selected gages.

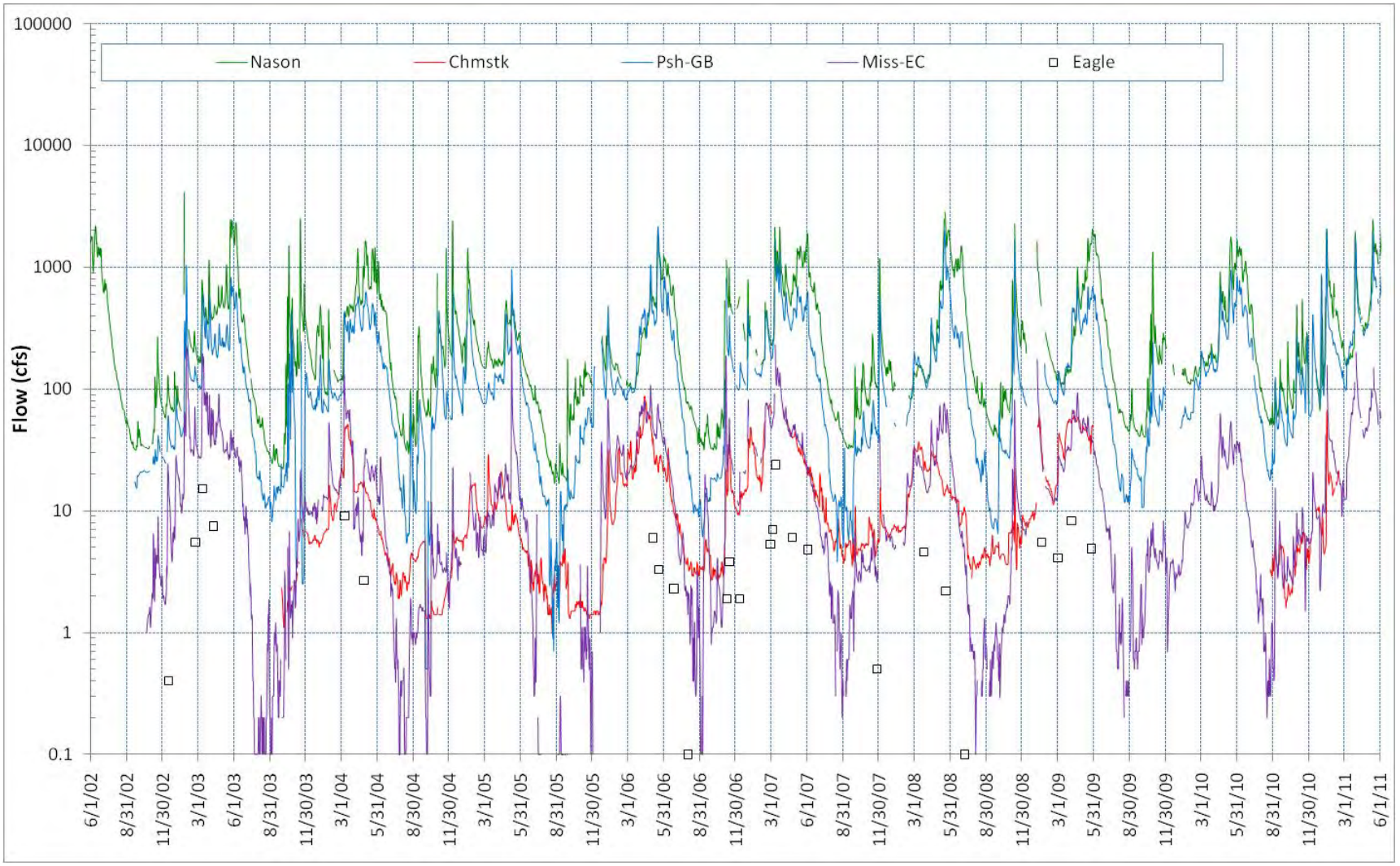

Figure 19. Measured flows at the Ecology “Eagle Creek near Mouth” gaging station, with flows from other selected gages.

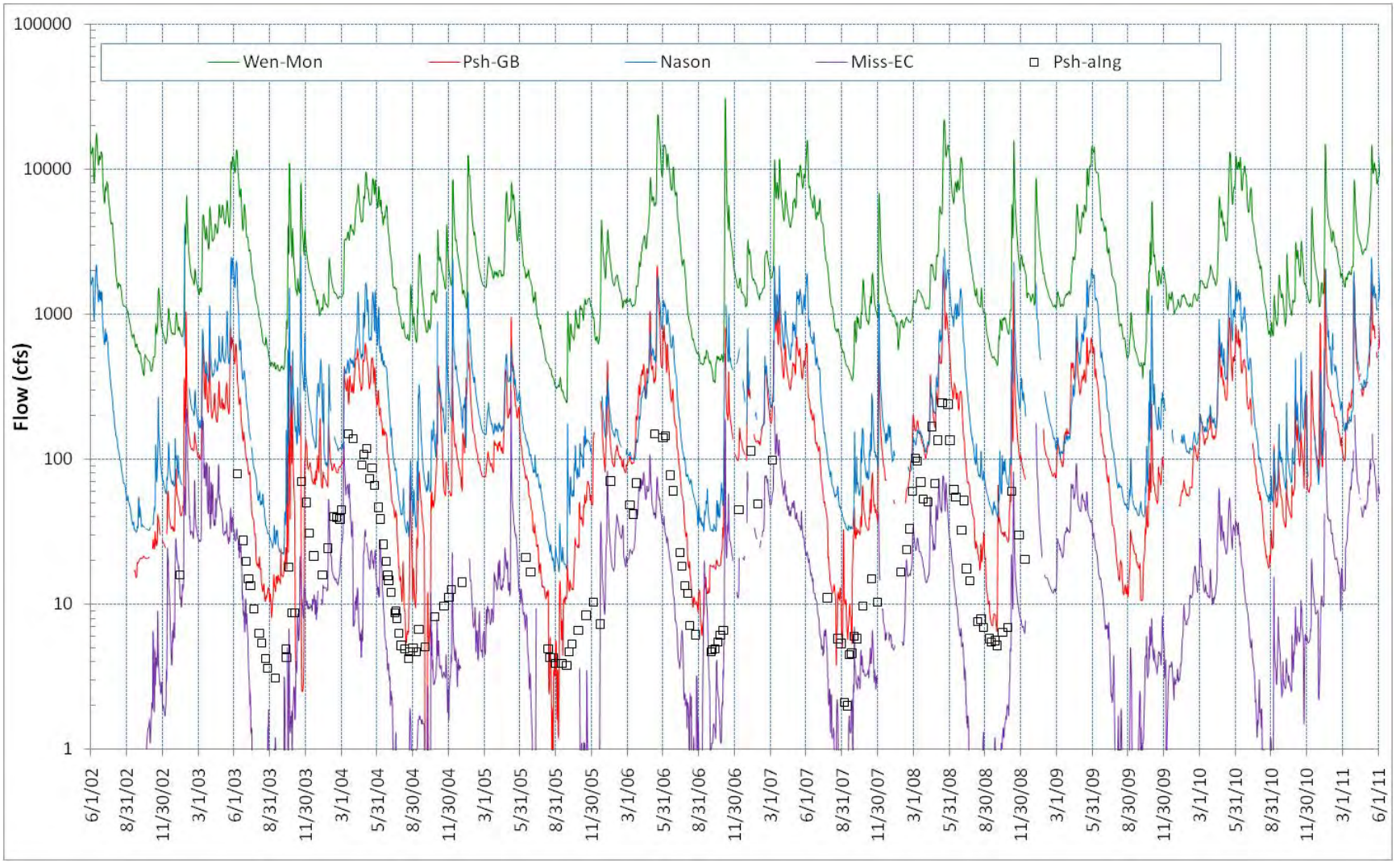

Figure 20. Measured flows at the Ecology “Peshastin Creek above Ingalls” gaging station, with flows from other selected gages.

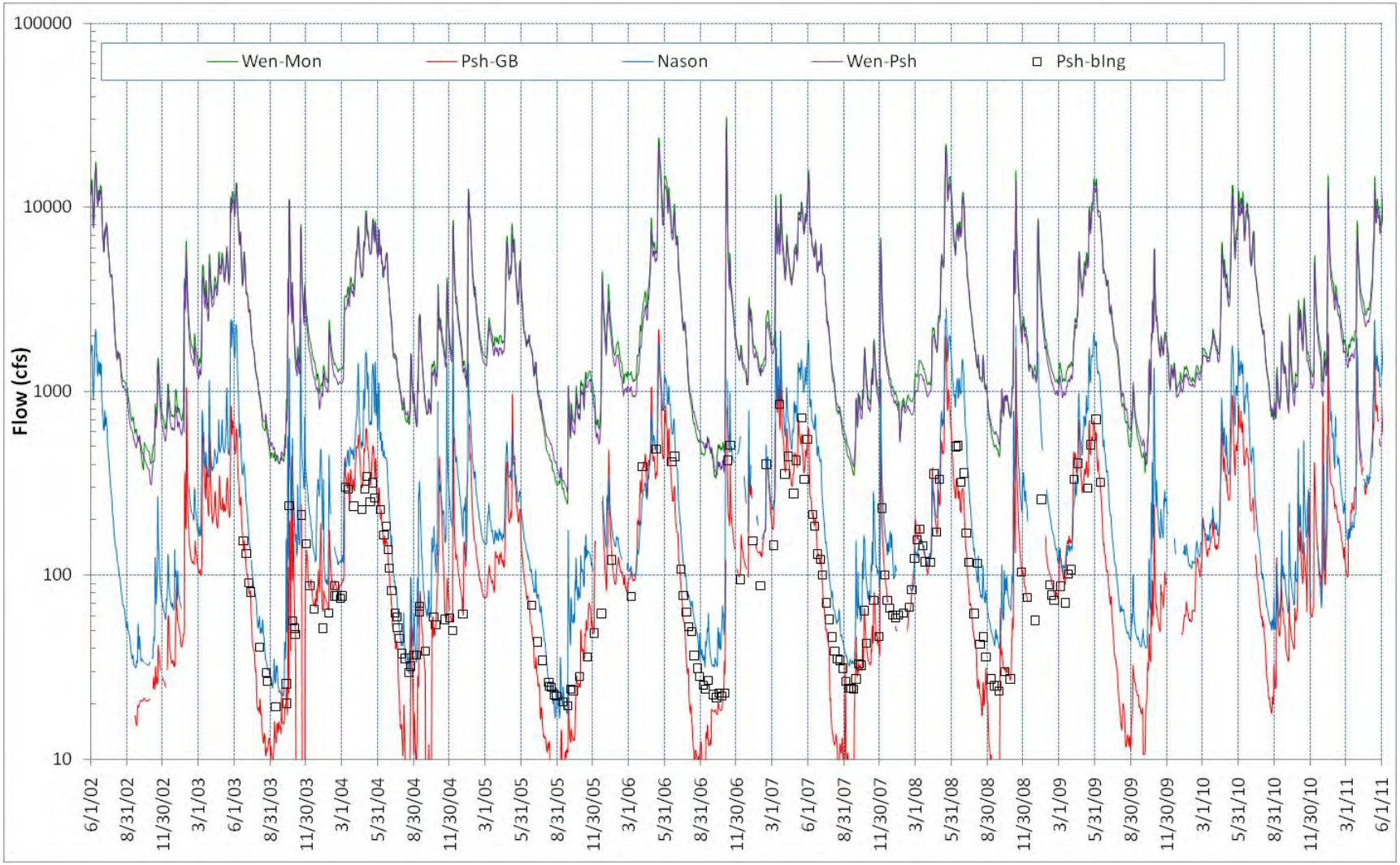

Figure 21. Measured flows at the Ecology “Peshastin Creek below Ingalls” gaging station, with flows from other selected gages.

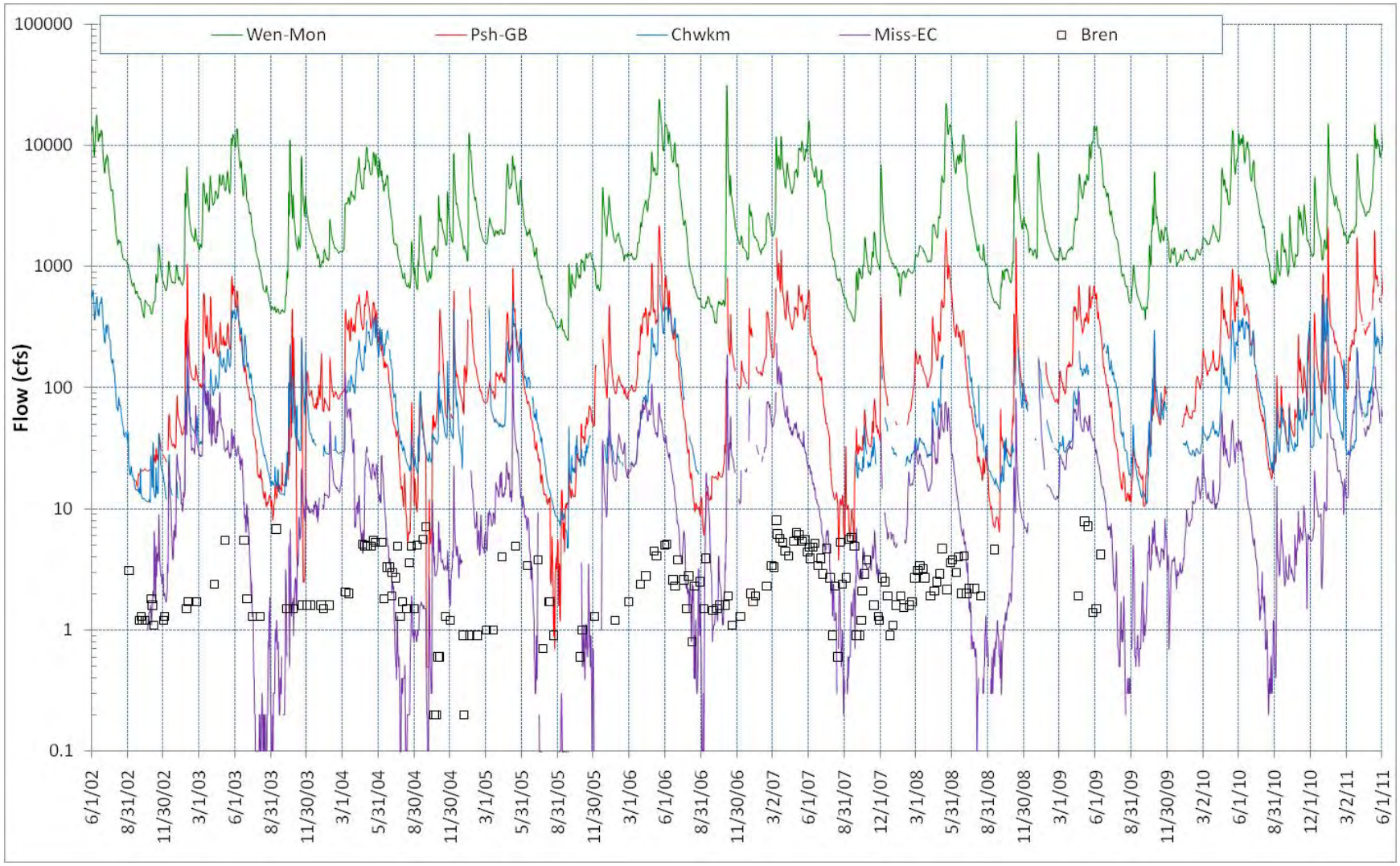

Figure 22. Measured flows at the Ecology “Brender Creek near Cashmere” gaging station, with flows from other selected gages.

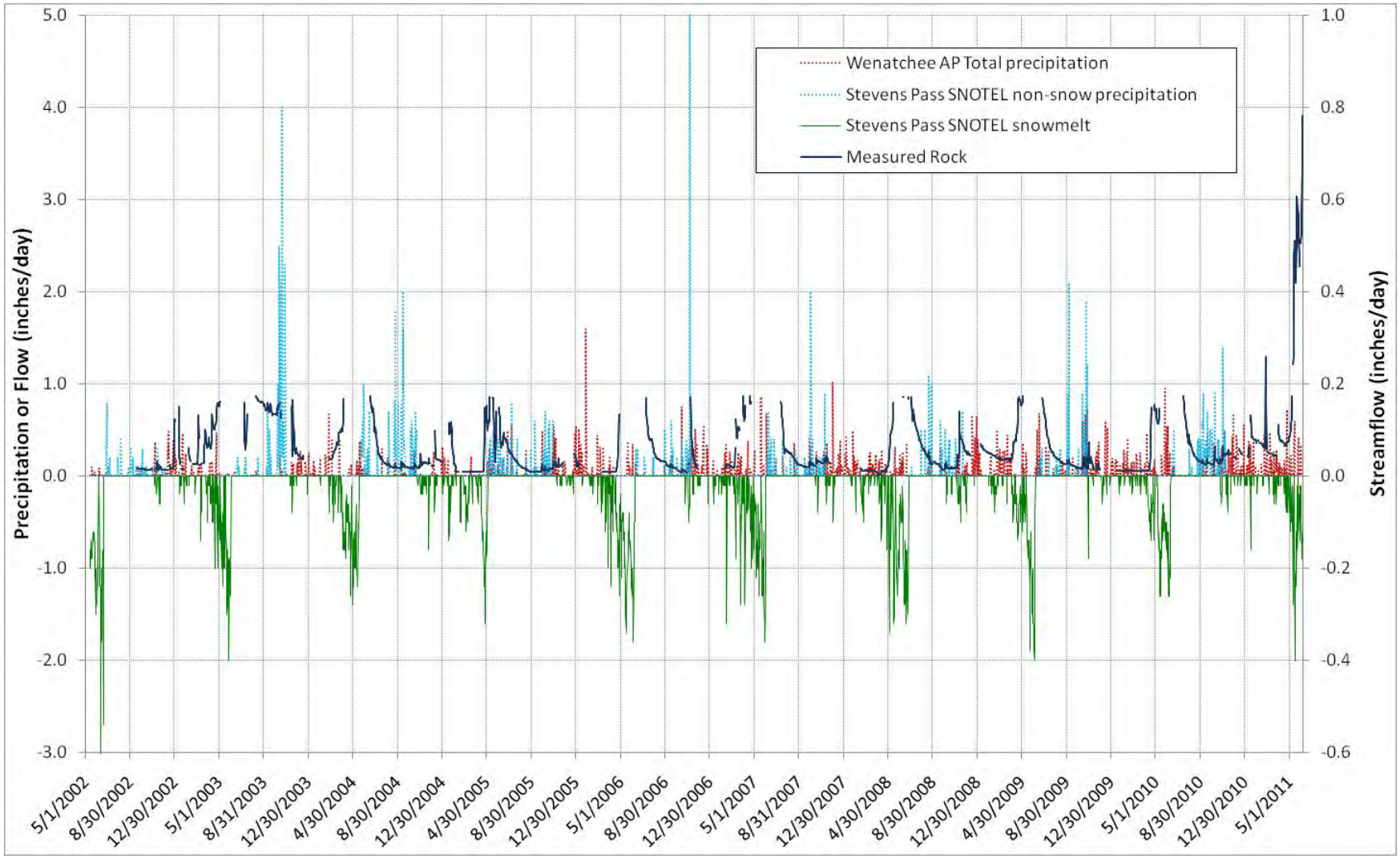

Figure 23. Measured areal flows at the Ecology "Rock Creek near Mouth" gaging station, with precipitation and snowmelt data.

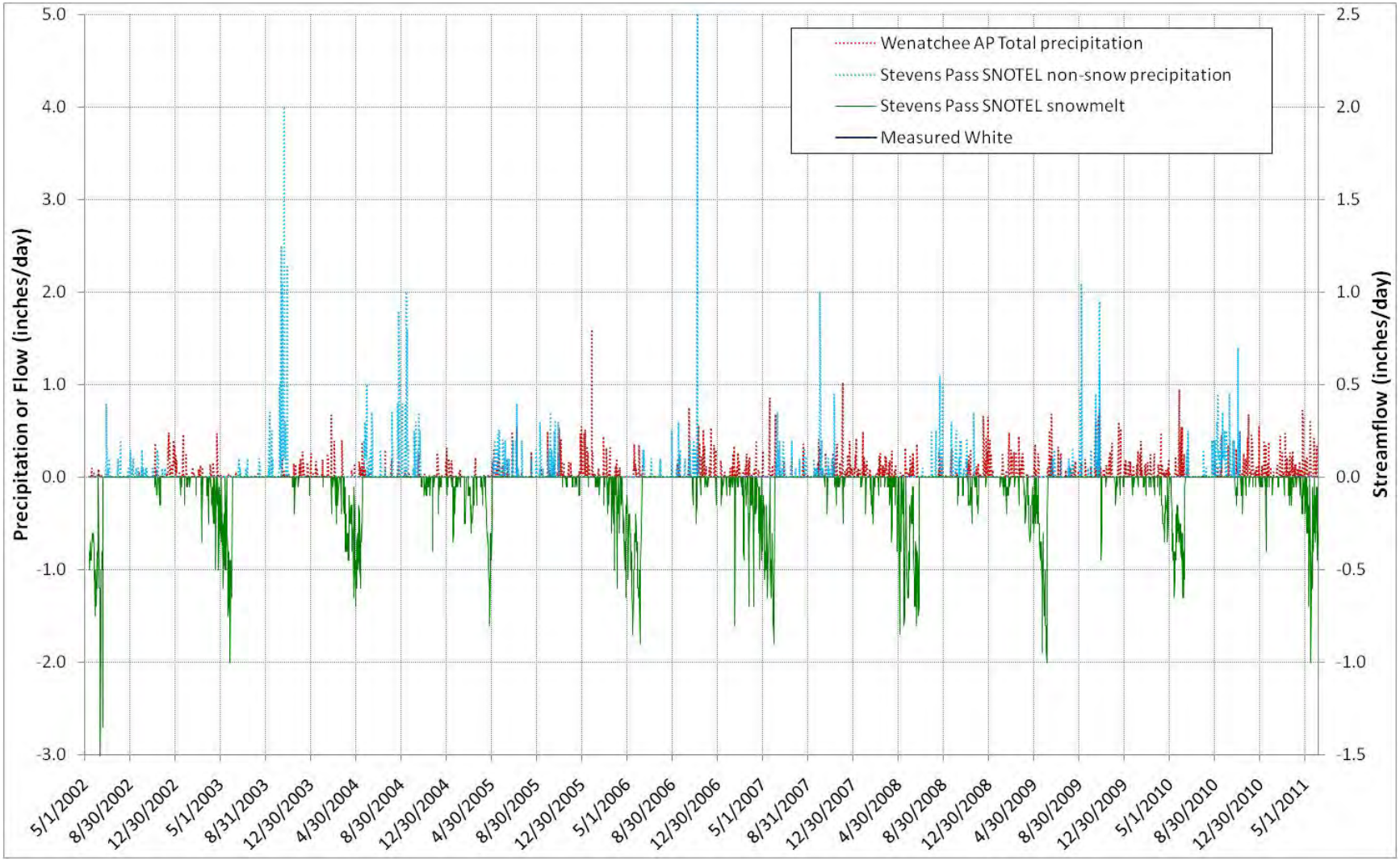

Figure 24. Measured areal flows at the Ecology “White River near Plain” gaging station, with precipitation and snowmelt data.

