Water Year 2006
Overview of Surface Water Monitoring Data for SC, SAR and Flow in the Tongue River Watershed

This cover photo shows Otter Creek, near Ashland

Prepared by: Andrew L. Bobst, Hydrologist, BLM-Miles City Field Office

April, 2007

Introduction 3
Data Review 6
Main Stem Sites 8
Tongue River at Monarch, WY 8
Tongue River at State Line, near Decker, MT 9
Tongue River below Tongue River Dam, near Decker MT 10
Tongue River at Birney Day School Bridge, near Birney, MT 11
Tongue River below Brandenburg Bridge, near Ashland, MT 12
Tongue River above TY Diversion 13
Tongue River at Miles City, MT 14
Tributary Sites 16
Goose Creek near Acme, WY 16
Prairie Dog Creek near Acme, WY 17
Hanging Woman Creek near Birney, MT 18
Otter Creek at Ashland, MT 19
Pumpkin Creek near Miles City, MT 20
Conclusions 21
Acknowledgements: 22
References 22
Figures 23
Appendix A 95

Introduction

When Coal Bed Natural Gas (CBNG) is developed, the methane must be allowed to desorb from the coal so that it can flow to production wells. This desorption is typically achieved by pumping groundwater from the coal bed aquifer to reduce the hydrostatic pressure within the coal seam (allowing the methane to desorb) and create a pressure gradient within the aquifer. This pressure gradient causes methane to flow towards the pumping wells.

CBNG water in the Montana portion of the Powder River Structural Basin (PRB) is moderately saline, having a Specific Conductance (SC) on the order of 2,000 microSiemens per centimeter at 25 degrees Celsius (μS/cm). SC is the ability for water to conduct a current at 25 degrees Celsius, and it is proportional to salinity. High salinity irrigation water may result in decreased crop yields depending on the crop being grown (See Fig. 1). The technical definition of Electrical Conductivity EC is "the ability of water to conduct a current"; however the Montana Department of Environmental Quality (MDEQ) regulations define EC as "the ability of water to conduct an electrical current at 25ºC". Since this is the same as the technical definition of SC, the SC values discussed in this report are directly comparable to the EC standards.

CBNG water in Montana is a sodium-bicarbonate ($Na\text{-}HCO_3$) type water, while the Tongue River mainstem is more balanced; having Ca>Mg>Na and HCO_3>SO_4 (See Fig. 2). This dominance of sodium cations causes CBNG water to have a high Sodium Adsorption Ratio (SAR; which is a complex ratio of Na to Ca+Mg); typically between 30 and 60 (ALL, 2001). High SAR values may cause impacts to soil structure, and impair the ability for clay rich soils to infiltrate water (see Fig. 3). There is also little sulfate in water from productive coal seams (VanVoast, 2003). Much of the CBNG produced water in the PRB is managed through treated or untreated discharge to surface waters under National Pollutant Discharge Elimination System (NPDES) permits, implemented under the Clean Water Act.

In Montana, NPDES permitting is conducted by the Montana Department of Environmental Quality (MDEQ) under the Montana Pollutant Discharge Elimination System (MPDES) permit program. During Water Year 2006 (10/1/05 to 9/30/06), three CBNG MPDES permits were in use. One permit (Fidelity's MT0030457) allows for the discharge between 1,600 and 2,500 gallons per minute (gpm) of untreated water with the rate varying by season (See Table 1). This permit has been in use since September 1999 and the most recent modification took effect on April 1, 2006. Prior to this modification this permit was limited to 1,600 gpm of untreated discharge. Fidelity also has a MPDES permit for treated discharge into the Tongue River (MT0030724); this permit became active April 1, 2006. Fidelity's treated water permit allows for the discharge of 1,700 gpm year round; however the quality of the water allowed to be discharged varies by season (See Table 2). The final MPDES permit (Pinnacle Gas Resources' (PGR) MT0030660) allows for the discharge of up to 1,122 gpm of treated CBNG water, with SAR < 3 and EC < 1000 μS/cm.

Table 1: MPDES Permit MT0030457
Variation in allowed Discharge

Dates	Discharge Allowed (gpm)
11/1 to 2/28	2,500
3/1 to 6/30	2,375
7/1 to 10/31	1,600

Table 2: MPDES Permit MT0030724 Variation in allowed Discharge

Dates	Instantaneous Maximum Discharge (gpm)	Average Monthly Total Suspended Solids (mg/L)	Average Monthly Total Nitrogen (mg/L)	Average Monthly SAR	Average Monthly SC (uS/cm)
11/1 to 2/28	1700	25	1.2	5	1,500
3/1 to 6/30	1700	25	1.3	3	1,000
7/1 to 10/31	1700	25	1.1	3	1,000

In Wyoming, NPDES discharge permitting is conducted by the Wyoming Department of Environmental Quality (WDEQ) under the Wyoming Pollutant Discharge Elimination System (WYPDES). Within Wyoming, two permits were originally issued in 1999 allowing for the direct discharge of untreated CBNG water to surface waters in the Tongue River watershed. Both permits were renewed in April, 2004. Currently, these permits authorize the discharge of 135 gpm from 11 discharge points to Goose Creek, and 40 gpm from three discharge points to the Tongue River. More recently, the "Brinkerhoff" permits were issued in the Prairie Dog Creek watershed for discharge of untreated water into impoundments. A permit for the discharge of treated water into Prairie Dog Creek has also been approved by the WDEQ. This permit, establishes a dissolved sodium effluent limit of 50 milligrams per liter (mg/L) and an EC effluent limit of 1000 μS/cm. Within the Wyoming portion of Hanging Woman Creek there is a WYPDES permit for the discharge of untreated CBNG water to 13 off-channel impoundments (WY0053023), and a WPDES permit for the discharge of untreated CBNG water to one on-channel impoundment (WY0052407).

Several other factors have potential impacts on the Tongue River system. The Decker Coal mines near Decker, MT, discharge excess water from pit dewatering into the Tongue River Reservoir under MPDES permits. The Tongue River Reservoir reduces the variability in flow and water quality downstream of it. Irrigation withdrawals and return flows occur along the entire length of the river. The TY diversion dam near Miles City diverts a significant portion of the water in the river during low flow periods.

In response to the potential for CBNG development in this area, the MDEQ and Northern Cheyenne Tribe have developed surface water quality standards for EC and SAR in the Tongue River watershed. These standards provide criteria against which to compare the monitoring data. These standards are summarized in Table 3 below. It should be noted that the MDEQ standards have been reviewed and approved by the United States Environmental Protection Agency (EPA), and therefore have Clean Water Act standing. The Northern Cheyenne Tribe has been granted “Treatment as a State” (TAS) status by

the EPA; however their standards have not been approved by the EPA. Thus, the Northern Cheyenne standards do not have Clean Water Act standing. Also, note that irrigation season standards are different from the non-irrigation season, and the MDEQ and Northern Cheyenne have defined the irrigation season differently. The irrigation season standards developed by the MDEQ are applicable year-round to the Tongue River above the Tongue River Dam. MDEQ standards are applicable at the Wyoming-Montana state line; however they are not applicable in Wyoming.

The Montana Board of Environmental Review (BER) has modified the standards which apply to CBNG in Montana; however this report only considers those standards which were in force during water year 2006. The most substantial change adopted by the BER was to designate EC and SAR "harmful" parameters. This change has not yet been approved by the EPA, and so is not in force at this time.

TABLE 3: MDEQ and Northern Cheyenne Surface Water Standards Applicable for Water Year 2006 for EC and SAR in the Tongue River Watershed (from MDEQ, 2003a and Greystone and ALL, 2003)

Irrigation Season[1]						
	MDEQ			Northern Cheyenne		
	Tongue River	Tributaries	Tongue River Reservoir	Tongue River Southern Boundary	Tongue River Northern Boundary	Tributaries
EC (μS/cm) Monthly Mean	1000	500	1000	1000	1500	1500
Not to Exceed	1500	500	1500	2000	2000	2000
SAR Monthly Mean	3.0	3.0	3.0	---	---	---
Not to Exceed	4.5	4.5	4.5	2.0	3.0	3.0

Non-Irrigation Season[1]						
	MDEQ			Northern Cheyenne		
	Tongue River	Tributaries	Tongue River Reservoir	Tongue River Southern Boundary	Tongue River Northern Boundary	Tributaries
EC (μS/cm) Monthly Mean	1500	500	1000	---	---	---
Not to Exceed	2500	500	1500	2000	2000	2000
SAR Monthly Mean	5.0	5.0	3.0	---	---	---
Not to Exceed	7.5	7.5	4.5	2.0	3.0	3.0

1: The Irrigation Season specified by the MDEQ is from March 1st to October 31st while the Irrigation Season specified by the Northern Cheyenne is from April 1st to November 15th.

For fiscal year 2006 the United States Congress appropriated funding for the USGS to conduct surface-water-quality monitoring in the Tongue River watershed to collect and disseminate data to stakeholders and the general public, as well as to State and Federal

agencies tasked with managing and regulating CBNG development. Since this congressional funding was not sufficient to fully fund this network, the US Bureau of Land Management (BLM), MDEQ, WDEQ, Wyoming State Engineer's Office (WSEO), Montana Department of Natural Resource Conservation (MDNRC), T & Y Irrigation District, and the Northern Cheyenne Tribe also provided funding for this network (See Map 1).

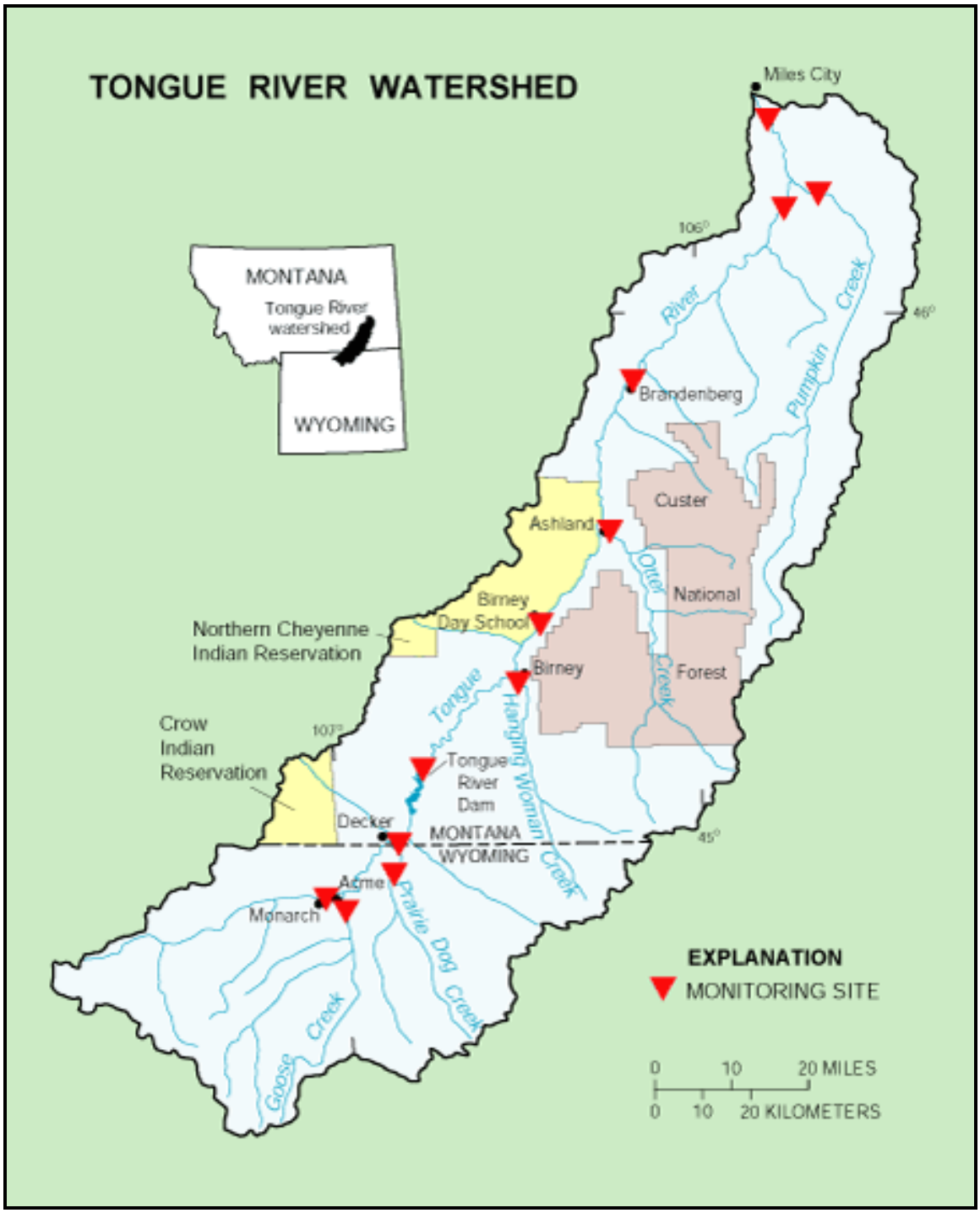
During water year 2006 SC and flow were measured and SAR was estimated by the U.S. Geological Survey in real time for some stations. In this report the daily mean values for SC and daily mean estimated SAR values are used. These data are considered provisional by the USGS because they were retrieved from the USGS web site prior to final USGS approval. Final values may be slightly different due to revisions made during final quality-assurance and review. SAR was estimated at some stations from the relationship between SC and SAR. The estimation procedure is discussed in detail at http://tonguerivermonitoring.cr.usgs.gov/index.htm. The SC-SAR equations used to estimate the SAR data reviewed in this report were developed from 2004-2005 data. At some sites, the relationship between SC and SAR was not sufficiently robust to provide a reliable estimation of SAR, and so SAR was not estimated.

Surface water-quality samples were also obtained under this program. Although these samples were analyzed by the USGS for many parameters, this report will focus on SC, SAR, and flow. SC and SAR are considered to be the parameters most likely to be affected by CBNG development (MDEQ, 2003b), and SC and SAR in the natural system fluctuate significantly with flow. Alkalinity data has also been plotted for the mainstem stations due to concerns of effects from HCO_3 on aquatic life (Skaar et al., 2006). The pH of samples obtained from the mainstem sties in water year 2006 ranged from 7.8 to 8.9. Within this pH range alkalinity is predominantly related to the HCO_3 concentration (Drever, 1997). An expanded set of analytical data, and additional information about this network are available from the USGS project website at http://tonguerivermonitoring.cr.usgs.gov/index.htm.

Data Review

For all sites, please see the figures section for graphical display of the data. Complete data sets can be obtained at http://tonguerivermonitoring.cr.usgs.gov/index.htm.

For each station a summary of the daily mean flow, daily mean SC, and daily mean estimated SAR data collected during water year 2006 are presented. Analytical SC and SAR data are also presented. Comparisons are made to the MDEQ and Northern Cheyenne surface water standards for EC and SAR where they are applicable. For comparison to the monthly mean EC and SAR standards, the monthly mean values are calculated as the simple average of all the daily mean and analytical measurements recorded during each calendar month, so long as at least nine values were available. Note that within the figures section, the daily mean and analytical data are combined when discussing the range of values recorded. SC vs. Flow, SAR vs. Flow, and SC vs. SAR with historical data are presented in graphical form to allow evaluation of 2006 data in context.



Map 1 shows the Tongue River Watershed as it extends from Wyoming into Montana. Also shown are major streams, and major land-ownership patterns (USFS, Northern Cheyenne Reservation, and Crow Reservation). The locations of the 12 surface water monitoring sites (3 in Wyoming, 9 in Montana), which are the subject of this report, are also shown. Figure obtained from http://tonguerivermonitoring.cr.usgs.gov/index.htm

Main Stem Sites

Tongue River at Monarch, WY

Table 4: Summary of USGS Monitoring Data
Tongue River at Monarch
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	16	45
		Max	938	91
	SC (uS/cm)	Min	159	438
		Max	578	438
	Estimated SAR	Min	0.1	0.4
		Max	0.5	0.4
Analytical Values	SC (uS/cm)	Min	216	455
		Max	503	456
	SAR	Min	0.2	0.4
		Max	0.6	0.4
Monthly Mean*	SC (uS/cm)	Min	230	---
		Max	535	---
	SAR	Min	0.2	---
		Max	0.5	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Flow and SC were measured continuously at this site. SAR was estimated from the SC data. Water-quality samples were also collected. There are no CBNG discharges upstream of this station. Some irrigation diversion/return flow occurs upstream of this station.

Daily mean flow values ranged from 16 to 938 cfs, with the mean being 133 cfs. These flows are somewhat less than flows during water years 2004-2005 (see Fig. 4).

Daily mean SC data collected at this station ranged from 159 to 578 μS/cm. Daily mean estimated SAR at this station ranged from 0.1 to 0.5. Analytical SC values at this site ranged from 216 to 503 μS/cm. Analytical SAR values at this site ranged from 0.2 to 0.6. Monthly mean SC values ranged from 230 to 535 μS/cm. Monthly mean SAR values ranged from 0.2 to 0.5 (see Fig. 5).

SC vs. Flow, SAR vs. Flow, SC vs. SAR and Alkalinity vs. Flow charts in the figures section present the 2006 data along with historical data (see Figs. 6-9).

Tongue River at State Line, near Decker, MT

Table 5: Summary of USGS Monitoring Data
Tongue River at State Line
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	10	80
		Max	1390	193
	SC (uS/cm)	Min	175	651
		Max	1060	941
	Estimated SAR	Min	0.4	0.8
		Max	1.6	1.3
Analytical Values	SC (uS/cm)	Min	322	648
		Max	893	820
	SAR	Min	0.4	0.7
		Max	1.6	1.0
Monthly Mean*	SC (uS/cm)	Min	370	745
		Max	889	818
	SAR	Min	0.5	0.9
		Max	1.2	1.1

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Flow and SC were measured in continuously at this site. SAR was estimated from the SC data. Water-quality samples were also collected. Wyoming CBNG discharges, some of Fidelity's CBNG discharges in Montana, and irrigation diversions/return flows occur upstream from this station.

Daily mean flow values ranged from 10 to 1390 cfs, with the mean being 180 cfs. The historical record for this site (1960-2005) indicates that daily mean flows at this station in an "average" year range from 155 to 1950 cfs with the mean being 436 cfs (see Fig. 10). The flows observed here are substantially greater than those seen at Monarch due to the addition of Goose and Prairie Dog Creeks (See Map 1).

Daily mean SC data collected at this station ranged from 175 to 1060 μS/cm. Daily mean estimated SAR at this station ranged from 0.4 to 1.6. Analytical SC values at this site ranged from 322 to 893 μS/cm. Analytical SAR values at this site ranged from 0.4 to 1.6. Monthly mean SC values ranged from 370 to 889 μS/cm. Monthly mean SAR values ranged from 0.5 to 1.2. All recorded SC and SAR values collected at this station were below the applicable MDEQ Standards (see Fig. 11). Note that irrigation season standards apply year-round upstream of the reservoir.

SC vs. Flow, SAR vs. Flow, SC vs. SAR and Alkalinity vs. Flow charts in the figures section present the 2006 data along with historical data (see Figs. 12-15).

A simple trend analysis was conducted for this station comparing 1986-1999 data to 2000-2006 data (See Appendix A). This analysis indicates that when values are normalized for flow, SAR has increased and SC has decreased. It appears that this is due to decreased Ca and Mg rather than increased Na. SO4 values have also decreased, supporting the hypothesis that the decreased Ca and Mg result from reduced overland and irrigation return flow inputs.

Tongue River below Tongue River Dam, near Decker MT

Table 6: Summary of USGS Monitoring Data
Tongue River below Dam
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	56	103
		Max	379	220
	SC (uS/cm)	Min	490	556
		Max	751	757
	Estimated SAR	Min	---	---
		Max	---	---
Analytical Values	SC (uS/cm)	Min	558	550
		Max	775	728
	SAR	Min	0.7	0.8
		Max	1.2	1.0
Monthly Mean*	SC (uS/cm)	Min	534	561
		Max	714	725
	SAR	Min	---	---
		Max	---	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Flow and SC were measured continuously at this site. Water-quality samples were also collected. Wyoming CBNG discharges, Fidelity's CBNG discharges, irrigation diversions/return flows, the Tongue River Reservoir, and the Decker Coal Mines occur upstream from this station. The PGR's CBNG discharge is located just downstream from this location.

Daily mean flow values ranged from 56 to 379 cfs, with the mean being 175 cfs. The historical record for this site (1939-2005) indicates that daily mean flows at this station in an "average" year ranges from 166 to 1530 cfs with the mean being 429 cfs (see Fig. 16). Flows at this station are strongly regulated by Tongue River Dam operations (See Map 1).

Daily mean SC data collected at this station ranged from 490 to 757 µS/cm. Daily mean SAR was not estimated at this station. Analytical SC values at this site ranged from 550 to 775 µS/cm. Analytical SAR values at this site ranged from 0.7 to 1.2. Monthly mean SC values ranged from 534 to 725 µS/cm. There were not sufficient data available to calculate monthly mean SAR values. All recorded SC and SAR values collected at this station were below the applicable MDEQ Standards (see Fig. 17).

SC vs. Flow, SAR vs. Flow, SC vs. SAR and Alkalinity vs. Flow charts in the figures section present the 2006 data along with historical data (see Figs. 18-21).

Tongue River at Birney Day School Bridge, near Birney, MT

Table 7: Summary of USGS Monitoring Data
Tongue River at Birney Day School
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	54	100
		Max	361	220
	SC (uS/cm)	Min	495	---
		Max	774	---
	Estimated SAR	Min	---	---
		Max	---	---
Analytical Values	SC (uS/cm)	Min	545	562
		Max	770	756
	SAR	Min	0.8	0.8
		Max	1.2	1.1
Monthly Mean*	SC (uS/cm)	Min	541	---
		Max	749	---
	SAR	Min	---	---
		Max	---	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Flow and SC were measured continuously at this site. Water-quality samples were also collected. Wyoming CBNG discharges, Fidelity's CBNG discharges, the Decker Coal Mines, the Tongue River Dam, PGR's CBNG discharges, and irrigation diversions/return flows occur upstream from this station.

Mean daily flows ranged from 54 to 361 cfs, with the mean being 166 cfs. The historical record for this site (1979-2005) indicates that daily mean flows at this station in an "average" year ranges from 153 to 1,210 cfs with the mean being 369 cfs (see Fig. 22). Flows at this station are strongly regulated by Tongue River Dam operations.

Daily mean SC data collected at this station ranged from 495 to 774 µS/cm. Daily mean SAR was not estimated at this station. Analytical SC values at this site ranged from 545 to 770 µS/cm. Analytical SAR values at this site ranged from 0.8 to 1.2. Monthly mean SC values ranged from 541 to 749 µS/cm. There were not sufficient data available to calculate monthly mean SAR values. All recorded SC and SAR values were below the applicable MDEQ and Northern Cheyenne Standards for this site (see Fig. 23).

SC vs. Flow, SAR vs. Flow, SC vs. SAR and Alkalinity vs. Flow charts in the figures section present the 2006 data along with historical data (see Figs. 24-27).

Tongue River below Brandenburg Bridge, near Ashland, MT

Table 8: Summary of USGS Monitoring Data
Tongue River at Brandenburg Bridge
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	58	100
		Max	333	241
	SC (uS/cm)	Min	546	665
		Max	914	680
	Estimated SAR	Min	0.9	---
		Max	1.6	---
Analytical Values	SC (uS/cm)	Min	561	647
		Max	898	847
	SAR	Min	0.9	1.0
		Max	1.7	1.4
Monthly Mean*	SC (uS/cm)	Min	628	---
		Max	885	---
	SAR	Min	1.1	---
		Max	1.6	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Flow and SC were measured continuously at this site. SAR was estimated from the SC data. Water-quality samples were also collected. Wyoming CBNG discharges, Fidelity's CBNG discharges, the Decker Coal Mines, the Tongue River Dam, PGR' CBNG discharges, and irrigation diversions/return flows occur upstream from this station.

Daily mean flows during Water Year 2006 ranged from 58 to 333 cfs, with the mean being 164 cfs. The historical record for this site (1973-2005) indicates that daily mean flows at this station in an "average" year ranges from 160 to 1430 cfs with the mean being 417 cfs (see Fig. 28). Flows at this station are strongly regulated by Tongue River Dam operations.

Daily mean SC data collected at this station ranged from 546 to 914 μS/cm. Daily mean estimated SAR at this station ranged from 0.9 to 1.6. Analytical SC values at this site ranged from 561 to 898 μS/cm. Analytical SAR values at this site ranged from 0.9 to 1.7. Monthly mean SC values ranged from 628 to 885 μS/cm. Monthly mean SAR values ranged from 1.1 to 1.6. All recorded EC and SAR values were below the applicable MDEQ and Northern Cheyenne Standards for this site (see Fig. 29).

SC vs. Flow, SAR vs. Flow, SC vs. SAR and Alkalinity vs. Flow charts in the figures section present the 2006 data along with historical data (see Figs. 30-33).

Tongue River above TY Diversion

Table 9: Summary of USGS Monitoring Data
Tongue River above TY Diversions
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	54	100
		Max	1220	250
	SC (uS/cm)	Min	470	---
		Max	1000	---
	Estimated SAR	Min	---	---
		Max	---	---
Analytical Values	SC (uS/cm)	Min	602	690
		Max	963	865
	SAR	Min	1.2	1.2
		Max	2.5	1.5
Monthly Mean*	SC (uS/cm)	Min	617	---
		Max	919	---
	SAR	Min	---	---
		Max	---	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Flow and SC were measured continuously at this site. Water-quality samples were also collected. Wyoming CBNG discharges, Fidelity's CBNG discharges, the Decker Coal Mines, the Tongue River Dam, PGR's CBNG discharges, and irrigation diversions/return flows occur upstream from this station.

Daily mean flows ranged from 54 to 1220 cfs, with the mean being 165 cfs. These flows are somewhat less than water year 2005 (the only other year of record; see Fig. 34). Flows at this station are strongly regulated by Tongue River Dam operations.

Daily mean SC data collected at this station ranged from 470 to 1000 µS/cm. Daily mean SAR was not estimated at this station. Analytical SC values at this site ranged from 602 to 963 µS/cm. Analytical SAR values at this site ranged from 1.2 to 2.5. Monthly mean SC values ranged from 617 to 919 µS/cm, with a mean of 797 µS/cm. There were not sufficient data available to calculate monthly mean SAR values. All recorded SC and SAR values were below the applicable MDEQ Standards for this site (see Fig. 35).

SC vs. Flow, SAR vs. Flow, SC vs. SAR and Alkalinity vs. Flow charts in the figures section present the 2006 data along with historical data (see Figs. 36-39).

Tongue River at Miles City, MT

Table 10: Summary of USGS Monitoring Data
Tongue River at Miles City
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	6.9	90
		Max	1360	280
	SC (uS/cm)	Min	465	---
		Max	1320	---
	Estimated SAR	Min	0.9	---
		Max	3.1	---
Analytical Values	SC (uS/cm)	Min	613	722
		Max	1360	908
	SAR	Min	1.5	1.4
		Max	3.8	1.6
Monthly Mean*	SC (uS/cm)	Min	665	---
		Max	1193	---
	SAR	Min	1.5	---
		Max	2.8	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Shading indicates value is in excess of the applicable standard.

Flow and SC were measured continuously at this site. SAR was estimated from the SC data. Water-quality samples were also collected. Wyoming CBNG discharges Fidelity's CBNG discharges, the Decker Coal Mines, the Tongue River Dam, PGR' CBNG discharges, irrigation diversions/return flows, and the TY Diversion dam occur upstream from this station.

The portion of the Tongue River immediately upstream from this station (from the TY diversion dam just above Pumpkin Creek to the mouth) is listed as impaired on the MDEQ's current (2004) 303(d) list, and this reach is also listed on the Draft 2006 list. The probable cause of impairment is identified as "Low Flow Alteration", and the identified probable source are "Dam Construction" and "Flow Regulation/Modification". Much of the water in the Tongue is diverted for irrigation at the diversion during low flows (See Fig. 34). Water diverted at the TY diversion dam is either consumed, flows to the Yellowstone River as irrigation return flow, or returns to the Tongue River as irrigation return flow. As such, during low flow periods, irrigation return flows as well as inflows from ground and surface water potentially could have a large affect on the quality of the water flowing through this lower reach of the Tongue River, and monitored at the Miles City station.

Daily mean flows ranged from 6.9 to 1360 cfs, with the mean being 145 cfs. The historical record for this site (1938-2005) indicates that daily mean flows at this station in an "average" year ranges from 152 to 1490 cfs with the mean being 403 cfs (see Fig. 40). Flows at this station are strongly regulated by Tongue River Dam operations and the operation of the TY diversion dam.

Daily mean SC data collected at this station ranged from 465 to 1320 µS/cm. Daily mean estimated SAR at this station ranged from 0.9 to 3.1. Analytical SC values at this site ranged from 613 to 1360 µS/cm. Analytical SAR values at this site ranged from 1.4 to 3.8. Monthly mean SC values ranged from 665 to 1193 µS/cm. Monthly mean SAR values ranged from 1.5 to 2.8. The monthly mean SC values recorded in June, July, August and September were greater than the monthly mean irrigation season standard (1000

μS/cm). All other SC and SAR values were below the applicable MDEQ standards for this site (see Fig. 41).

SC vs. Flow, SAR vs. Flow, SC vs. SAR and Alkalinity vs. Flow charts in the figures section present the 2006 data along with historical data (see Figs. 42-46).

Tributary Sites

Goose Creek near Acme, WY

Table 11: Summary of USGS Monitoring Data
Goose Creek near Acme
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	3.3	39
		Max	541	88
	SC (uS/cm)	Min	209	---
		Max	961	---
	Estimated SAR	Min	0.3	---
		Max	0.9	---
Analytical Values	SC (uS/cm)	Min	315	661
		Max	860	720
	SAR	Min	0.4	0.6
		Max	0.9	0.6
Monthly Mean*	SC (uS/cm)	Min	543	---
		Max	878	---
	SAR	Min	0.6	---
		Max	0.8	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Flow and SC data were collected continuously at this station. SAR was estimated from the SC data. Water-quality samples were also collected. The 1999 WYPDES permits allow for the direct discharge of approximately 0.3 cfs (135 gpm) of untreated CBNG water to Goose Creek from 11 discharge points upstream from this station. Irrigation diversions/return flows are also occurring upstream from this station.

Daily mean flows ranged from 3.3 to 541 cfs, with the mean being 67 cfs. The historical record for this site (1984-2005) indicates that daily mean flows at this station in an "average" year ranges from 48 to 705 cfs with the mean being 153 cfs (see Fig. 47).

Daily mean SC data collected at this station ranged from 209 to 961 μS/cm. Daily mean estimated SAR at this station ranged from 0.3 to 0.9. Analytical SC values at this site ranged from 315 to 860 μS/cm. Analytical SAR values at this site ranged from 0.4 to 0.9. Monthly mean SC values ranged from 543 to 878 μS/cm. Monthly mean SAR values ranged from 0.6 to 0.8 (see Fig. 48).

SC vs. Flow, SAR vs. Flow, and SC vs. SAR charts in the figures section present the 2006 data along with historical data (see Figs. 49-51).

Prairie Dog Creek near Acme, WY

Table 12: Summary of USGS Monitoring Data
Prairie Dog Creek near Acme
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	0.0	6.2
		Max	60	34
	SC (uS/cm)	Min	703	---
		Max	2630	---
	Estimated SAR	Min	0.5	---
		Max	2.8	---
Analytical Values	SC (uS/cm)	Min	1070	1590
		Max	2500	1740
	SAR	Min	1.0	1.2
		Max	2.7	1.5
Monthly Mean*	SC (uS/cm)	Min	1049	---
		Max	2446	---
	SAR	Min	0.9	---
		Max	2.5	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Flow and SC data were collected continuously at this station. SAR was estimated from the SC data. Water-quality samples were also collected. The "Brinkerhoff" permits allow for the discharge of untreated water into impoundments within the Prairie Dog Creek watershed. A permit for the discharge of treated water into Prairie Dog Creek has also been approved by WDEQ; this permit allows for the discharge of treated CBNG water with dissolved sodium less than 50 mg/l and EC<1000 µS/cm (Zygmunt, pers. com., 2006). Irrigation diversions/return flows also occur upstream from this station.

Daily mean flows during Water Year 2006 ranged from 0 to 60 cfs, with the mean being 14 cfs. The historical record for this site (1970-2005) indicates that daily mean flows at this station in an "average" year ranges from 12 to 262 cfs with the mean being 37 cfs (see Fig. 52).