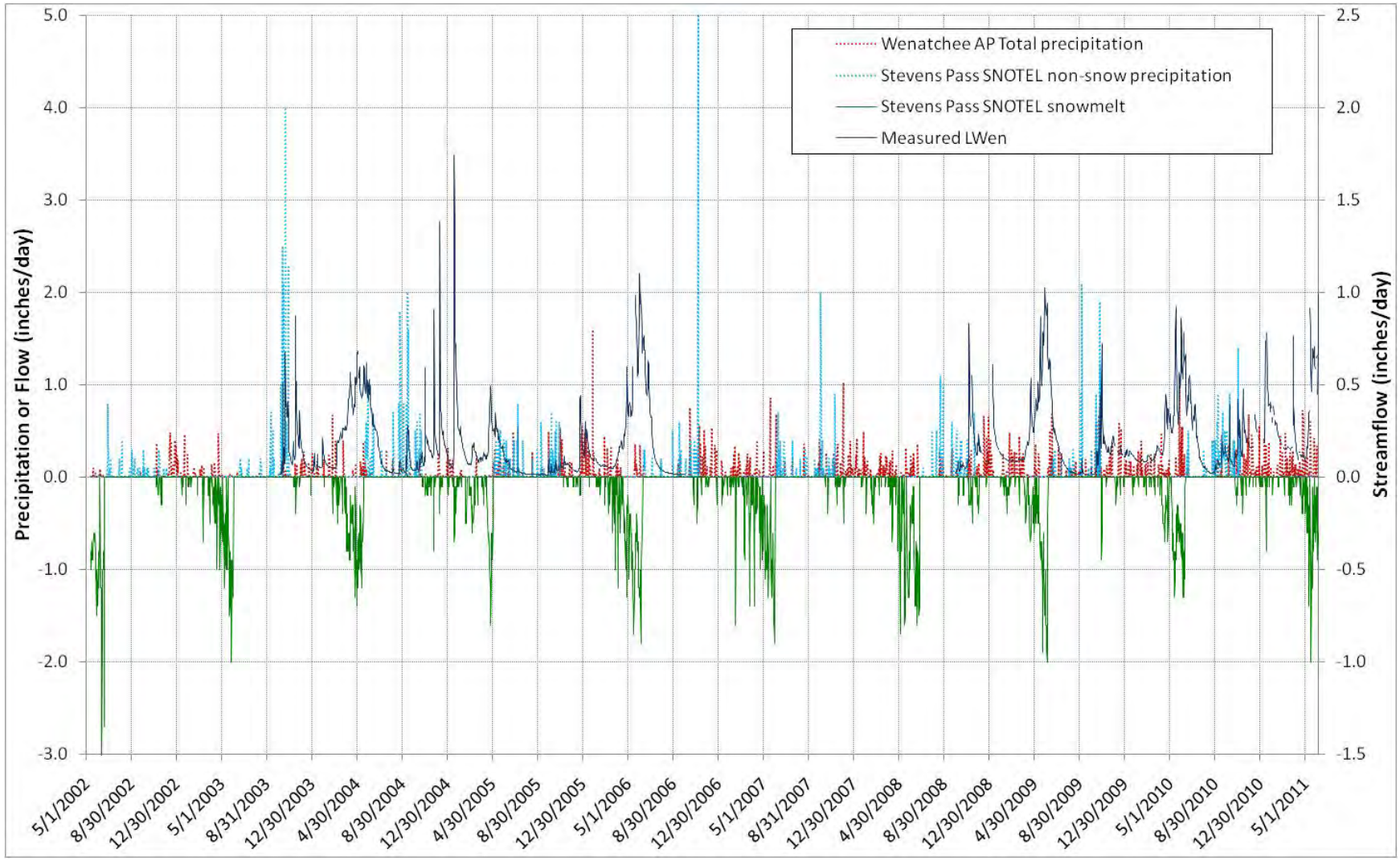

Figure 25. Measured areal flows at the Ecology "Little Wenatchee River below Rainy Creek" gaging station, with precipitation and snowmelt data.

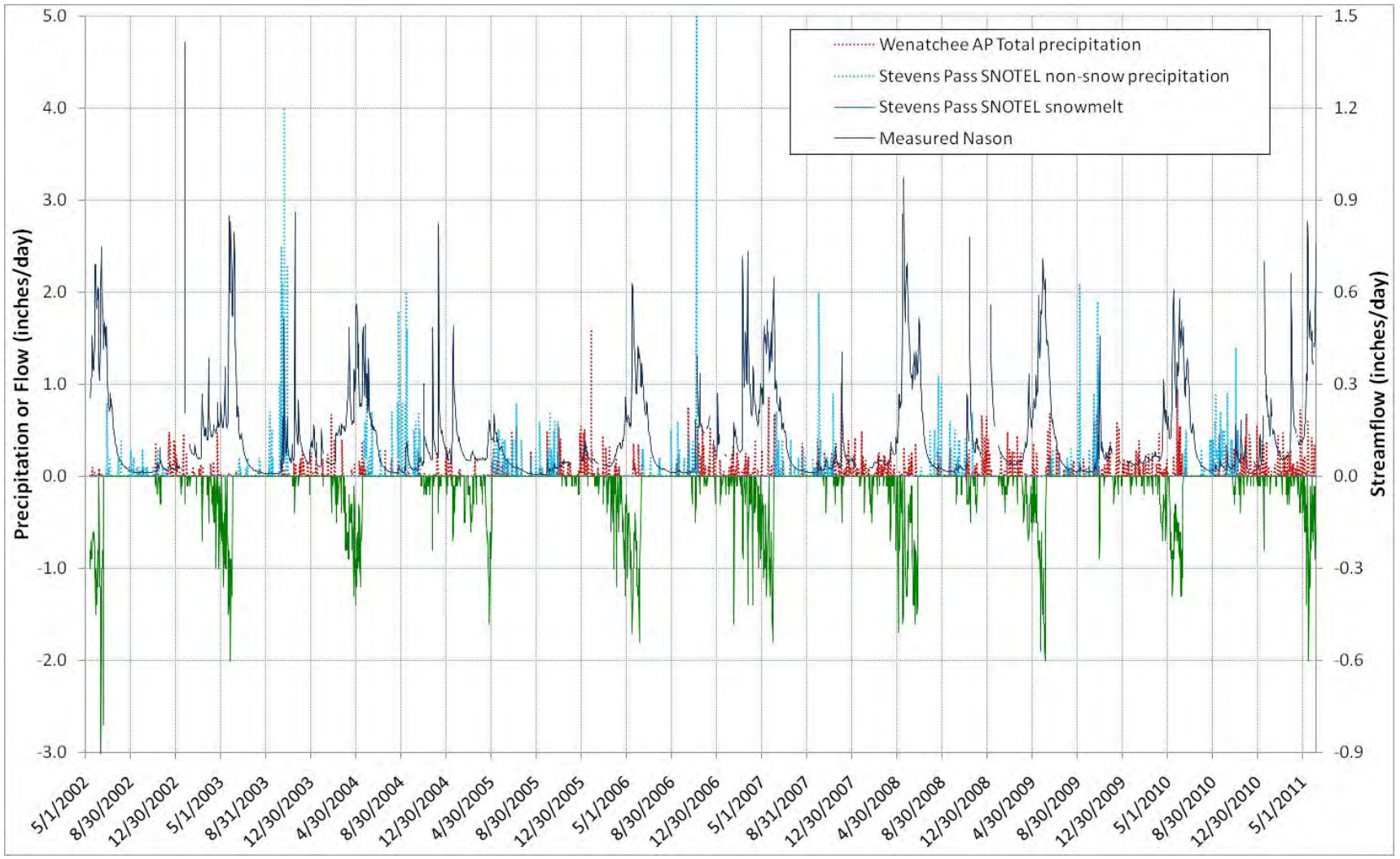

Figure 26. Measured areal flows at the Ecology "Nason Creek near mouth" gaging station, with precipitation and snowmelt data.

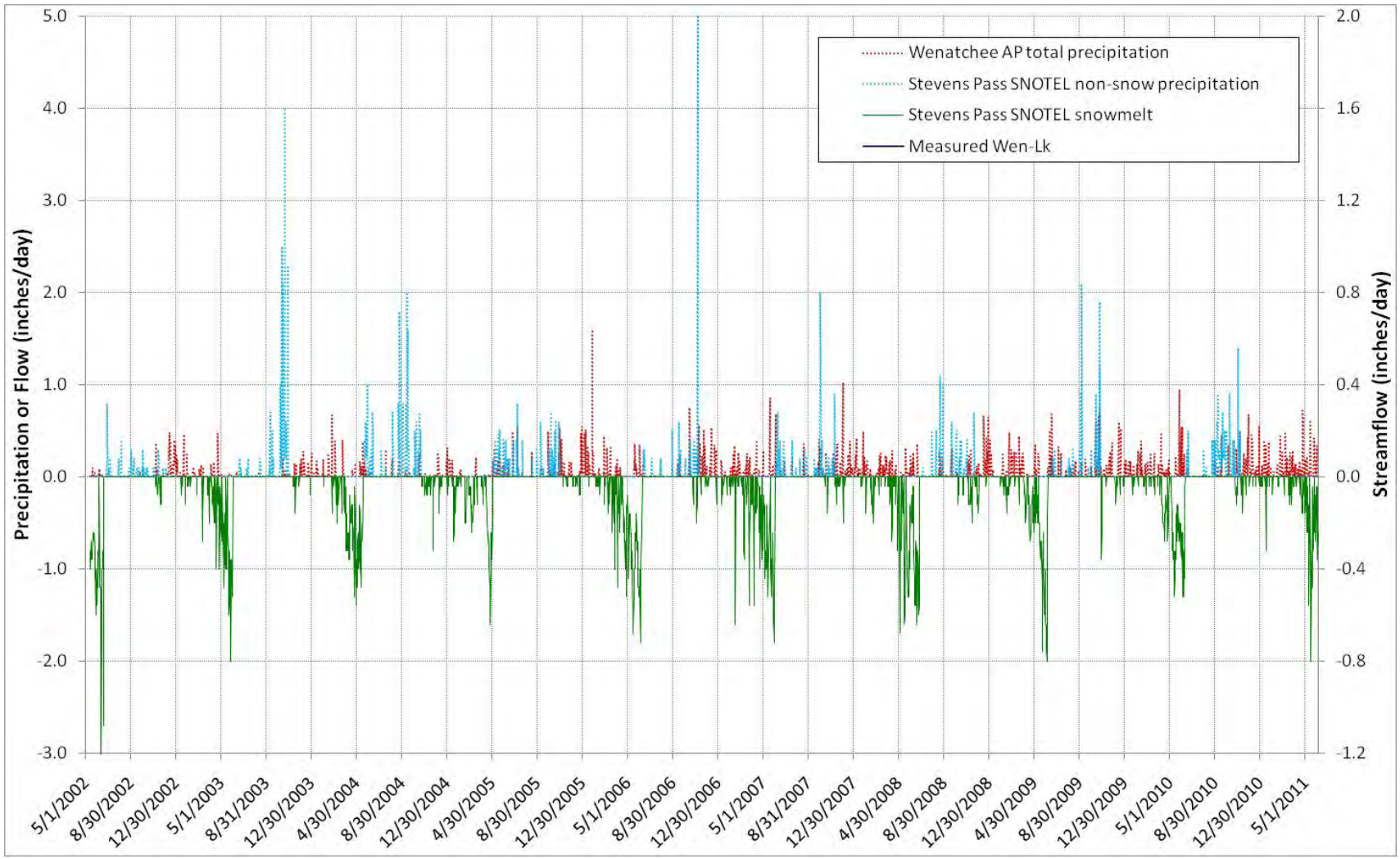

Figure 27. Measured areal flows at the Ecology "Wenatchee River below Lake Wenatchee" gaging station, with precipitation and snowmelt data.

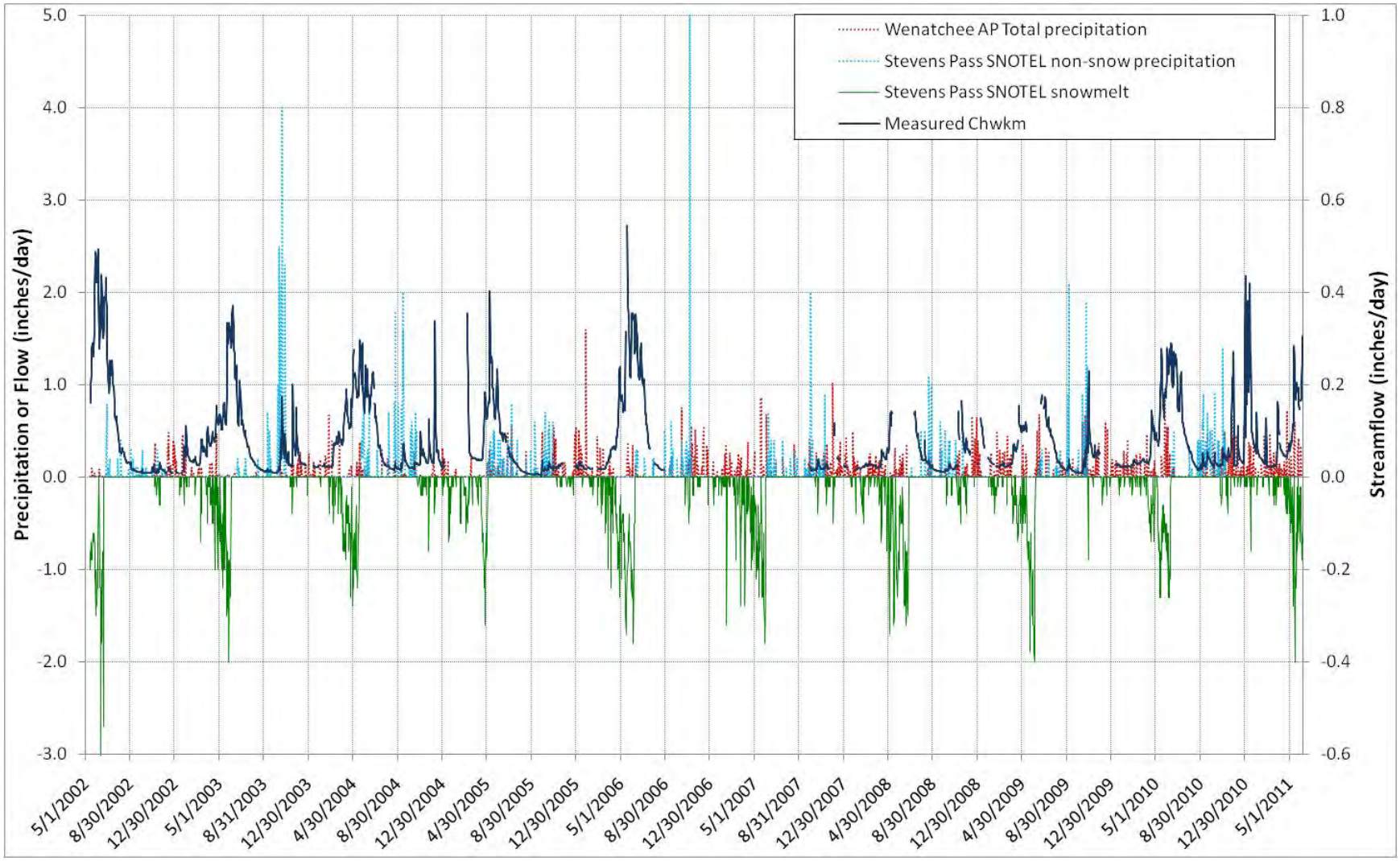

Figure 28. Measured areal flows at the Ecology “Chiwaukum Creek near mouth” gaging station, with precipitation and snowmelt data.

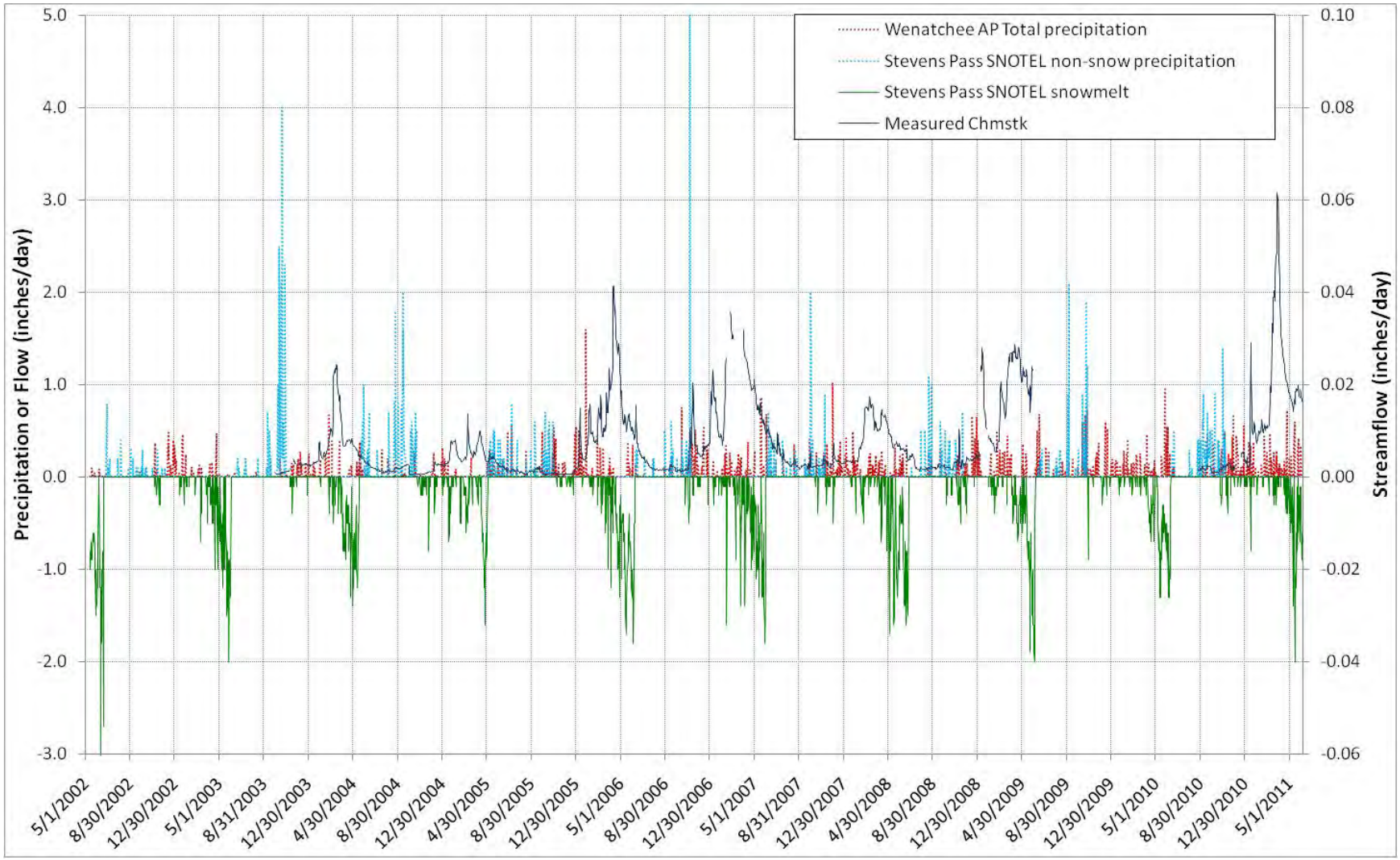

Figure 29. Measured areal flows at the Ecology “Chumstick Creek near mouth” gaging station, with precipitation and snowmelt data.

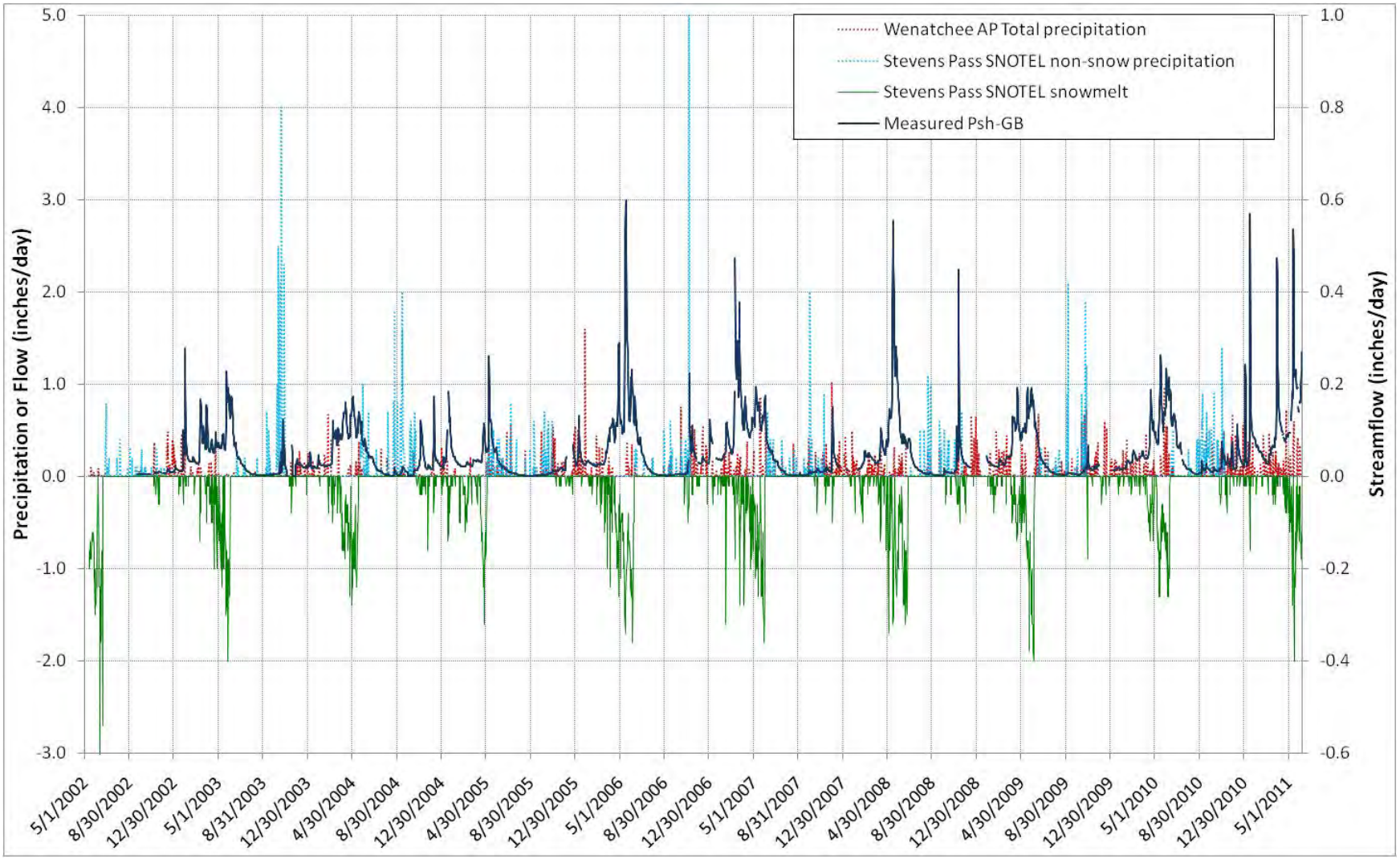

Figure 30. Measured areal flows at the Ecology "Peshastin Creek at Green Bridge Road" gaging station, with precipitation and snowmelt data.