Daily mean SC data collected at this station ranged from 703 to 2630 µS/cm. Daily mean estimated SAR at this station ranged from 0.5 to 2.8. Analytical SC values at this site ranged from 1070 to 2500 µS/cm. Analytical SAR values at this site ranged from 1.0 to 2.7. Monthly mean SC values ranged from 1049 to 2446 µS/cm. Monthly mean SAR values ranged from 0.9 to 2.5 (see Fig. 53).

SC vs. Flow, SAR vs. Flow, and SC vs. SAR charts in the figures section present the 2006 data along with historical data (see Figs. 54-56).

Hanging Woman Creek near Birney, MT

Table 13: Summary of USGS Monitoring Data
Hanging Woman Creek near Birney
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	0.0	0.0
		Max	0.4	0.15
	SC (uS/cm)	Min	1990	---
		Max	2710	---
	Estimated SAR	Min	4.2	---
		Max	5.2	---
Analytical Values	SC (uS/cm)	Min	1750	1870
		Max	2300	2080
	SAR	Min	3.3	3.4
		Max	4.5	3.5
Monthly Mean*	SC (uS/cm)	Min	2178	---
		Max	2436	---
	SAR	Min	4.4	---
		Max	4.8	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Shading indicates value is in excess of the applicable standard.

Flow and SC data were collected continuously at this station. SAR was estimated from the SC data. Water-quality samples were also collected. Nance Petroleum Corporation has permits for the discharge of untreated CBNG water into impoundments within the Wyoming portion of the Hanging Woman Creek watershed. Irrigation diversions/return flows are also occurring upstream from this station.

Daily mean flows during Water Year 2006 ranged from 0 to 0.4 cfs, with the mean being 0.1 cfs. The historical record for this site (1973-2005) indicates that daily mean flows at this station in an "average" year ranges from 0.35 to 77 cfs with the mean being 3 cfs (see Fig. 57).

Daily mean SC data collected at this station ranged from 1990 to 2710 µS/cm. Daily mean estimated SAR at this station ranged from 4.2 to 5.2. Analytical SC values at this site ranged from 1750 to 2300 µS/cm. Analytical SAR values at this site ranged from 3.3 to 4.5. Monthly mean SC values ranged from 2178 to 2436 µS/cm. Monthly mean SAR values ranged from 4.4 to 4.8. All recorded SC values were far in excess of the MDEQ's EC standard (500 µS/cm). SAR values were often in excess of the MDEQ's SAR standards (see Fig. 58).

SC vs. Flow, SAR vs. Flow, and SC vs. SAR charts in the figures section present the 2006 data along with historical data (see Figs. 59-61).

Otter Creek at Ashland, MT

Table 14: Summary of USGS Monitoring Data
Otter Creek near Birney
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	0.1	0.9
		Max	4.7	2.1
	SC (uS/cm)	Min	1890	---
		Max	3200	---
	Estimated SAR	Min	4.8	---
		Max	6.9	---
Analytical Values	SC (uS/cm)	Min	2130	2830
		Max	3120	3130
	SAR	Min	5.1	6.1
		Max	6.9	6.3
Monthly Mean*	SC (uS/cm)	Min	2283	---
		Max	2903	---
	SAR	Min	5.4	---
		Max	6.4	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Shading indicates value is in excess of the applicable standard.

Flow and SC were measured continuously at this site. SAR was estimated from the SC data. Water-quality samples were also collected. No CBNG discharge is occurring upstream of this station. Irrigation diversions/return flows occur upstream from this station.

Daily mean flows ranged from 0.1 to 4.7 cfs, with the mean being 1.4 cfs. The historical record for this site (1972-2005) indicates that daily mean flows at this station in an "average" year ranges from 0.6 to 32 cfs with the mean being 4 cfs (see Fig. 62).

Daily mean SC data collected at this station ranged from 1890 to 3200 µS/cm. Daily mean estimated SAR at this station ranged from 4.8 to 6.9. Analytical SC values at this site ranged from 2130 to 3130 µS/cm. Analytical SAR values at this site ranged from 5.1 to 6.9. Monthly mean SC values ranged from 2283 to 2903 µS/cm. Monthly mean SAR values ranged from 5.4 to 6.4. All recorded SC values were far in excess of the MDEQ's EC standard (500 µS/cm). Most of the recorded SAR values were in excess of the MDEQ's SAR standards (see Fig. 63).

SC vs. Flow, SAR vs. Flow, and SC vs. SAR charts in the figures section present the 2006 data along with historical data (see Figs. 64-66).

Pumpkin Creek near Miles City, MT

Table 15: Summary of USGS Monitoring Data
Pumpkin Creek near Birney
Water Year 2006

			Irrigation Season	Non-Irrigation Season
Daily Means	Flow (cfs)	Min	0.0	0.0
		Max	1480	20
	SC (uS/cm)	Min	362	---
		Max	3190	---
	Estimated SAR	Min	---	---
		Max	---	---
Analytical Values	SC (uS/cm)	Min	321	1640
		Max	2530	2200
	SAR	Min	3.9	9.5
		Max	15.5	10.2
Monthly Mean*	SC (uS/cm)	Min	623	---
		Max	2005	---
	SAR	Min	---	---
		Max	---	---

* Monthly Mean Values are calculated by taking the simple mean of all daily mean and analytical samples collected during each calendar month, provided that at least 9 values were available.

Shading indicates value is in excess of the applicable standard.

Flow and SC were measured continuously at this site. Water-quality samples were also collected. CBNG discharge is not occurring upstream of this station. Irrigation diversions/return flows are occurring upstream from this station.

Daily mean flows ranged from 0 to 1480 cfs, with the mean being 16 cfs. The historical record for this site (1972-2005) indicates that daily mean flows at this station in an "average" year ranges from 0.01 to 141 cfs with the mean being 14 cfs (see Fig. 67).

Daily mean SC data collected at this station ranged from 362 to 3190 µS/cm. Daily mean SAR was not estimated at this station. Analytical SC values at this site ranged from 321 to 2530 µS/cm. Analytical SAR values at this site ranged from 3.9 to 15.5. Monthly mean SC values ranged from 623 to 2005 µS/cm. There were not sufficient data available to calculate monthly mean SAR values. Most recorded SC values were in excess of the MDEQ's EC standard (500 µS/cm). Most of the recorded SAR values were in excess of the MDEQ's SAR standards (see Fig. 68).

SC vs. Flow, SAR vs. Flow, and SC vs. SAR charts in the figures section present the 2006 data along with historical data (see Figs. 69-71).

Conclusions

During Water Year 2006 (October 1, 2005-September 30, 2006) flows within the Tongue River watershed were lower than historical. SC and SAR can be correlated with flow so an evaluation of SC and SAR must also take flow into account.

The main stem stations showed that the MDEQ and Northern Cheyenne surface water standards for SC and SAR were not exceeded, except at the Miles City station. The mean monthly SC values at Miles City were greater than the mean monthly irrigation season SC standard during June, July, August and September. These exceedances appear to be primarily due to the combination of diversion of the relatively good quality Tongue River water at the T&Y diversion dam and probable inflows of water with poorer water quality from irrigation return flows, ground water, and tributaries.

The tributary stations showed that the MDEQ surface water standards for SC and SAR were typically exceeded by existing conditions. In some cases the existing conditions resulted in water quality values that were always in excess of the SC and SAR standards. These exceedances, even in watersheds where little or no CBNG development has occurred, indicate that existing conditions are higher than the standards.

Although it had been hoped that a detailed statistical trend analysis could be completed this year for several stations, a preliminary review of the data indicated that trends would not be discernable due to the high variability of the data, and the lack of an obvious trend. A longer "Post CBNG" record will be needed to test for a trend in order to distinguish between natural variation caused by climatic changes and anthropogenic-caused variations resulting from land-use or water-use activities. Statistical trends typically require a minimum of 5-10 years of data to acquire sufficient resolution of interannual and seasonal variations that can detect trends arising from human influences. Evaluation of the potential for a statistical analysis will be ongoing.

A simple trend analysis for the Tongue River at the State Line was conduced, comparing 1986-1999 data to 2000-2006 data (See Appendix A). This analysis indicates that flow corrected SC values have decreased and flow corrected SAR values have increased. This increase in SAR is due to decreased calcium (Ca) and magnesium (Mg) inputs. It appears that this decrease in Ca and Mg is a result of decreased Ca-Mg sulfate inputs which may be attributable to drought conditions (decreased overland flow inputs) and changes in irrigation practices (increased use of center pivots and side rolls resulting in less irrigation return flow).

At this time the SC vs. Flow, SAR vs. Flow, and Alkalinity vs. Flow charts do not appear to show noticeable changes. The SC vs. SAR charts for the state line and at Miles City may be showing slight increases in the relative proportion of sodium (Na) to Ca and Mg. As discussed above, this is likely due to drought conditions and changes in irrigation practices.

Acknowledgements:

The thoughtful reviews provided for this paper are greatly appreciated. Reviews were provided by Melanie Clark, USGS, Cheyenne, WY; Jim Lloyd, MDEQ, Helena, MT; David Nimick, USGS, Helena, MT; Mike Philbin, BLM, Billings, MT; Mark Jacobson, MSU, Billings, MT; and Irma Torres, BLM, Miles City, MT.

References

ALL, 2001, Water Resources Technical Report, Montana statewide oil and gas environmental impact statement and amendment of the Powder River and Billings resource management plans. Prepared for the US Department of the Interior, Bureau of Land Management, Miles City Field Office.

Ayers, R. S., and Westcot, D.W., 1985, Water Quality for Agriculture, FAO Irrigation and Drainage paper 29 (Rev 1), Food and Agriculture Organization of the United Nations.

Drever, J.I., 1997, The geochemistry of natural waters: surface and groundwater environments, Simon and Schuster, Upper Saddle River, New Jersey, 436 pgs.

Greystone and ALL, 2003, Surface Water Quality Analysis Technical Report prepared in support of the MT and WY FEISs.

Hansen, B.R., Gratton, S. R., and Fulton A., 1999, Agricultural Salinity and Drainage, University of California Irrigation Program, University of California, Davis.

Montana Department of Environmental Quality, 2003a, ARM Title 17, Chapter 30, Section 17.30.670.

Montana Department of Environmental Quality, 2003b, Record of Decision for the Montana Statewide Oil and Gas Environmental Impact Statement (http://www.deq.state.mt.us/coalbedmethane/pdf/RODAug7_03.pdf).

Skaar, D., Farag, A., and Harper, D., 2006, Toxicity of Sodium Bicarbonate to Fish from Coal-Bed Natural Gas Production in the Tongue and Powder River Drainages, Montana and Wyoming, USGS Fact sheet 2006-3092, 4 pgs.

U.S.Geological Survey, 2006, Tongue River Surface-Water-Quality Monitoring Network, http://tonguerivermonitoring.cr.usgs.gov/index.htm.

VanVoast, W.A., 2003, Geochemical signature of formation waters associated with coalbed methane, AAPG Bulletin, v. 87, no. 4 (April 2003), pp. 667–676.

Zygmunt, Jennifer, 2006, WY-DEQ, Personal Communication, 4/28/06.

Figures

Figure 1: Comparison of Crop Yield to SC (Salinity) and Recorded 2006 SC Values in the Tongue River Watershed

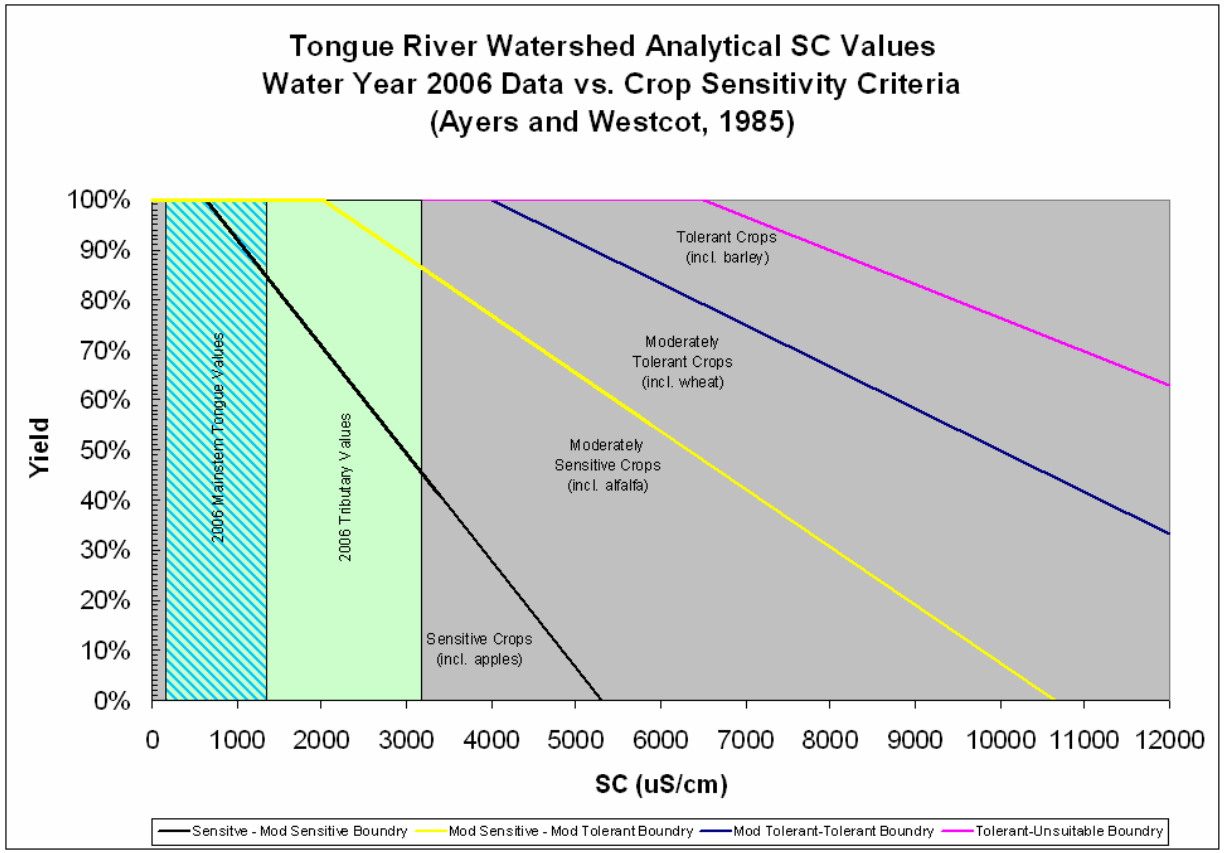


Figure 1 shows the range of SC values recorded during water year 2006 compared to yield vs. salinity curves for representative crops. Note that yield comparisons are made to that which would be attained using low salinity irrigation water, and assumes that all other factors are equal. Mainstem values ranged from 159 to 1360 uS/cm. The high end of these values would be expected to cause approximately a 15% drop in the yield of sensitive crops. Tributary values ranged from 216 to 3200 uS/cm. The high end of these values would be expected to cause approximately a 13% drop in the yield of moderately sensitive crops, and approximately a 54% drop in the yield of sensitive crops.

Figure 2: Comparison of Stiff Plots for CBNG and Surface Waters

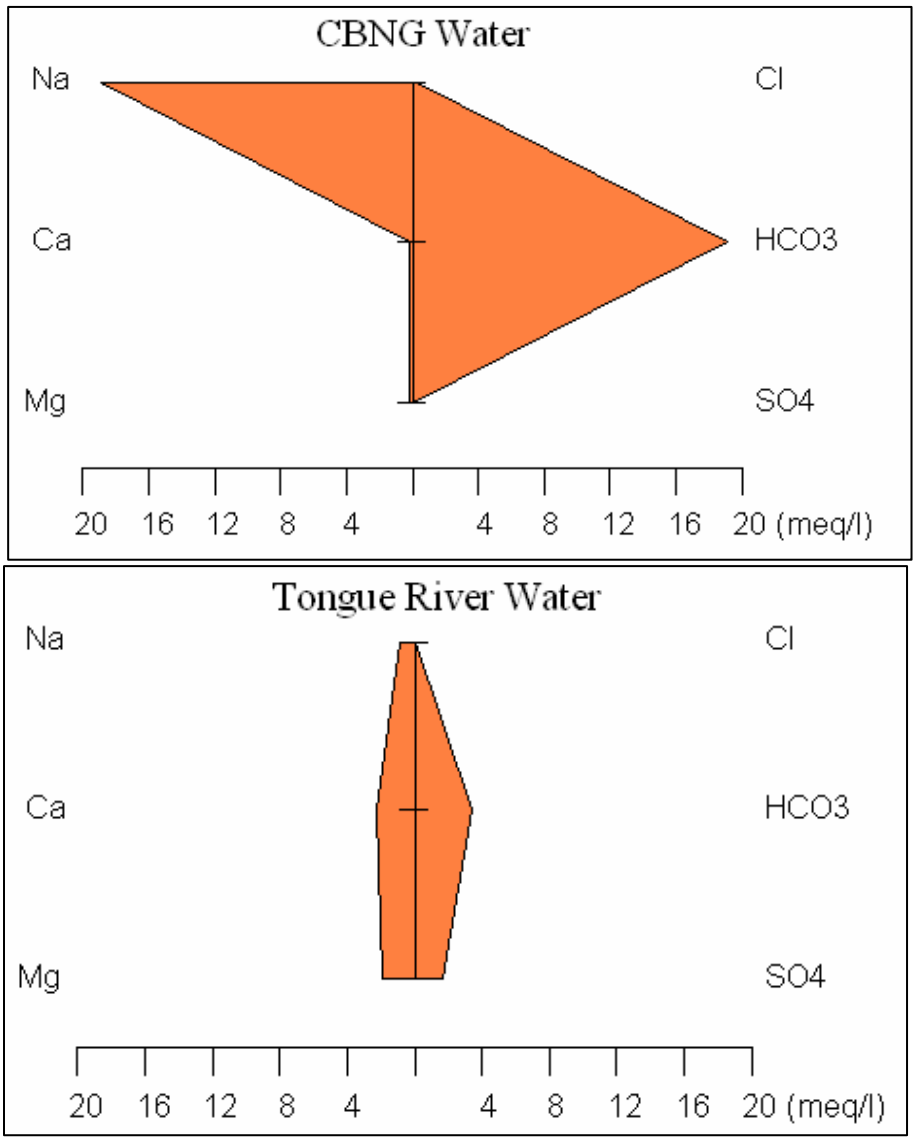


Figure 2 shows a comparison of the major ions in a representative sample of CBNG water from a well near Decker, MT, and from the Tongue River at the State Line USGS station. The CBNG water is dominated by Na and HCO_3 while the surface water sample is relatively balanced with Ca>Mg>Na and HCO_3>SO_4.

Figure 3: Comparison of Infiltration Criteria and Recorded 2006 SC and SAR Values in the Tongue River Watershed

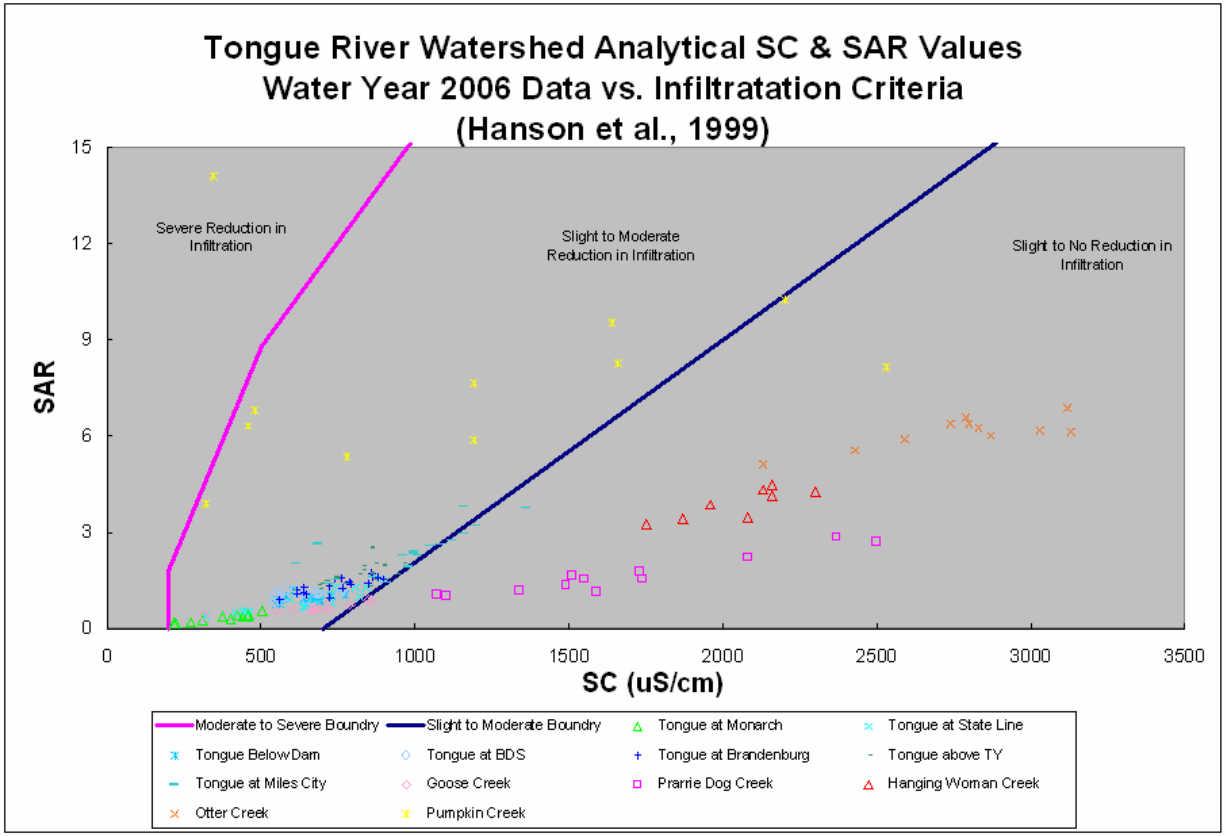


Figure 3 shows water quality data from water year 2006 in the Tongue River Watershed compared to the infiltration criteria developed by Hanson et al. (1999). Mainstem and Goose Creek values fall primarily within the Slight to Moderate reduction in infiltration field due to their relatively low SC values. Pumpkin Creek Values fall primarily within the Severe and Slight to Moderate reduction in infiltration fields due to its having relatively high SAR values relative to SC. Other tributaries fall within the Slight to No reduction in infiltration field.

Figure 4: Tongue River at Monarch, WY

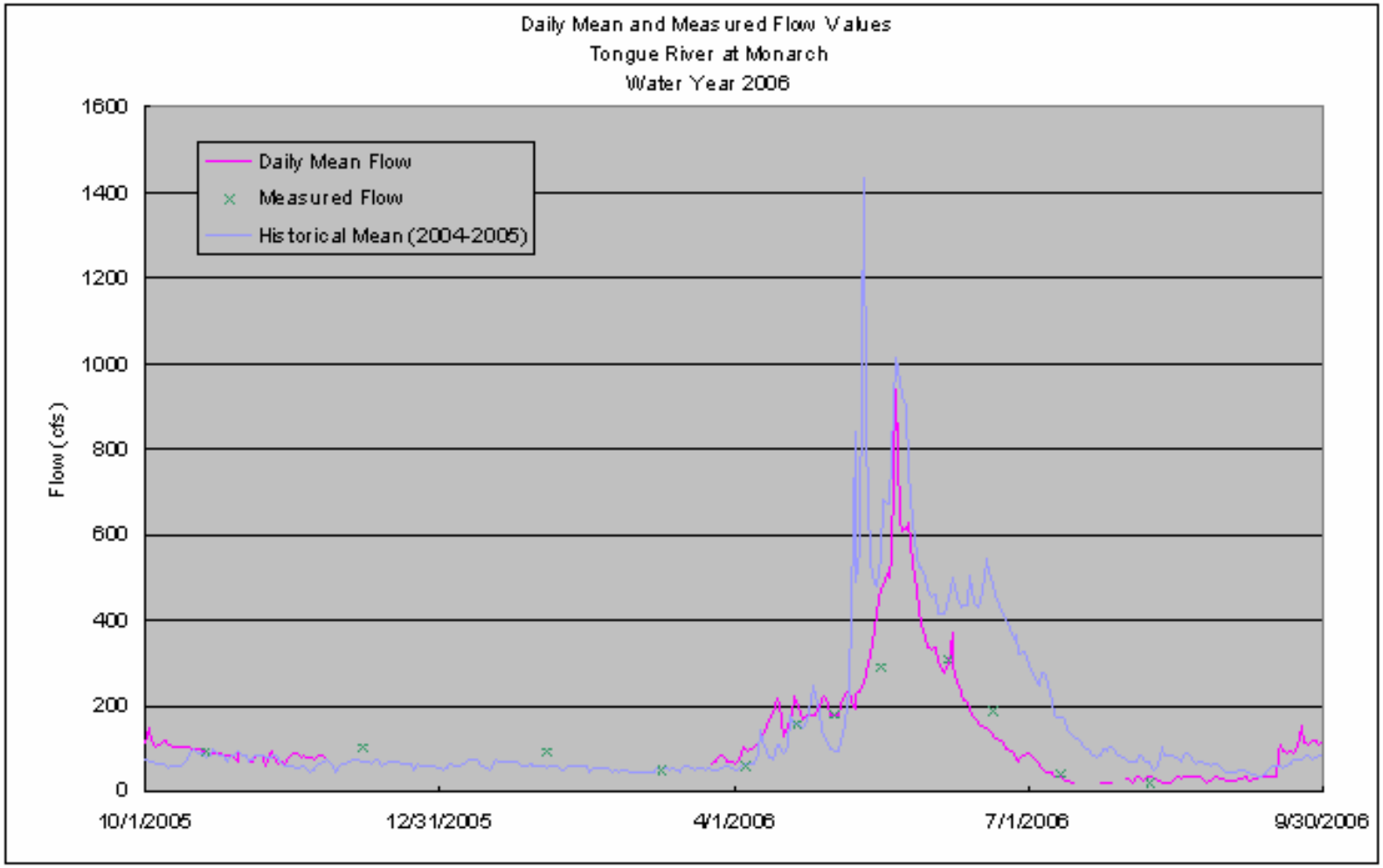
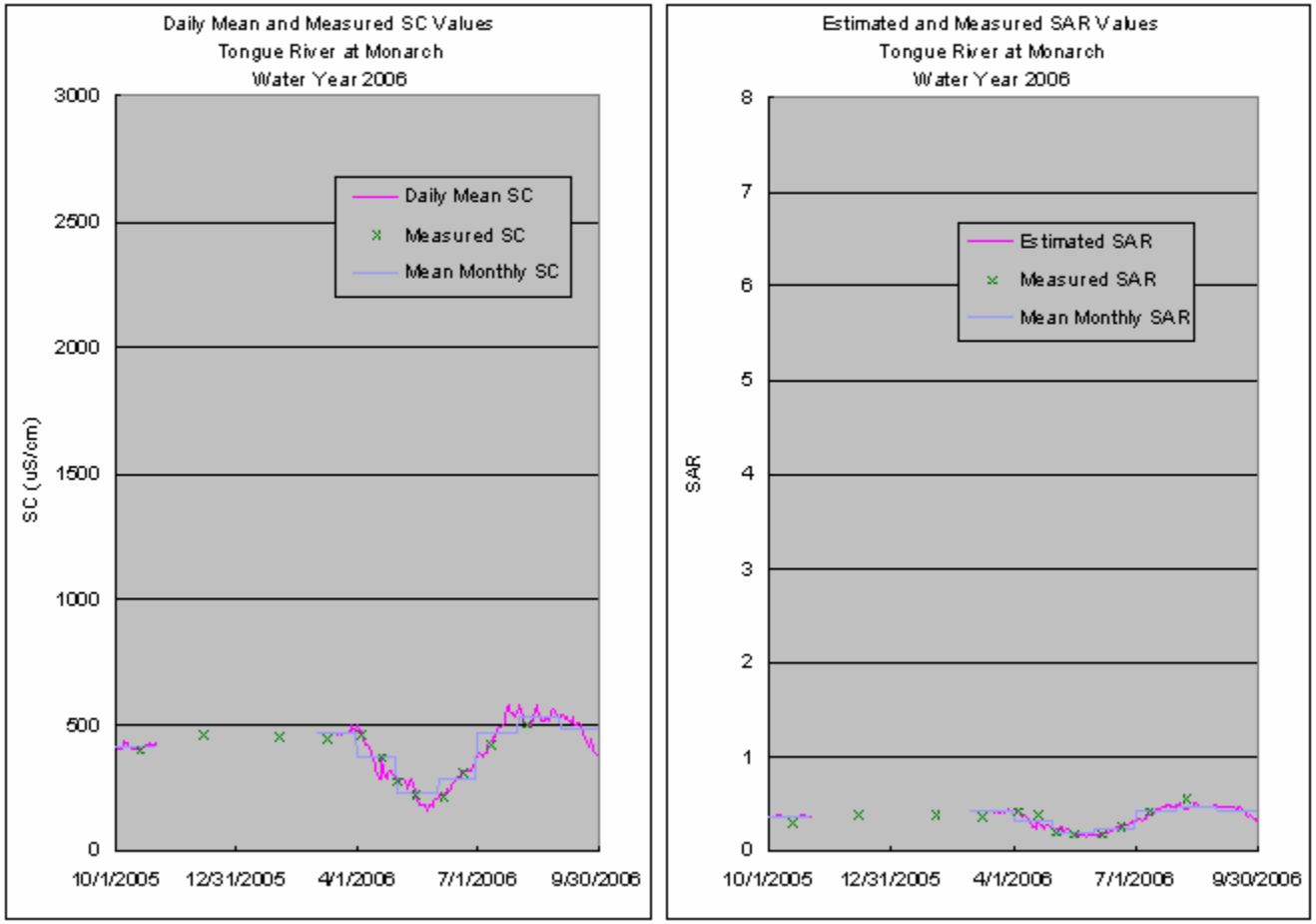


Figure 4 shows daily mean and field measurements of flow in a time series plot for water year 2006 for the Tongue River at Monarch. Daily mean flow values ranged from 16 to 938 cfs. Historical daily mean flow values are also shown. Flows were somewhat less than historical.

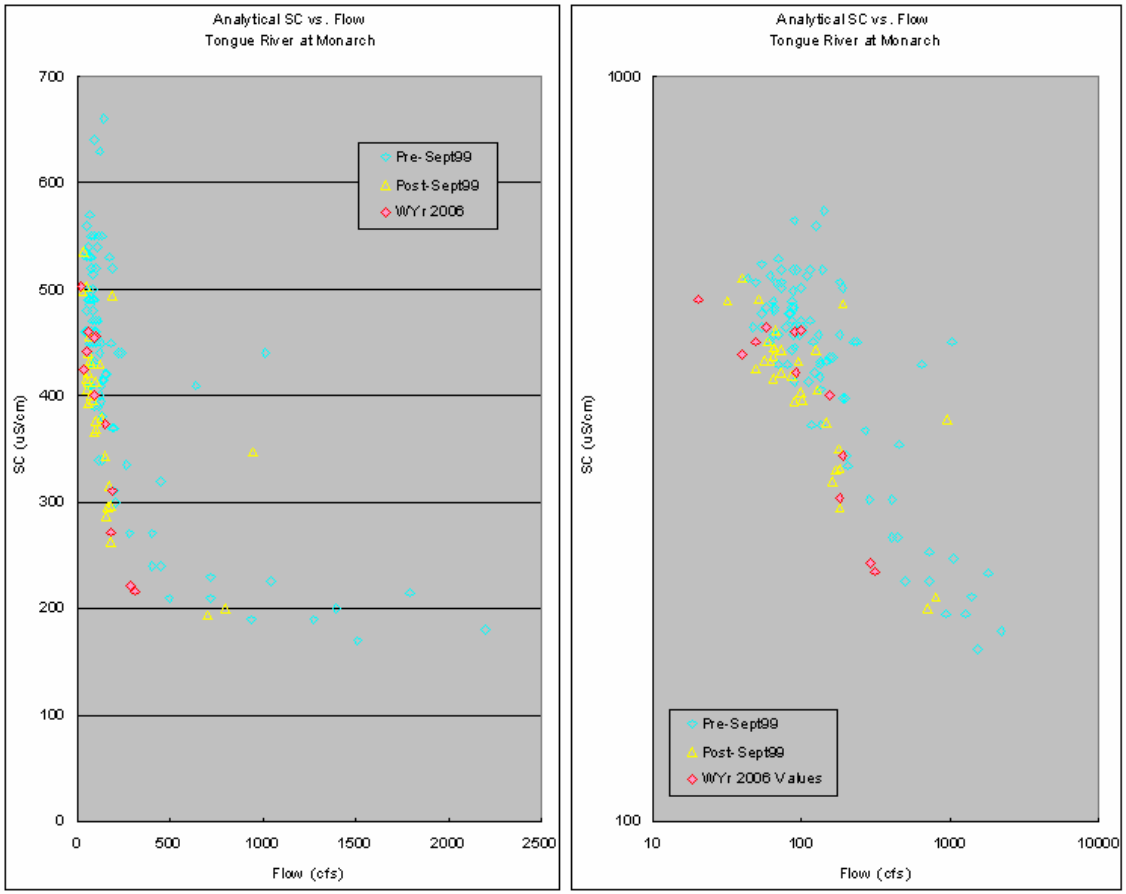
Figure 5: Tongue River at Monarch, WY



A **B**

Figure 5 shows analytical and daily mean SC values (A) and analytical and daily mean estimated SAR values (B) in time series plots for water year 2006 for the Tongue River at Monarch. Monthly mean SC and SAR values are also shown. SC values ranged from 159 uS/cm to 578 uS/cm. SAR values ranged from 0.1 to 0.5.