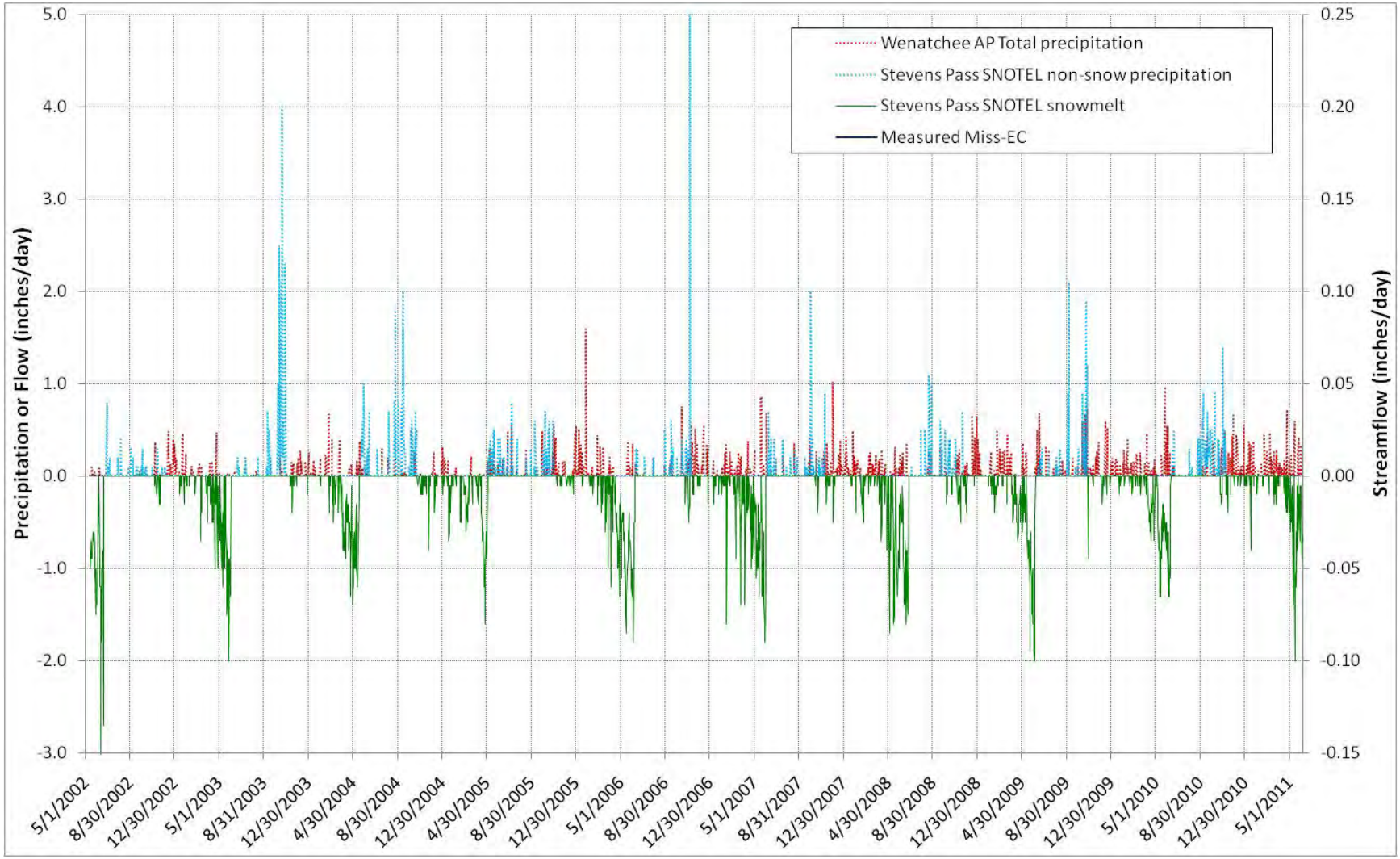

Figure 31. Measured areal flows at the Ecology “Mission Creek near Cashmere” gaging station, with precipitation and snowmelt data.

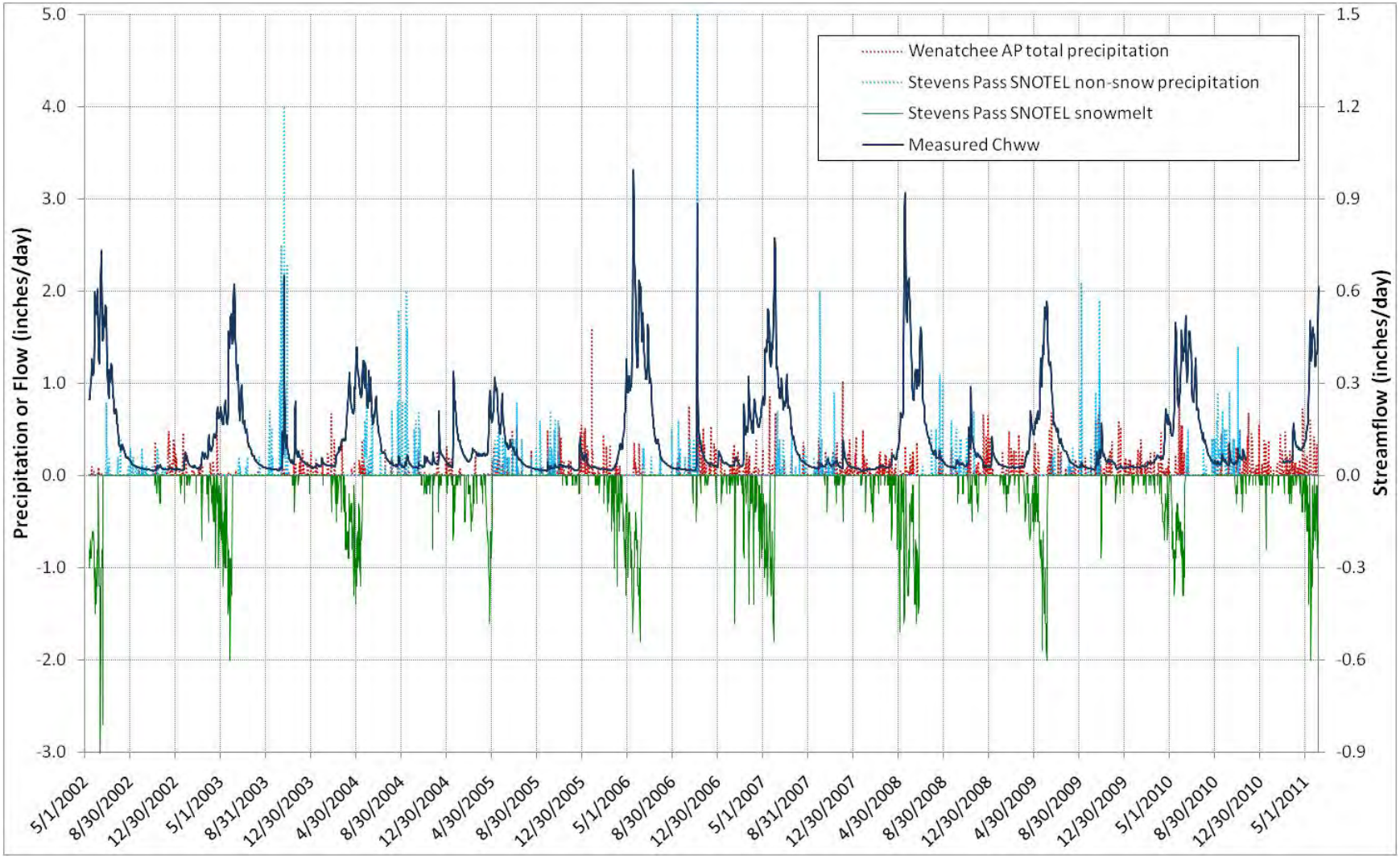

Figure 32. Measured areal flows at the USGS “Chiwawa River near Plain” gaging station, with precipitation and snowmelt data.

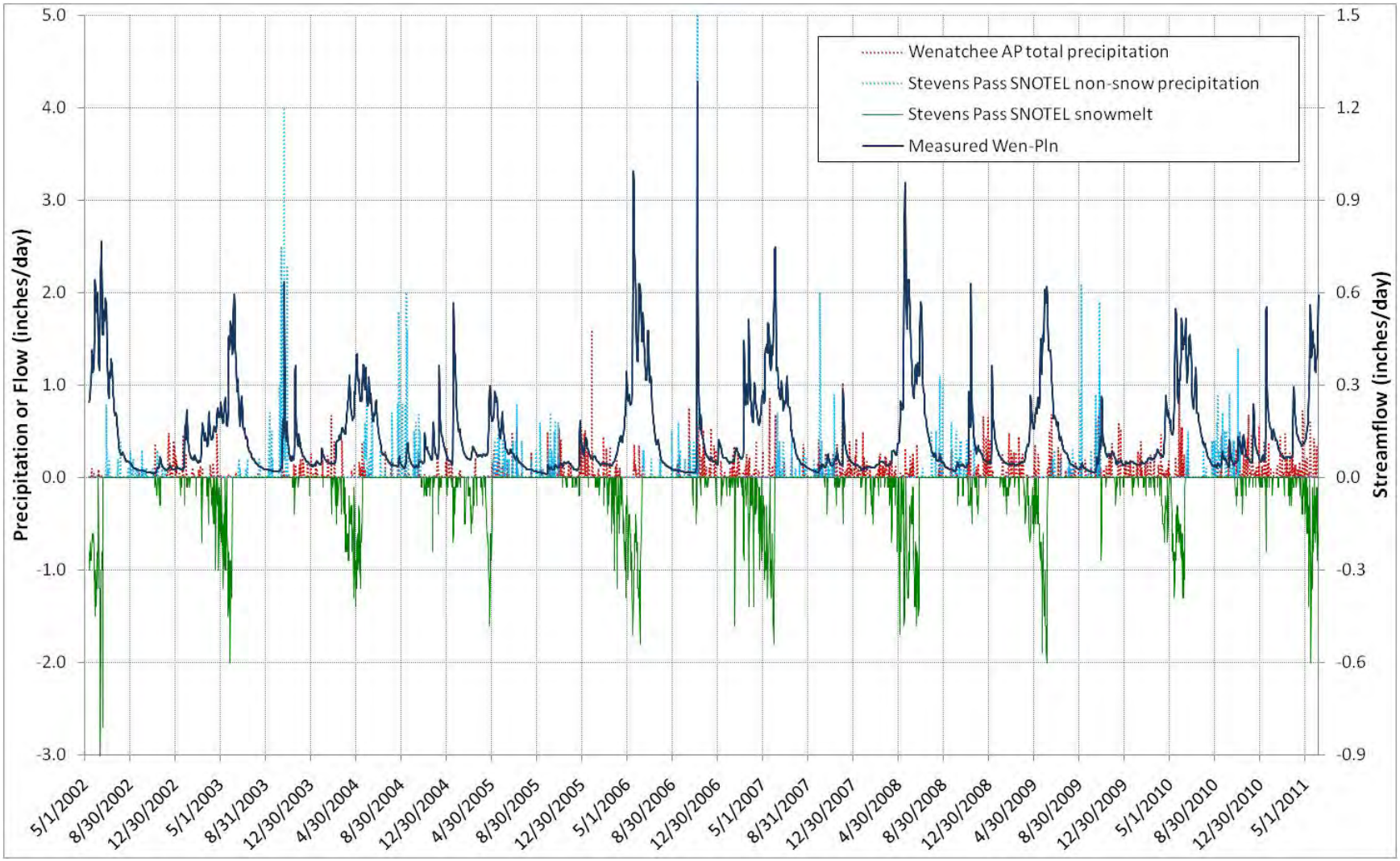

Figure 33. Measured areal flows at the USGS “Wenatchee River at Plain” gaging station, with precipitation and snowmelt data.

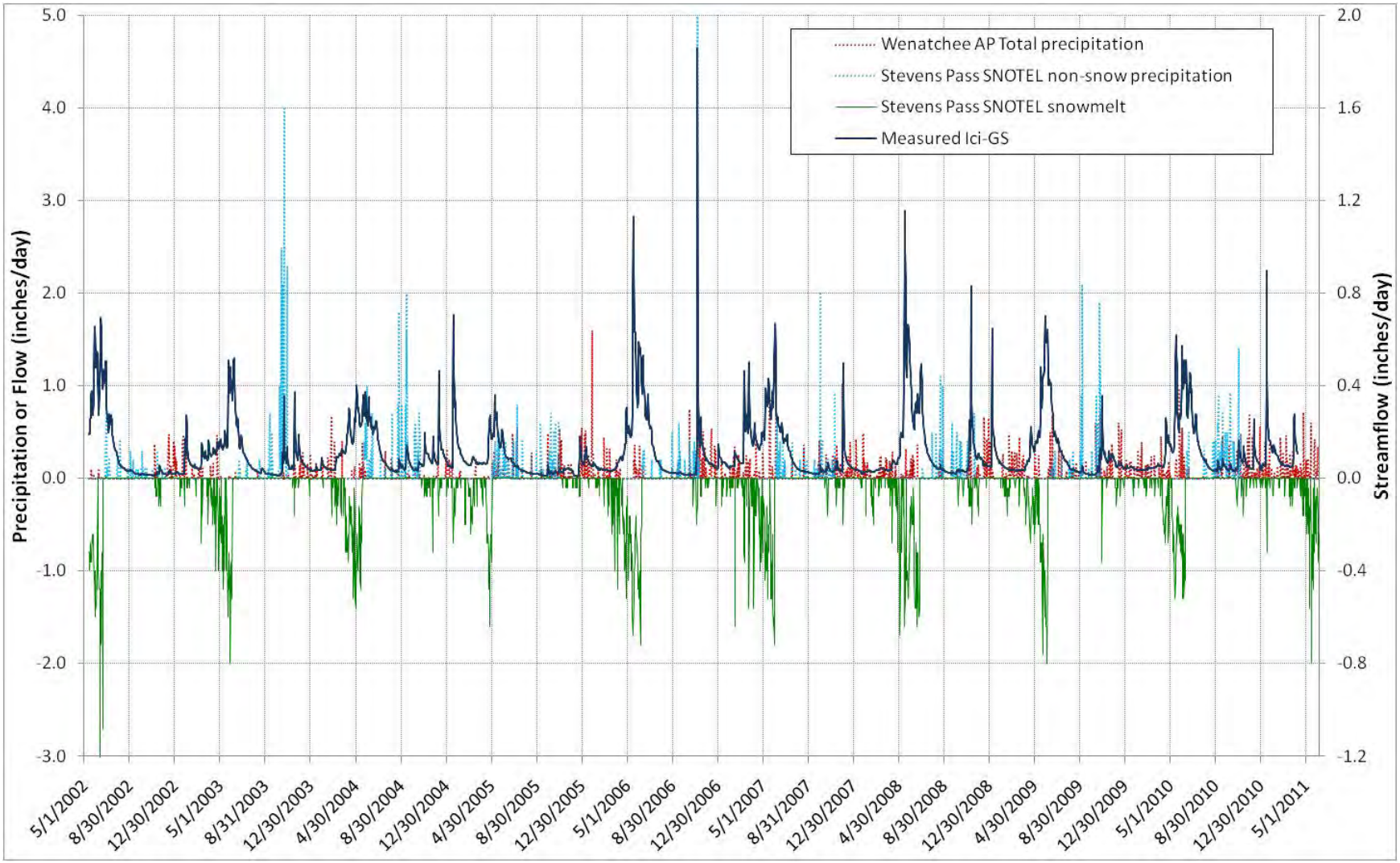

Figure 34. Measured areal flows at the USGS "Icicle Creek above Snow Creek near Leavenworth" gaging station, with precipitation and snowmelt data.

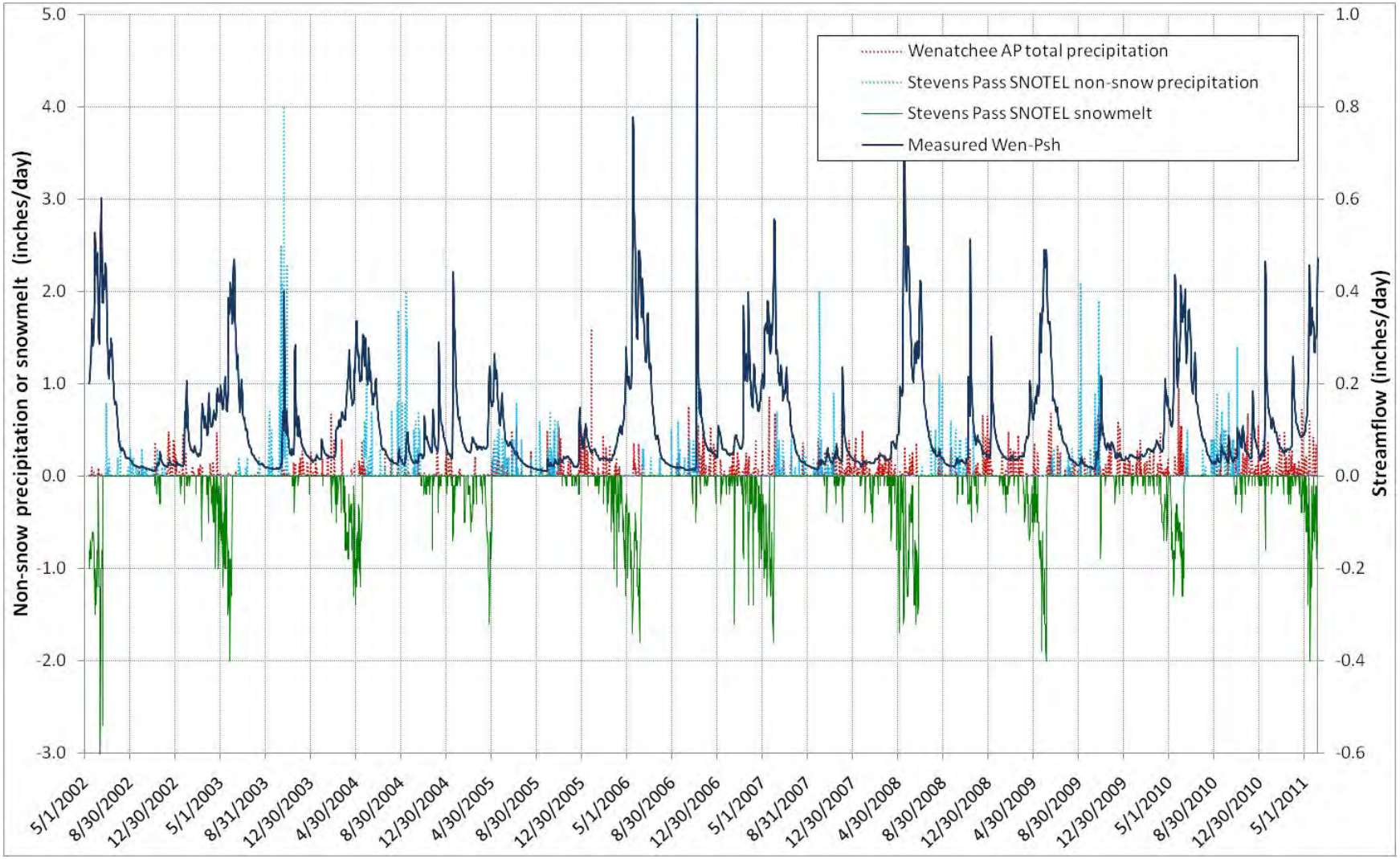

Figure 35. Measured areal flows at the USGS “Wenatchee River at Peshastin” gaging station, with precipitation and snowmelt data.

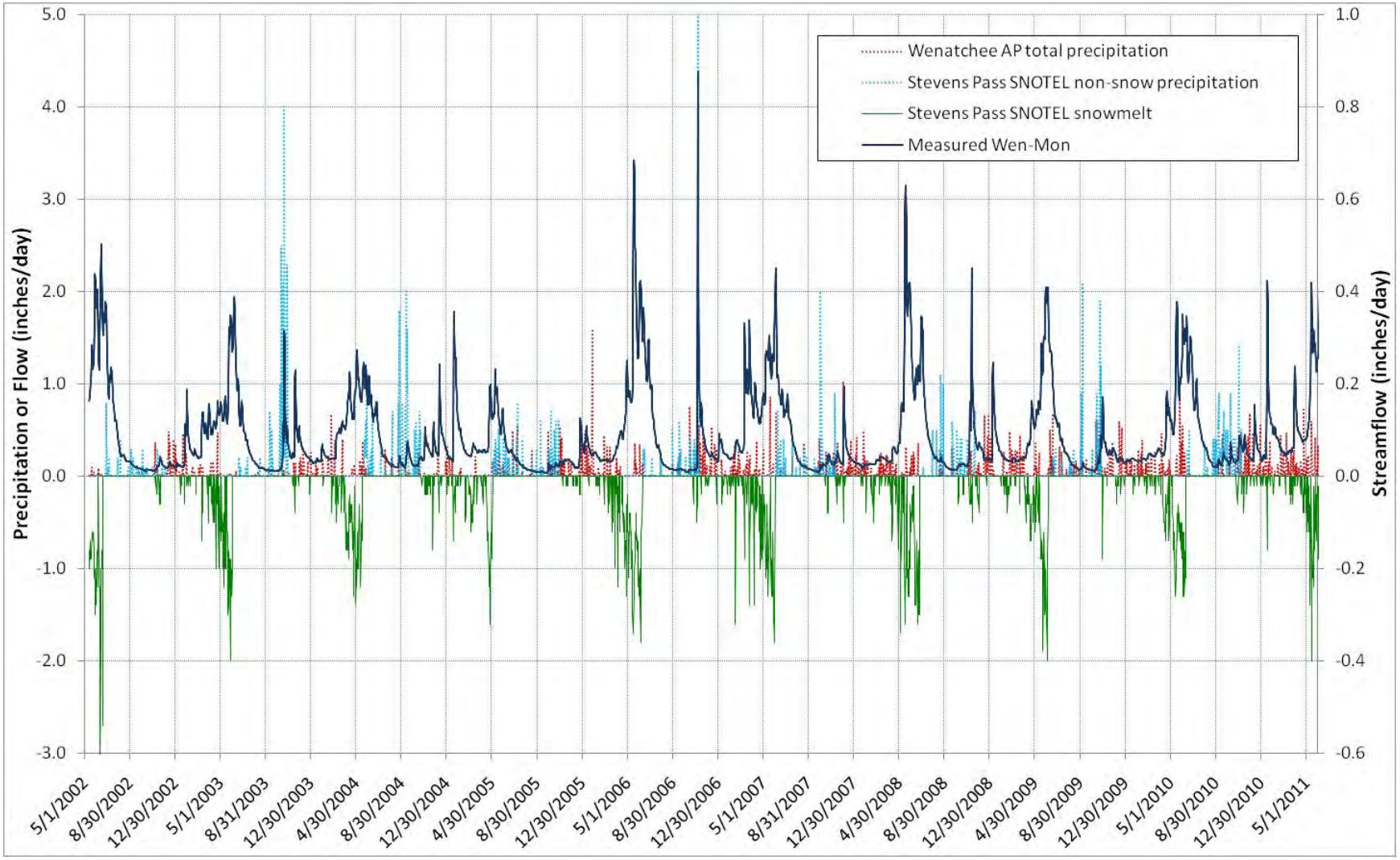

Figure 36. Measured areal flows at the USGS "Wenatchee River at Monitor" gaging station, with precipitation and snowmelt data.