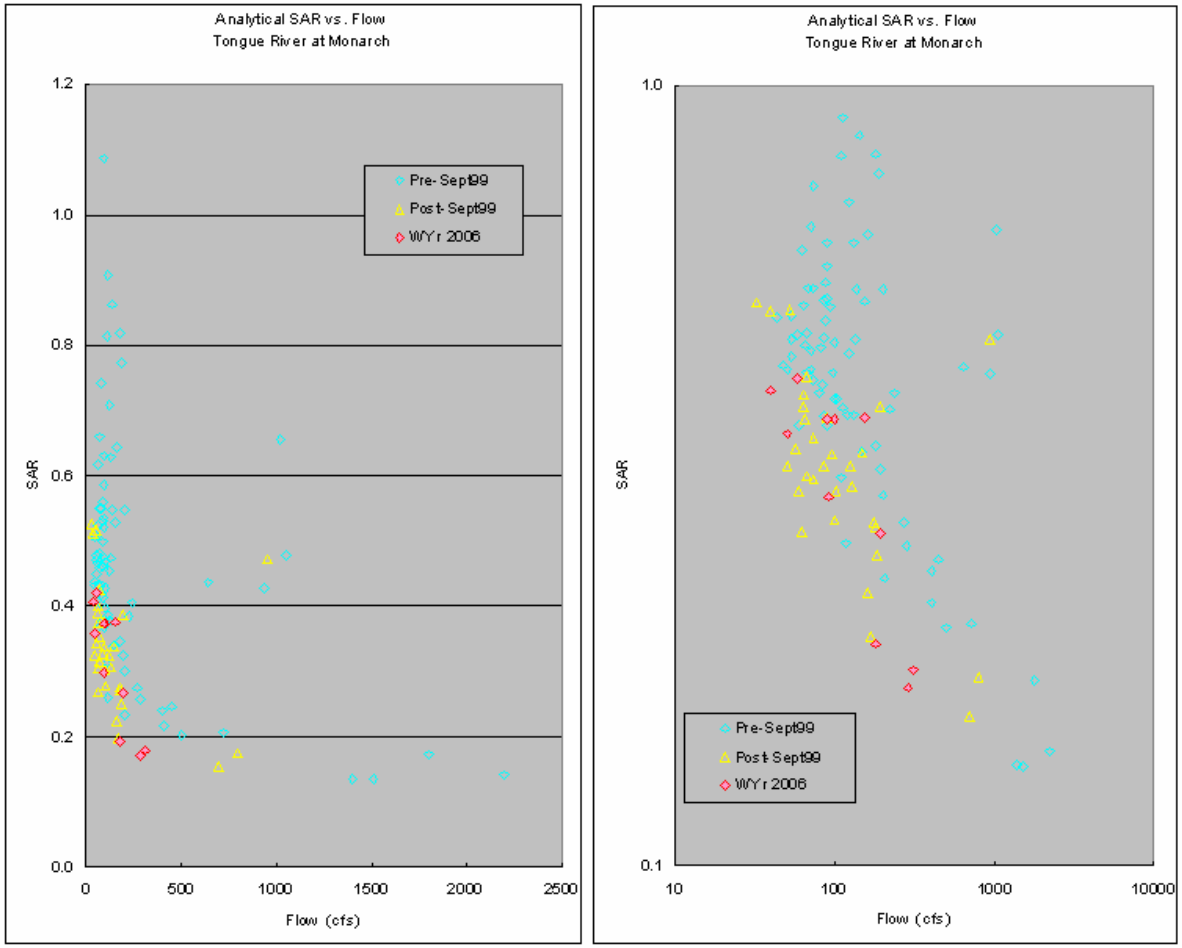
Figure 6: Tongue River at Monarch, WY



A **B**

Figure 6 shows analytical SC vs. Flow data for water year 2006 for the Tongue River at Monarch. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 7: Tongue River at Monarch, WY



A **B**

Figure 7 shows analytical SAR vs. Flow data for water year 2006 for the Tongue River at Monarch. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 8: Tongue River at Monarch, WY

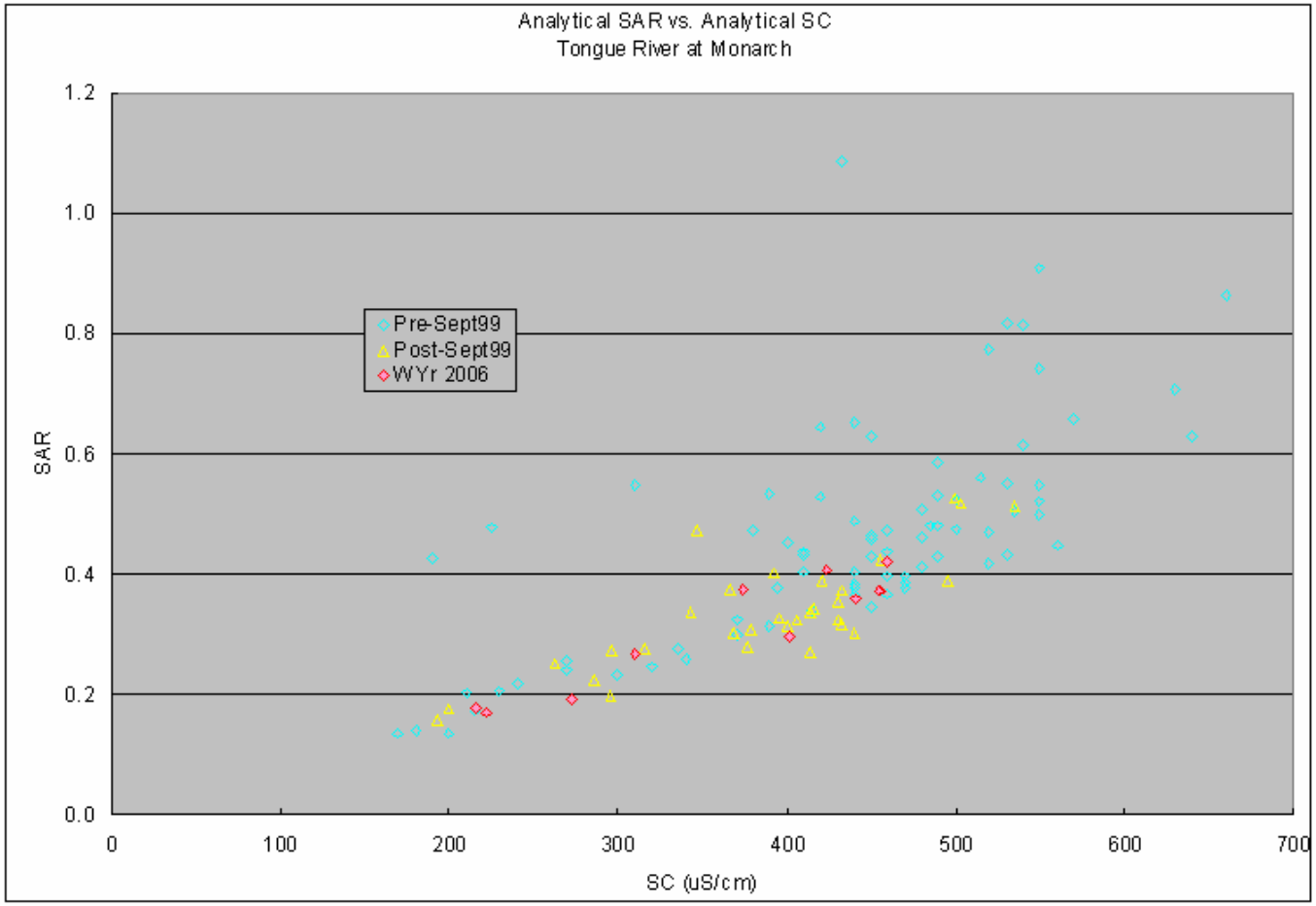
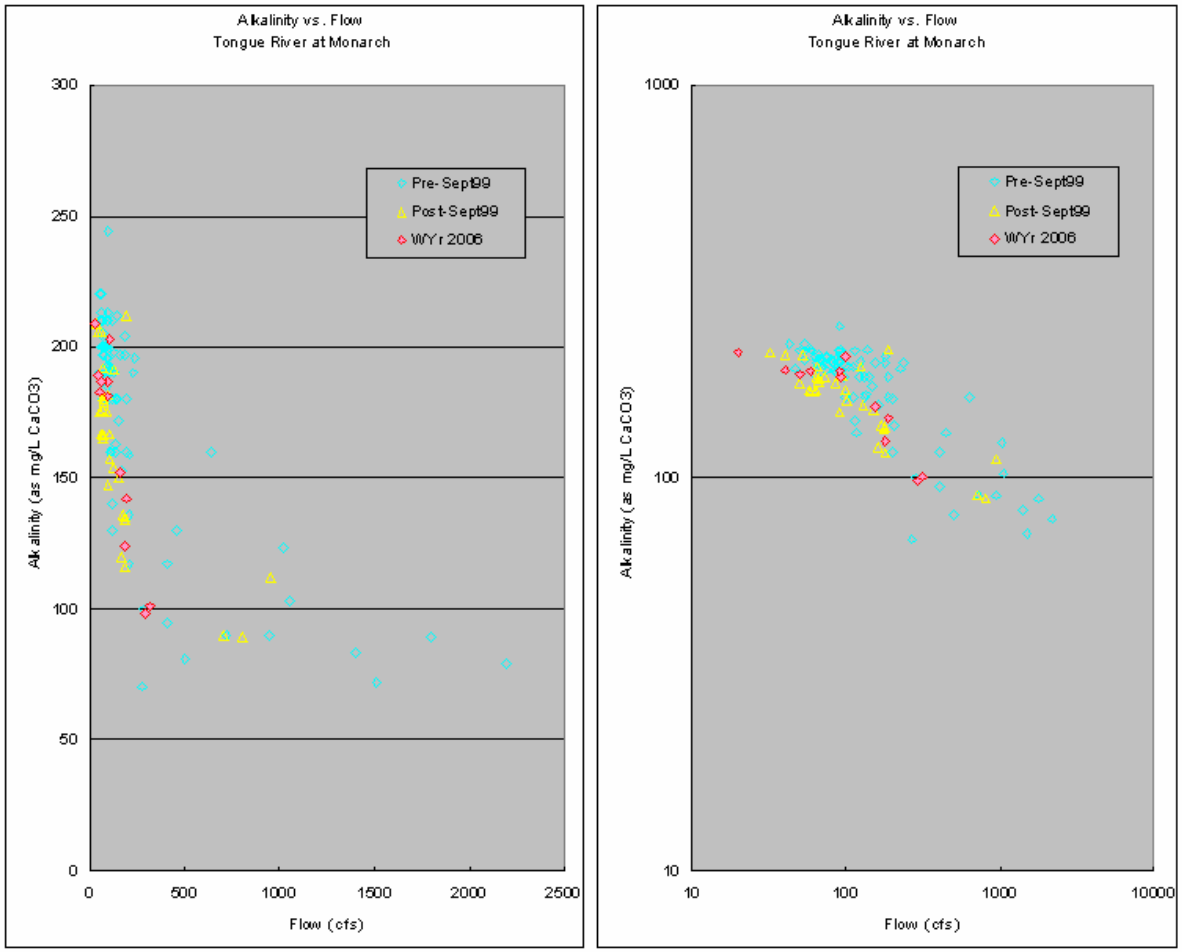


Figure 8 shows analytical SAR vs. analytical SC data for water year 2006 for the Tongue River at Monarch. Historical SAR vs. SC data are also shown to place the data in context.

Figure 9: Tongue River at Monarch, WY



A **B**

Figure 9 shows analytical Alkalinity vs. Flow data for water year 2006 for the Tongue River at Monarch. These data are charted on both linear (A) and logarithmic (B) scales. Historical Alkalinity vs. Flow data are also shown to place the data in context.

Figure 10: Tongue River at State Line, near Decker, MT

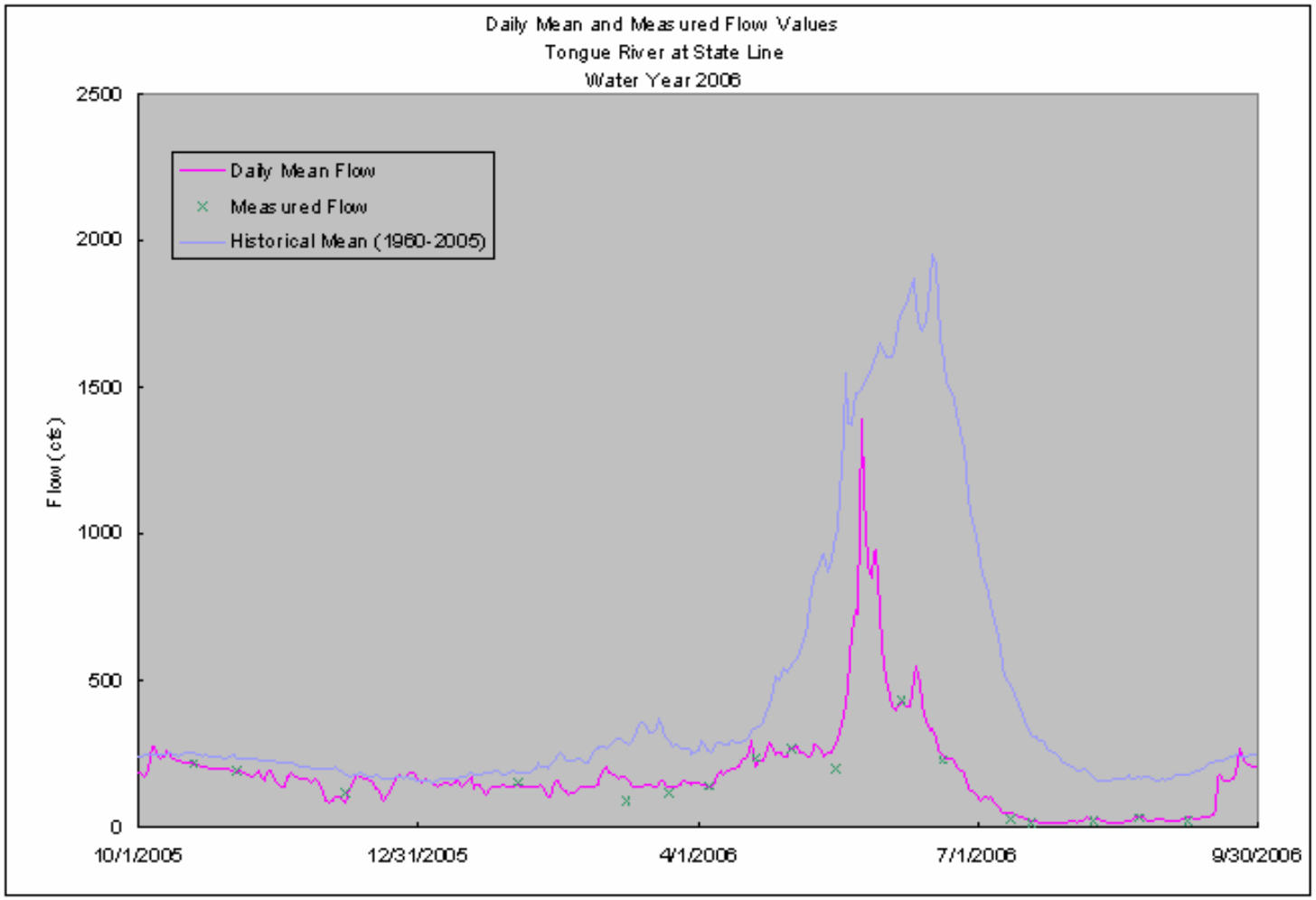
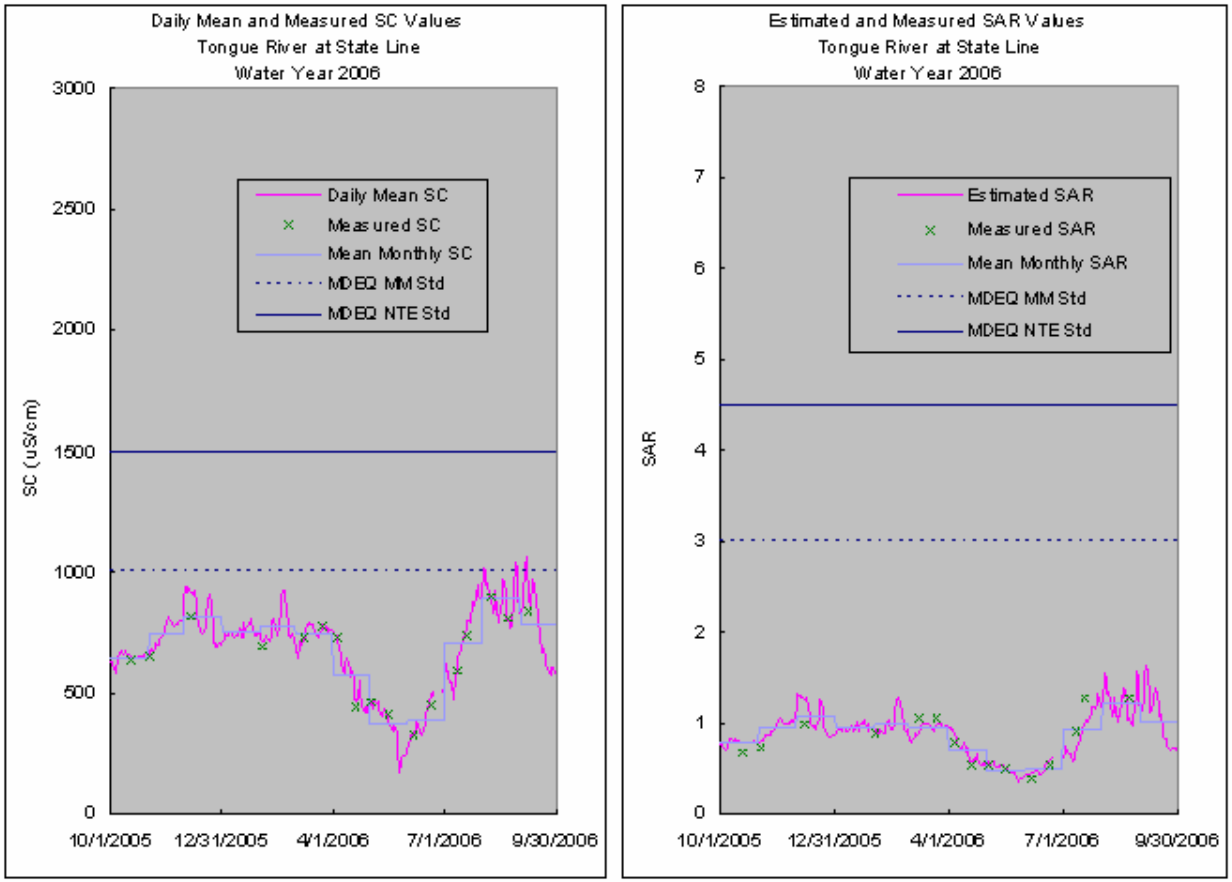


Figure 10 shows daily mean and field measurements of flow in a time series plot for water year 2006 for the Tongue River at the State Line. Daily Mean flow values during 2006 ranged from 10 to 1390 cfs. The historical average daily mean flow values are also shown. Flows were noticeably less than historical.

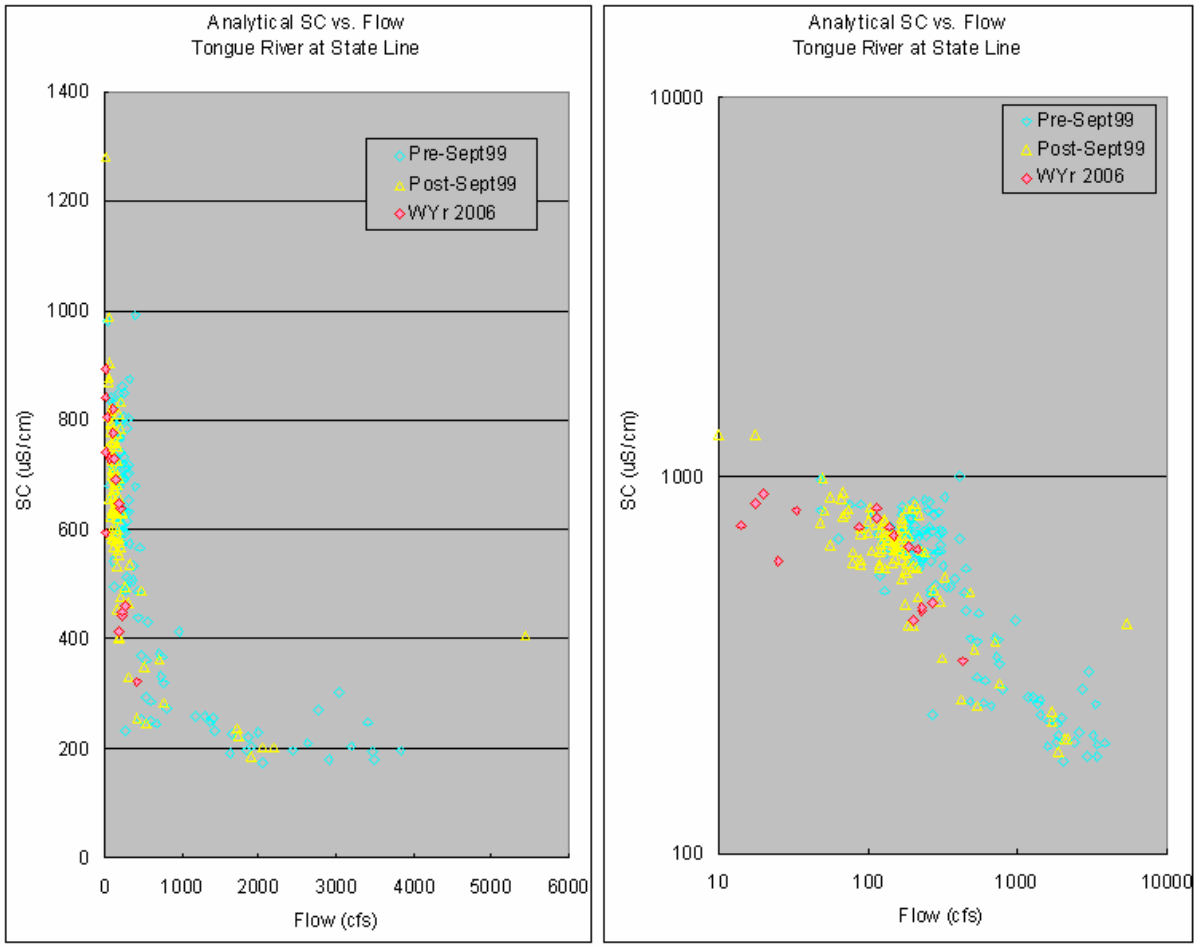
Figure 11: Tongue River at State Line, near Decker, MT



A **B**

Figure 11 shows analytical and daily mean SC values (A) and analytical and daily mean estimated SAR values (B) values in time series plots for water year 2006 for the Tongue River at the State Line. Monthly mean SC and SAR values are also shown. SC values ranged from 175 to 1060 uS/cm. SAR values ranged from 0.4 to 1.6. These values are compared to the instantaneous maximum and monthly mean standards developed by the MDEQ. Recorded values are below the applicable standards for the entire year. Note that the irrigation season standards apply year-round upstream of the reservoir.

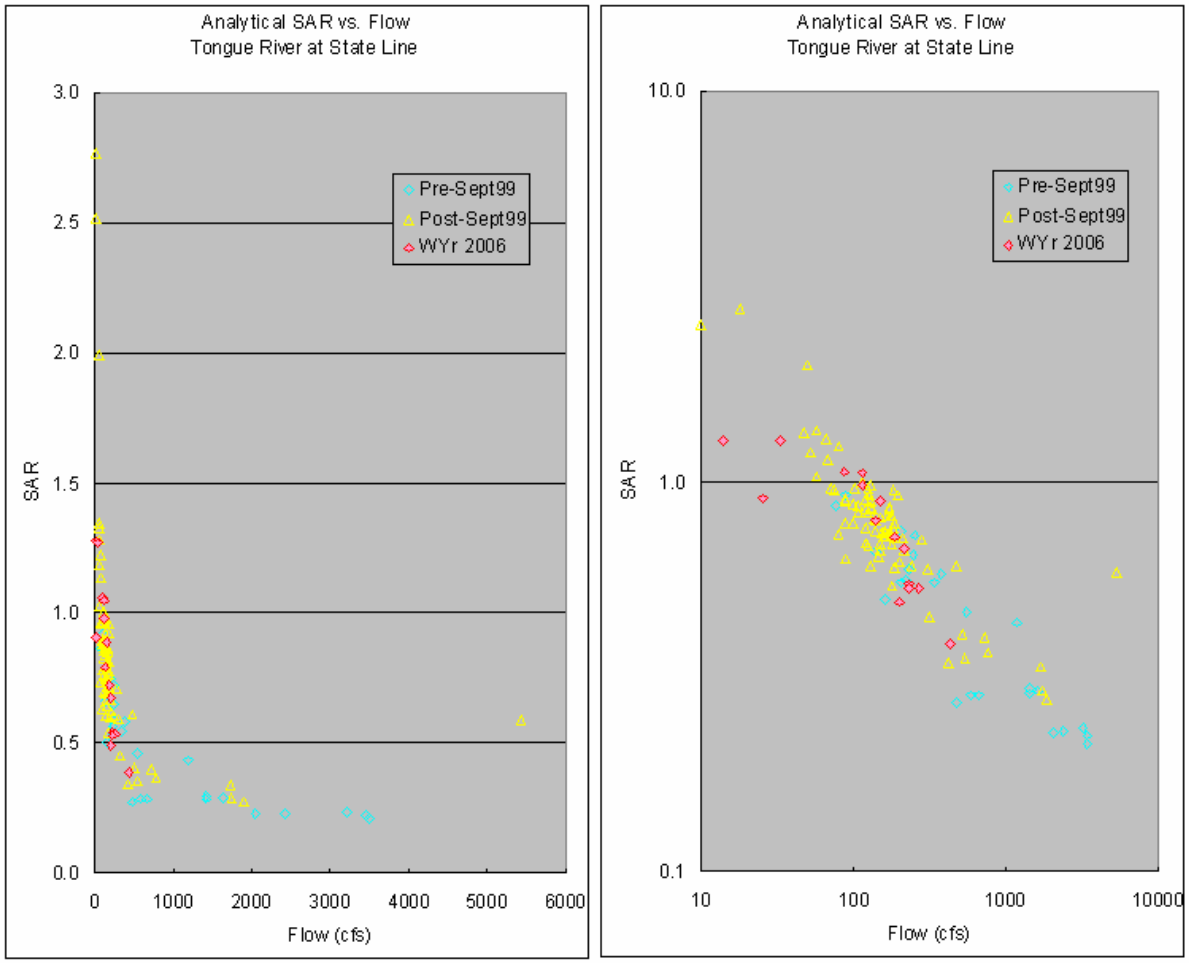
Figure 12: Tongue River at State Line, near Decker, MT



A **B**

Figure 12 shows analytical SC vs. Flow data for water year 2006 for the Tongue River at the State Line. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 13: Tongue River at State Line, near Decker, MT



A **B**

Figure 13 shows analytical SAR vs. Flow data for water year 2006 for the Tongue River at the State Line. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 14: Tongue River at State Line, near Decker, MT

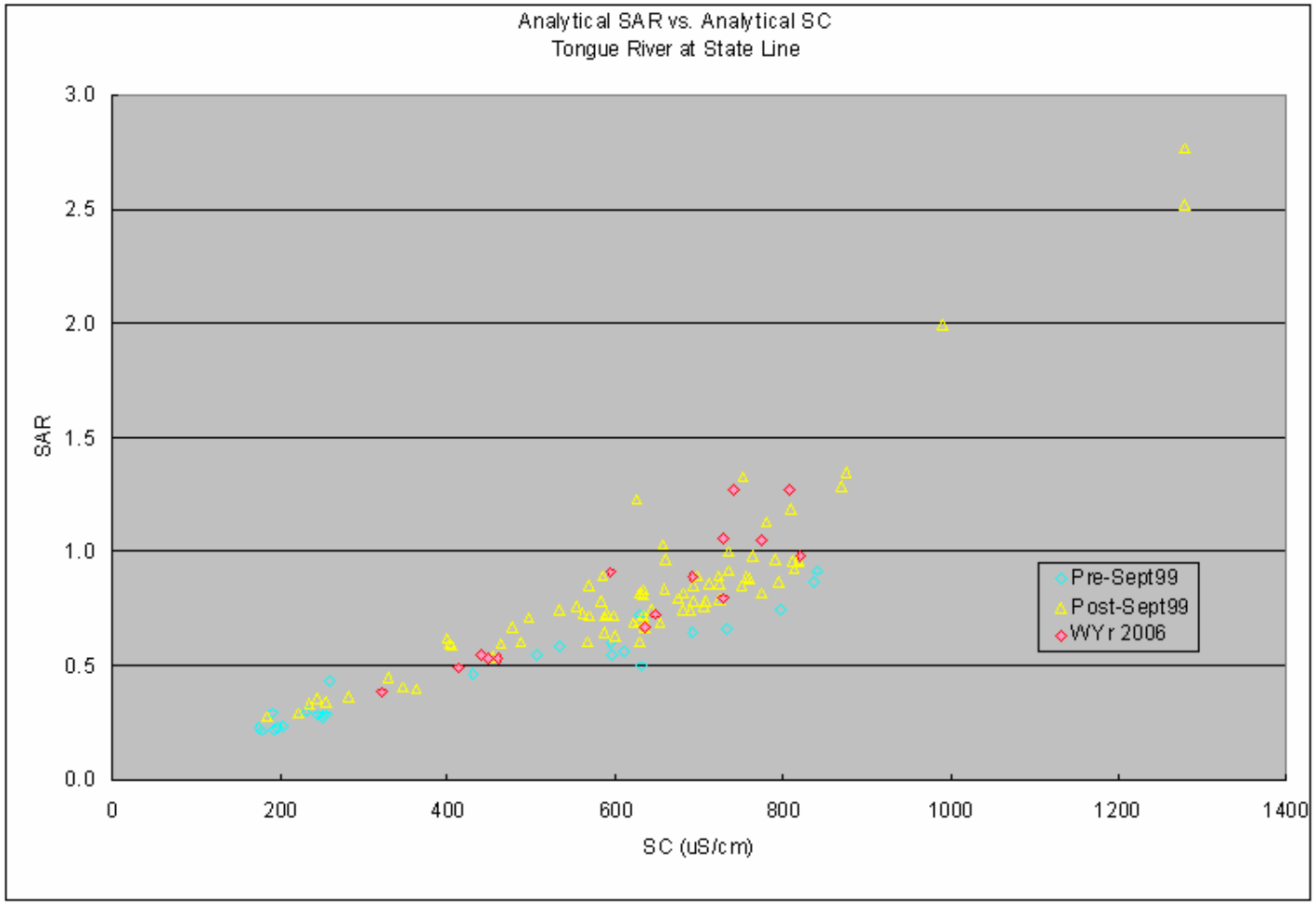
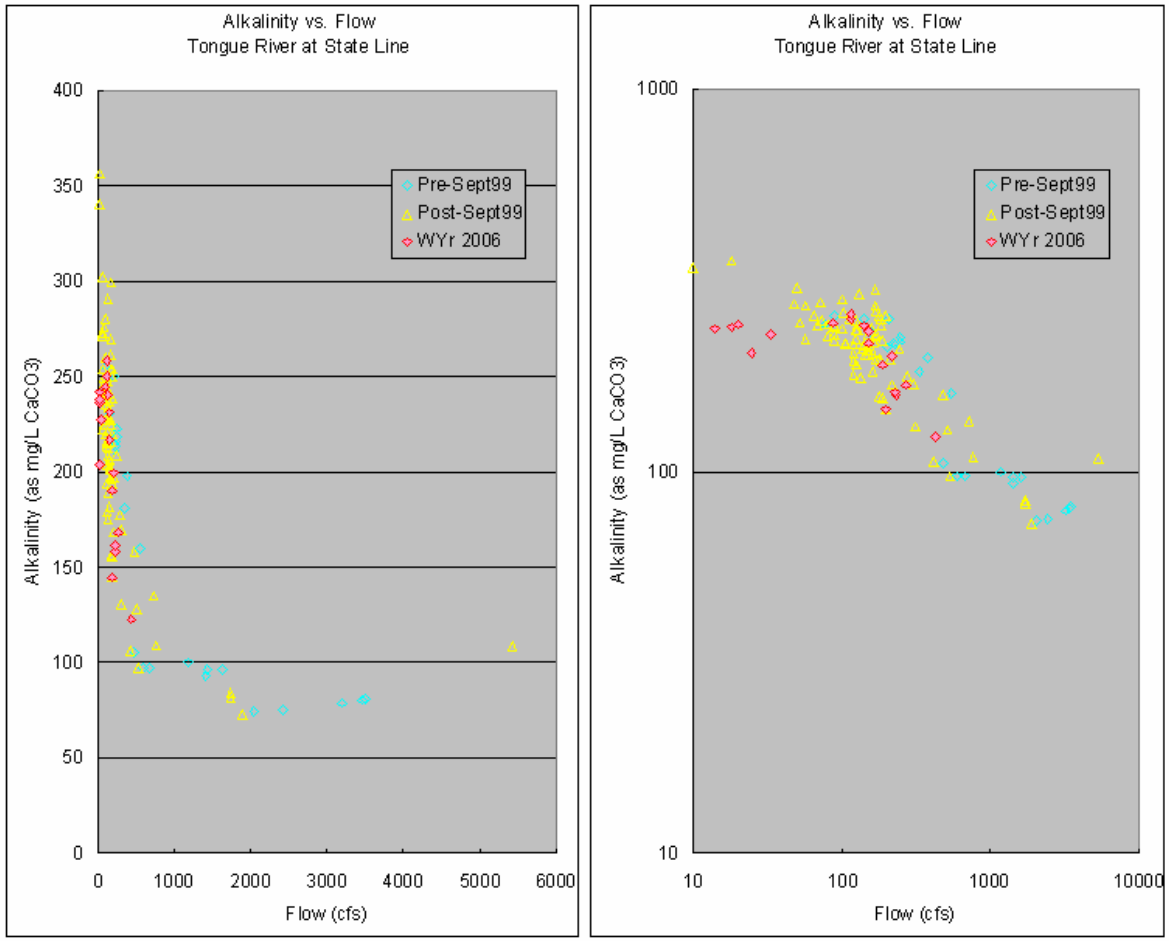


Figure 14 shows analytical SAR vs. analytical SC data for water year 2006 for the Tongue River at the State Line. Historical SAR vs. SC data are also shown to place the data in context.

Figure 15: Tongue River at State Line, near Decker, MT



A **B**

Figure 15 shows analytical Alkalinity vs. Flow data for water year 2006 for the Tongue River at the State Line. These data are charted on both linear (A) and logarithmic (B) scales. Historical Alkalinity vs. Flow data are also shown to place the data in context.

Figure 16: Tongue River at Tongue River Dam, near Decker, MT

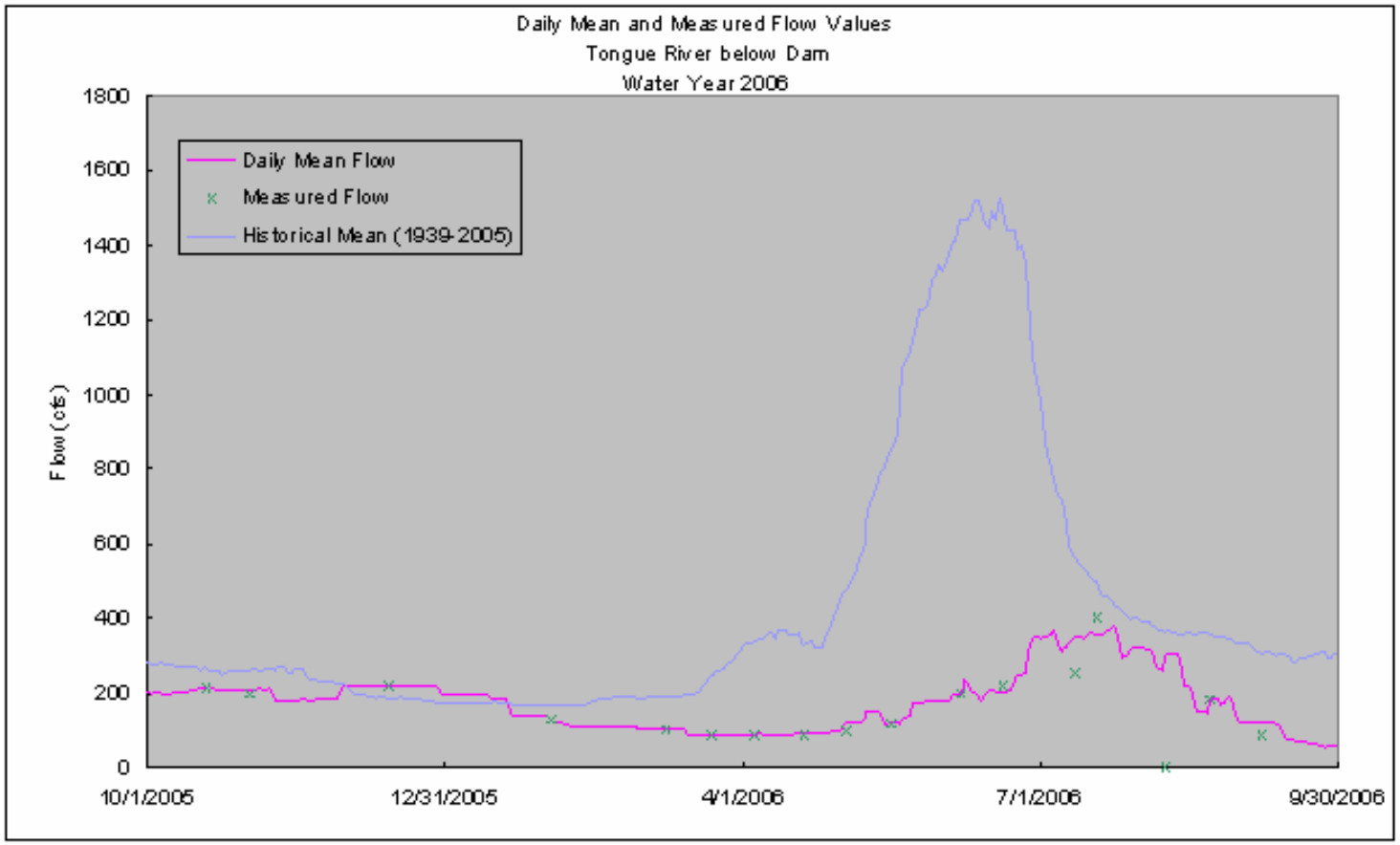
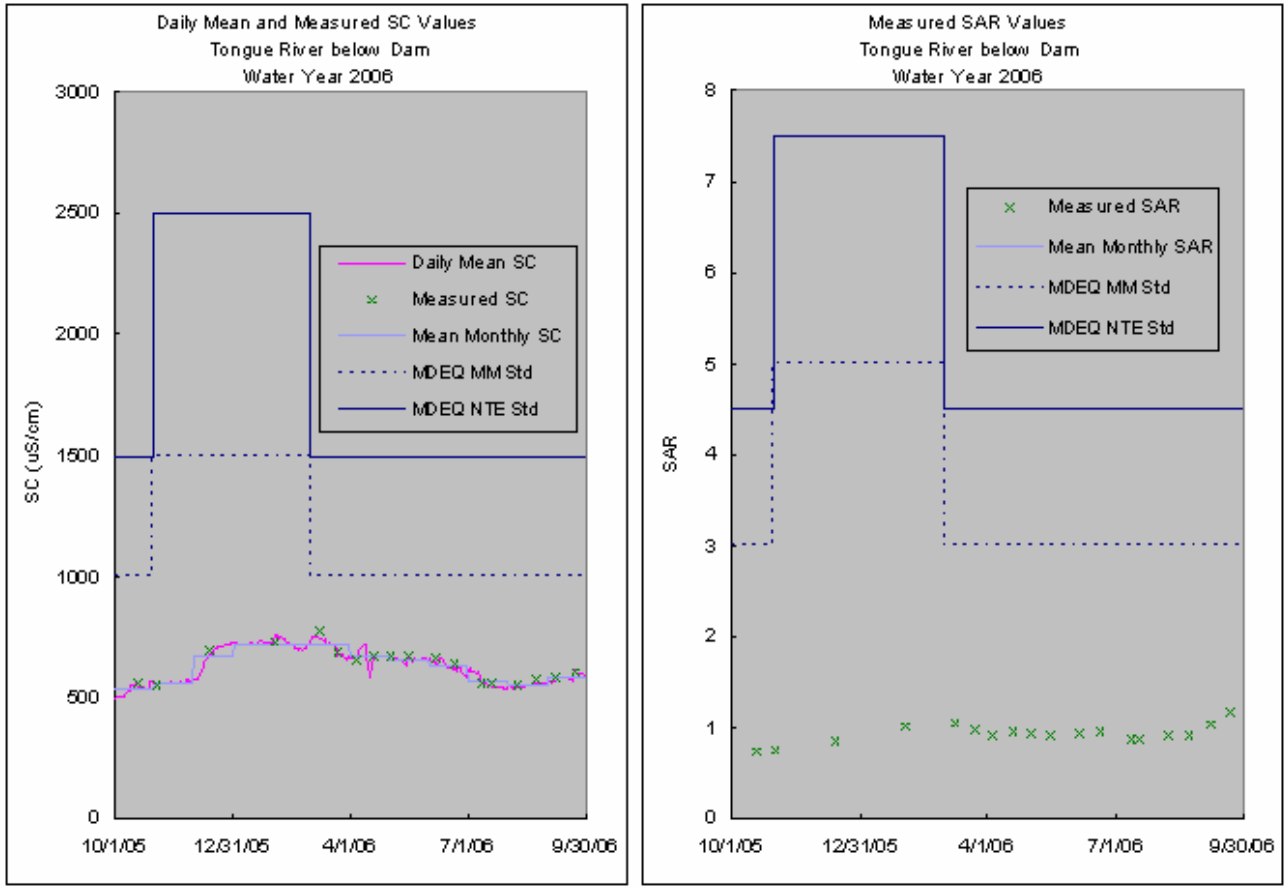


Figure 16 shows daily mean and field measurements of flow in a time series plot for water year 2006 for the Tongue River at Tongue River Dam, near Decker. The historical average daily mean flow values are also shown. Daily mean flow values during 2006 ranged from 56 to 379 cfs. Flows were noticeably less than historical. The noticeable decrease in peak flow at this station vs. the state line station (1390 vs. 379 cfs) is due to the presence of the reservoir.

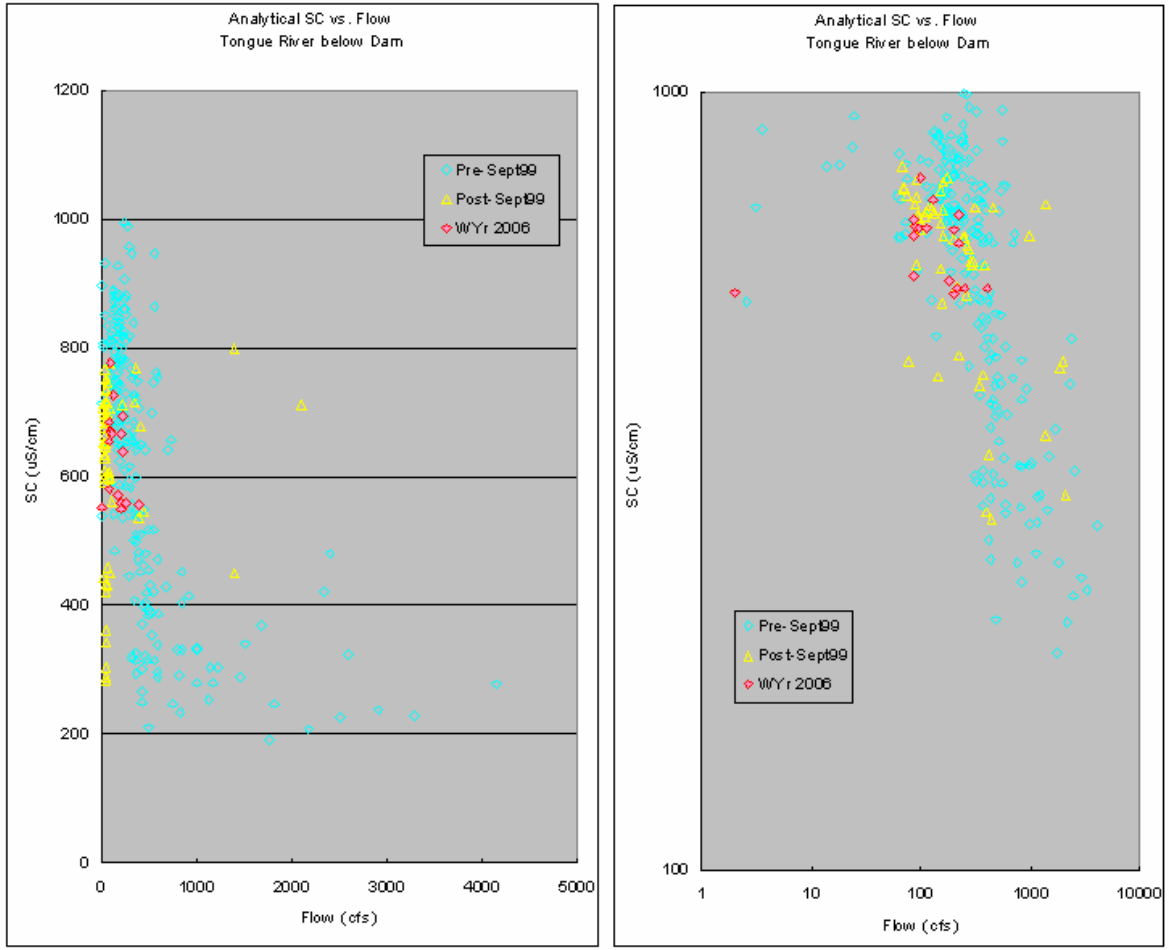
Figure 17: Tongue River at Tongue River Dam, near Decker, MT



A **B**

Figure 17 shows analytical and daily mean SC values (A) and analytical SAR values (B) values in time series plots for water year 2006 for the Tongue River at Tongue River Dam, near Decker. Daily mean SAR values were not estimated. Mean Monthly SC values are also shown. SC values ranged from 490 to 775 uS/cm. SAR values ranged from 0.7 to 1.2. These values are compared to the instantaneous maximum and monthly mean standards developed by the MDEQ. Recorded values are below the appropriate standards for the entire year.

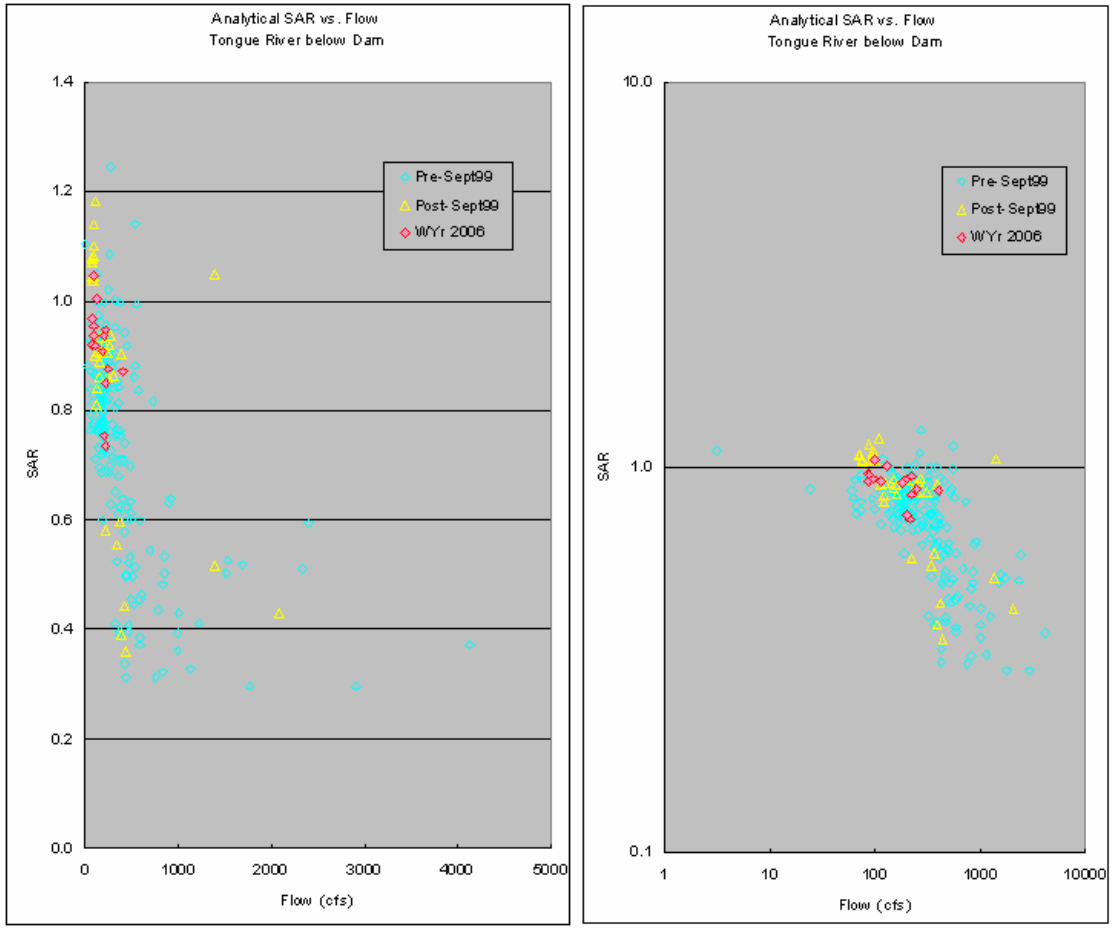
Figure 18: Tongue River at Tongue River Dam, near Decker, MT



A **B**

Figure 18 shows analytical SC vs. Flow data for water year 2006 for the Tongue River at Tongue River Dam, near Decker. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 19: Tongue River at Tongue River Dam, near Decker, MT



A **B**

Figure 19 shows analytical SAR vs. Flow data for water year 2006 for the Tongue River at Tongue River Dam, near Decker. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 20: Tongue River at Tongue River Dam, near Decker, MT

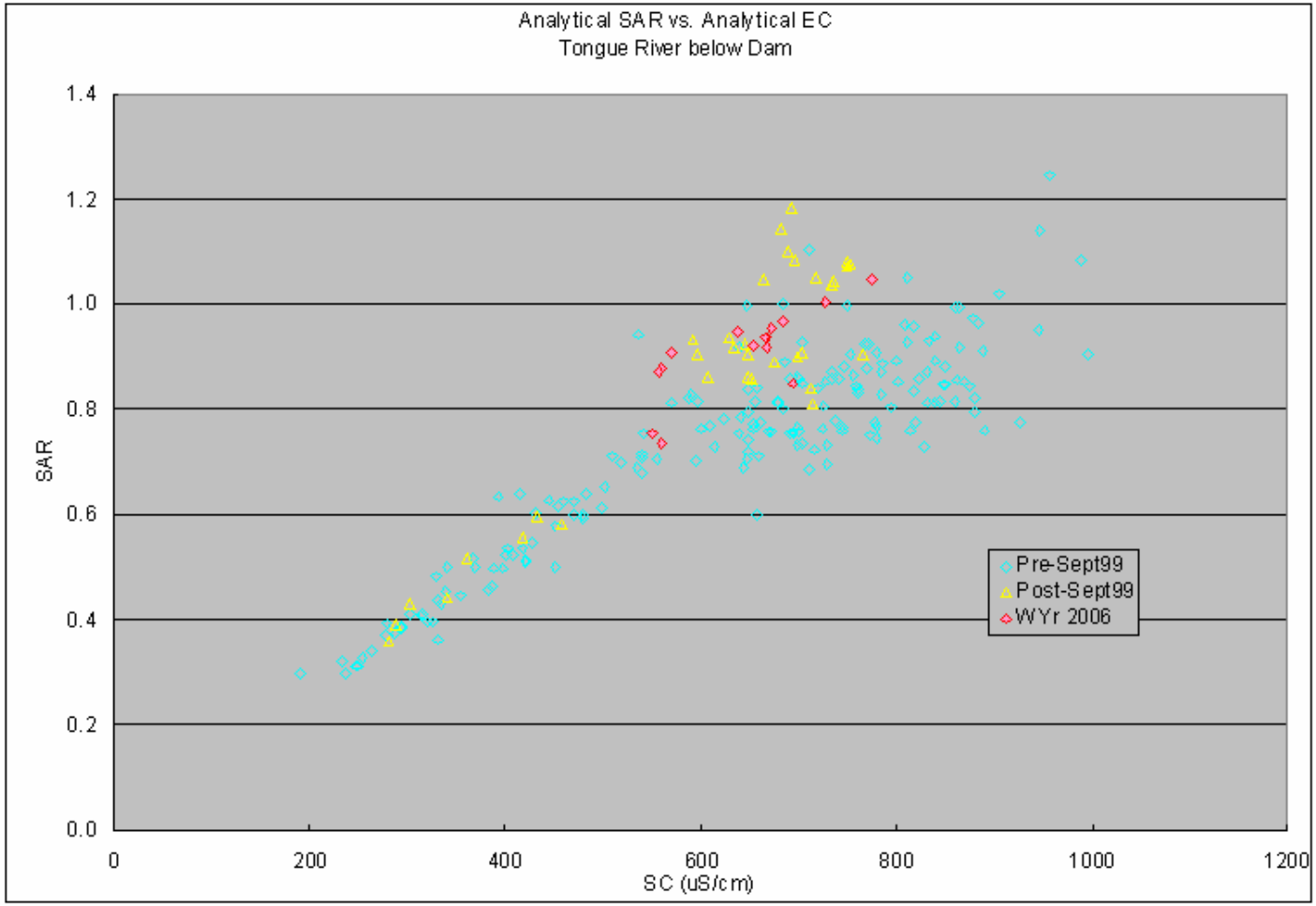
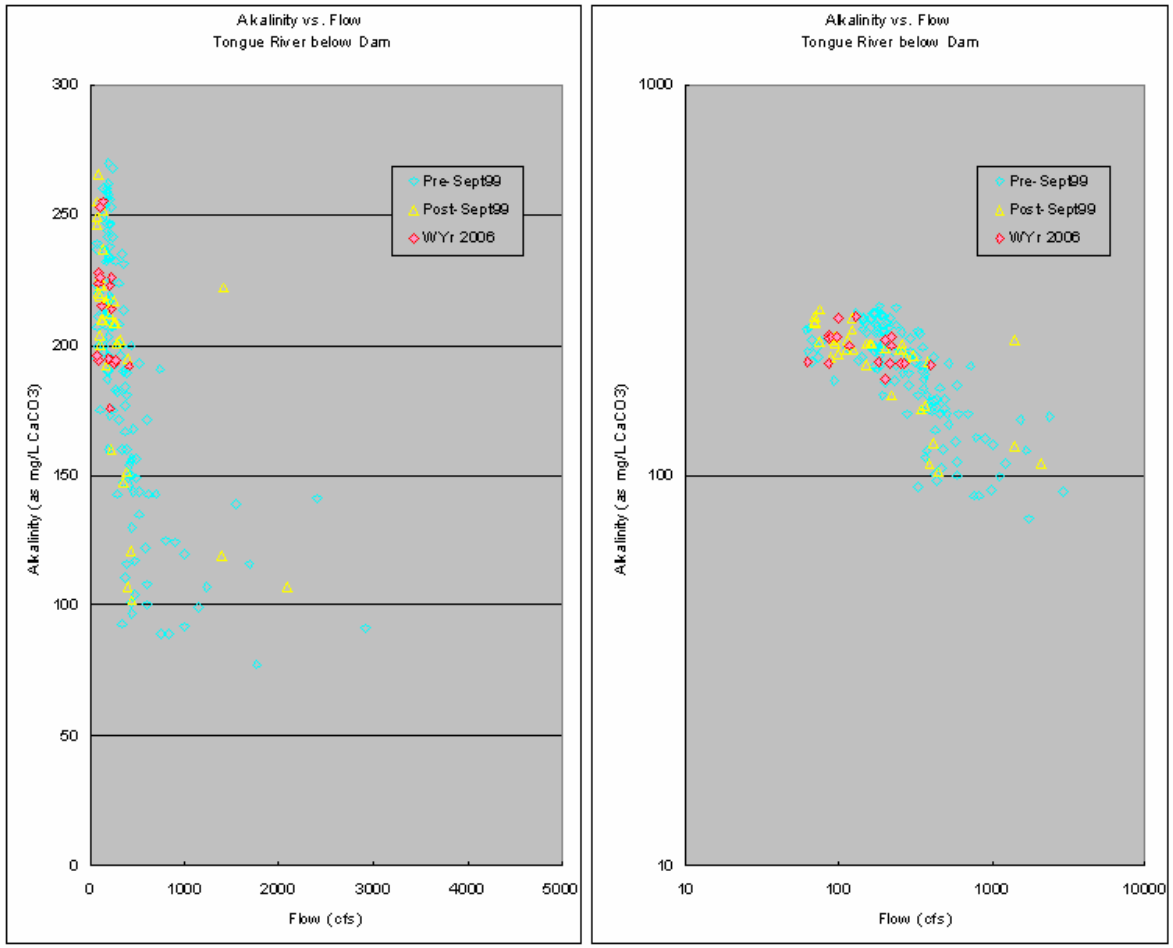


Figure 20 shows analytical SAR vs. analytical SC data for water year 2006 for the Tongue River at Tongue River Dam, near Decker. Historical SAR vs. SC data are also shown to place the data in context.

Figure 21: Tongue River at Tongue River Dam, near Decker, MT



A **B**

Figure 21 shows analytical Alkalinity vs. Flow data for water year 2006 for the Tongue River below the Dam. These data are charted on both linear (A) and logarithmic (B) scales. Historical Alkalinity vs. Flow data are also shown to place the data in context.

Figure 22: Tongue River at Birney Day School Bridge, near Birney, MT

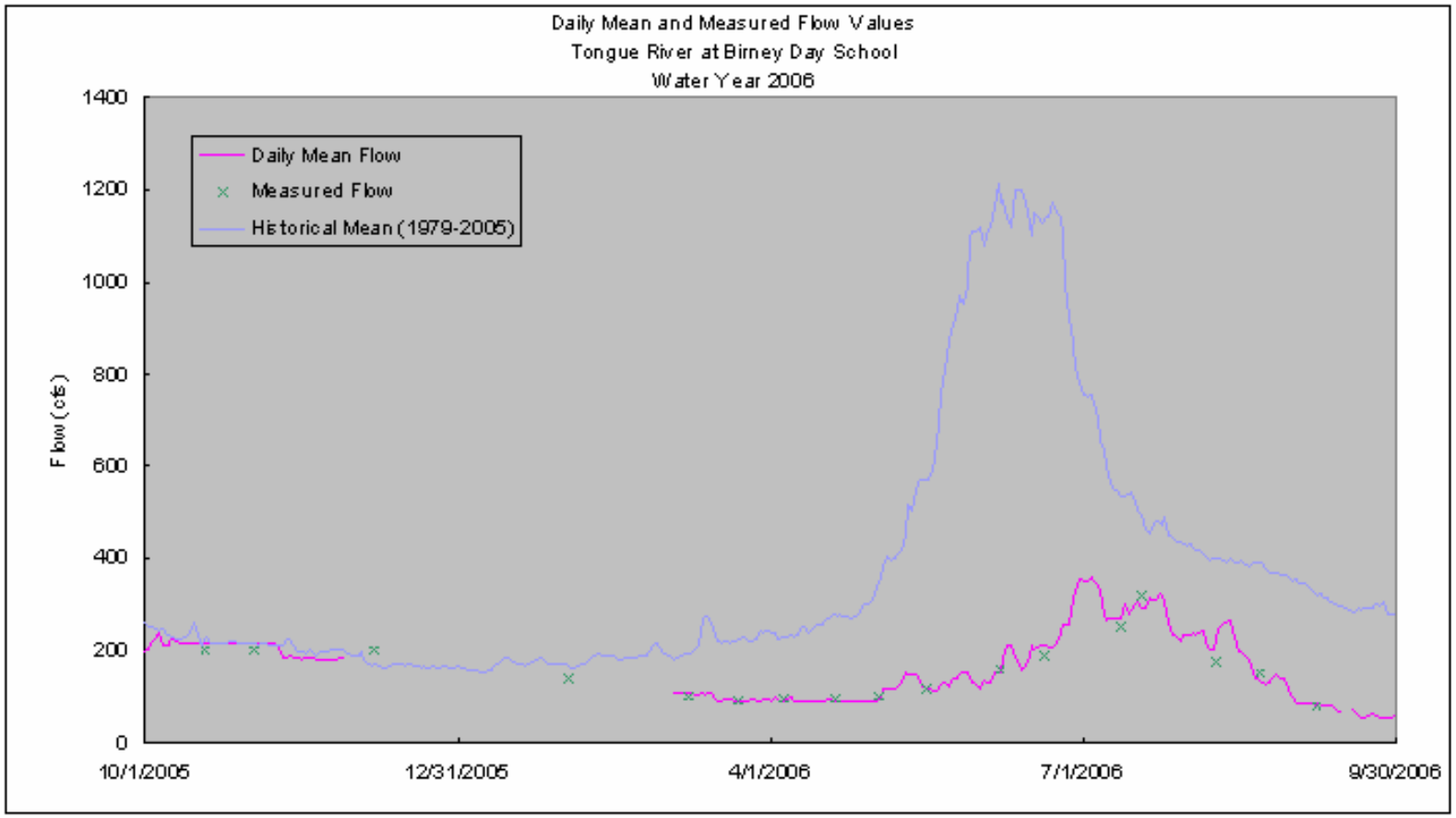
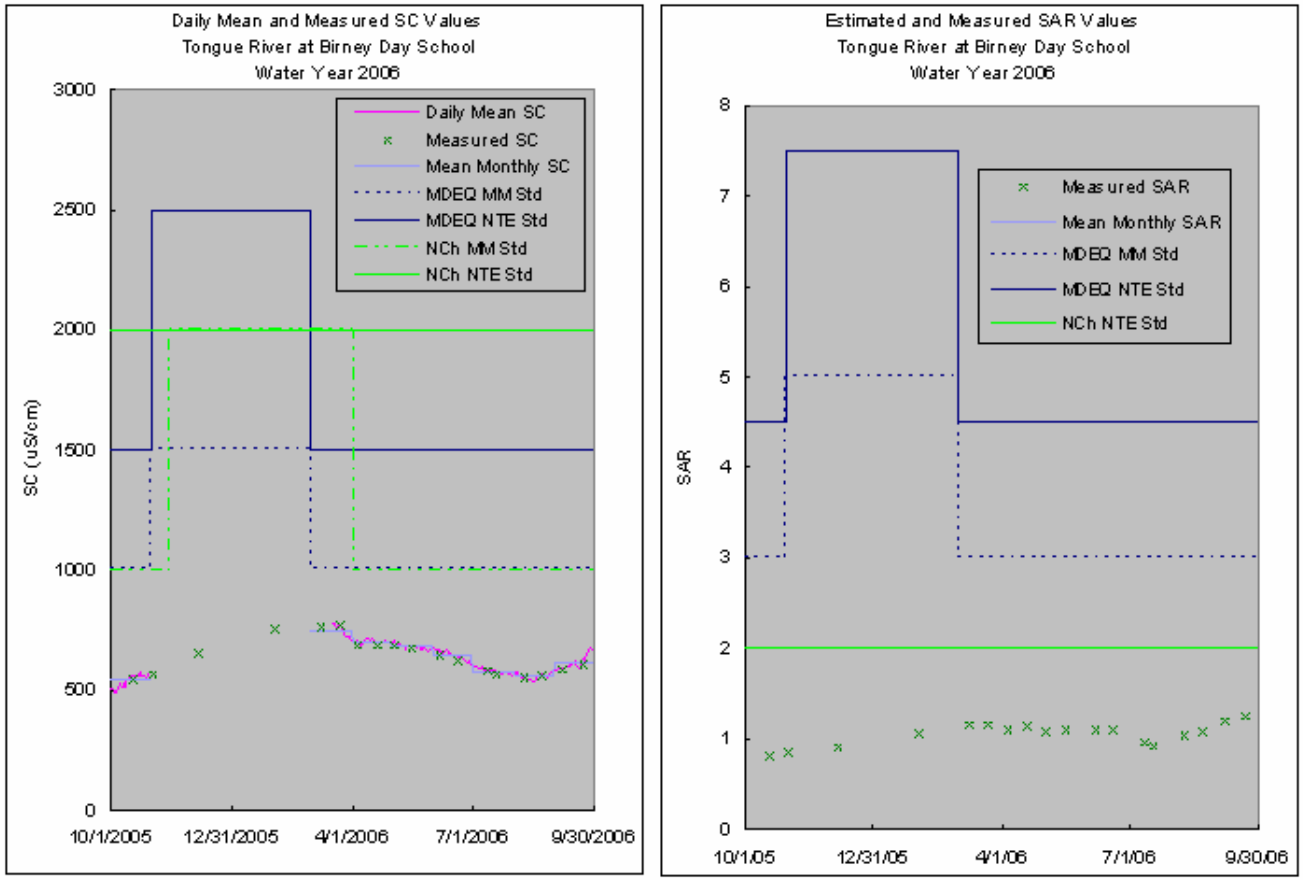


Figure 22 shows mean daily and field measurements of flow in a time series plot for water year 2006 for the Tongue River at Birney Day School Bridge, near Birney. The historical average mean daily flow values are also shown. Flow values ranged from 53 to 361 cfs. Flows were noticeably less than historical. Flows are strongly influenced by reservoir operations.