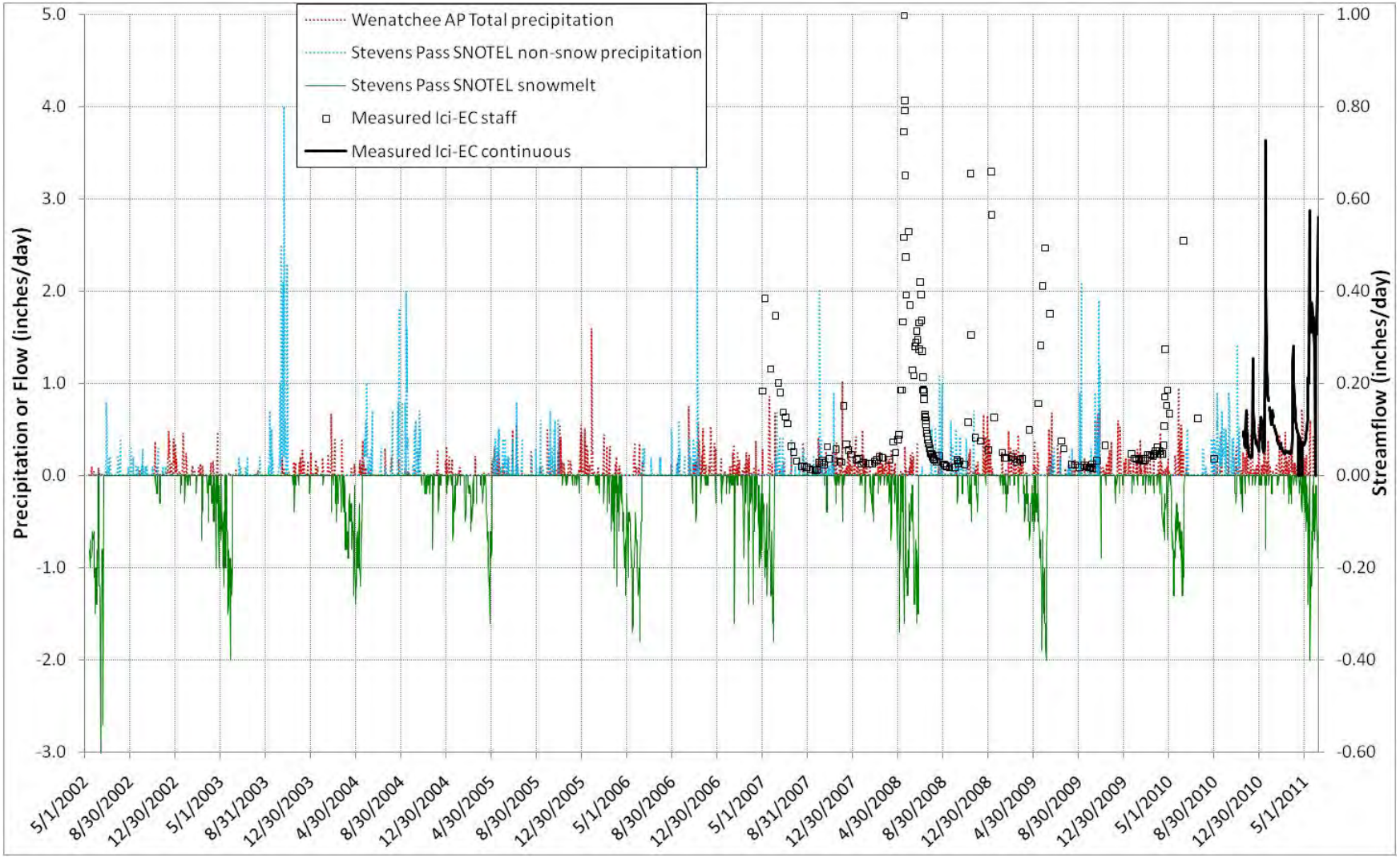

Figure 37. Measured areal flows at the Ecology “Icicle Creek near Leavenworth” gaging station, with precipitation and snowmelt data.

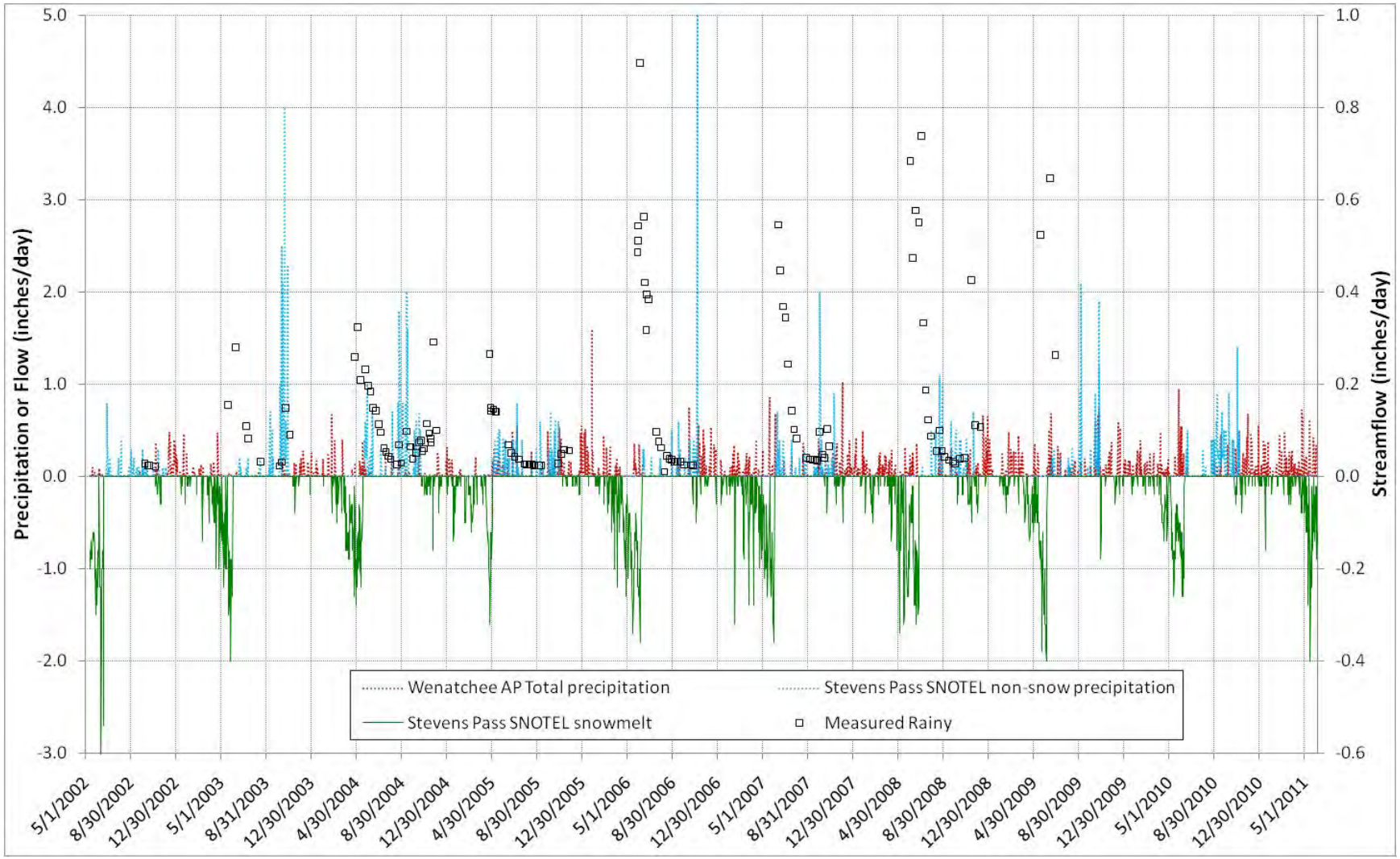

Figure 38. Measured areal flows at the Ecology “Rainy Creek near Mouth” gaging station, with precipitation and snowmelt data.

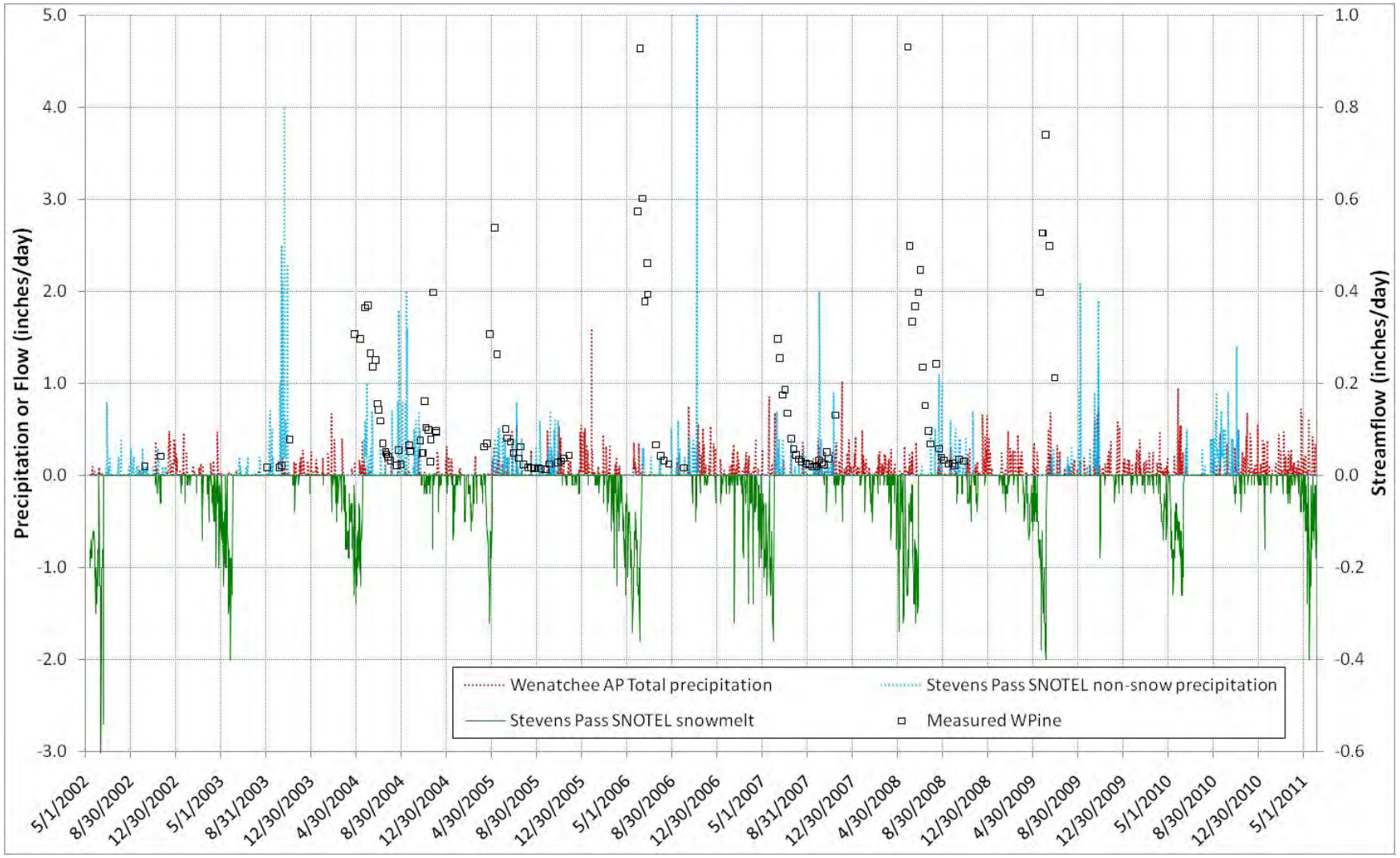

Figure 39. Measured areal flows at the Ecology “White Pine Creek at Mouth” gaging station, with precipitation and snowmelt data.

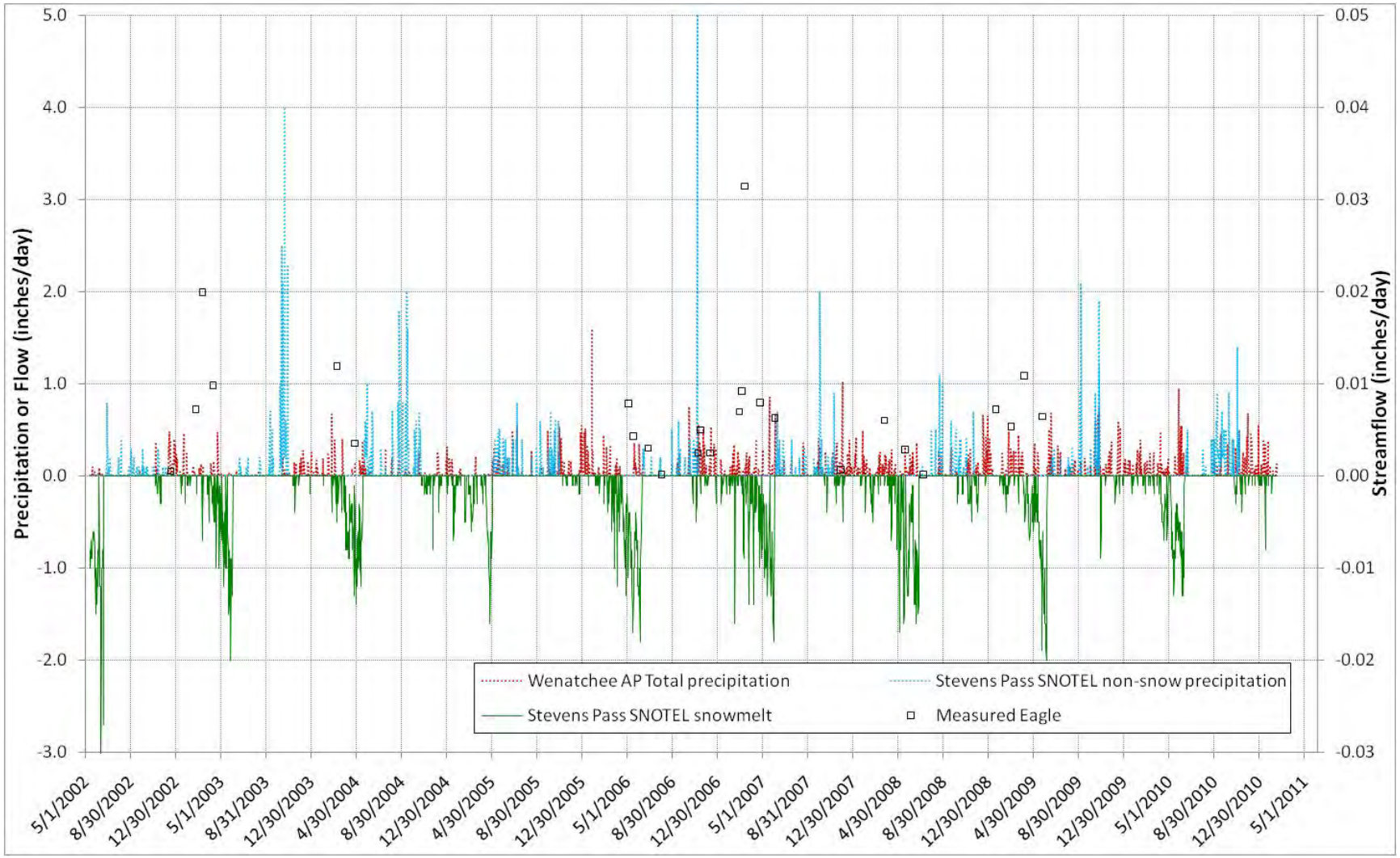

Figure 40. Measured areal flows at the Ecology “Eagle Creek near Mouth” gaging station, with precipitation and snowmelt data.

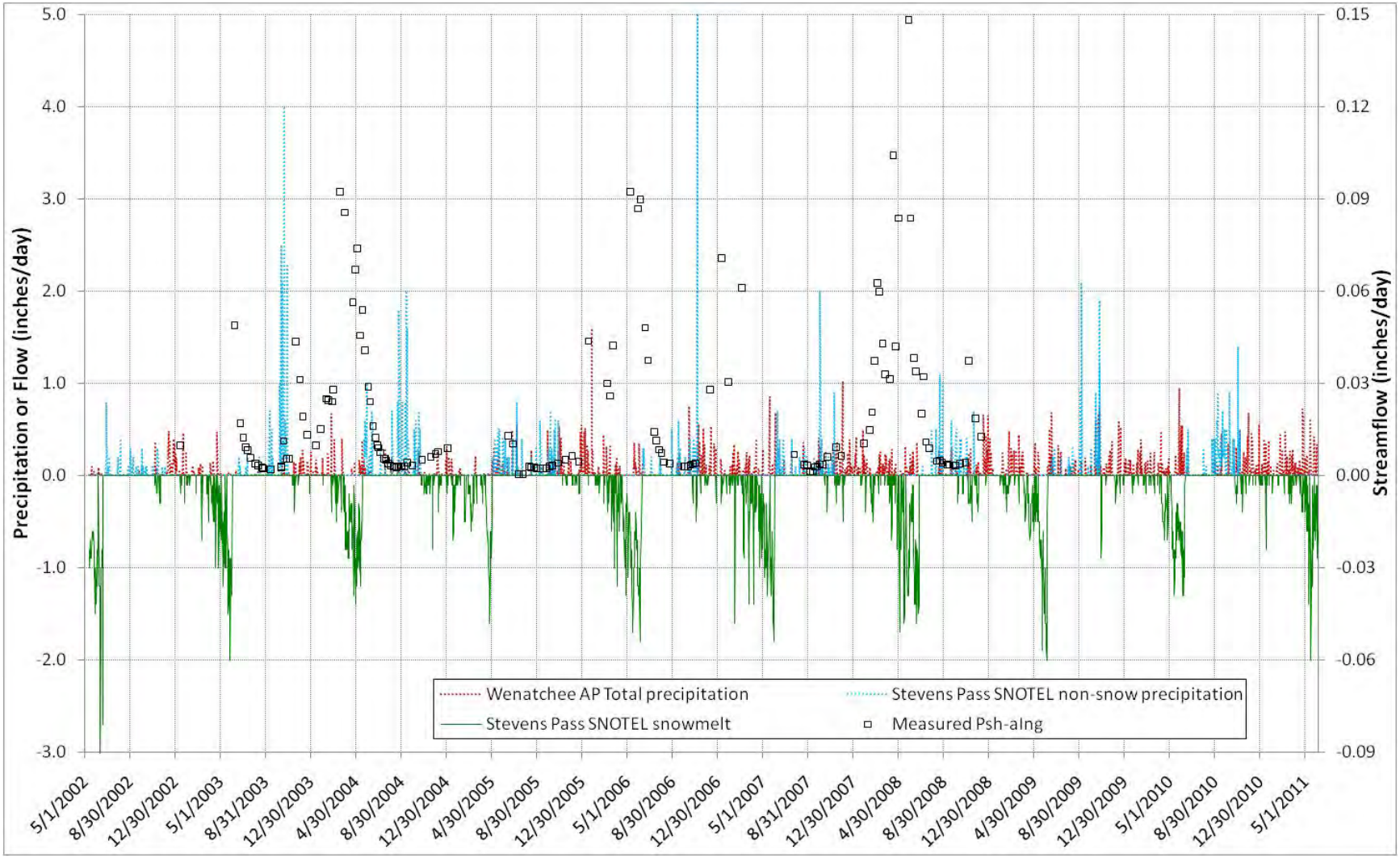

Figure 41. Measured areal flows at the Ecology “Peshastin Creek above Ingalls” gaging station, with precipitation and snowmelt data.

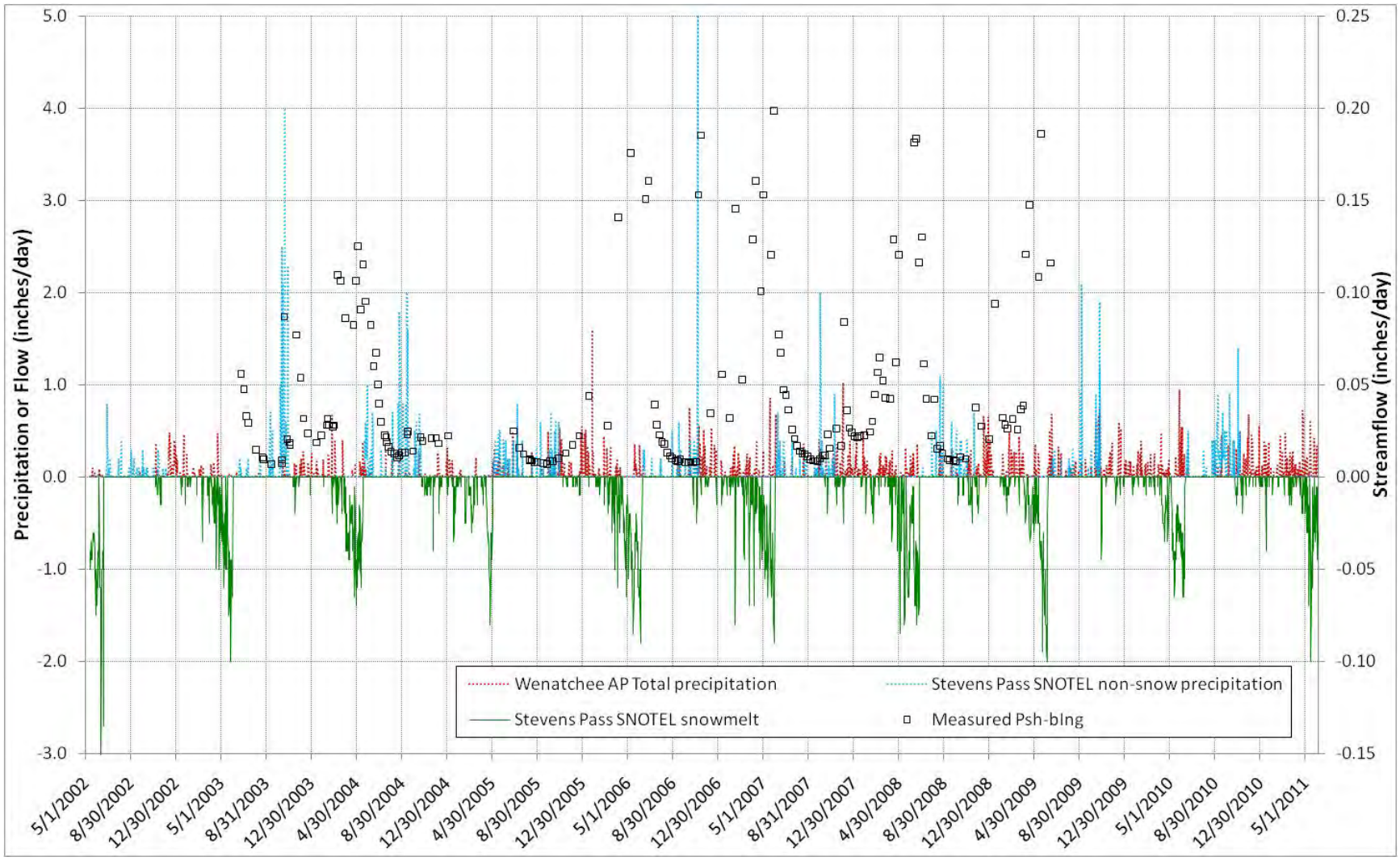

Figure 42. Measured areal flows at the Ecology “Peshastin Creek below Ingalls” gaging station, with precipitation and snowmelt data.