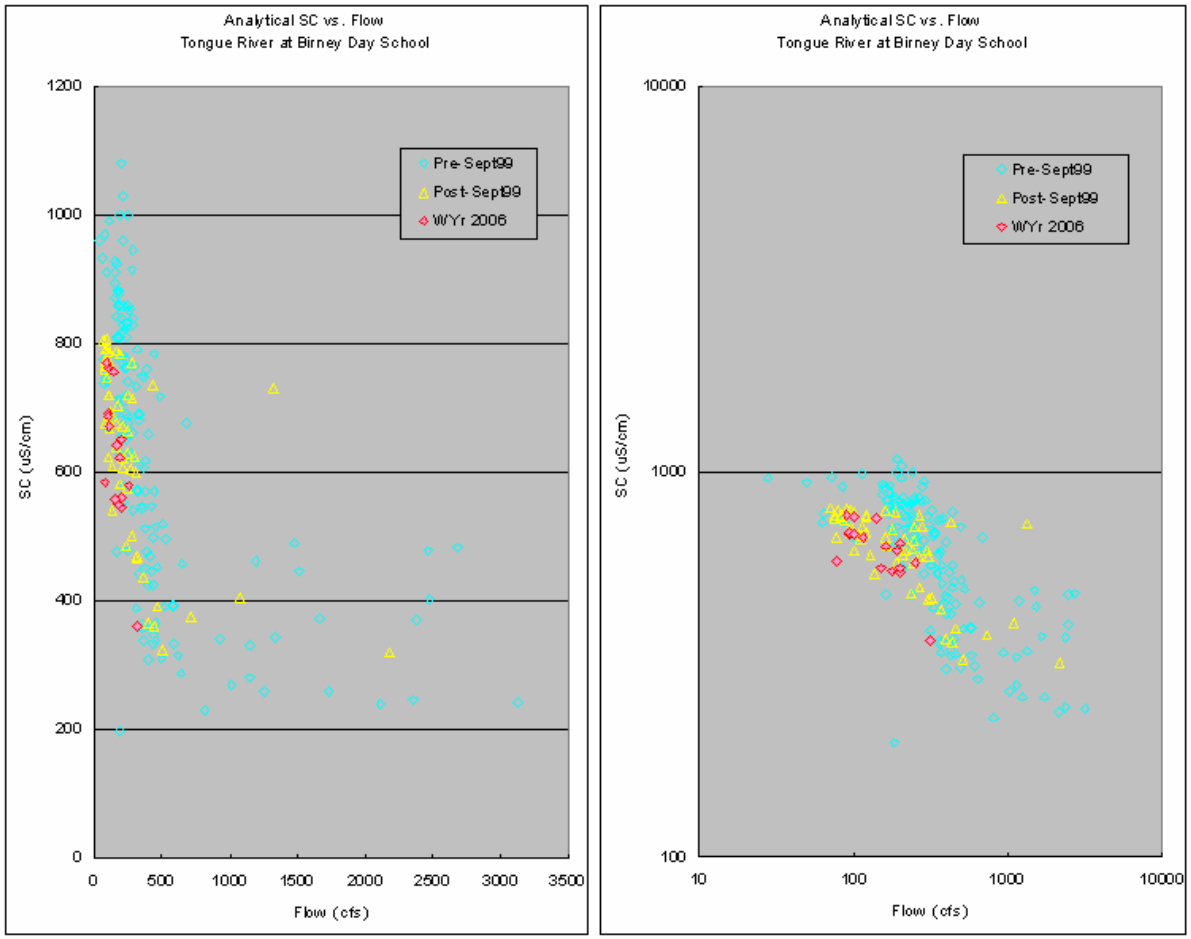
Figure 23: Tongue River at Birney Day School Bridge, near Birney, MT



A **B**

Figure 23 shows analytical and daily mean SC values (A) and analytical SAR values (B) values in time series plots for water year 2006 for the Tongue River at Birney Day School Bridge, near Birney. Daily mean SAR values were not estimated. Monthly mean SC values are also shown. SC values ranged from 495 to 774 uS/cm. SAR values ranged from 0.8 to 1.2. These values are compared to the instantaneous maximum and monthly mean standards developed by the MDEQ and the Northern Cheyenne Tribe. Recorded values are below the applicable standards for the entire year.

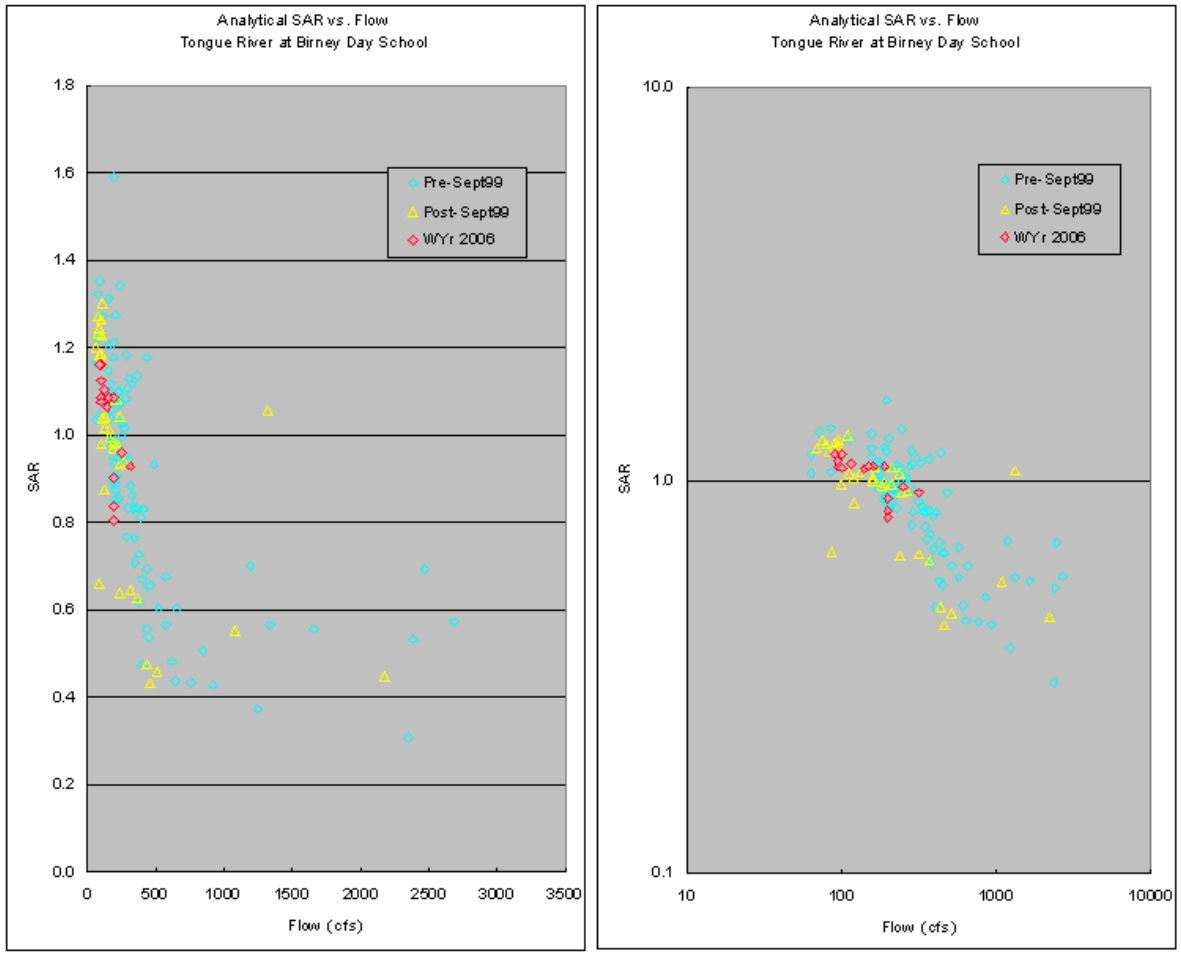
Figure 24: Tongue River at Birney Day School Bridge, near Birney, MT



A **B**

Figure 24 shows analytical SC vs. Flow data for water year 2006 for the Tongue River at Birney Day School Bridge, near Birney. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 25: Tongue River at Birney Day School Bridge, near Birney, MT



A **B**

Figure 25 shows analytical SAR vs. Flow data for water year 2006 for the Tongue River at Birney Day School Bridge, near Birney, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 26: Tongue River at Birney Day School Bridge, near Birney, MT

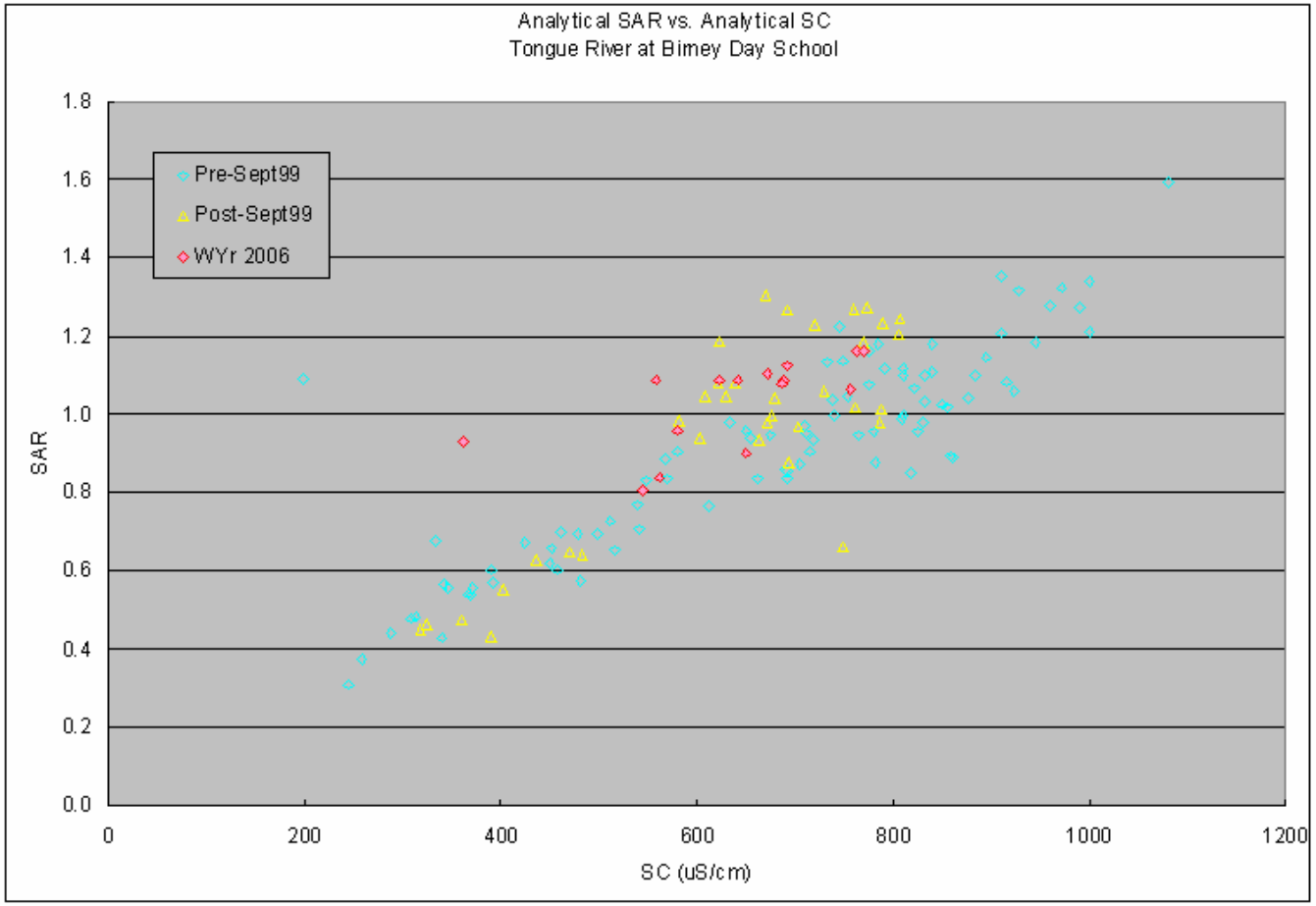
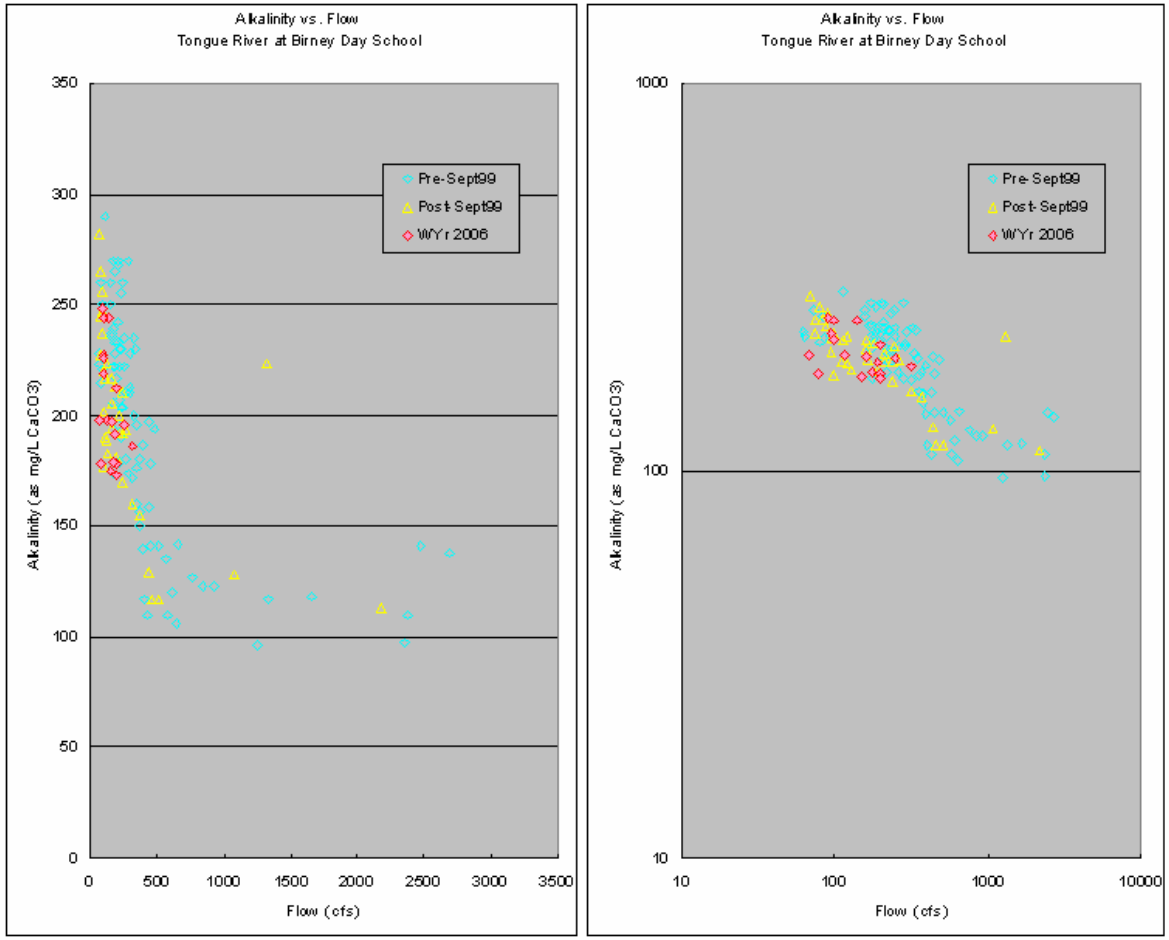


Figure 26 shows analytical SAR vs. analytical SC data for water year 2006 for the Tongue River at Birney Day School. Historical SAR vs. SC data are also shown to place the data in context.

Figure 27: Tongue River at Birney Day School Bridge, near Birney, MT



A **B**

Figure 27 shows analytical Alkalinity vs. Flow data for water year 2006 for the Tongue River at Birney Day School. These data are charted on both linear (A) and logarithmic (B) scales. Historical Alkalinity vs. Flow data are also shown to place the data in context.

Figure 28: Tongue River below Brandenburg Bridge, near Ashland, MT

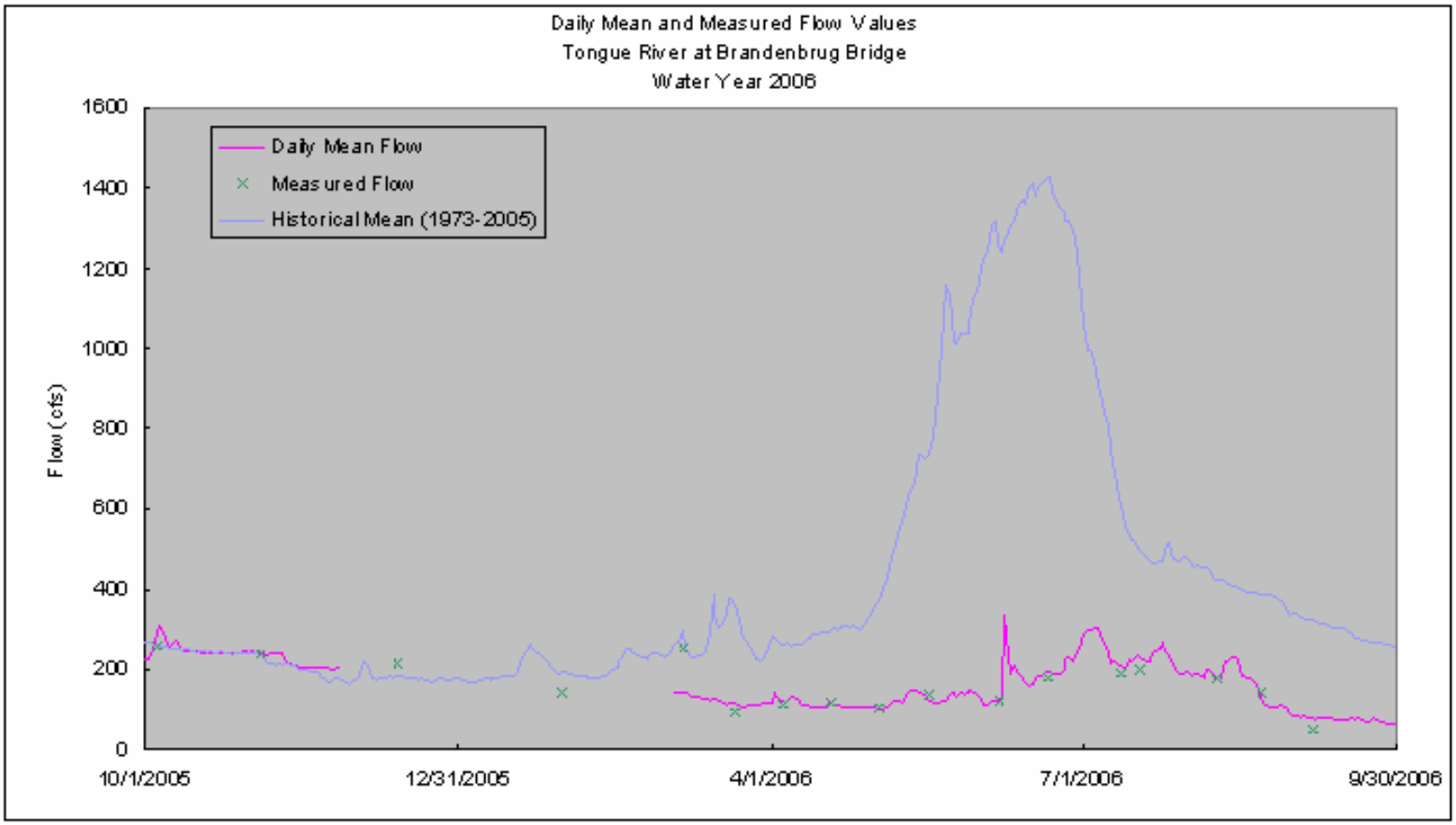
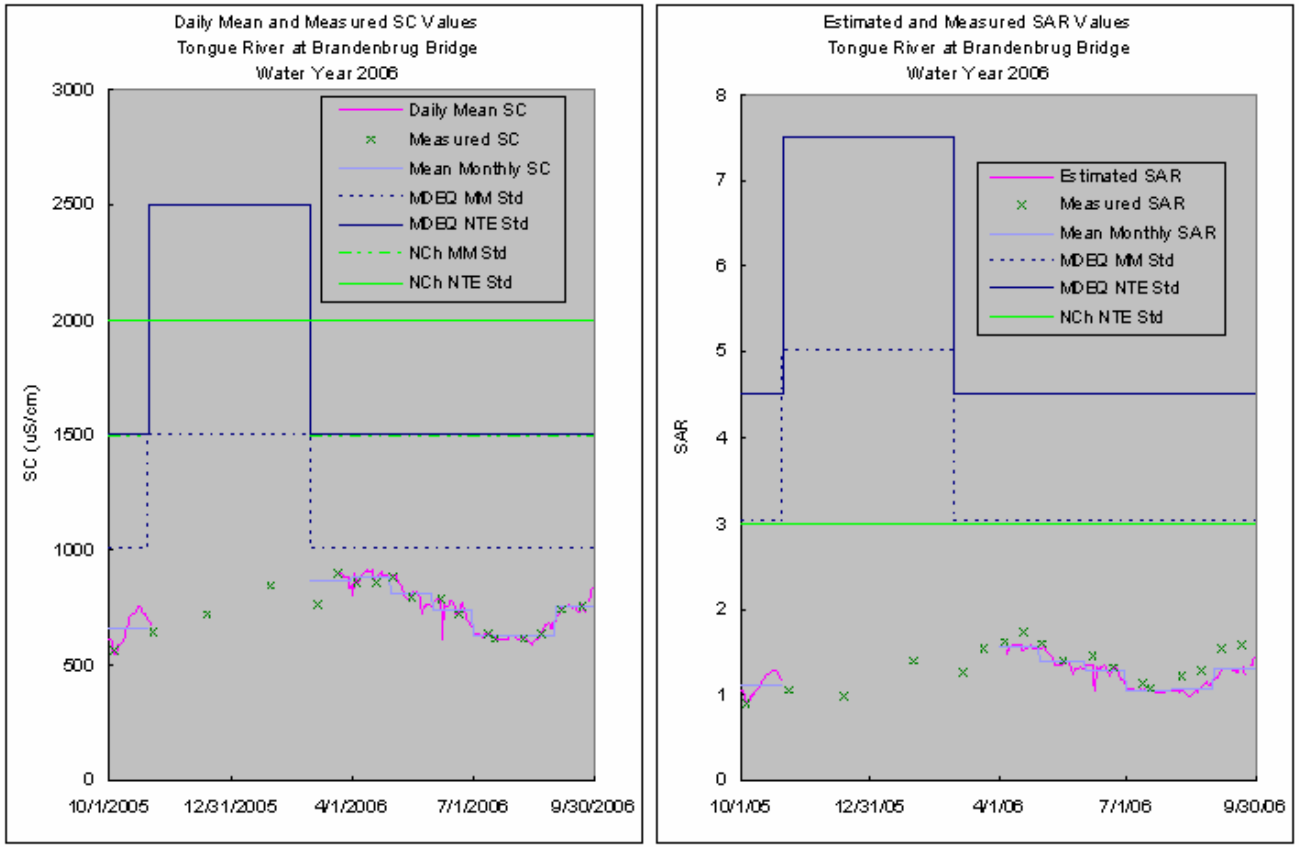


Figure 28 shows daily mean and field measurements of flow in a time series plot for water year 2006 for the Tongue River below Brandenburg Bridge. The historical average daily mean flow values are also shown. Daily mean flow values during 2006 ranged from 58 to 333 cfs. Daily mean flows were less than average for most of the year.

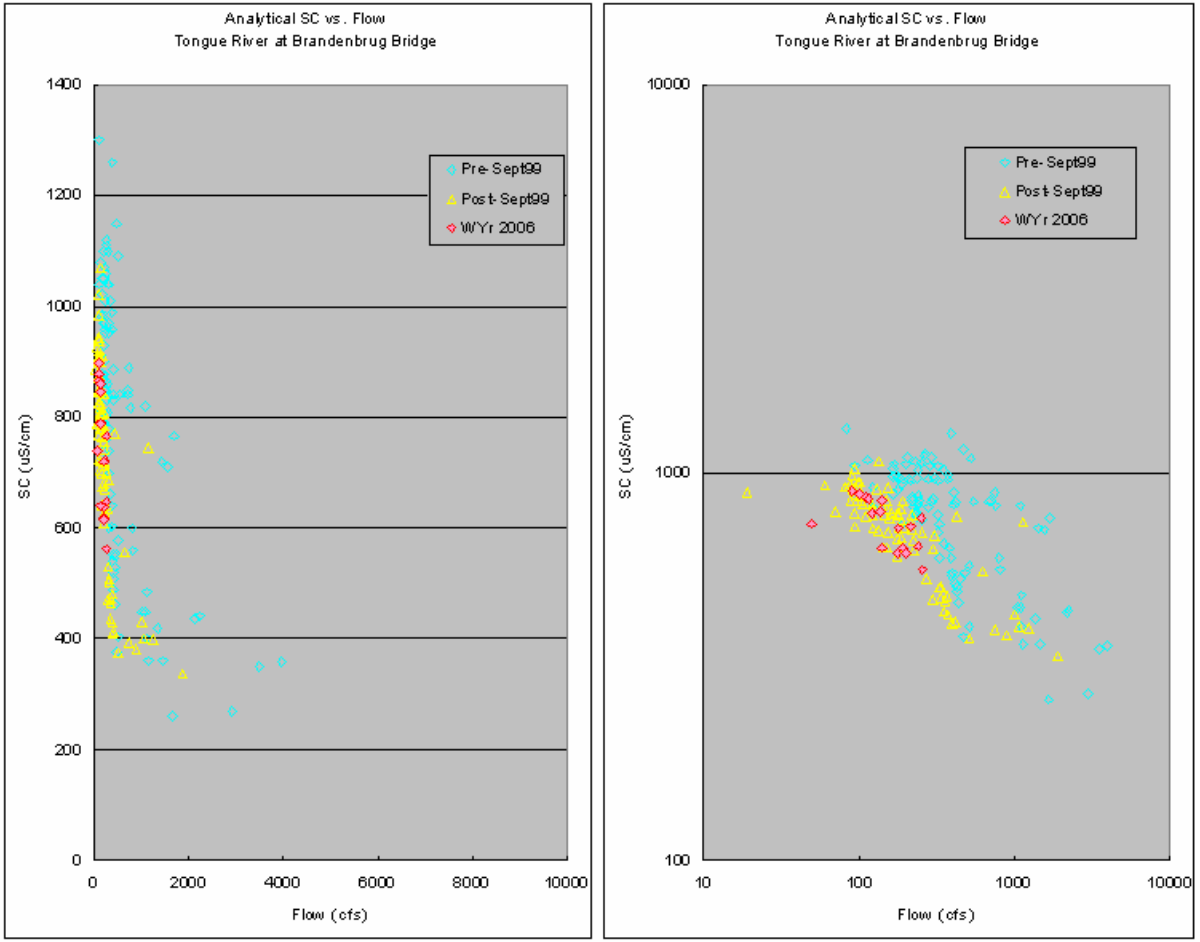
Figure 29: Tongue River below Brandenburg Bridge, near Ashland, MT



A **B**

Figure 29 shows analytical and daily mean SC values (A) and analytical and daily mean estimated SAR values (B) in time series plots for water year 2006 for the Tongue River below Brandenburg Bridge, near Ashland, MT. Monthly mean SC and SAR values are also shown. SC values ranged from 548 to 914 uS/cm. SAR values ranged from 0.9 to 1.7. These values are compared to the instantaneous maximum and monthly mean standards developed by the MDEQ and the Northern Cheyenne Tribe. Recorded values are below these standards for the entire year.

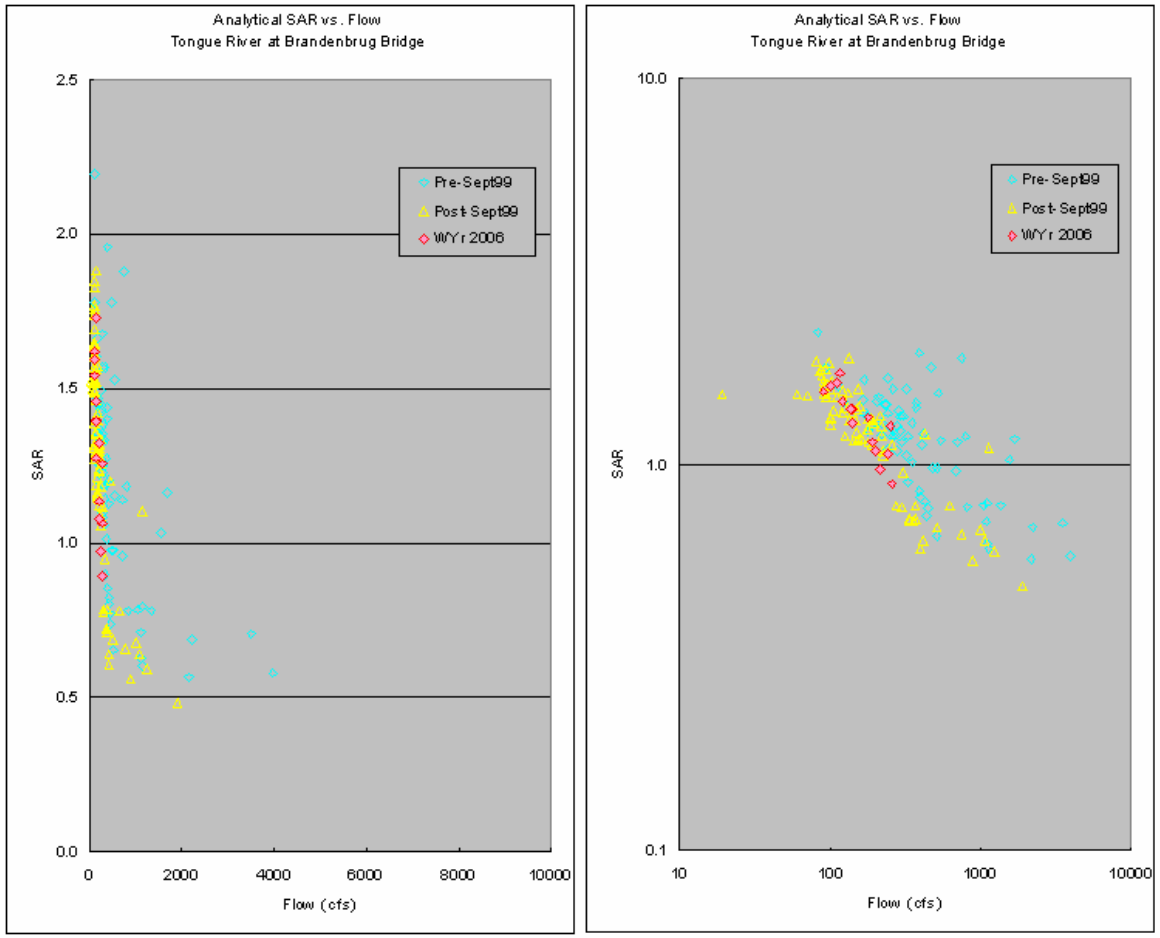
Figure 30: Tongue River below Brandenburg Bridge, near Ashland, MT



A **B**

Figure 30 shows analytical SC vs. Flow data for water year 2006 for the Tongue River below Brandenburg Bridge, near Ashland, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 31: Tongue River below Brandenburg Bridge, near Ashland, MT



A **B**

Figure 31 shows analytical SAR vs. Flow data for water year 2006 for the Tongue River below Brandenburg Bridge, near Ashland, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 32: Tongue River below Brandenburg Bridge, near Ashland, MT

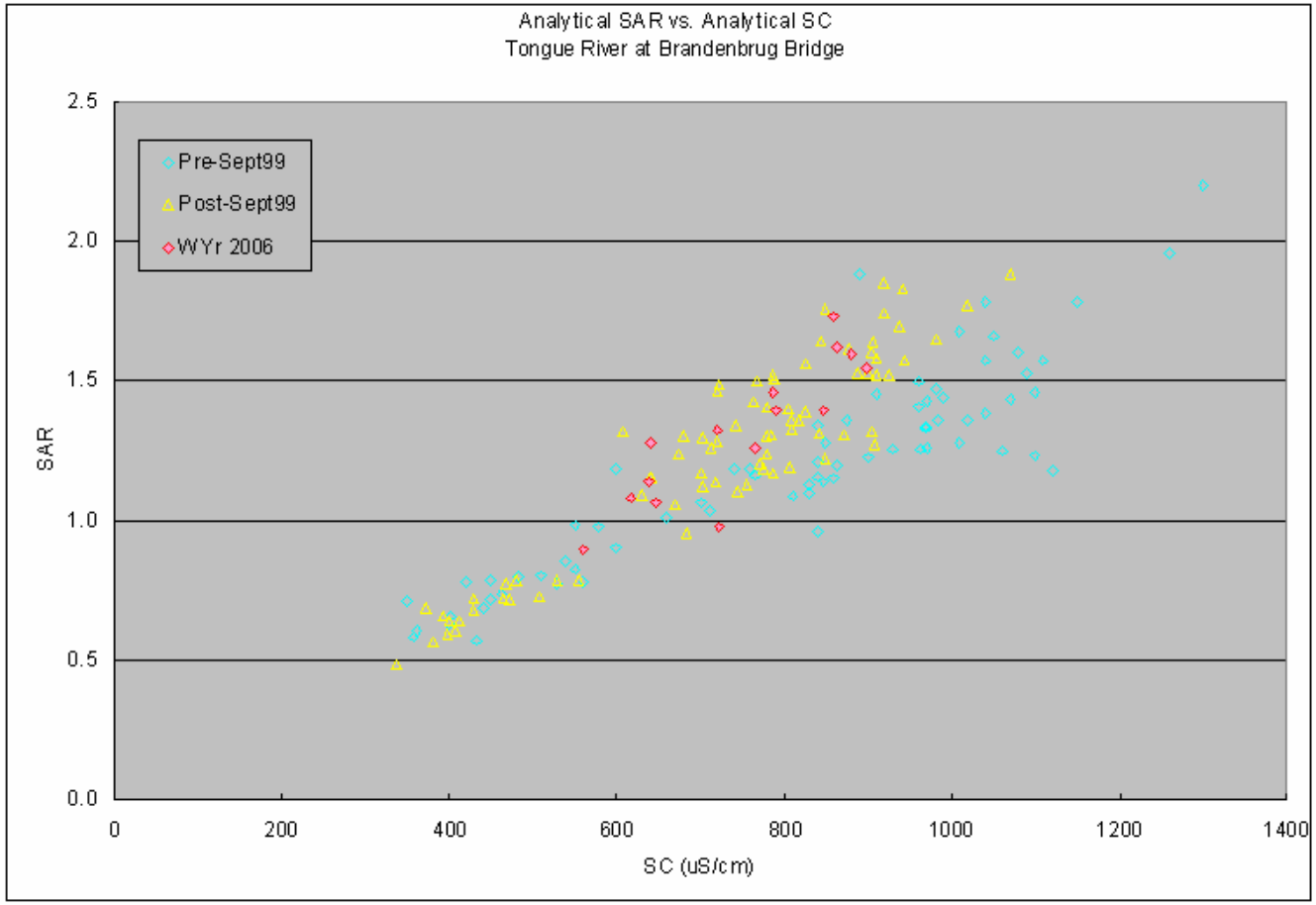
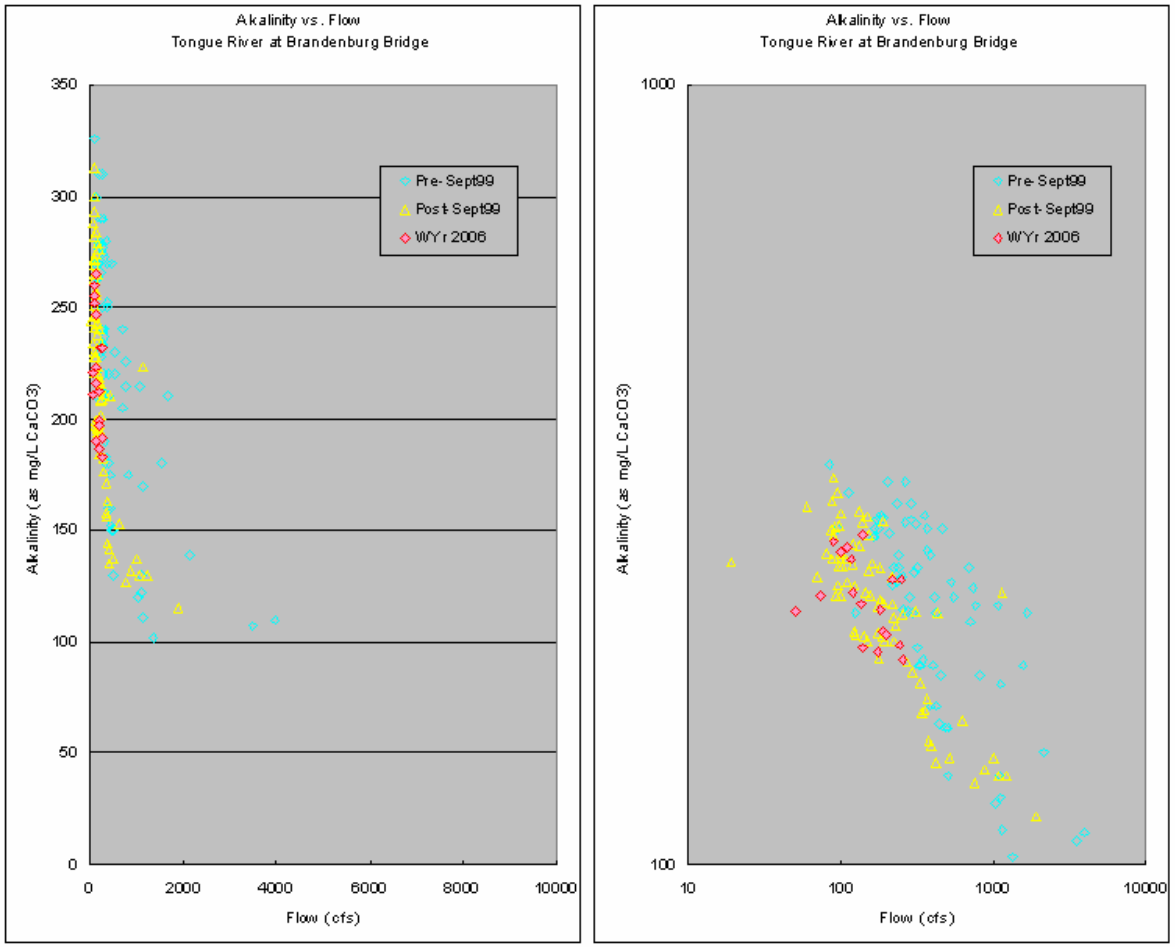


Figure 32 shows analytical SAR vs. analytical SC data for water year 2006 for the Tongue River below Brandenburg Bridge. Historical SAR vs. SC data are also shown to place the data in context.

Figure 33: Tongue River below Brandenburg Bridge, near Ashland, MT



A **B**

Figure 33 shows analytical Alkalinity vs. Flow data for water year 2006 for the Tongue River at Brandenburg Bridge. These data are charted on both linear (A) and logarithmic (B) scales. Historical Alkalinity vs. Flow data are also shown to place the data in context.

Figure 34: Tongue River above TY Diversion

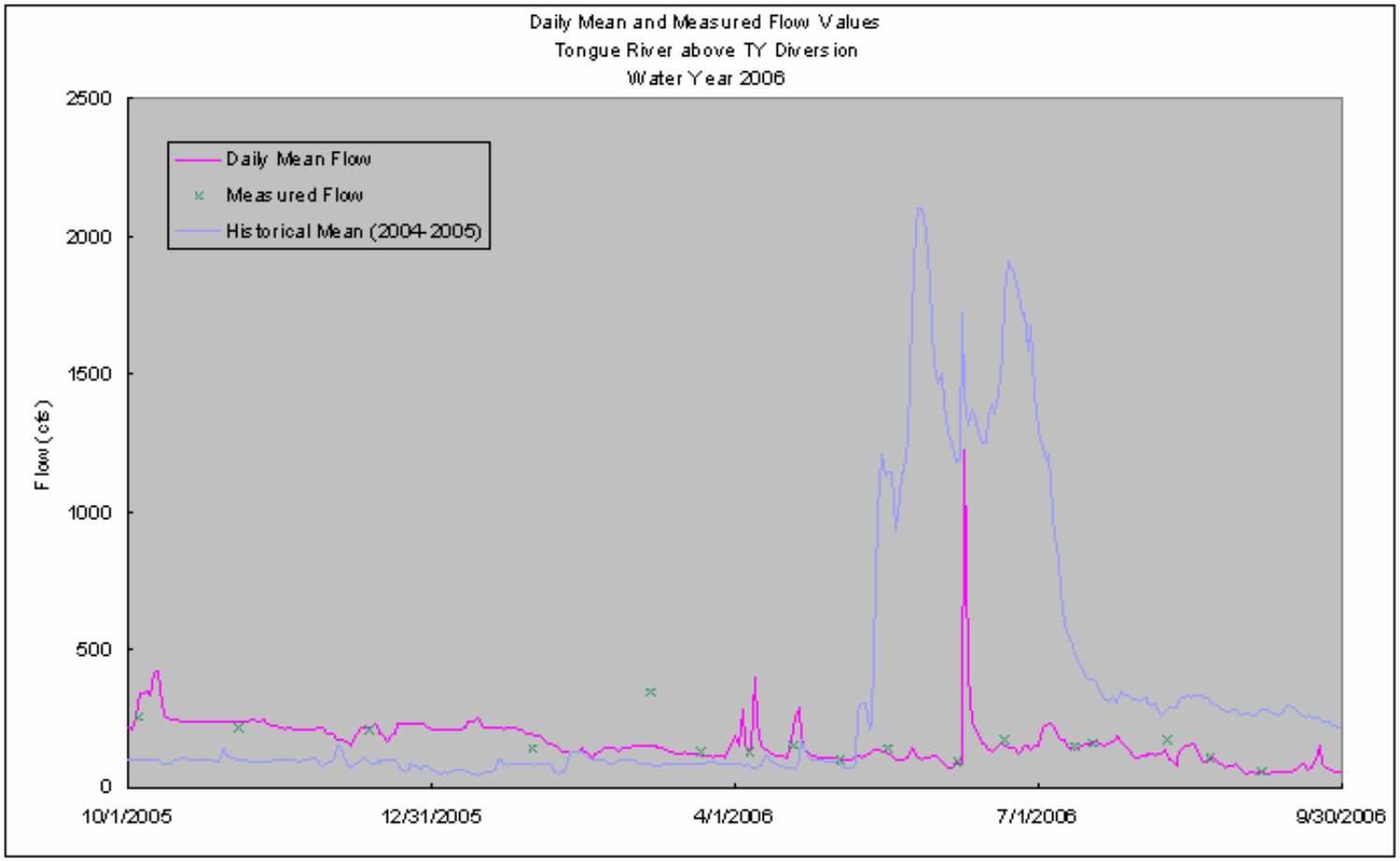
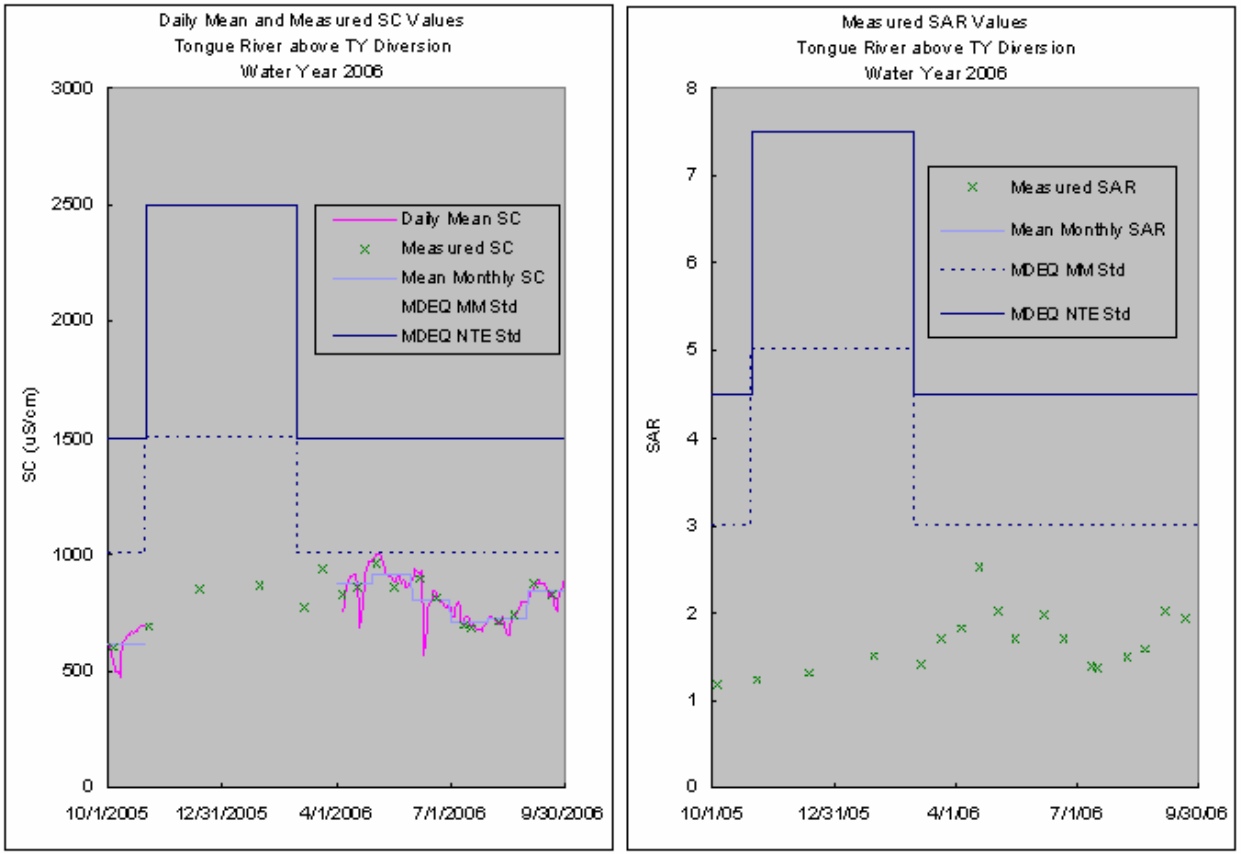


Figure 34 shows daily mean and field measurements of flow in a time series plot for water year 2006 for the Tongue River above the TY Diversion. The historical average daily mean flow values are also shown. Daily mean flow values during 2006 ranged from 54 to 1220 cfs.

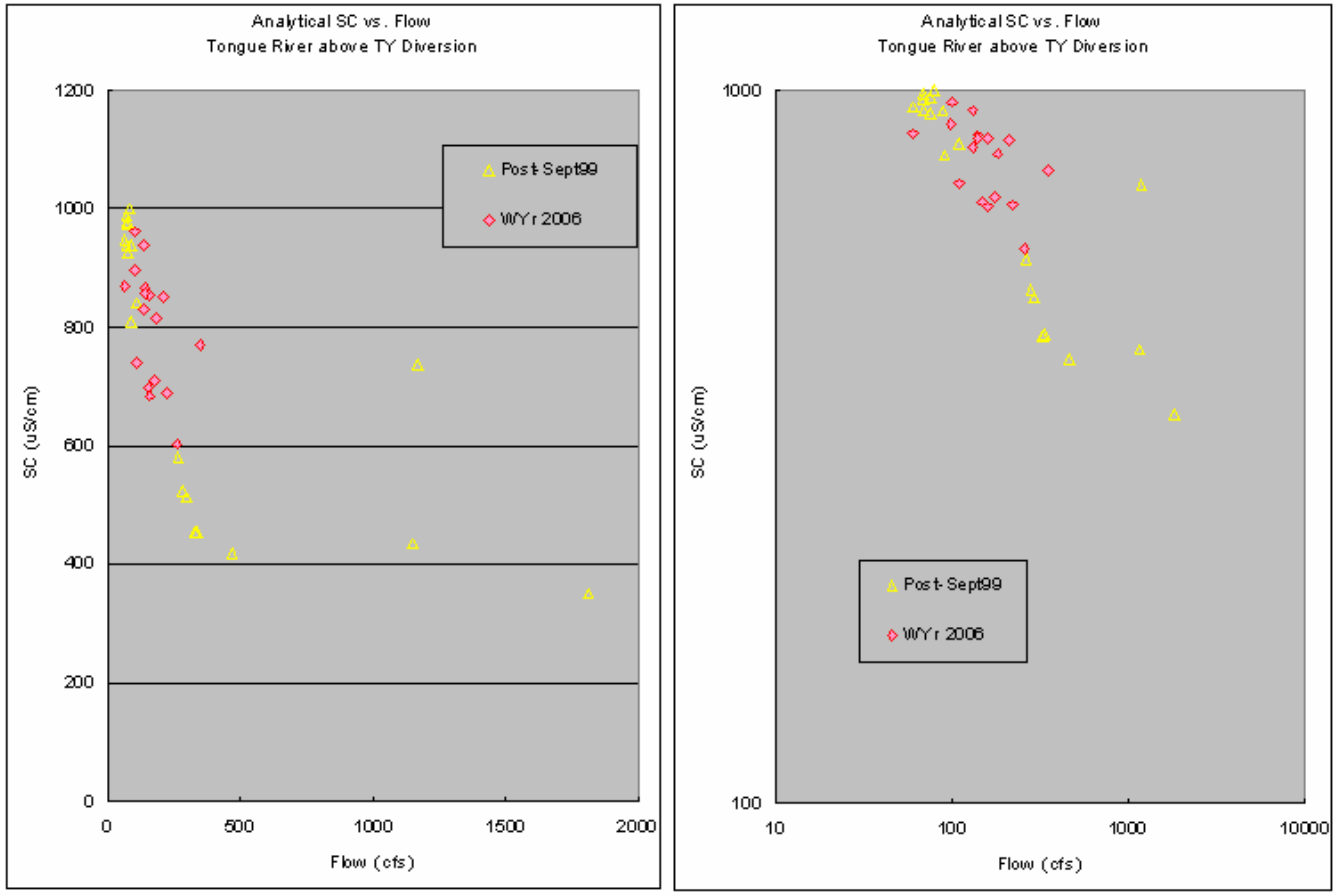
Figure 35: Tongue River above TY Diversion



A **B**

Figure 35 shows analytical and daily mean SC values (A) and analytical SAR values (B) in time series plots for water year 2006 for the Tongue River above the TY Diversion, near Miles City, MT. Monthly mean SC values are also shown. SC values ranged from 470 to 1000 uS/cm. SAR values ranged from 1.2 to 2.5. These values are compared to the instantaneous maximum and monthly mean standards developed by the MDEQ. Recorded values are below these standards for the entire year.

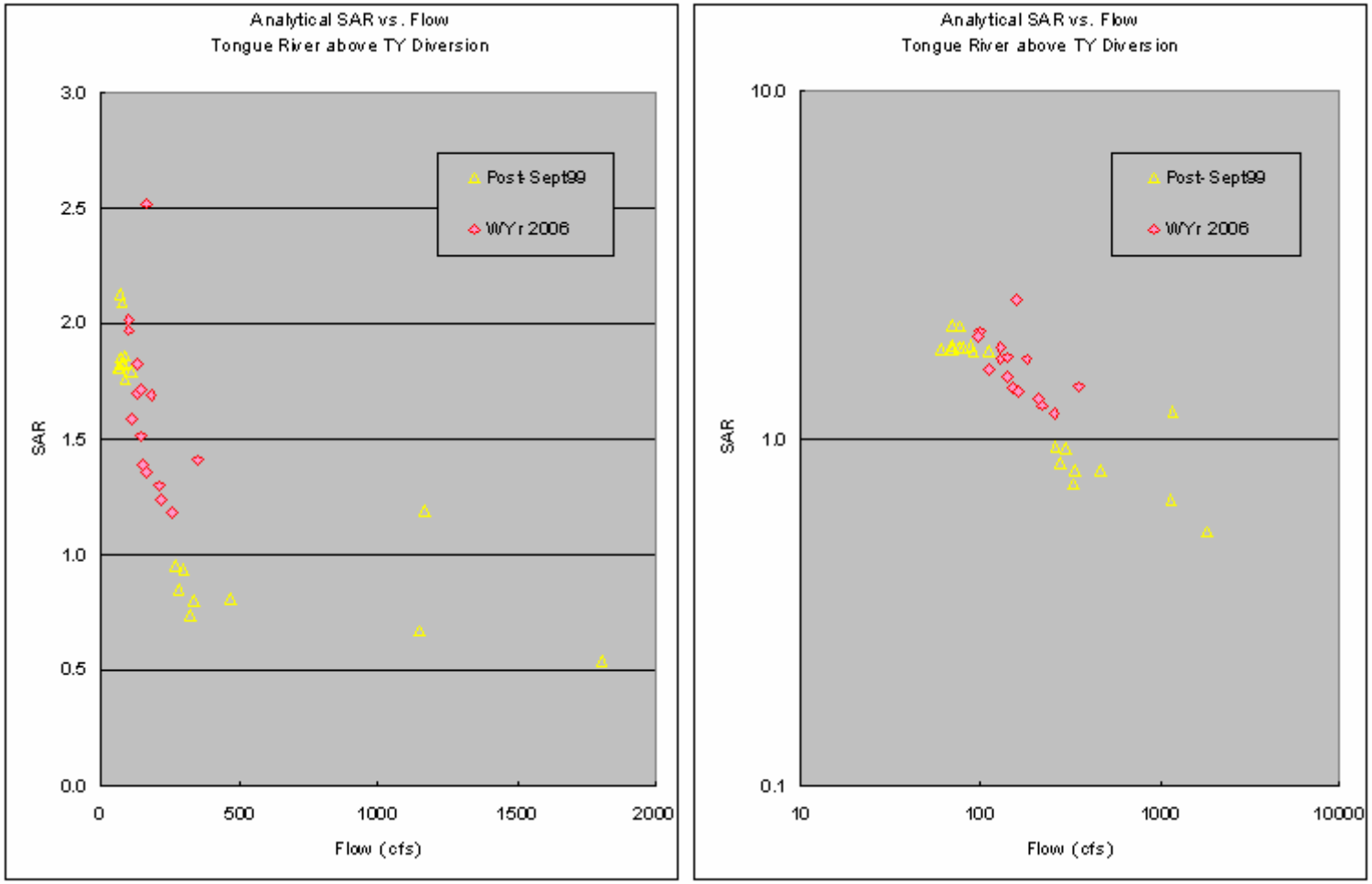
Figure 36: Tongue River above TY Diversion



A **B**

Figure 36 shows analytical SC vs. Flow data for water year 2006 for the Tongue River above the TY Diversion Dam, near Miles City, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 37: Tongue River above TY Diversion



A **B**

Figure 37 shows analytical SAR vs. Flow data for water year 2006 for the Tongue River above the TY Diversion Dam, near Miles City, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 38: Tongue River above TY Diversion

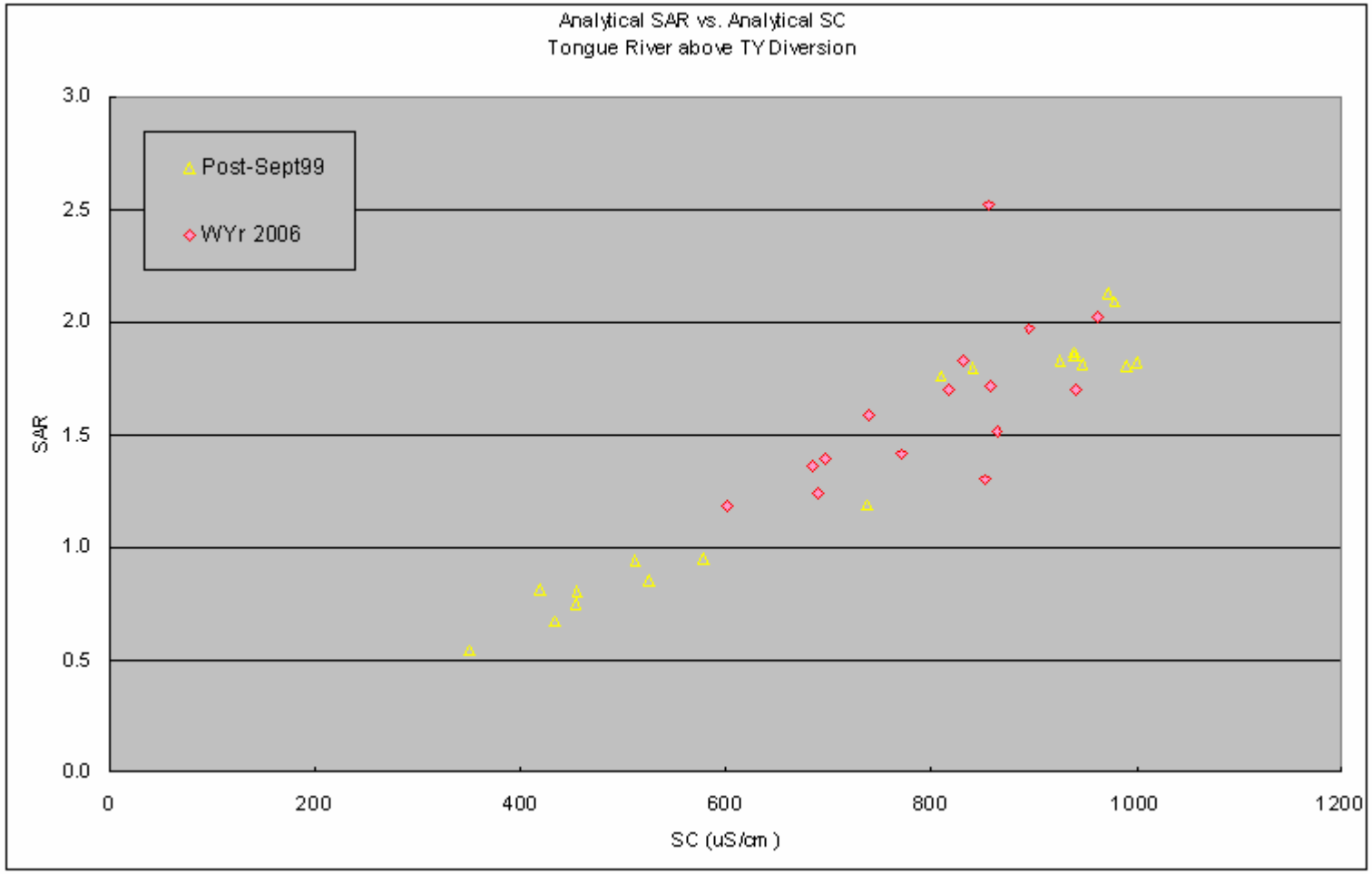
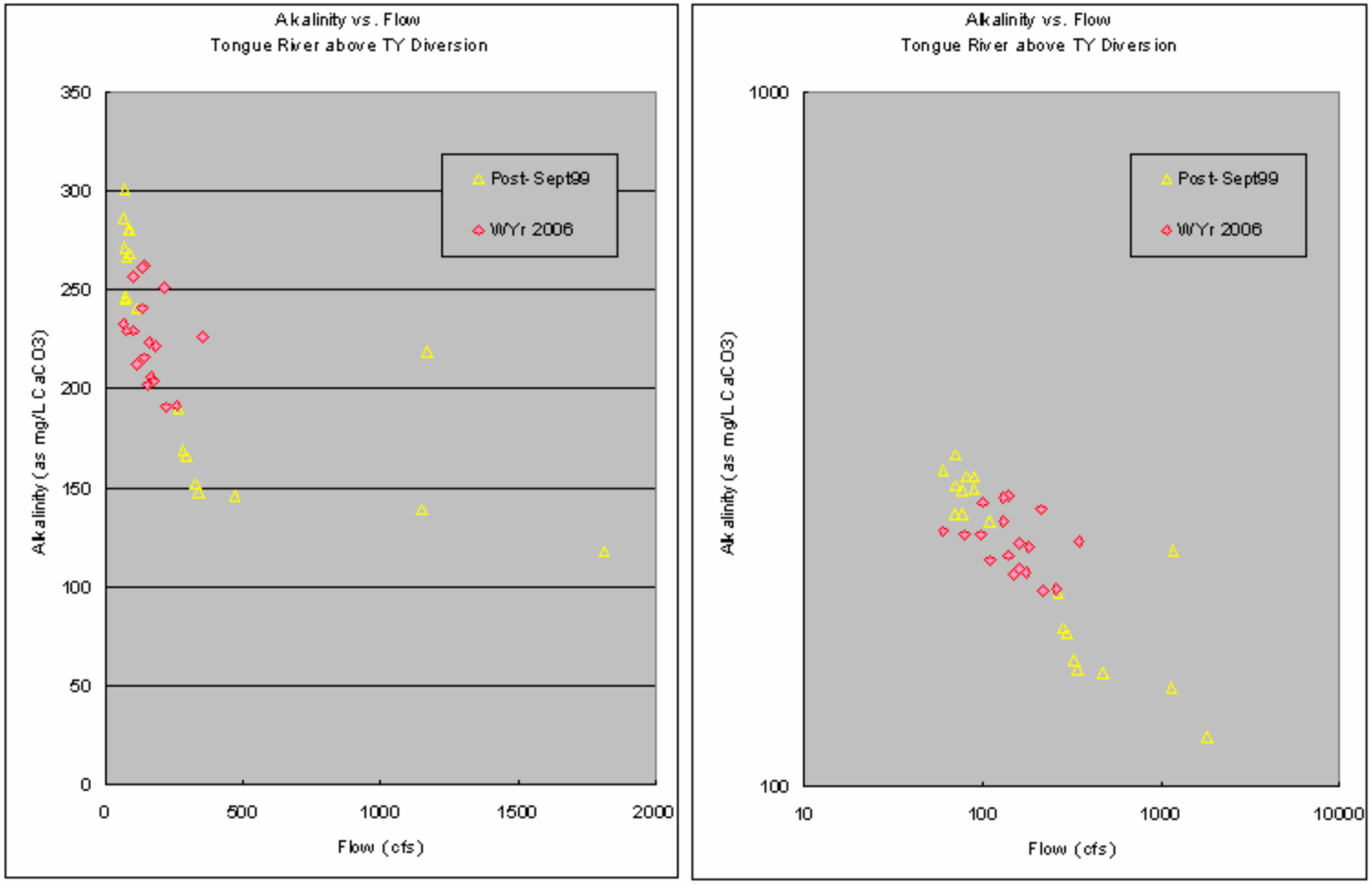


Figure 38 shows analytical SAR vs. analytical SC data for water year 2006 for the Tongue River above the TY Diversion Dam, near Miles City, MT. Historical SAR vs. SC data are also shown to place the data in context.