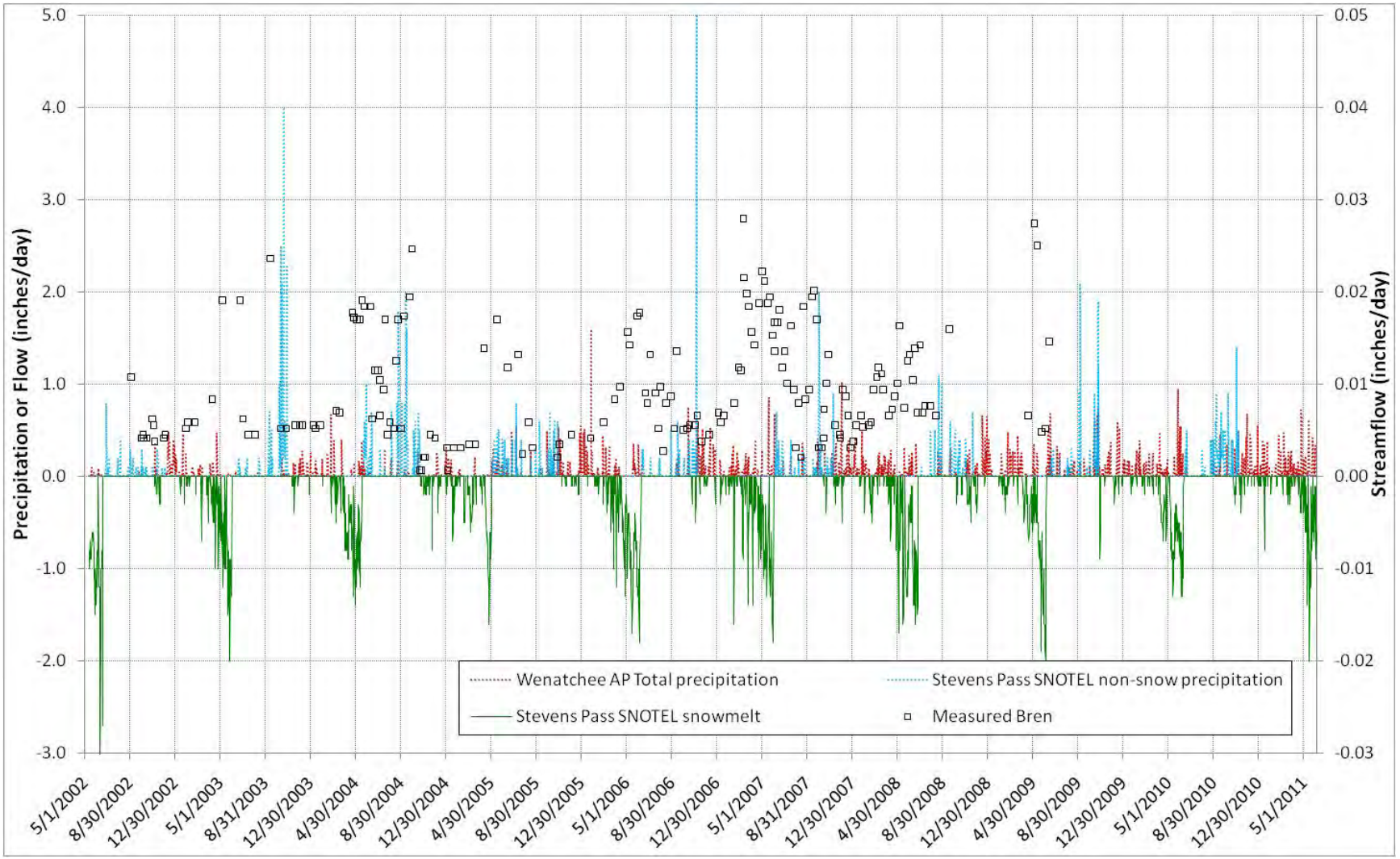

Figure 43. Measured areal flows at the Ecology “Brender Creek near Cashmere” gaging station, with precipitation and snowmelt data.

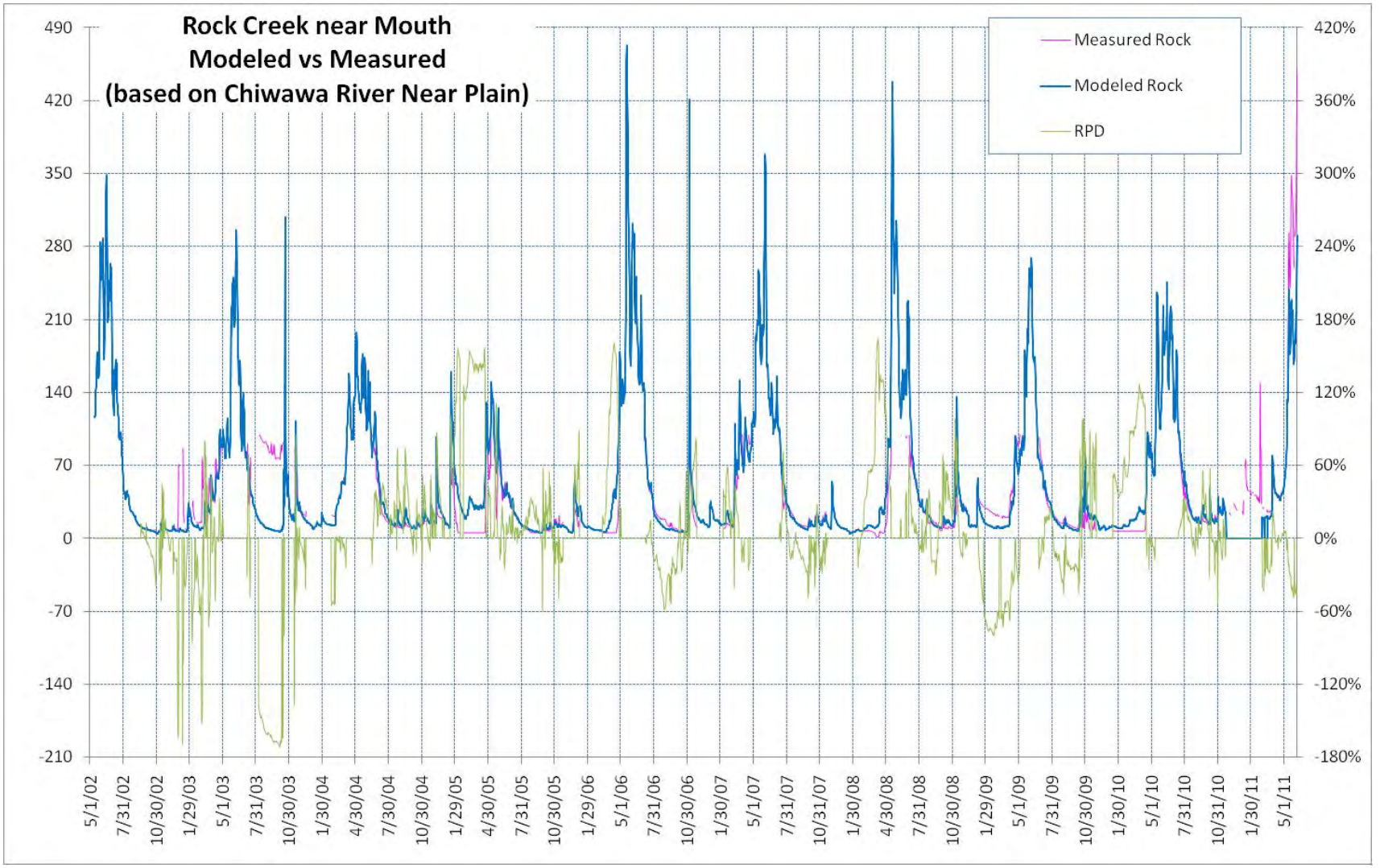

Figure 44. Measured flows at the Ecology "Rock Creek near Mouth" gaging station, and modeled flows based on the USGS "Chiwawa River near Plain" station, with relative percent difference of paired values.

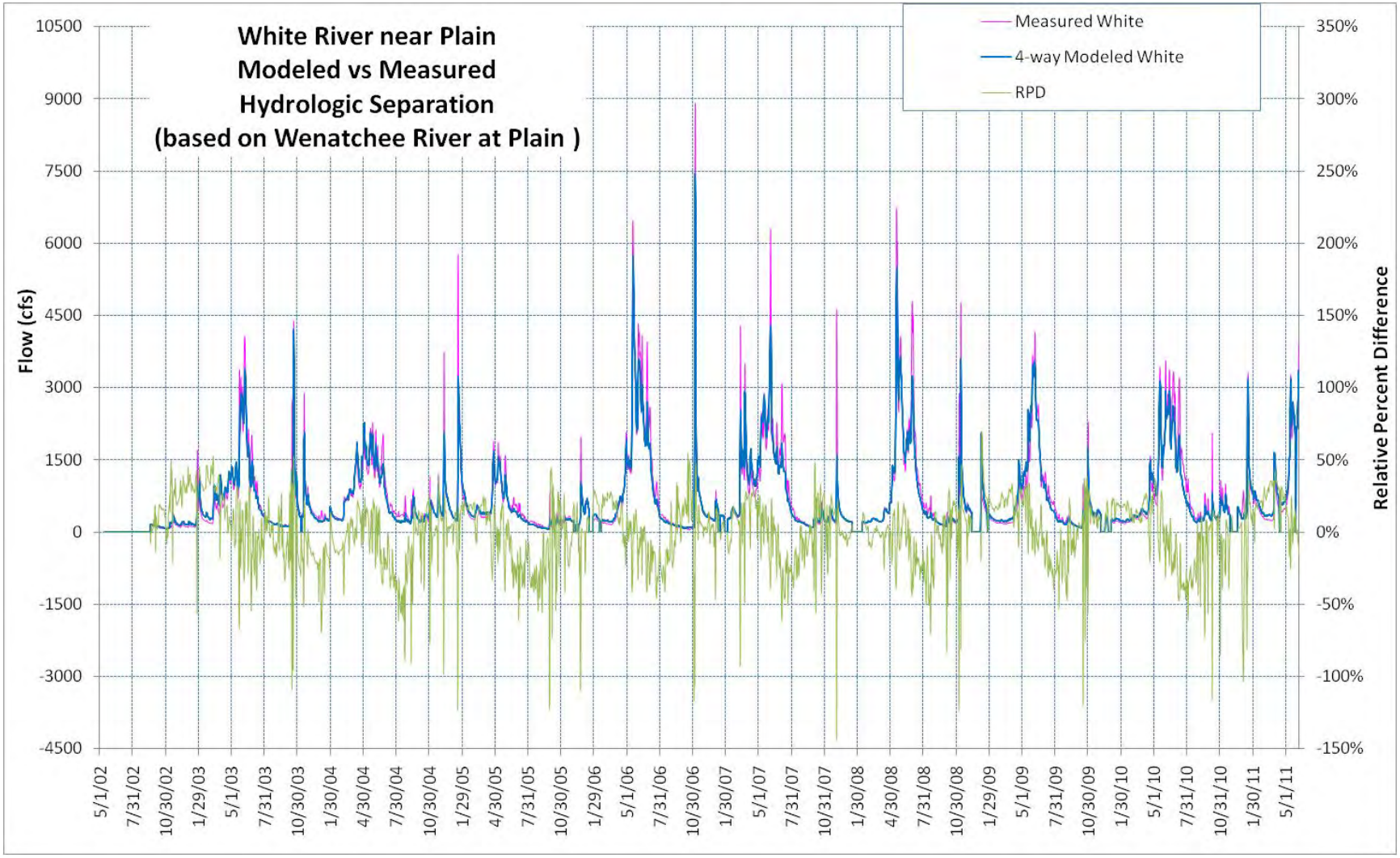

Figure 45. Measured flows at the Ecology "White River near Plain" gaging station, and modeled flows based on the USGS "Wenatchee River at Plain" station, with relative percent difference of paired values.

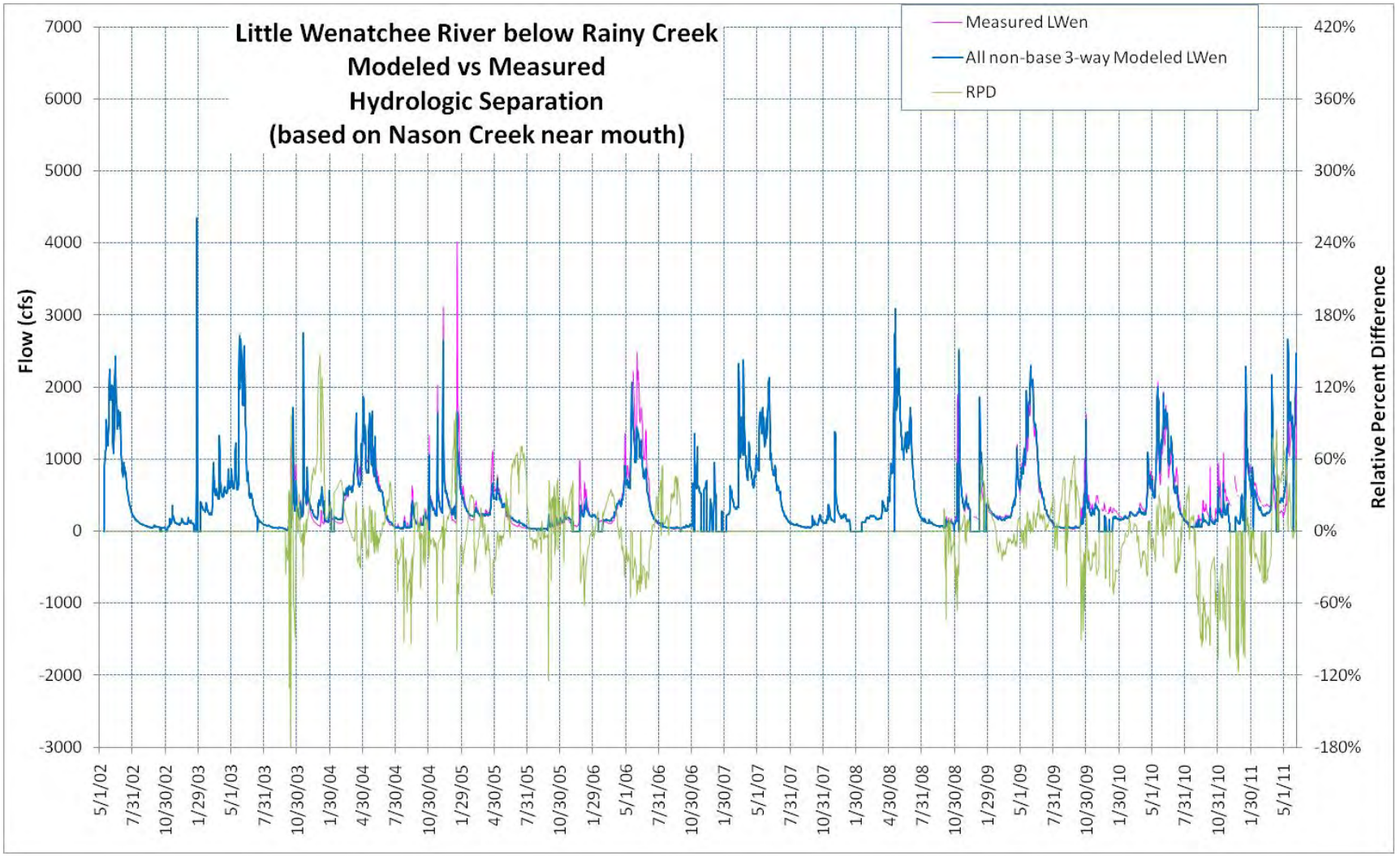

Figure 46. Measured flows at the Ecology "Little Wenatchee River below Rainy Creek" gaging station, and modeled flows based on the Ecology "Nason Creek near mouth" station, with relative percent difference of paired values.

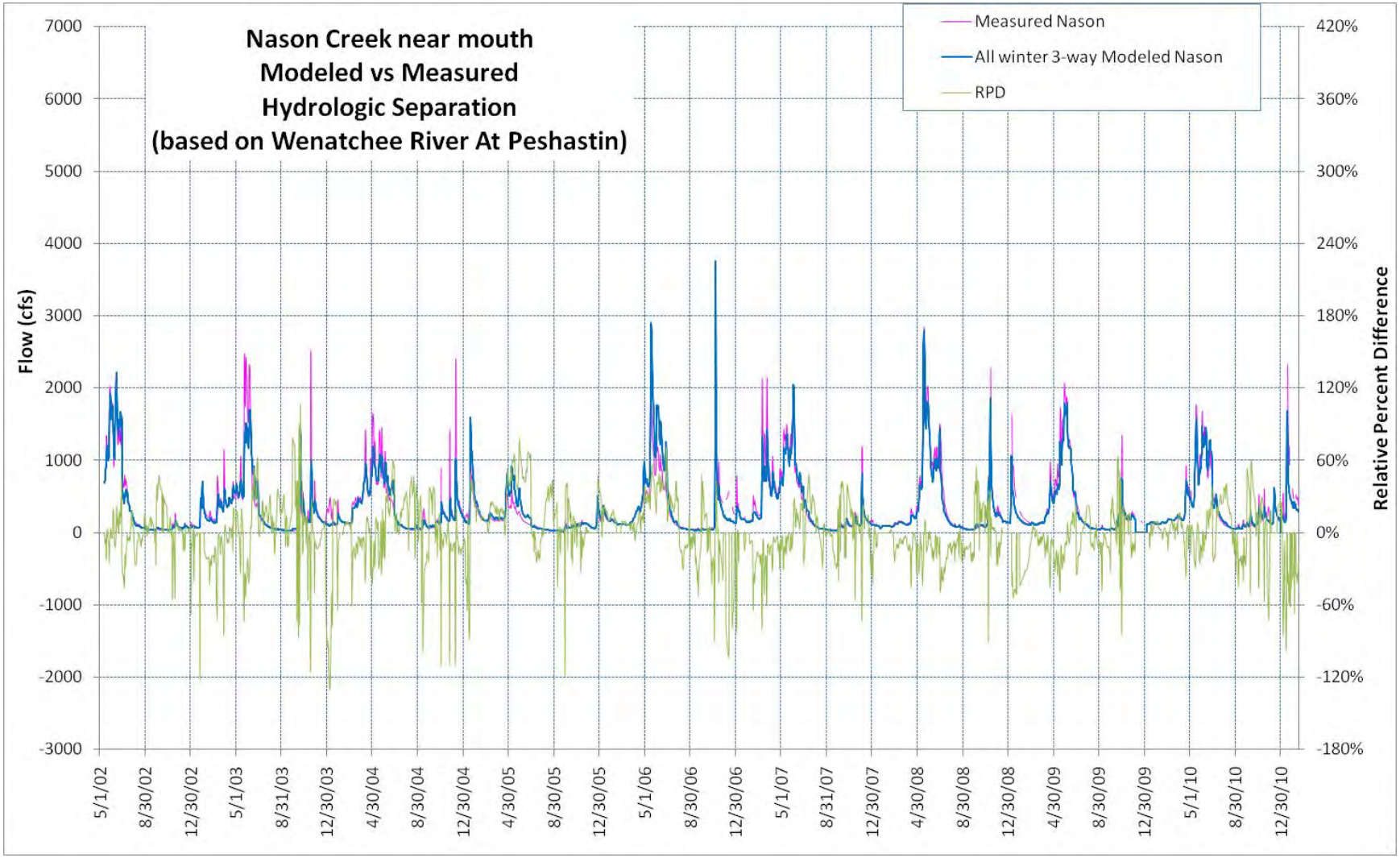

Figure 47. Measured flows at the Ecology "Nason Creek near mouth" gaging station, and modeled flows based on the USGS "Wenatchee River at Peshastin" station, with relative percent difference of paired values.