Figure 39: Tongue River above TY Diversion



A **B**

Figure 39 shows analytical Alkalinity vs. Flow data for water year 2006 for the Tongue River above the TY Diversion Dam. These data are charted on both linear (A) and logarithmic (B) scales. Historical Alkalinity vs. Flow data are also shown to place the data in context.

Figure 40: Tongue River at Miles City vs. Tongue River above TY

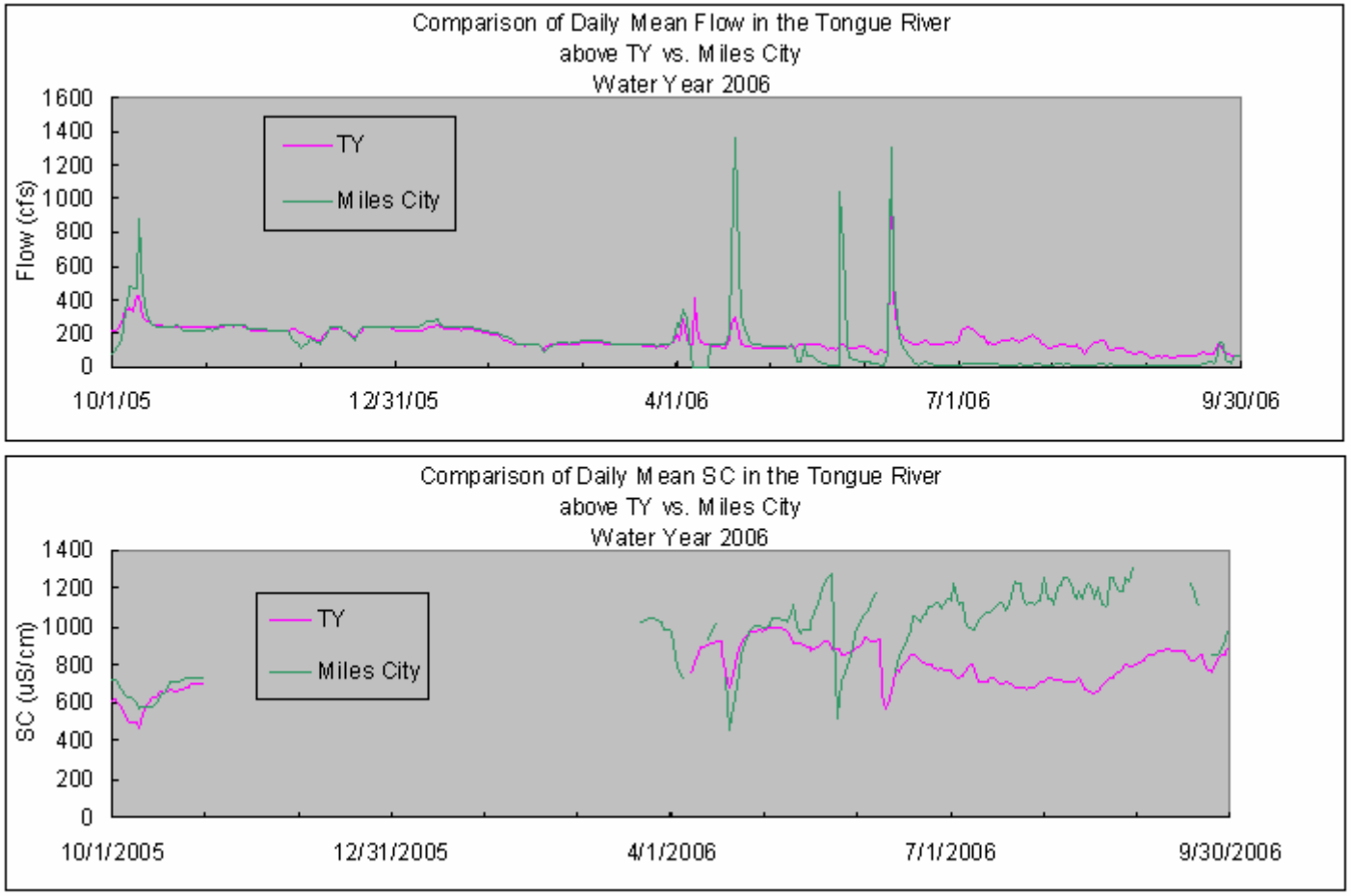


Figure 40 shows a comparison of flows and SC values measured above the TY diversion and at Miles City. During the non-irrigation season flow and SC values are comparable. During the irrigation season flows are substantially reduced at Miles City and SC values are substantially increased. This is believed to be primarily due to the diversion of water for irrigation at the TY diversion. Since little water flows past the diversion dam at low flows the water in the downstream portion (Miles City) is more representative of Pumpkin Creek and irrigation return flows than of the Tongue River for low flows during the irrigation season.

Figure 41: Tongue River at Miles City, MT

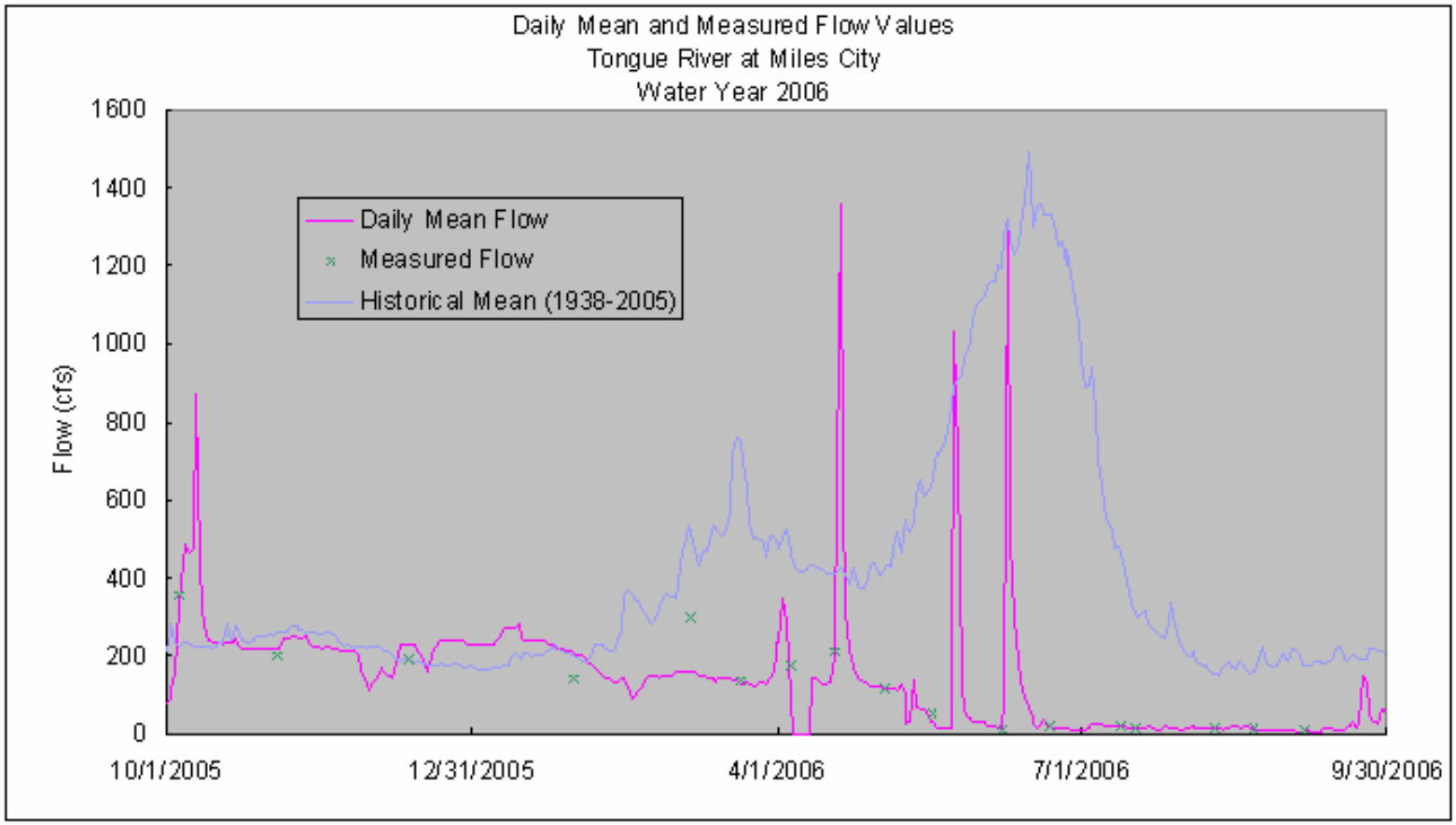
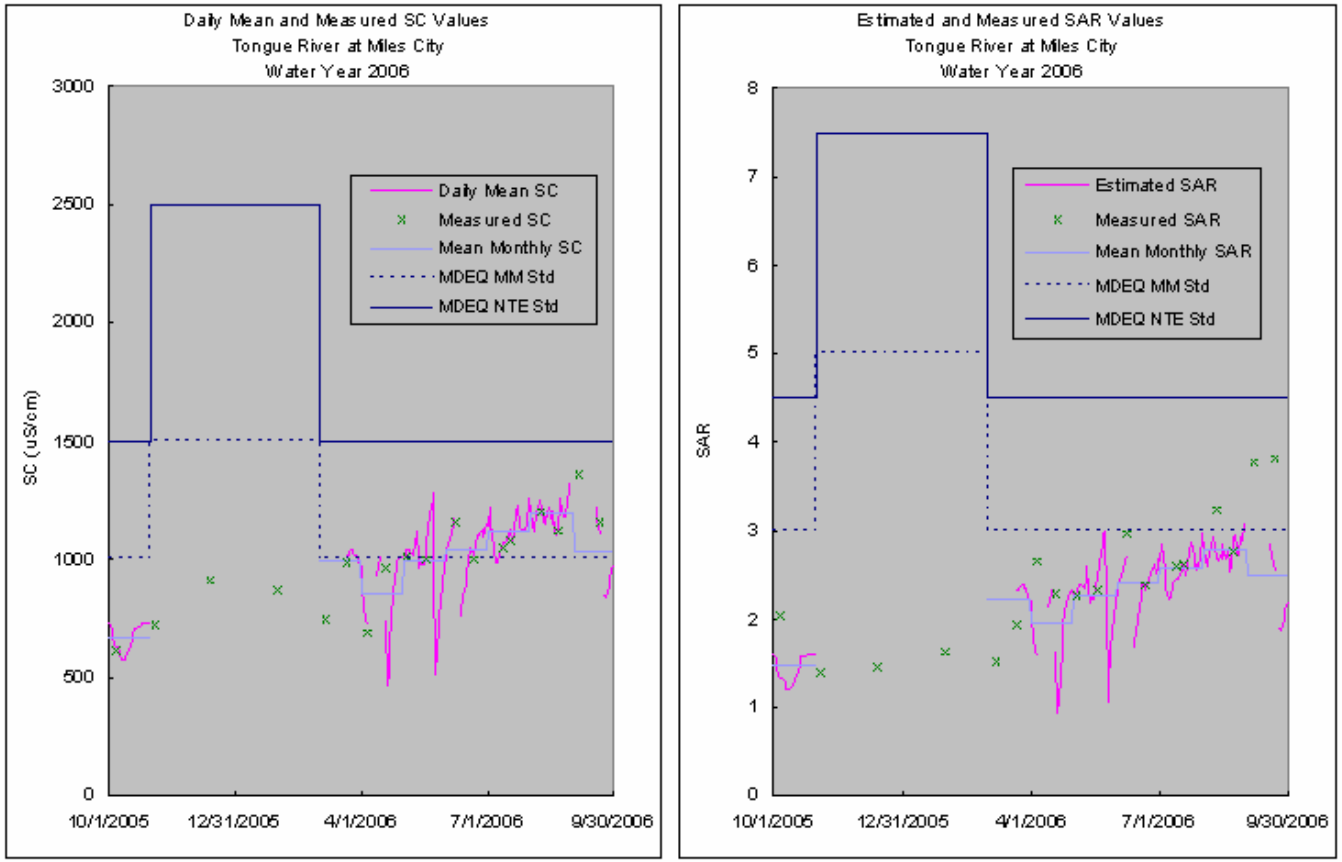


Figure 41 shows daily mean and field measurements of flow in a time series plot for water year 2006 for the Tongue River at Miles City, MT. The historical average daily mean flow values are also shown. Daily mean flow values during 2006 ranged from 6.9 to 1360 cfs. Flows were less than average for most of the year.

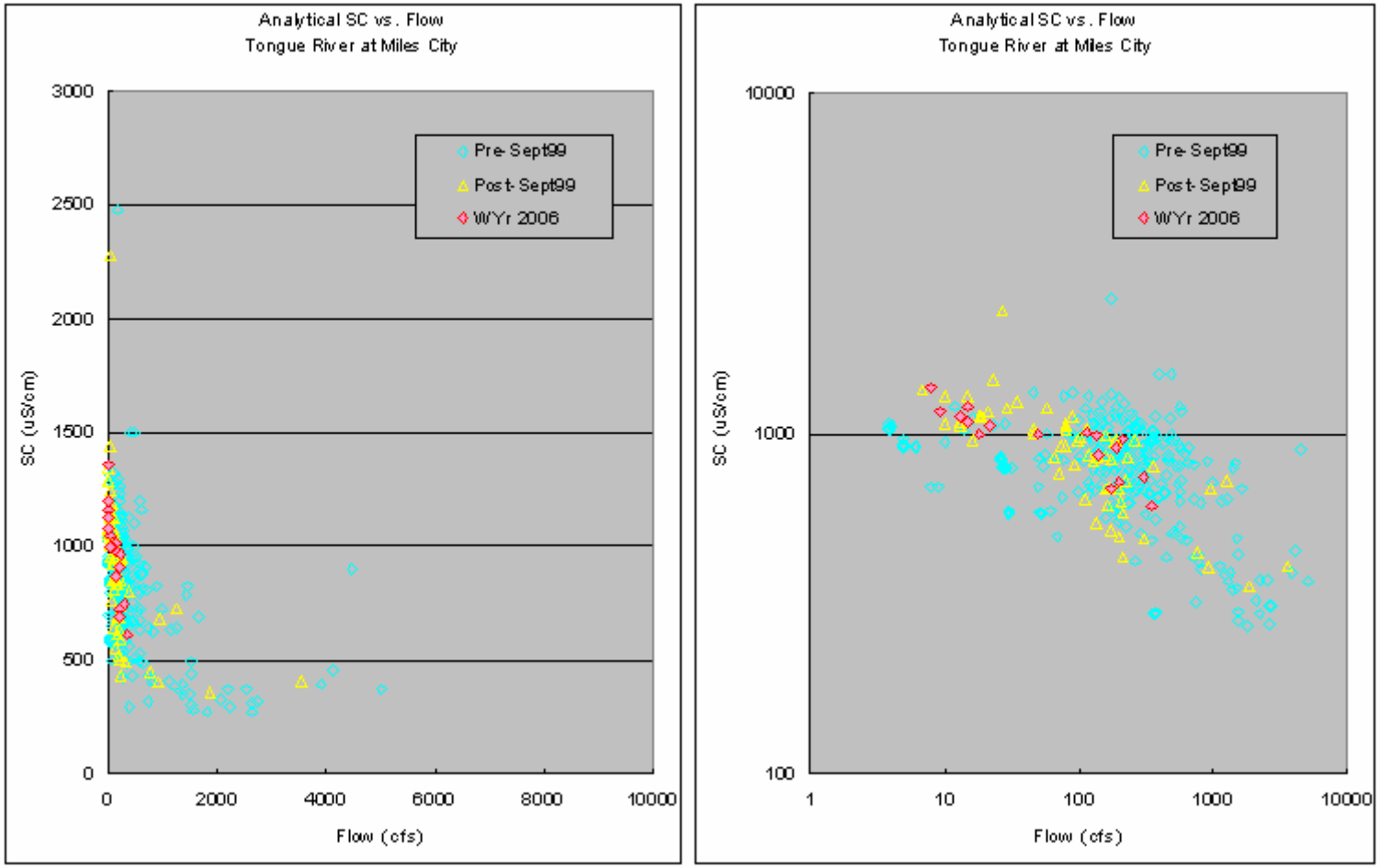
Figure 42: Tongue River at Miles City, MT



A **B**

Figure 42 shows analytical and daily mean SC values (A) and analytical and daily mean estimated SAR values (B) in time series plots for water year 2006 for the Tongue River at Miles City, MT. Monthly mean SC and SAR values are also shown. SC values ranged from 465 to 1360 uS/cm. SAR values ranged from 0.9 to 3.8. These values are compared to the instantaneous maximum and monthly mean standards developed by the MDEQ. The monthly mean SC values were above the MDEQ monthly mean standard for EC during June, July, August and September. All other values were below the standards.

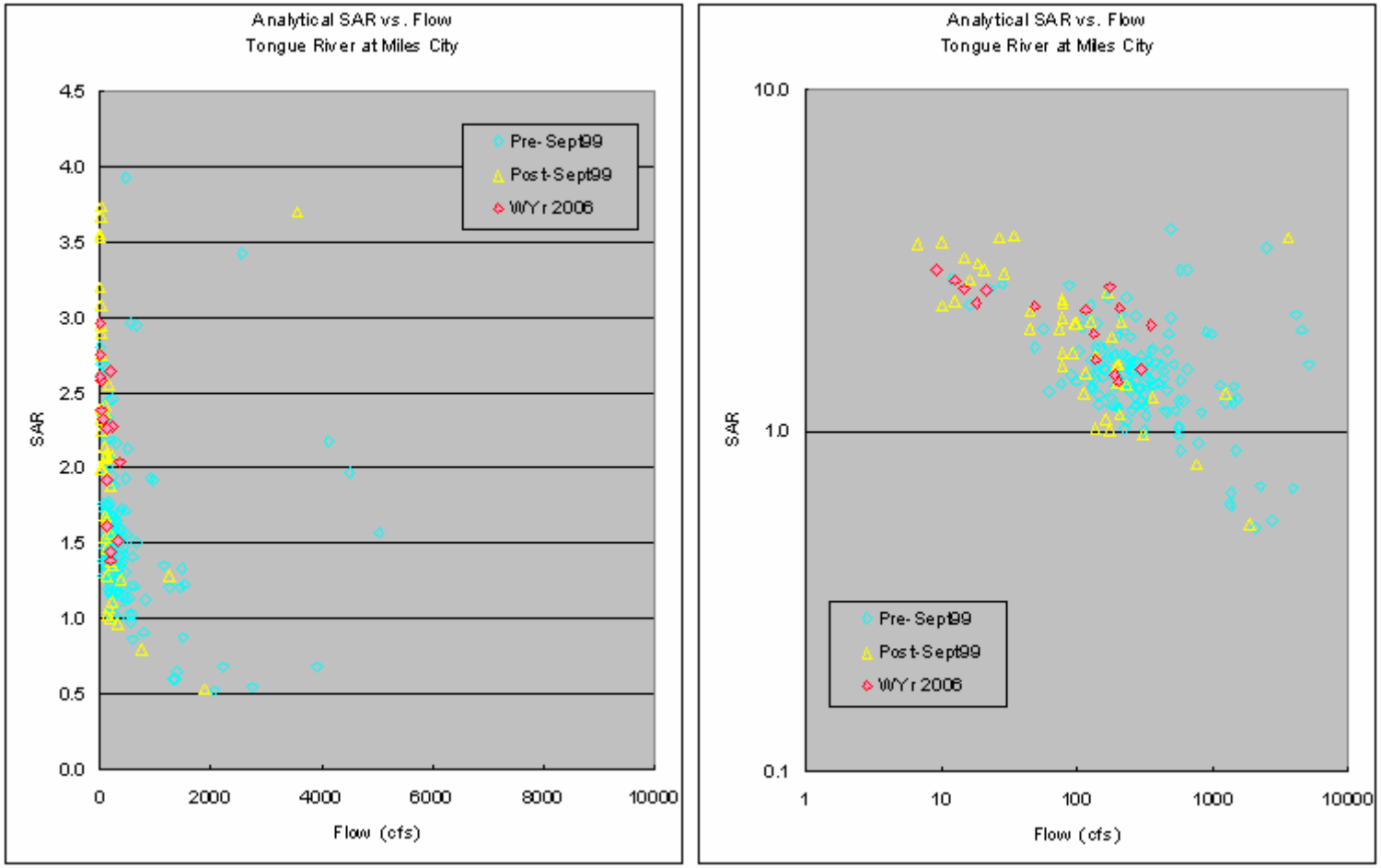
Figure 43: Tongue River at Miles City, MT



A **B**

Figure 43 shows analytical SC vs. Flow data for water year 2006 for the Tongue River at Miles City, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 44: Tongue River at Miles City, MT



A **B**

Figure 44 shows analytical SAR vs. Flow data for water year 2006 for the Tongue River at Miles City, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 45: Tongue River at Miles City, MT

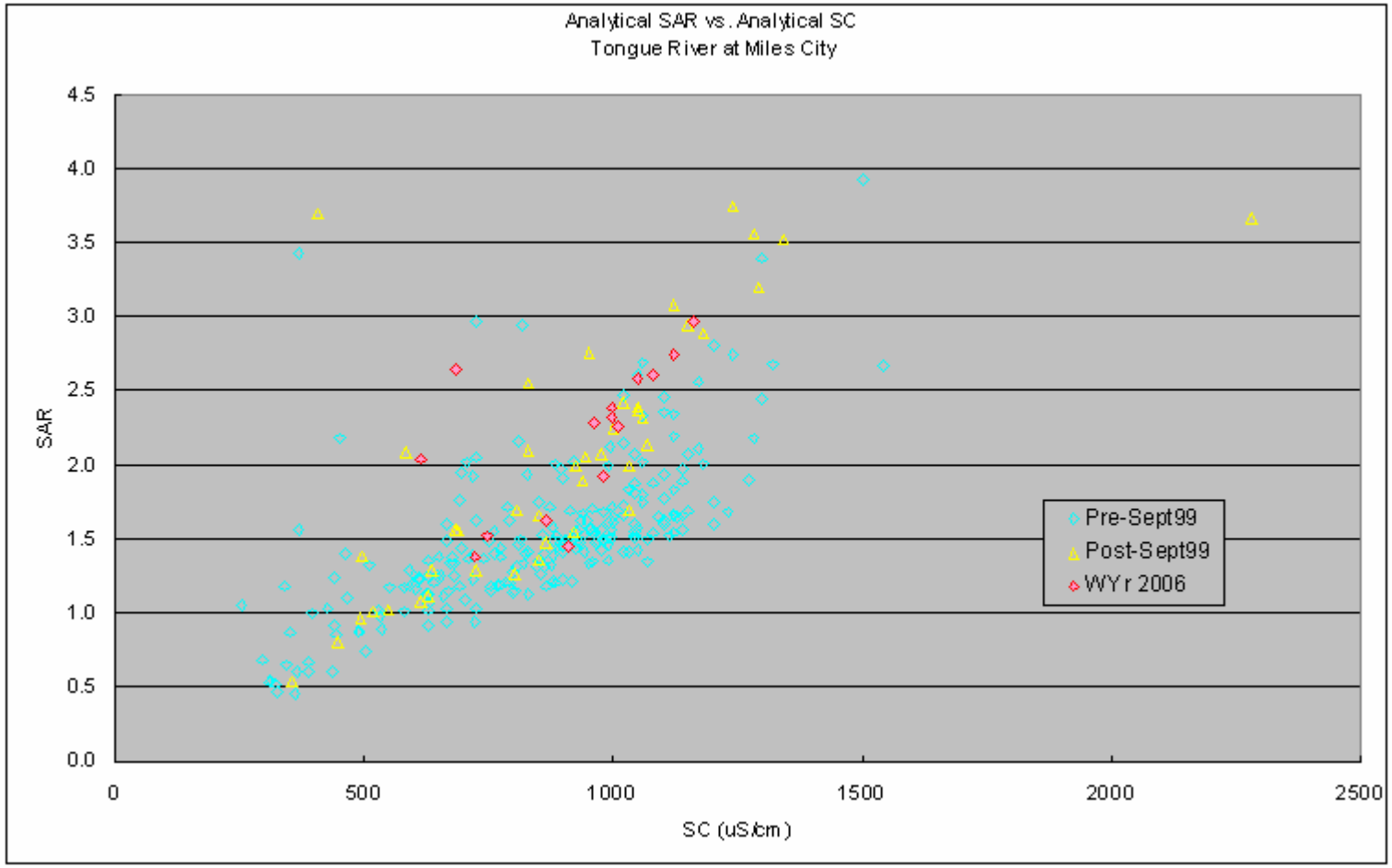
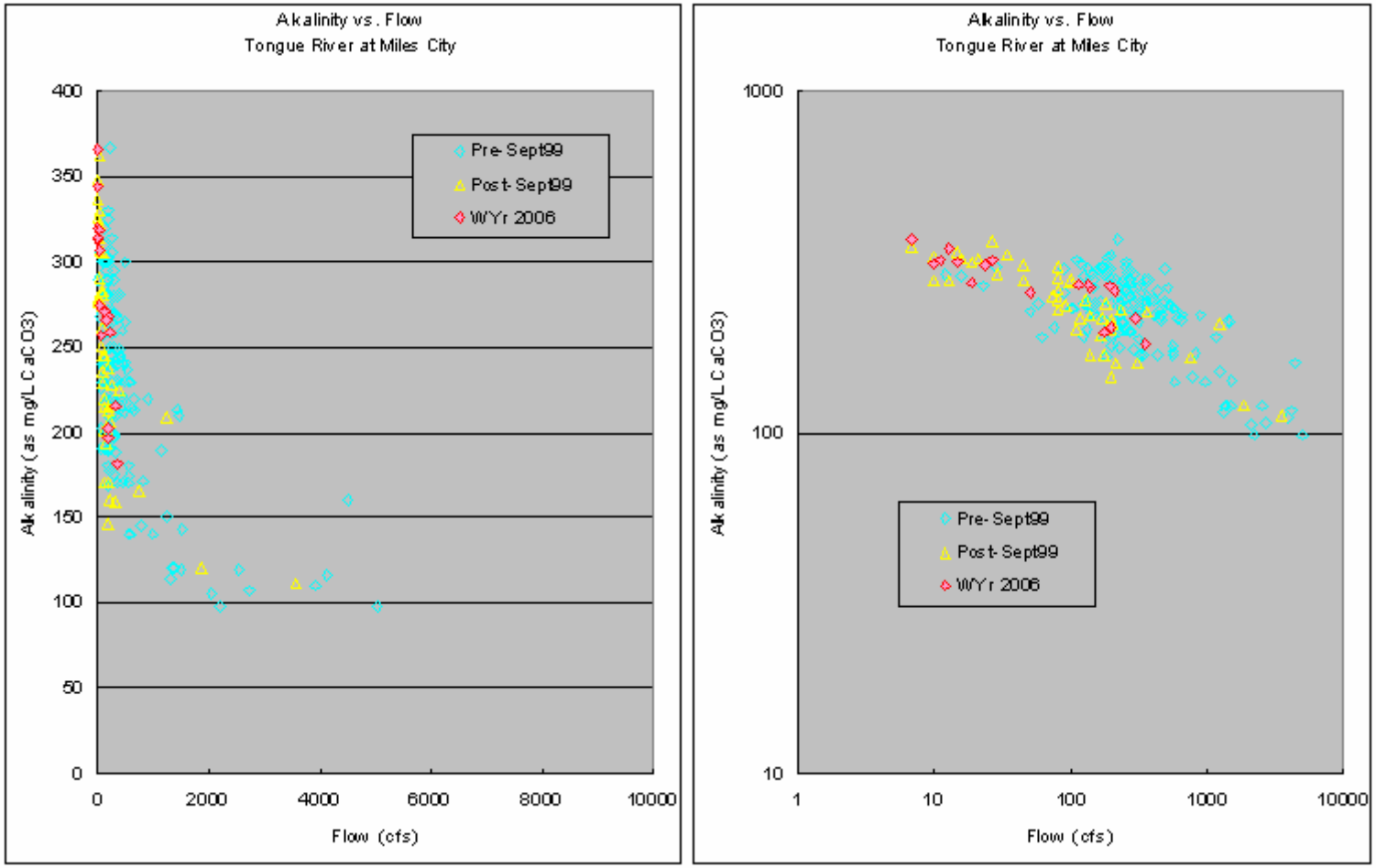


Figure 45 shows analytical SAR vs. analytical SC data for water year 2006 for the Tongue River at Miles City. Historical SAR vs. SC data are also shown to place the data in context.

Figure 46: Tongue River at Miles City, MT



A **B**

Figure 46 shows analytical Alkalinity vs. Flow data for water year 2006 for the Tongue River at Miles City. These data are charted on both linear (A) and logarithmic (B) scales. Historical Alkalinity vs. Flow data are also shown to place the data in context.