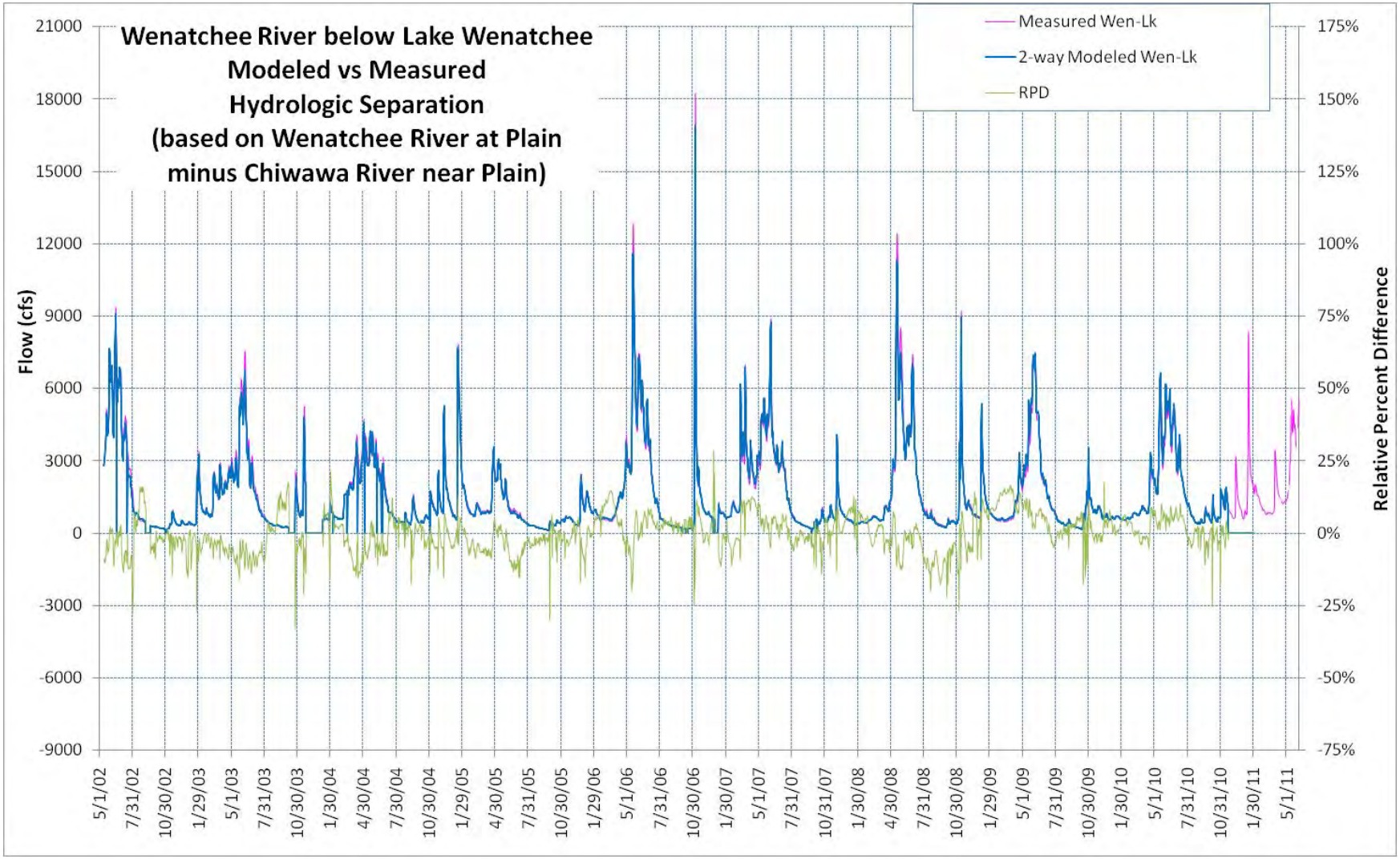

Figure 48. Measured flows at the Ecology "Wenatchee River below Lake Wenatchee" gaging station, and modeled flows based on the USGS "Wenatchee River at Plain" station minus USGS "Chiwawa River near Plain" station, with relative percent difference of paired values.

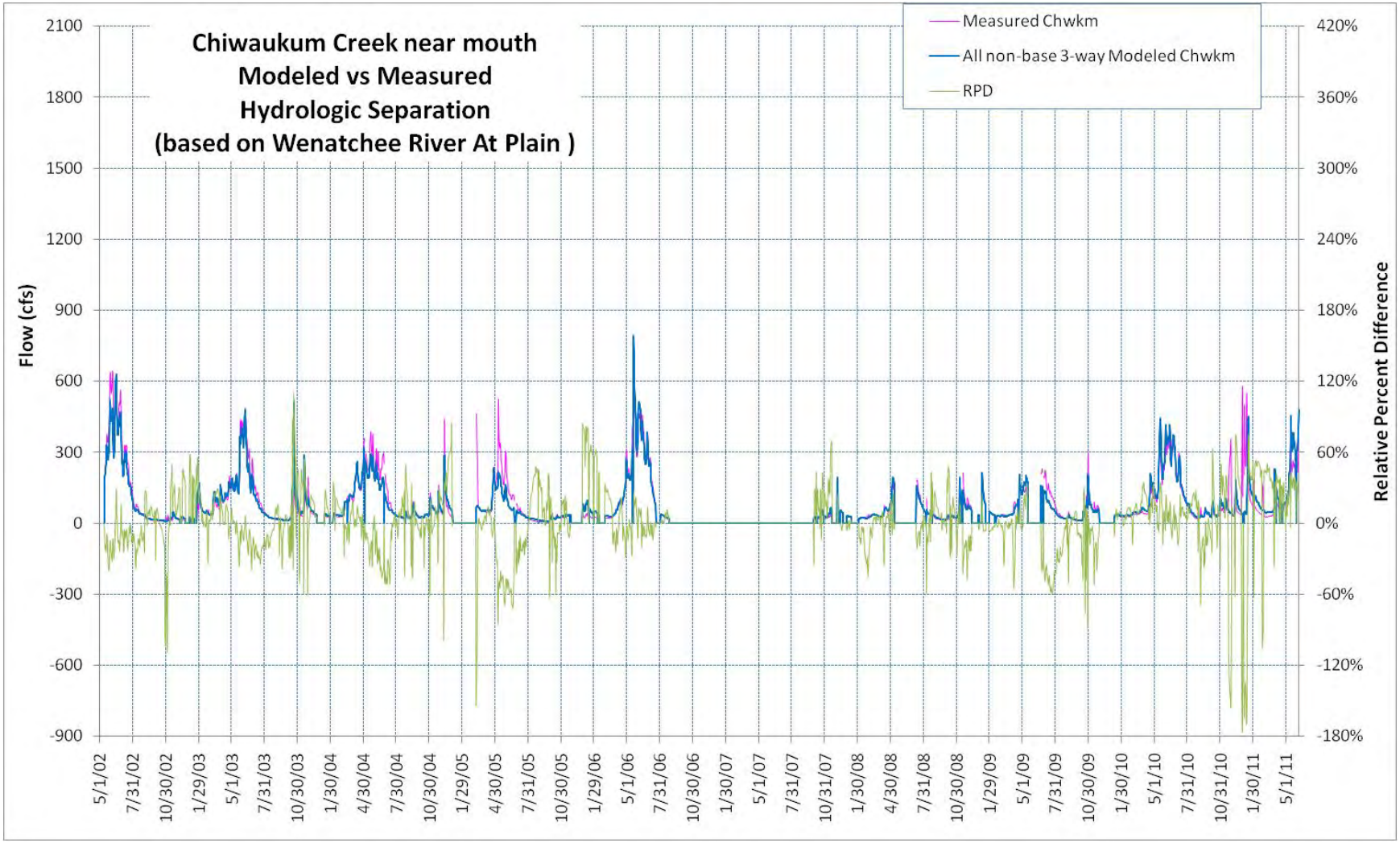

Figure 49. Measured flows at the Ecology “Chiwaukum Creek near mouth” gaging station, and modeled flows based on the USGS “Wenatchee River at Plain” station, with relative percent difference of paired values.

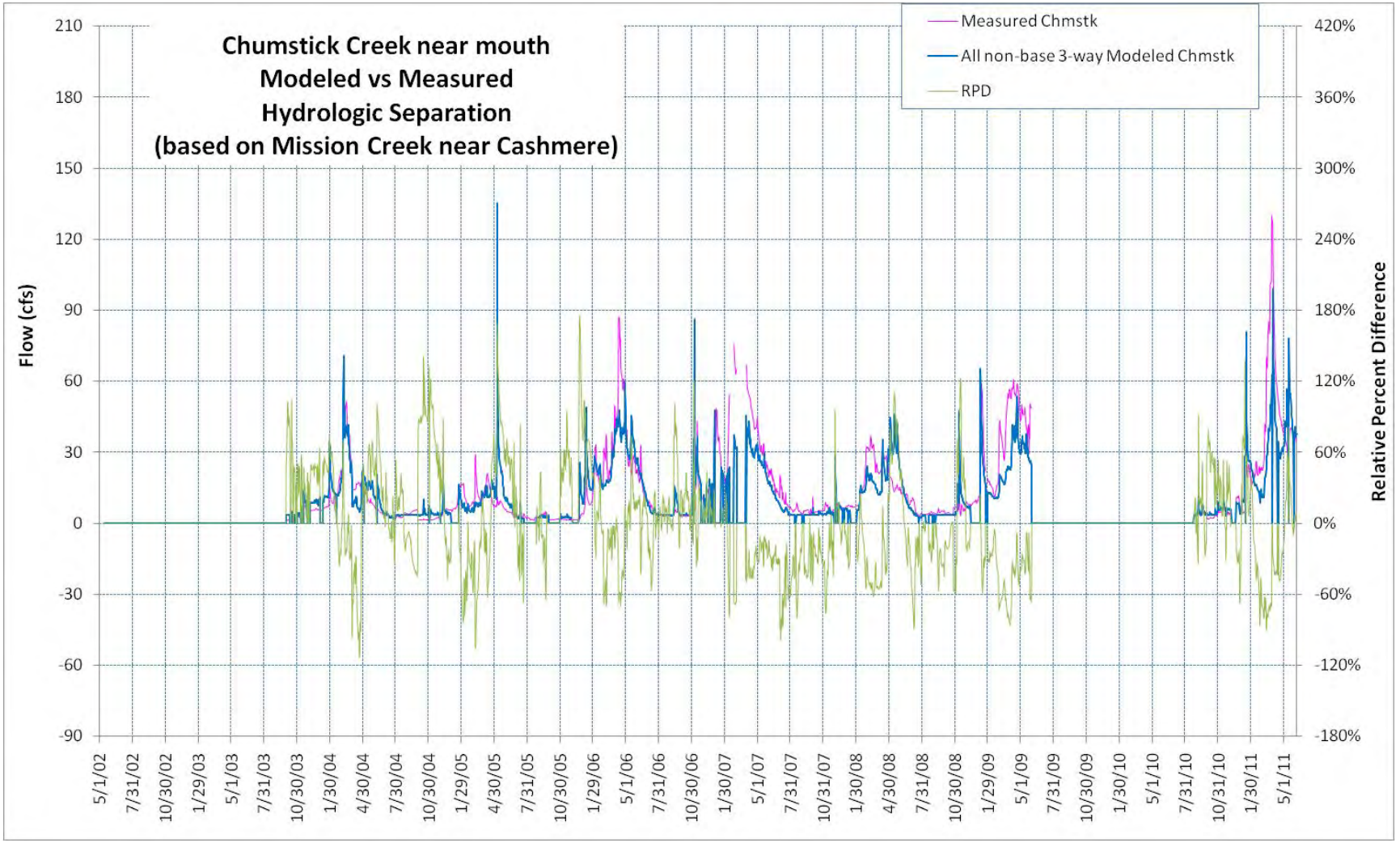

Figure 50. Measured flows at the Ecology "Chumstick Creek near mouth" gaging station, and modeled flows based on the Ecology "Mission Creek near Cashmere" station, with relative percent difference of paired values.

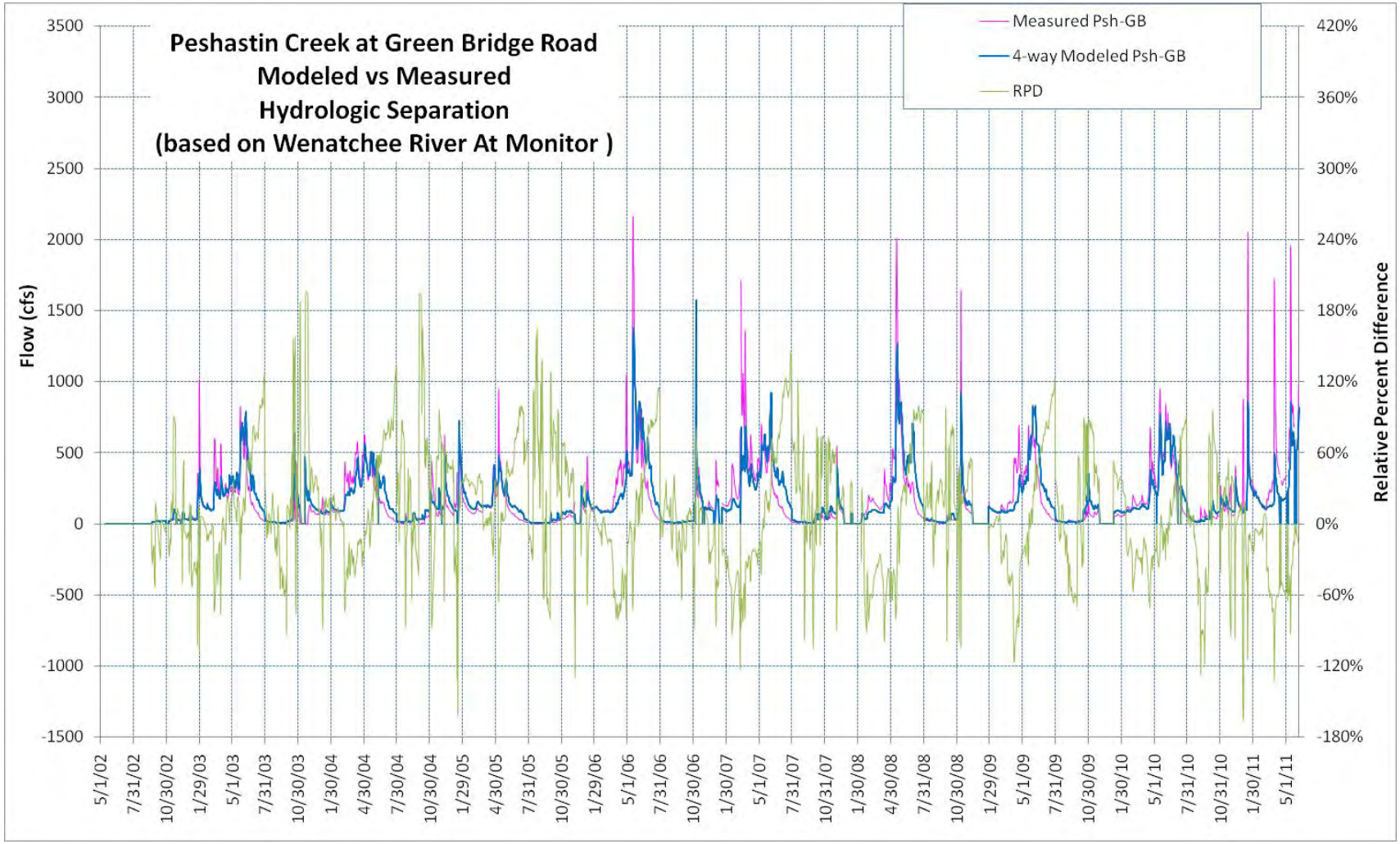

Figure 51. Measured flows at the Ecology “Peshastin Creek at Green Bridge Road” gaging station, and modeled flows based on the USGS “Wenatchee River at Monitor” station, with relative percent difference of paired values.

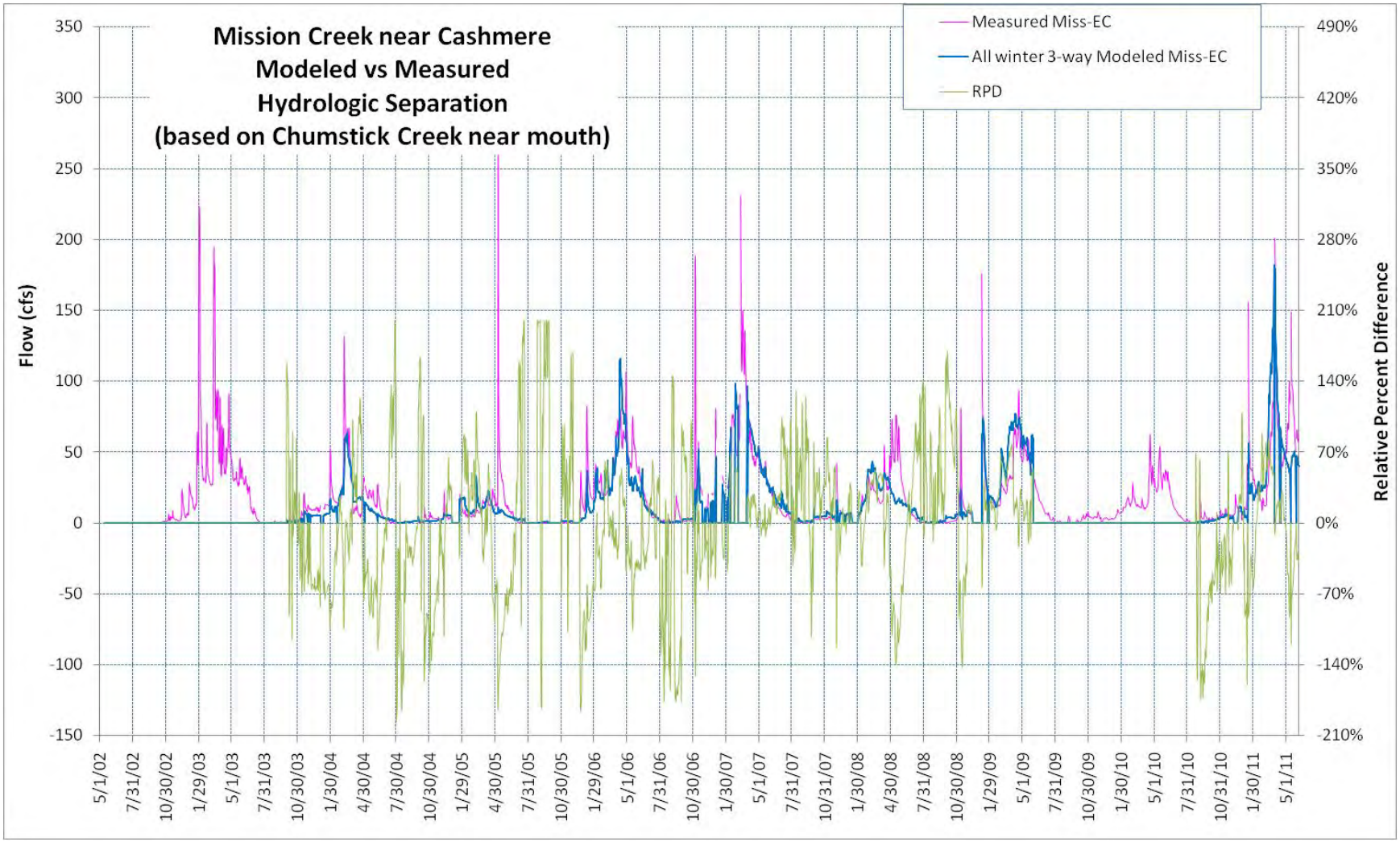

Figure 52. Measured flows at the Ecology "Mission Creek near Cashmere" gaging station, and modeled flows based on the Ecology "Chumstick Creek near mouth" station, with relative percent difference of paired values.

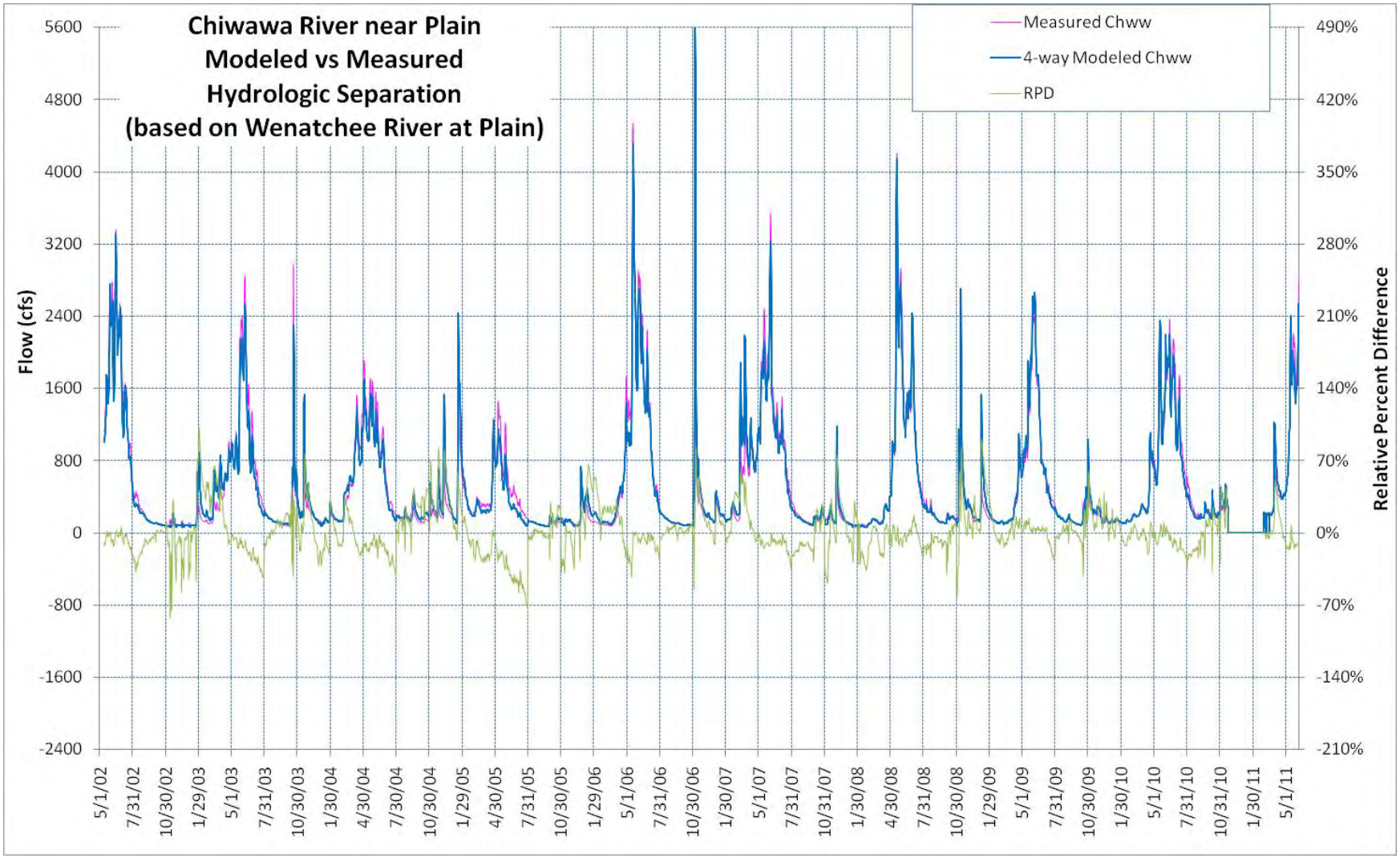

Figure 53. Measured flows at the USGS "Chiwawa River near Plain" gaging station, and modeled flows based on the USGS "Wenatchee River at Plain" station, with relative percent difference of paired values.

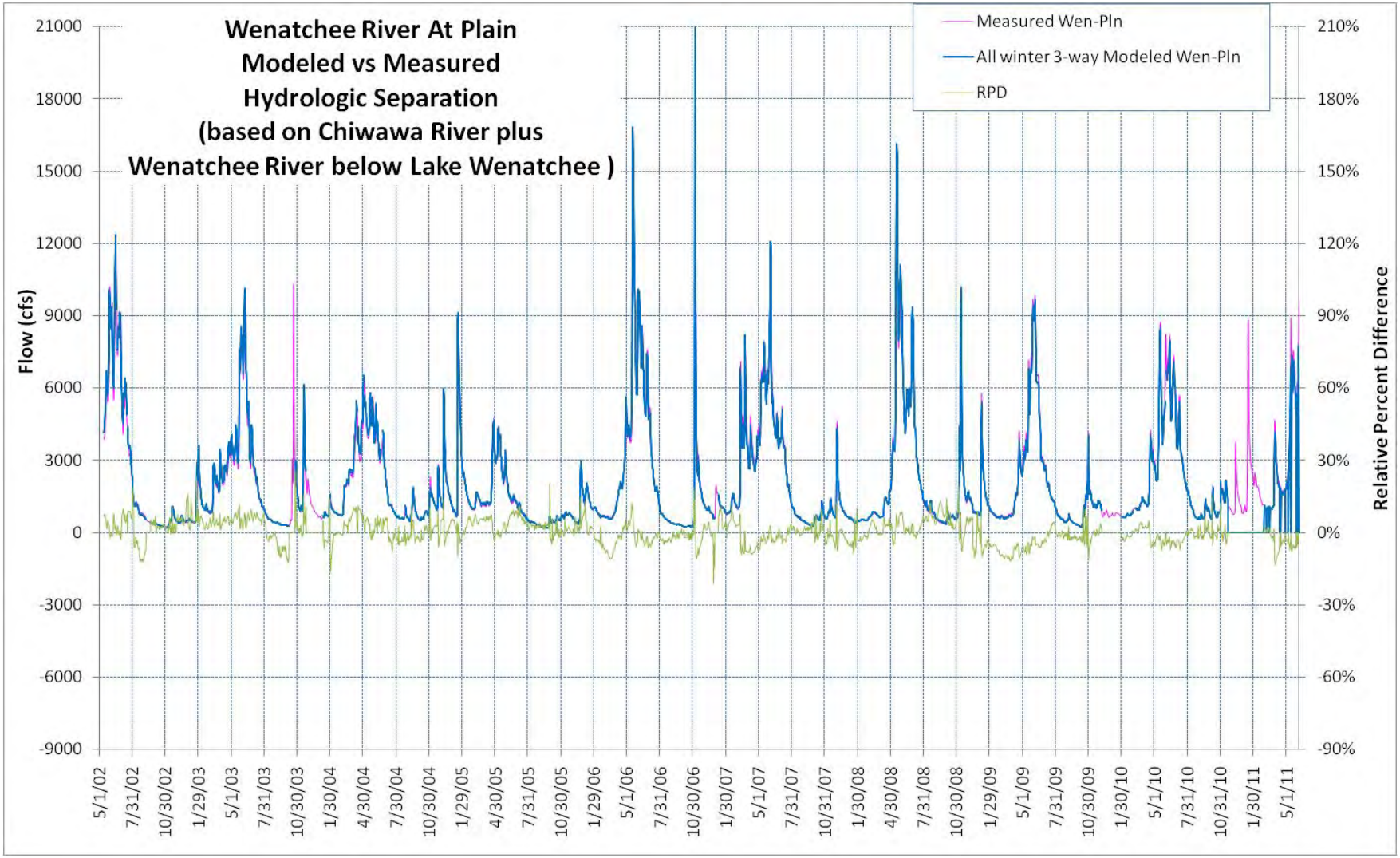

Figure 54. Measured flows at the USGS "Wenatchee River at Plain" gaging station, and modeled flows based on the USGS "Chiwawa River near Plain" station plus Ecology "Wenatchee River below Lake Wenatchee" station, with relative percent difference of paired values.

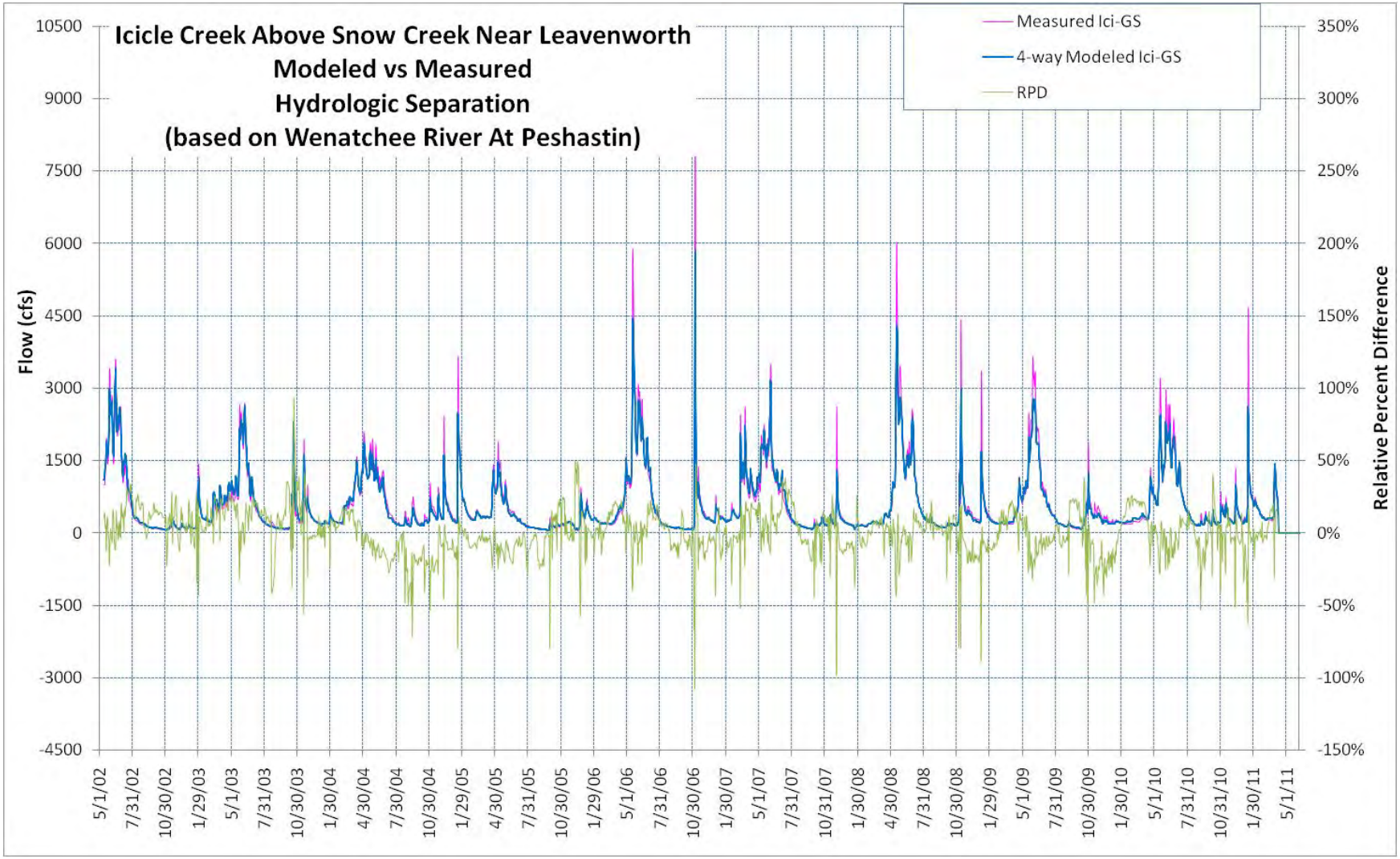

Figure 55. Measured flows at the USGS "Icicle Creek above Snow Creek near Leavenworth" gaging station, and modeled flows based on the USGS "Wenatchee River at Peshastin" station, with relative percent difference of paired values.

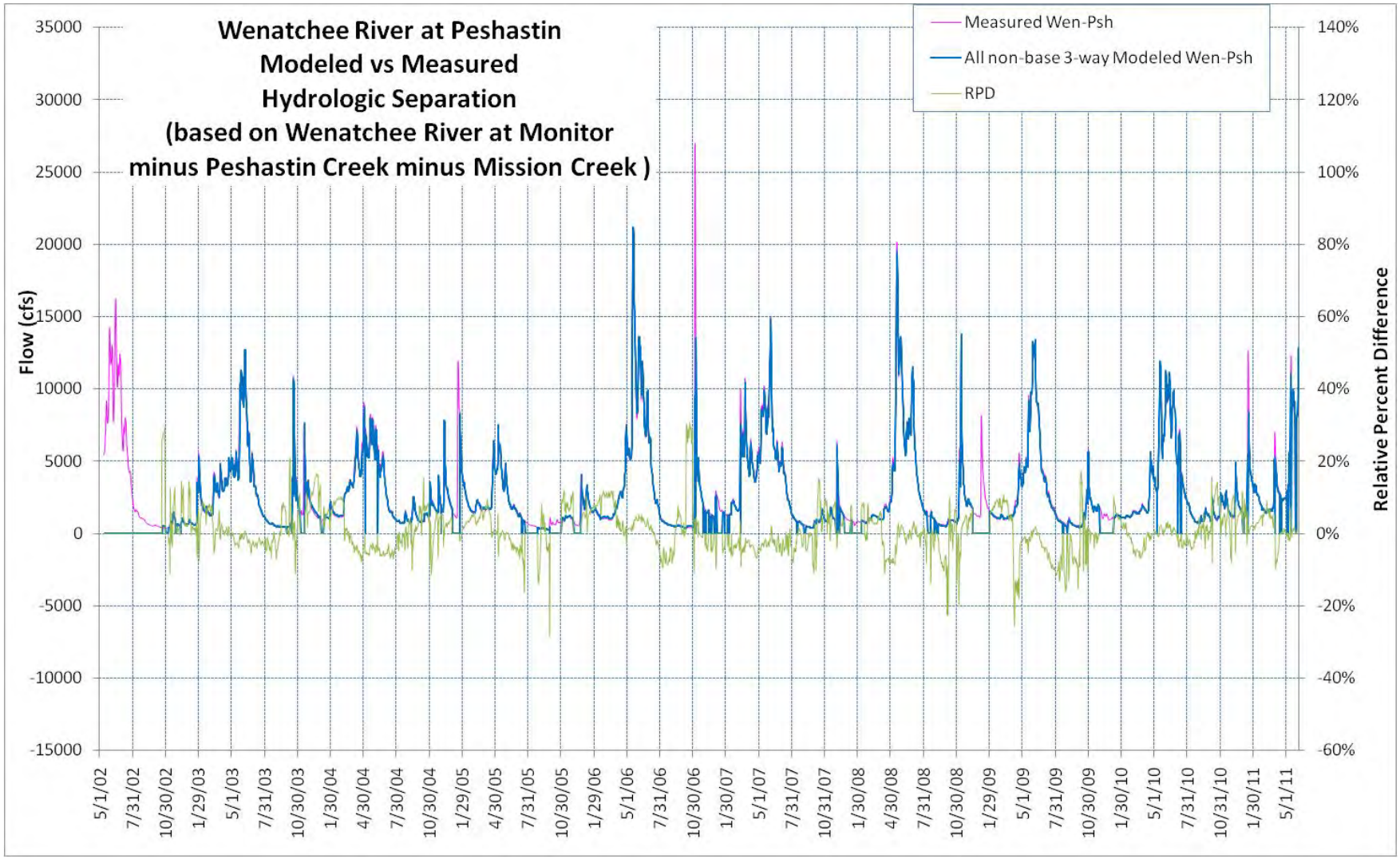

Figure 56. Measured flows at the USGS "Wenatchee River at Peshastin" gaging station, and modeled flows based on the USGS "Wenatchee River at Monitor" station minus the Ecology Peshastin and Mission Creek stations, with relative percent difference of paired values.

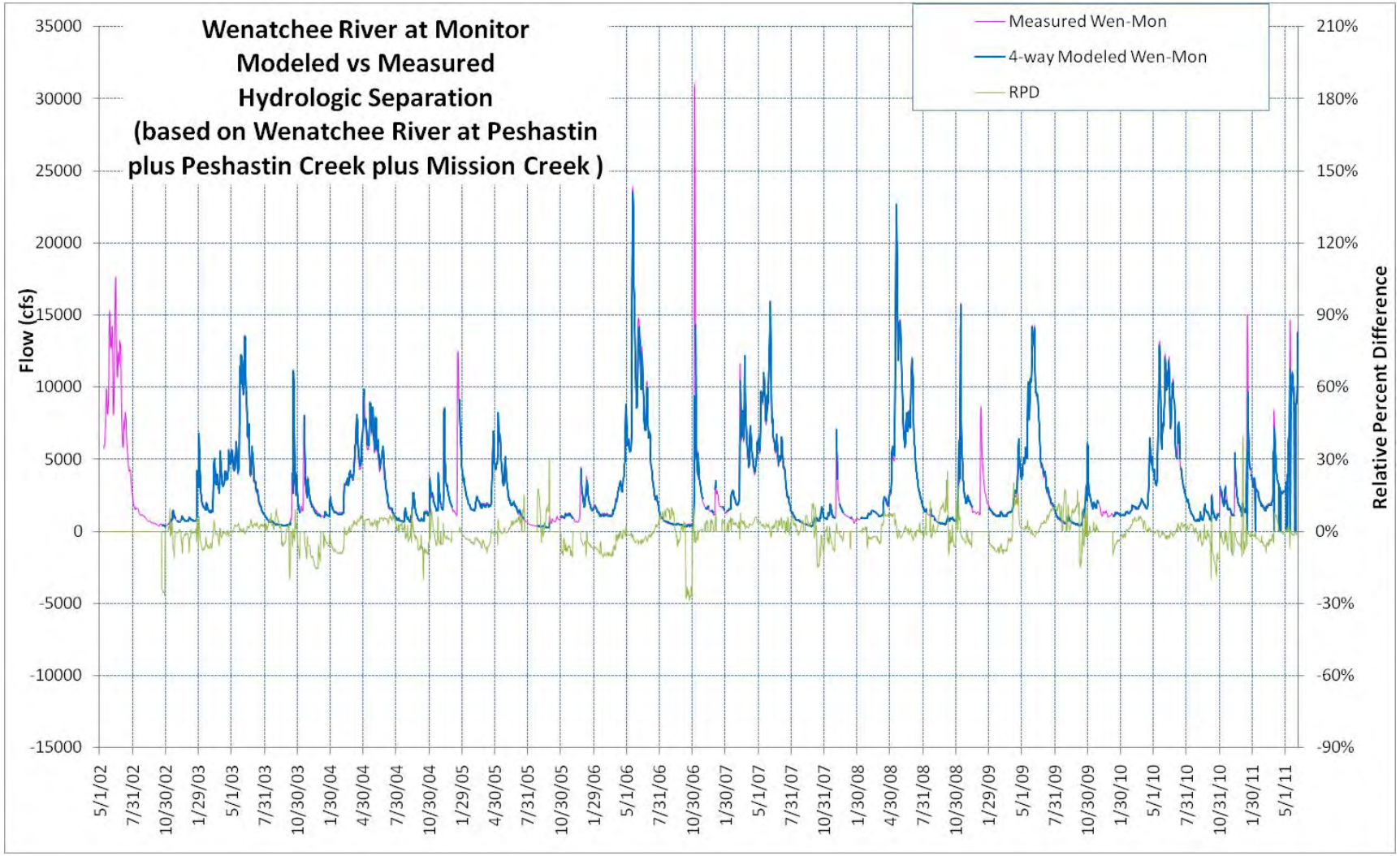

Figure 57. Measured flows at the USGS "Wenatchee River at Monitor" gaging station, and modeled flows based on the USGS "Wenatchee River at Peshastin" station plus the Ecology Peshastin and Mission Creek stations, with relative percent difference of paired values.

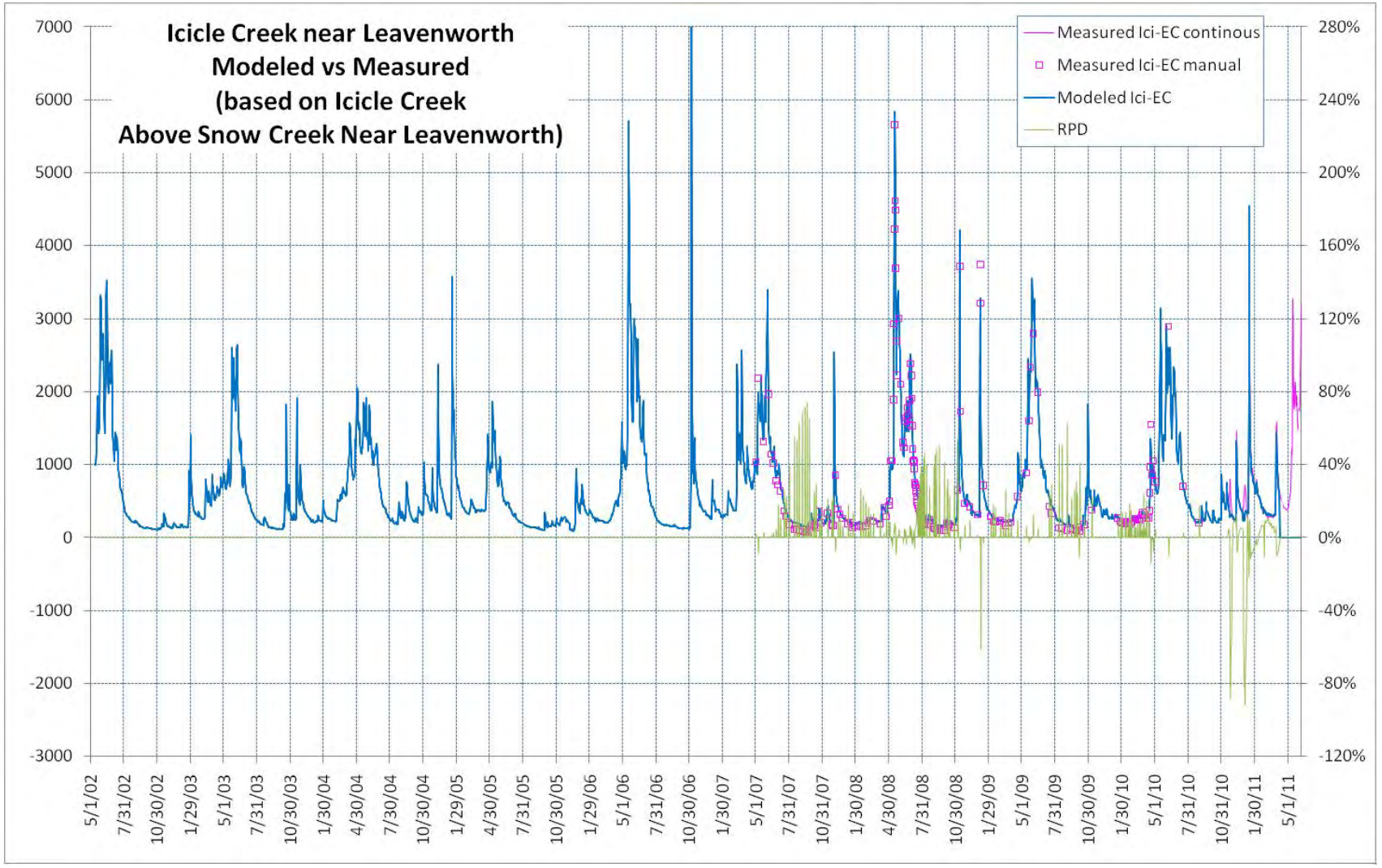

Figure 58. Measured flows at the Ecology "Icicle Creek near Leavenworth" gaging station, and modeled flows based on the USGS "Icicle Creek above Snow Creek near Leavenworth" station, with relative percent difference of paired values.

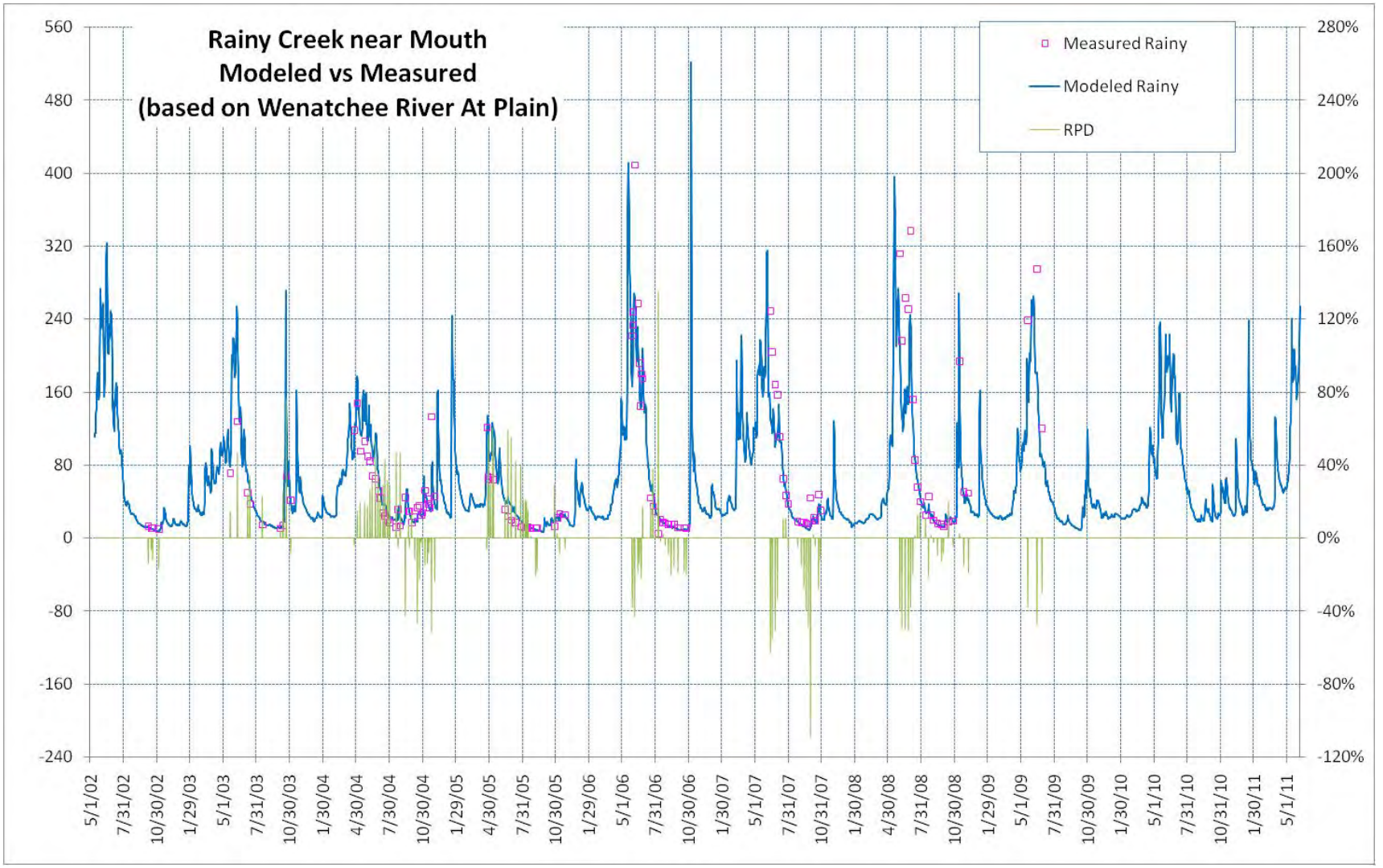

Figure 59. Measured flows at the Ecology "Rainy Creek near Mouth" gaging station, and modeled flows based on the USGS "Wenatchee River at Plain" station, with relative percent difference of paired values.

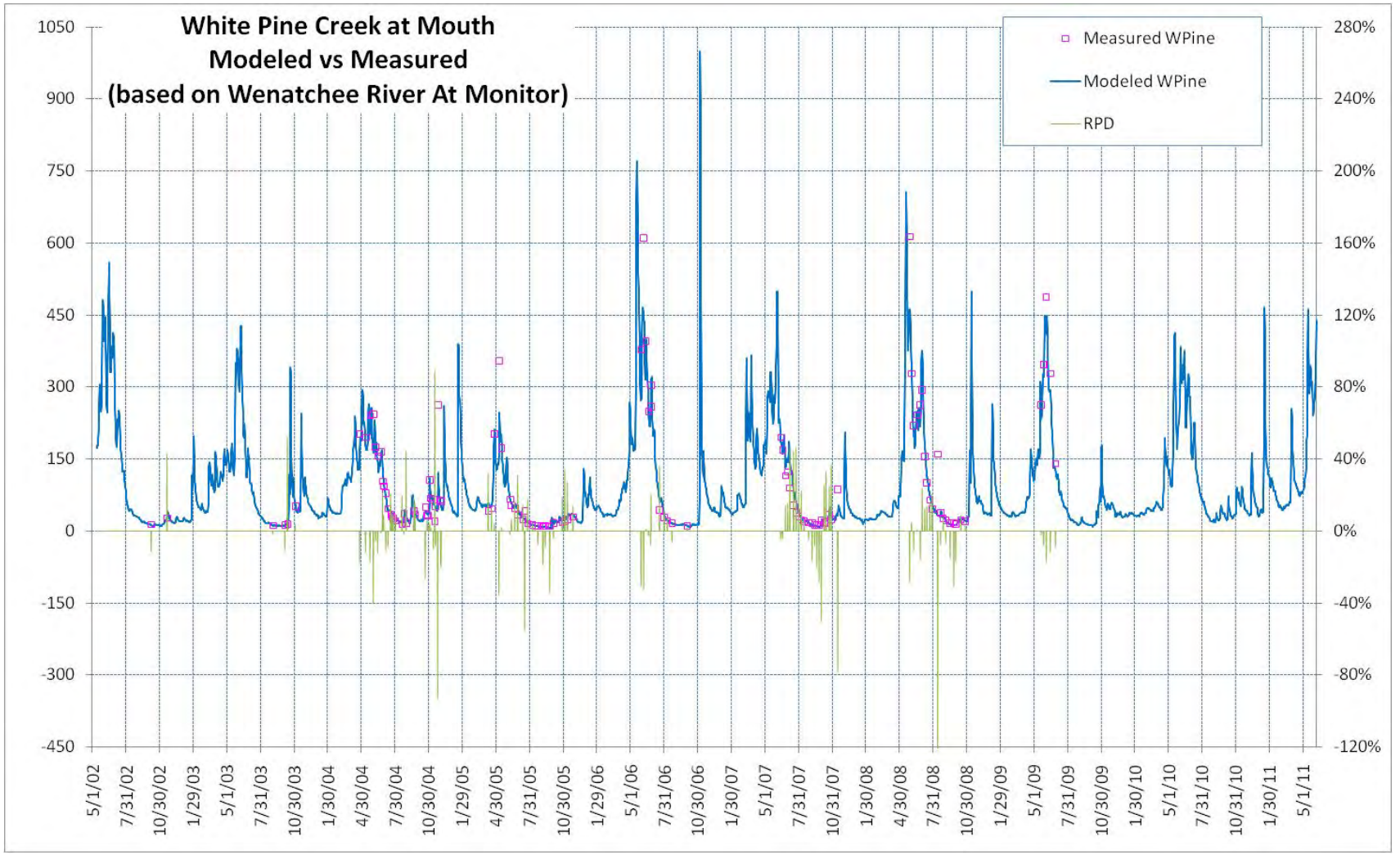

Figure 60. Measured flows at the Ecology "White Pine Creek at Mouth" gaging station, and modeled flows based on the USGS "Wenatchee River at Monitor" station, with relative percent difference of paired values.

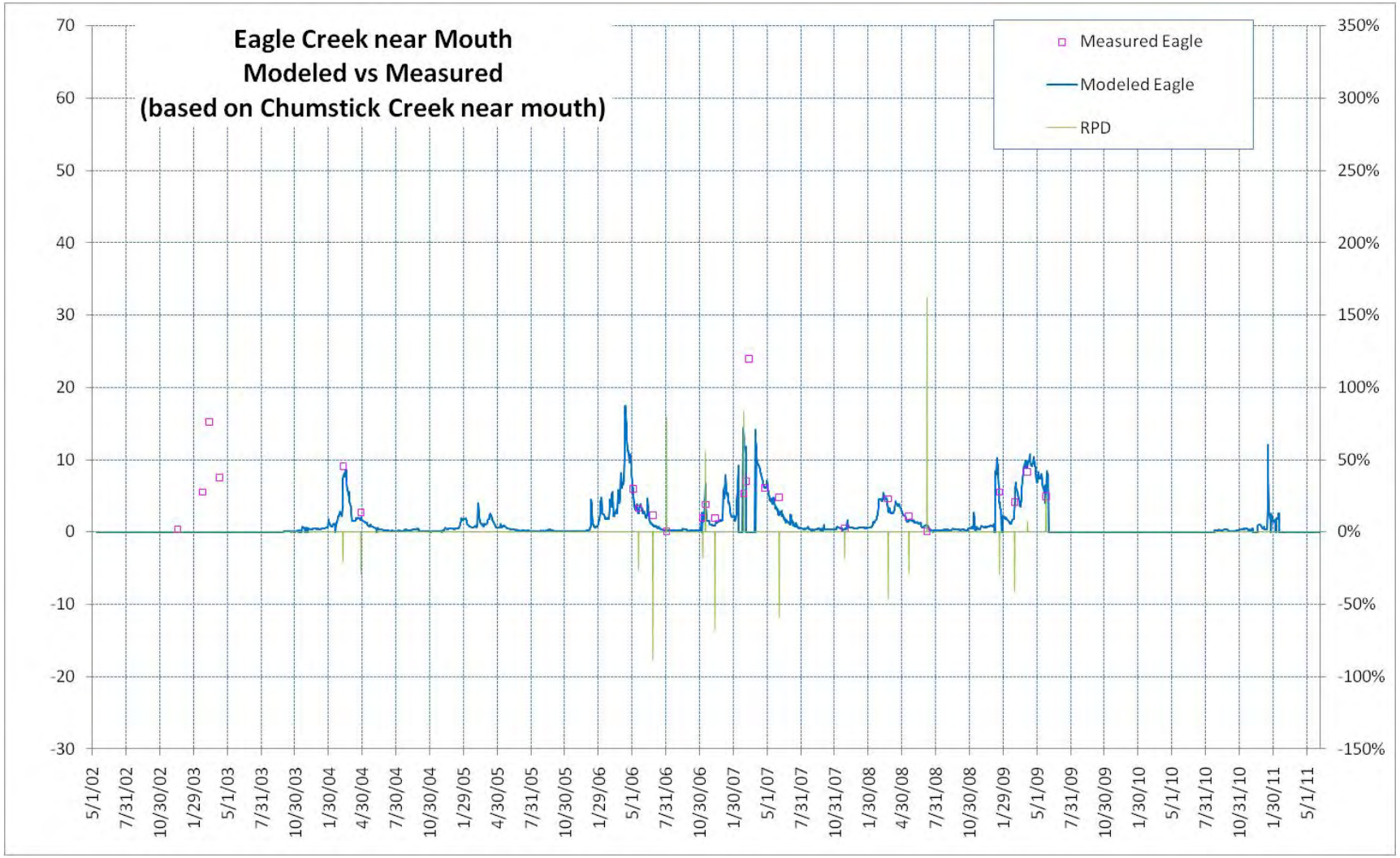

Figure 61. Measured flows at the Ecology "Eagle Creek near Mouth" gaging station, and modeled flows based on the Ecology "Chumstick Creek near mouth" station, with relative percent difference of paired values.

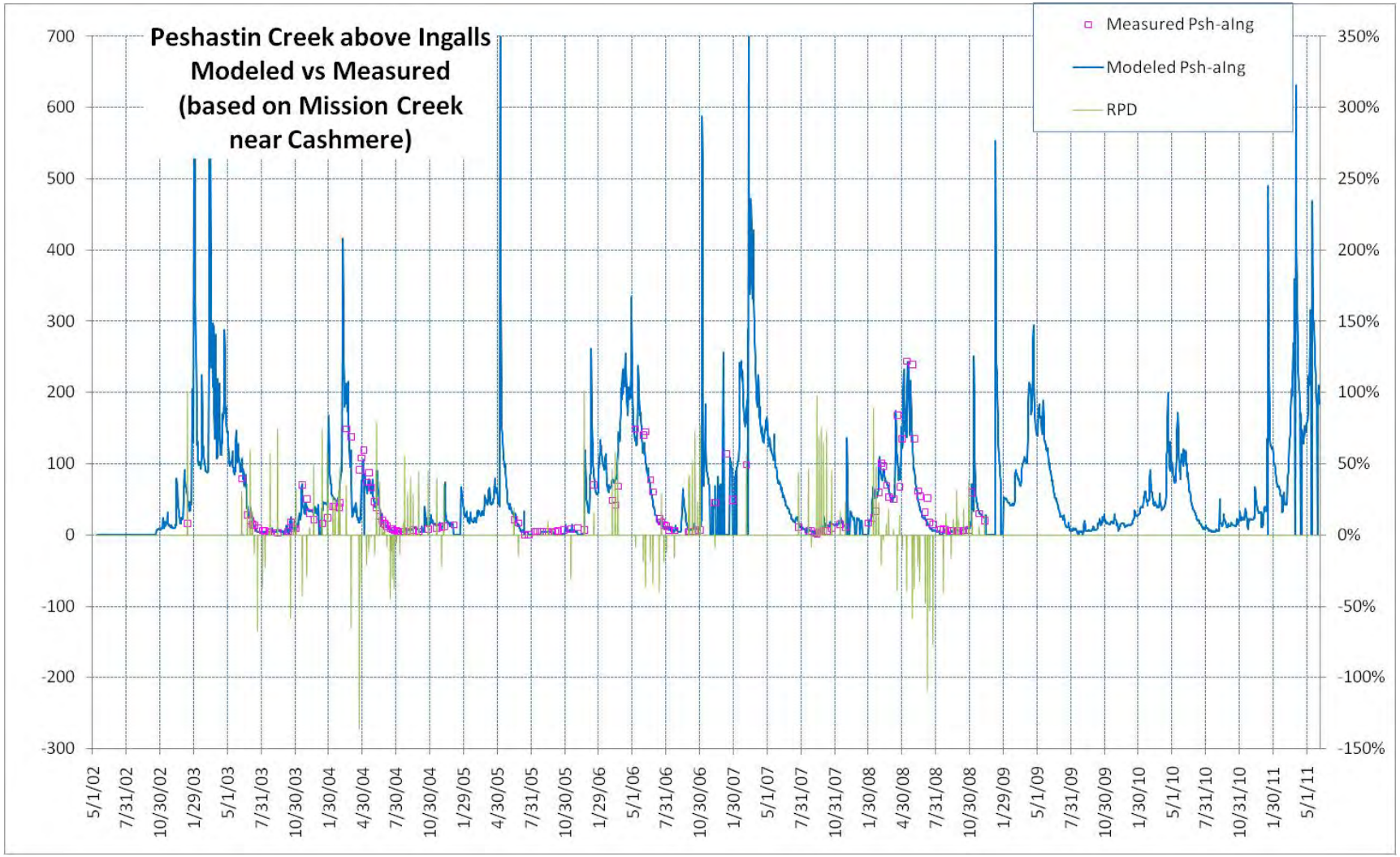

Figure 62. Measured flows at the Ecology “Peshastin Creek above Ingalls” gaging station, and modeled flows based on the Ecology “Mission Creek near Cashmere” station, with relative percent difference of paired values.

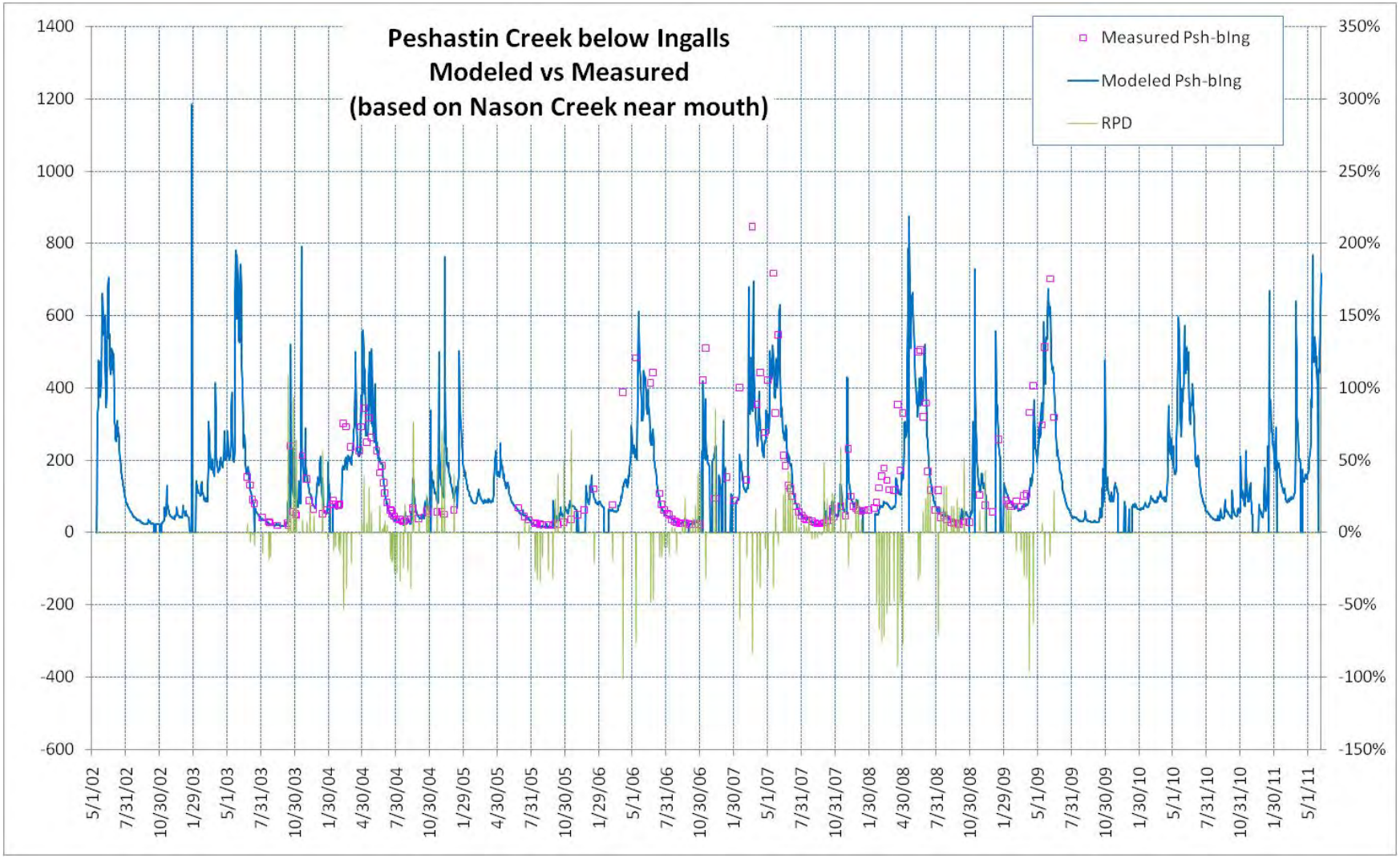

Figure 63. Measured flows at the Ecology "Peshastin Creek below Ingalls" gaging station, and modeled flows based on the Ecology "Nason Creek near mouth" station, with relative percent difference of paired values.

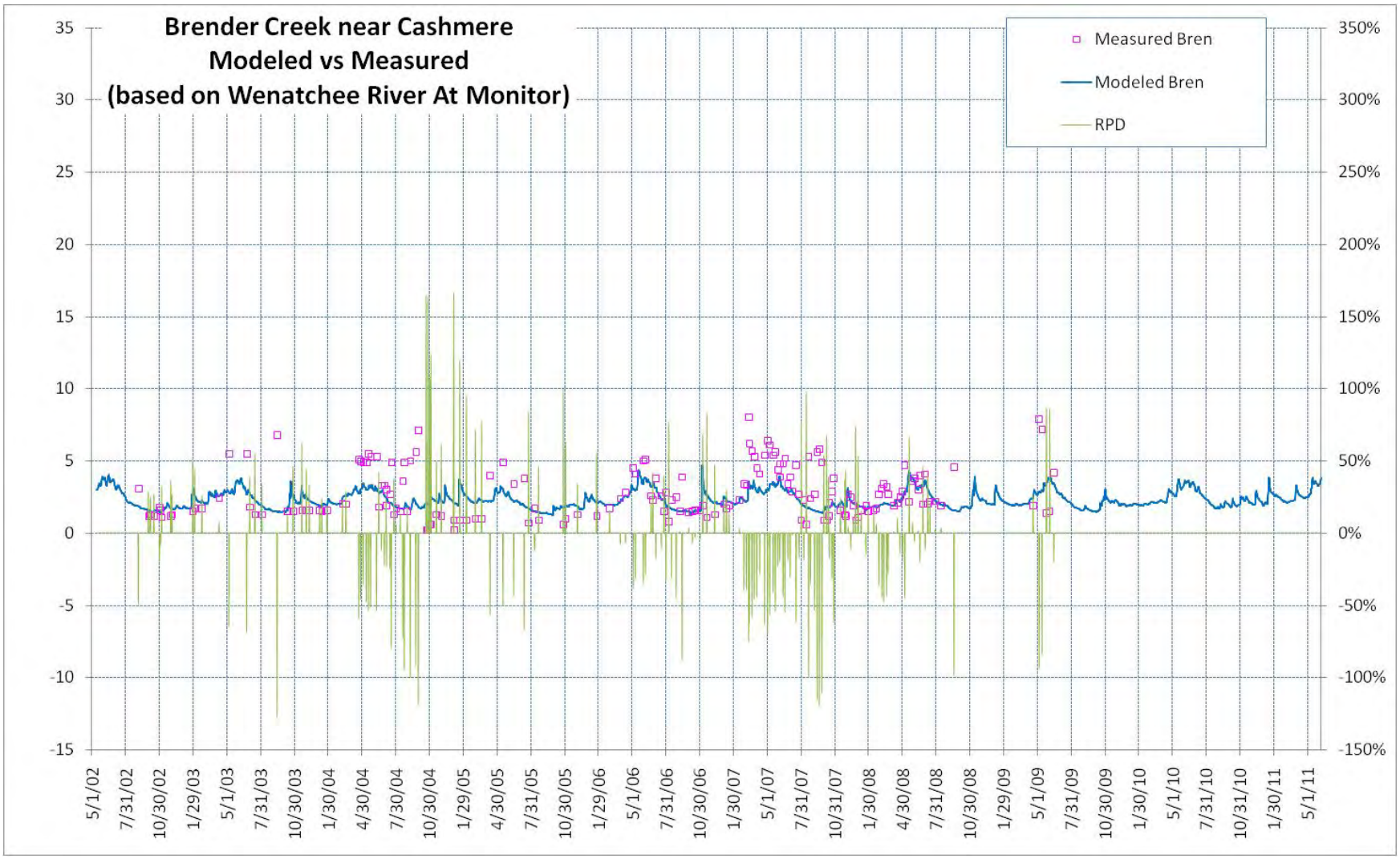

Figure 64. Measured flows at the Ecology "Brender Creek near Cashmere" gaging station, and modeled flows based on the "Wenatchee River at Monitor" station, with relative percent difference of paired values.

Appendix. Glossary Acronyms, and Abbreviations

Glossary

Areal flow: Surface water discharge per unit of watershed area, in units of length per time (for example, inches per day).

Baseflow: The component of total streamflow that originates from direct groundwater discharges to a stream.

Basin: A geographic area corresponding to a watershed in which all land and water areas drain or flow toward the lower elevation outlet of a central collector such as a stream, river, or lake.

Hydrologic: Relating to the scientific study of the waters of the earth, especially with relation to the effects of precipitation and evaporation upon the occurrence and character of water in streams, lakes, and on or below the land surface.

Reach: A specific portion or segment of a stream.

Stage height: Water-surface elevation above a gage datum, sometimes referred to as gage height.

Stormwater: The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snowmelt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, playfields, and from gravel roads and parking lots.

Streamflow: Discharge of water in a surface stream (river or creek).

Surface waters of the state: Lakes, rivers, ponds, streams, inland waters, salt waters, wetlands and all other surface waters and water courses within the jurisdiction of Washington State.

Telemetry: The automatic transmission of data by wire, radio, or other means from remote sources.

Watershed: The geographic area from which all land and water areas drain or flow toward the lower elevation outlet of a central collector such as a stream, river, or lake. Sometimes referred to as the drainage basin.

Water year (WY): An annual period defined by hydrologic characteristics. The water year used in this study is October 1 through September 30, and the number of the year represents the calendar year at the end of the water year. For example, “WY 2003” describes the water year beginning October 1, 2002 and ending September 30, 2003.

WRIA 45: Water Resource Inventory Area 45, which includes the Wenatchee River watershed (basin) and other neighboring small tributaries to the Columbia River.

Acronyms and Abbreviations

%RSD	Percent relative standard deviation
C	Celsius, a unit of temperature
cfs	Cubic feet per second
Deg	Degrees
EA	Environmental Assessment (Program)
Ecology	Washington State Department of Ecology
F	Fahrenheit, a unit of temperature
ID	Identification Code
Min	Minutes
n	Number of values
N	North
No.	Number
QAPP	Quality Assurance Project Plan
r^2	Coefficient of determination
RM	River mile
RPD	Relative percent difference
RSD	Relative standard deviation
Sec	Seconds
SNOTEL	Snowpack Telemetry system, U.S. Department of Agriculture
SWE	Snow water equivalent
U.S.	United States
USGS	United States Geological Survey
W	West
WAC	Washington Administrative Code
WRIA	Water Resource Inventory Area
WY	(See Glossary above)