Figure 47: Goose Creek near Acme, WY

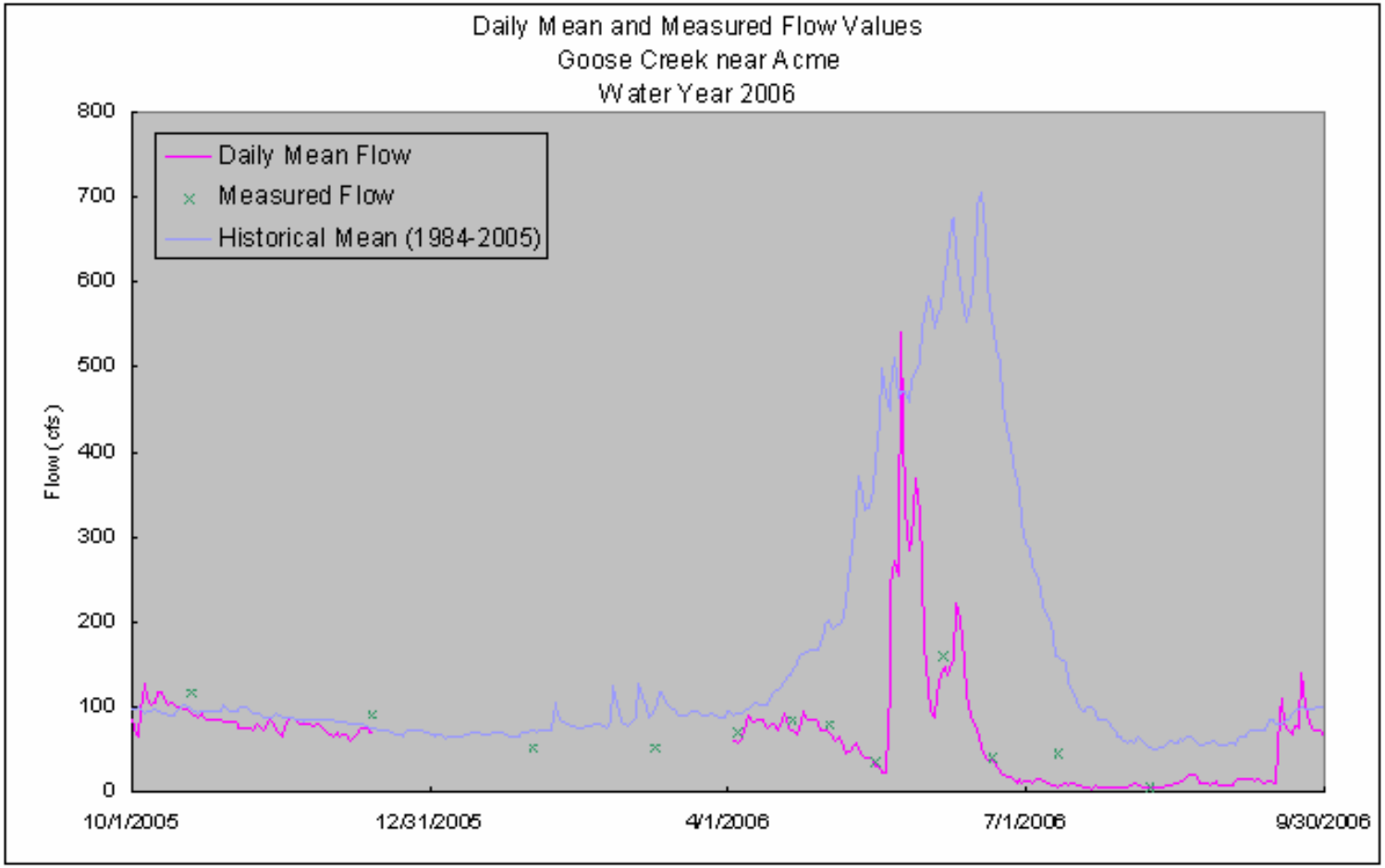
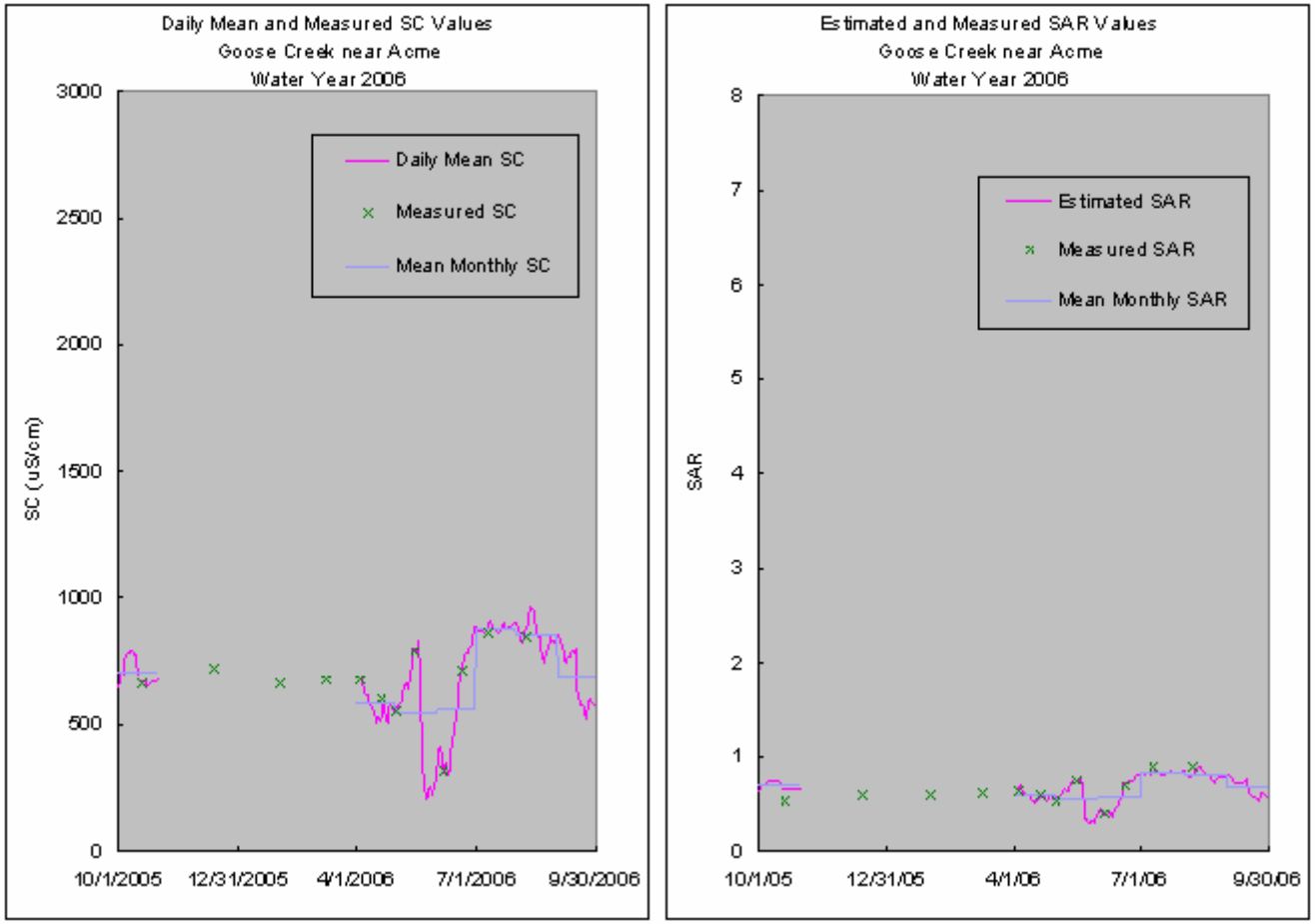


Figure 47 shows daily mean and field measurements of flow in a time series plot for water year 2006 for Goose Creek near Acme. The historical average daily mean flow values are also shown. Daily mean flow values during 2006 ranged from 3.3 to 541 cfs. Flows were less than average for most of the year.

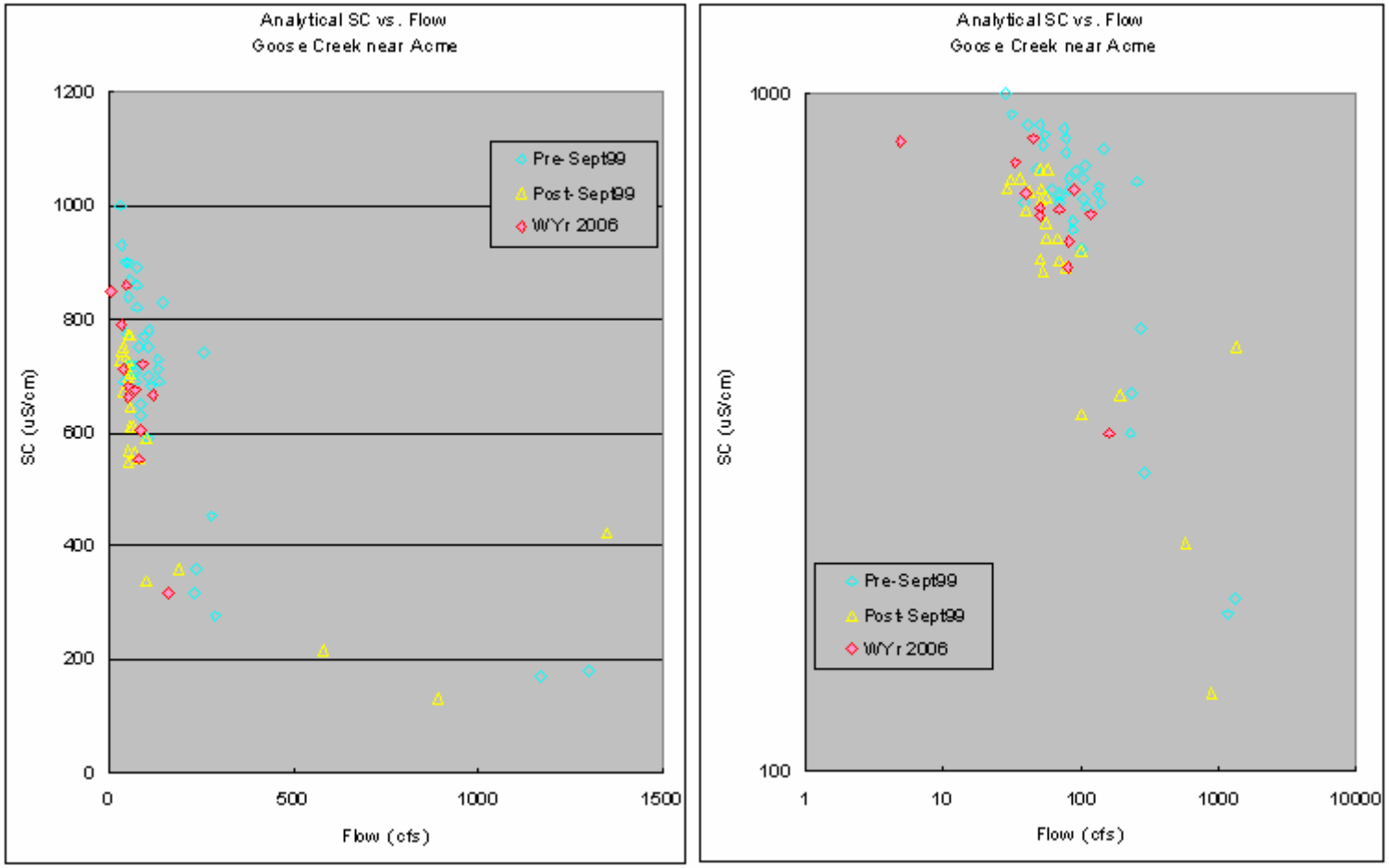
Figure 48: Goose Creek near Acme, WY



A **B**

Figure 48 shows analytical and daily mean SC values (A) and analytical and daily mean estimated SAR values (B) in time series plots for water year 2006 for Goose Creek near Acme, WY. Monthly mean EC and SAR values are also shown. SC values ranged from 209 to 961 uS/cm. SAR values ranged from 0.3 to 0.9.

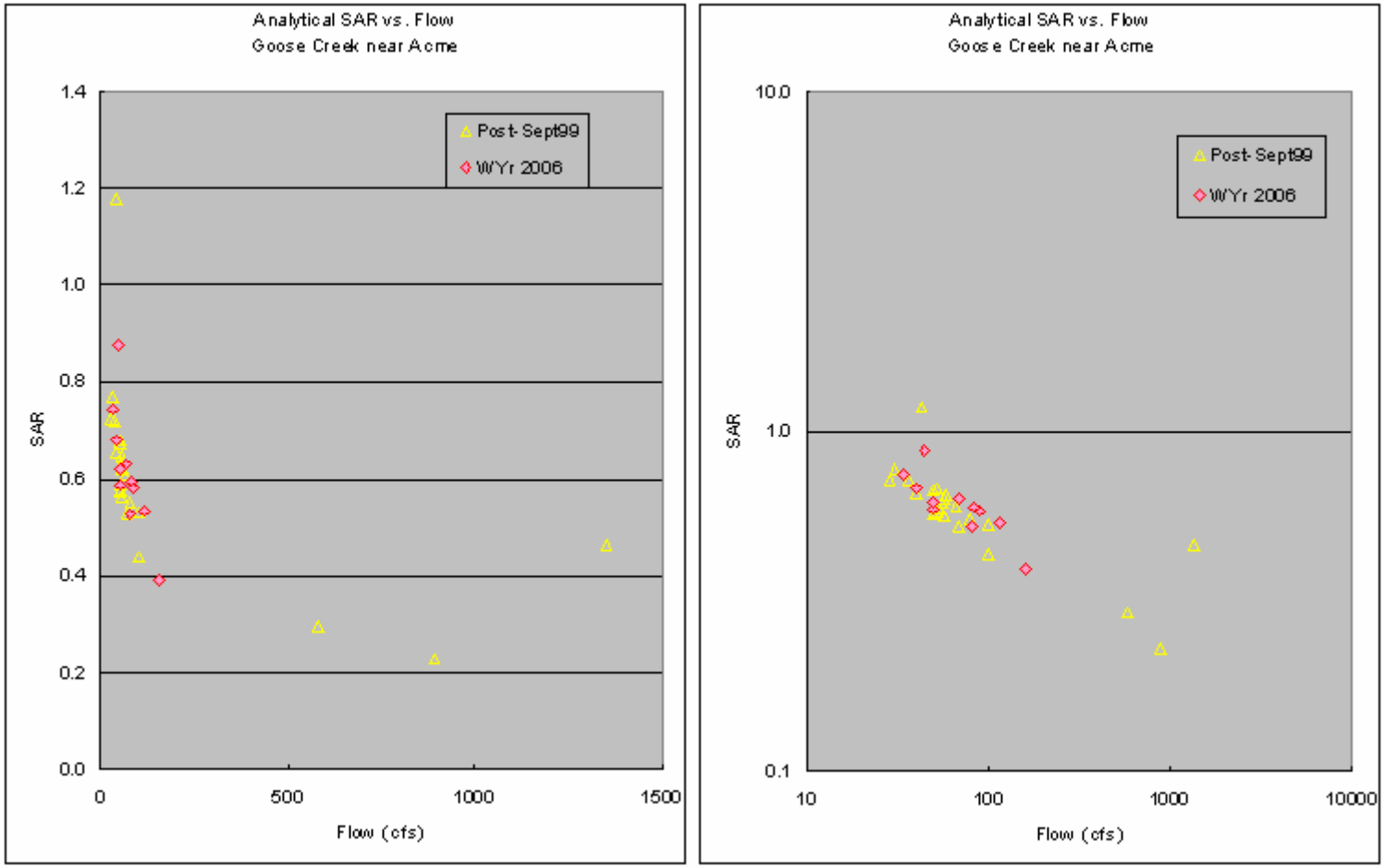
Figure 49: Goose Creek near Acme, WY



A **B**

Figure 49 shows analytical SC vs. Flow data for water year 2006 for Goose Creek near Acme, WY. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 50: Goose Creek near Acme, WY



A **B**

Figure 50 shows analytical SAR vs. Flow data for water year 2006 for Goose Creek near Acme, WY. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 51: Goose Creek near Acme, WY

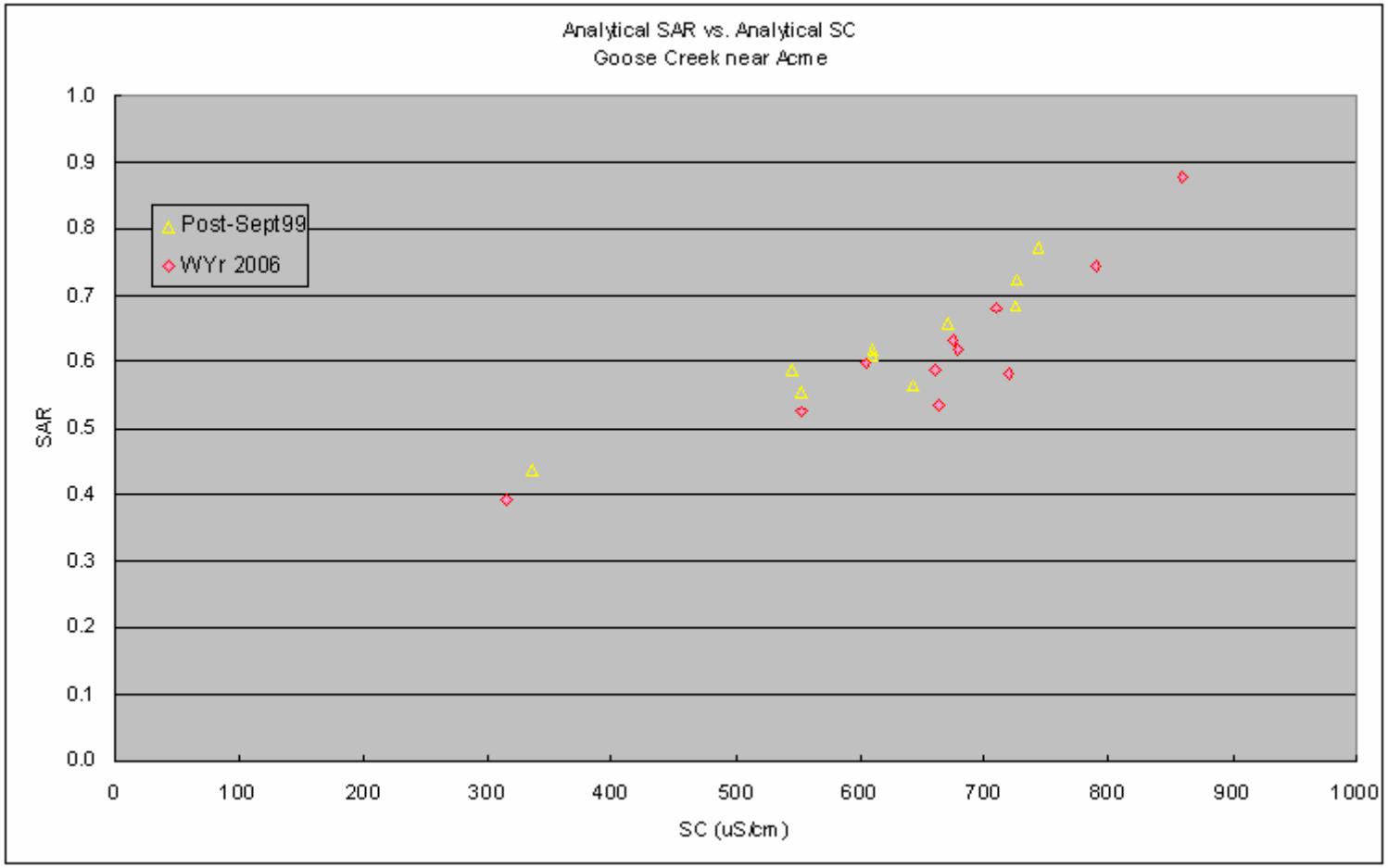


Figure 51 shows analytical SAR vs. analytical SC data for water year 2006 for Goose Creek near Acme, WY. Historical SAR vs. SC data are also shown to place the data in context.

Figure 52: Prairie Dog Creek near Acme, WY

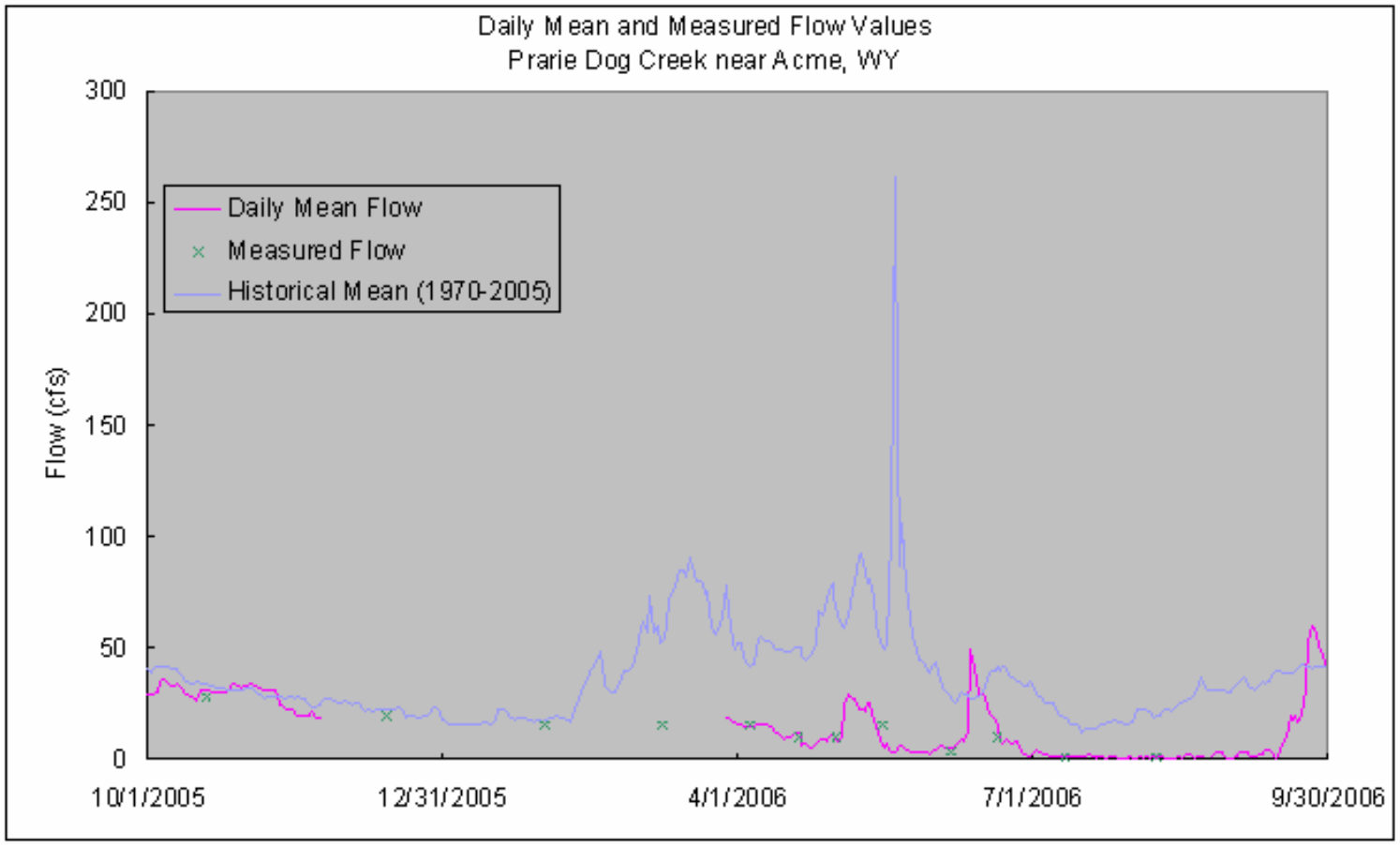
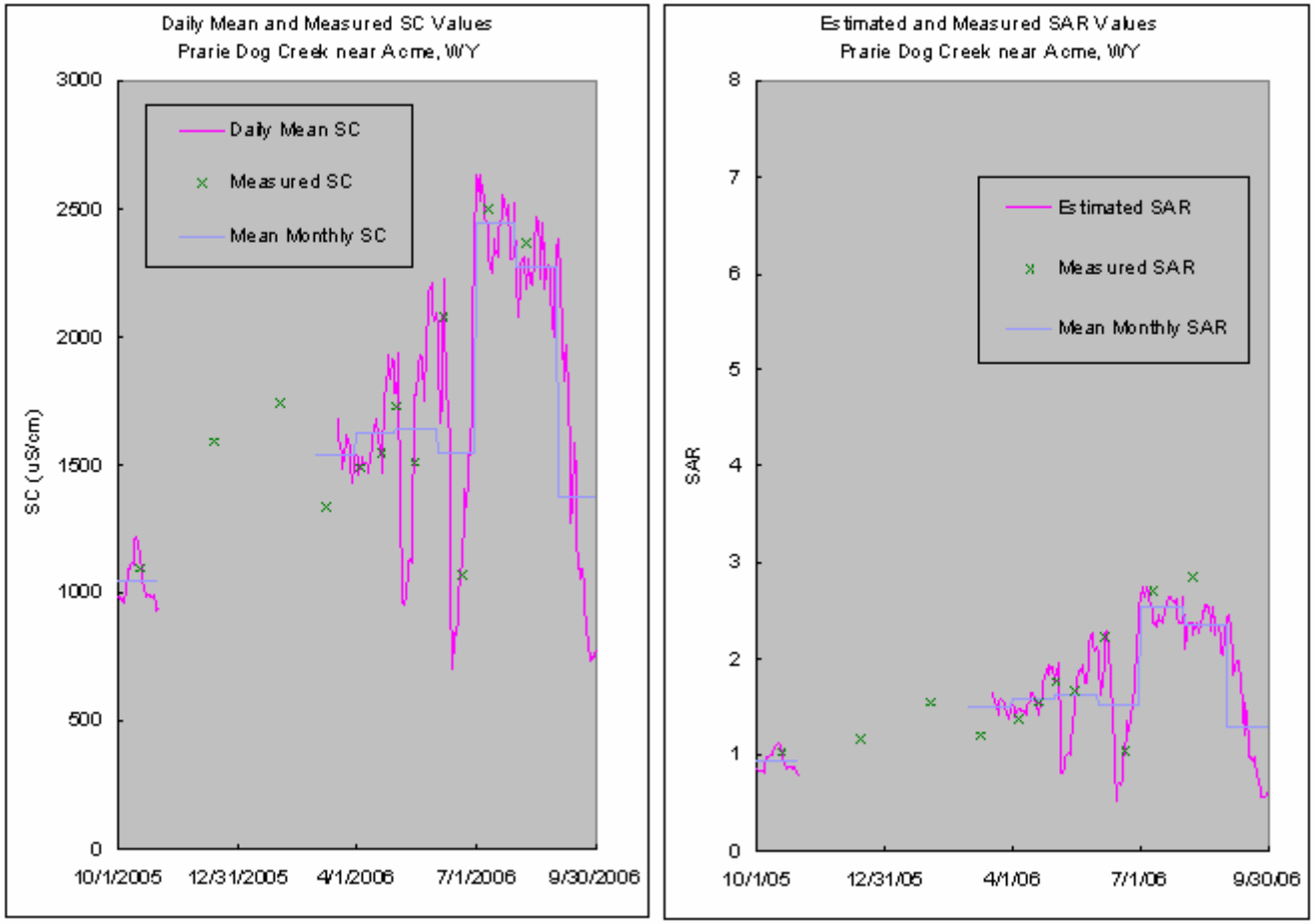


Figure 52 shows daily mean and field measurements of flow in a time series plot for water year 2006 for Prairie Dog Creek near Acme. The historical average daily mean flow values are also shown. Daily mean flow values during 2006 ranged from 0 to 60 cfs. Flows were less than average for most of the year.

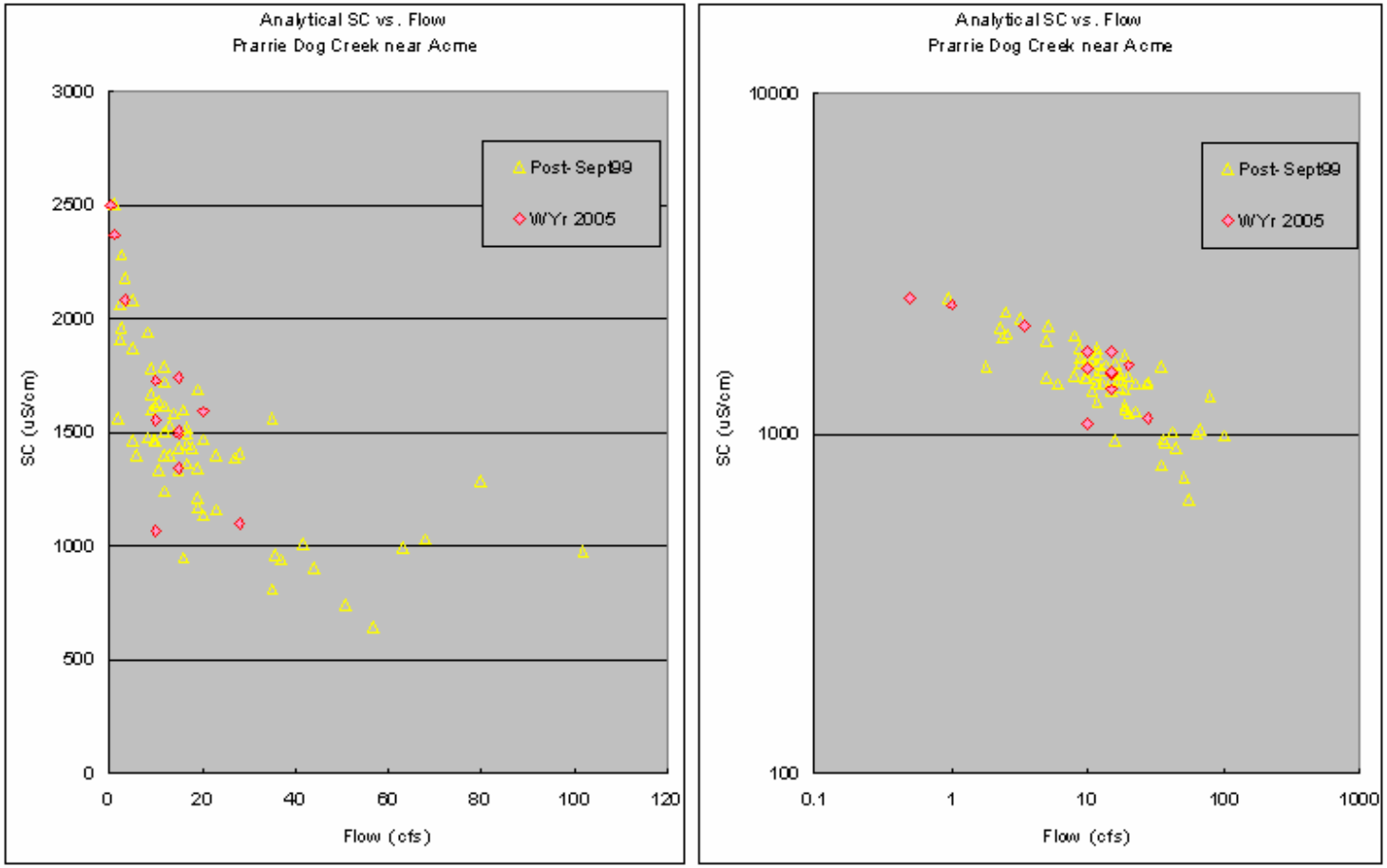
Figure 53: Prairie Dog Creek near Acme, WY



A **B**

Figure 53 shows analytical and daily mean SC values (A) and analytical and daily mean estimated SAR values (B) in time series plots for water year 2006 for Prairie Dog Creek near Acme, WY. Monthly mean SC and SAR values are also shown. SC values ranged from 703 to 2630 uS/cm. SAR values ranged from 0.5 to 2.8.

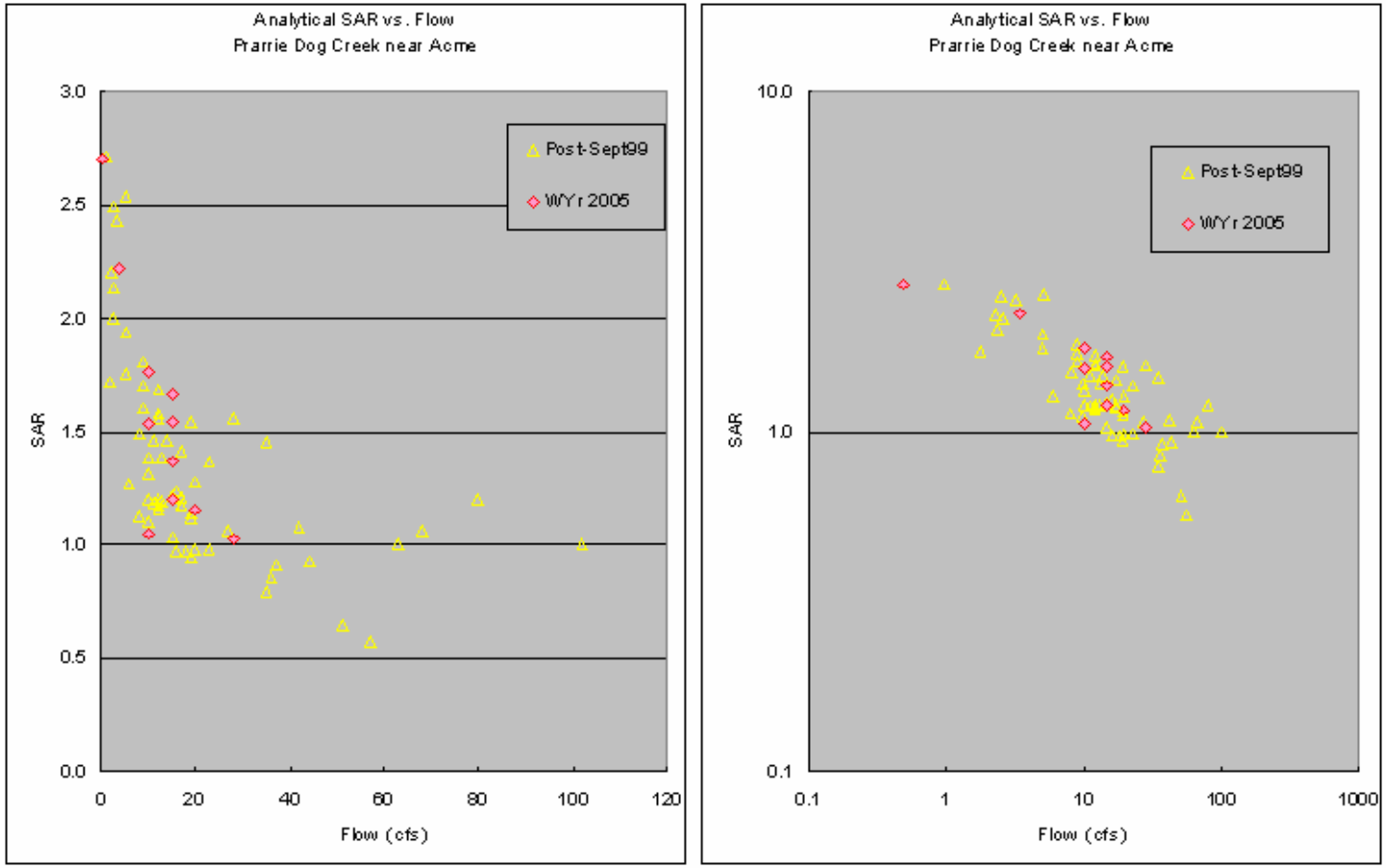
Figure 54: Prairie Dog Creek near Acme, WY



A **B**

Figure 54 shows analytical SC vs. Flow data for water year 2006 for Prairie Dog Creek near Acme, WY. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 55: Prairie Dog Creek near Acme, WY



A **B**

Figure 55 shows analytical SAR vs. Flow data for water year 2006 for Prairie Dog Creek near Acme, WY. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 56: Prairie Dog Creek near Acme, WY

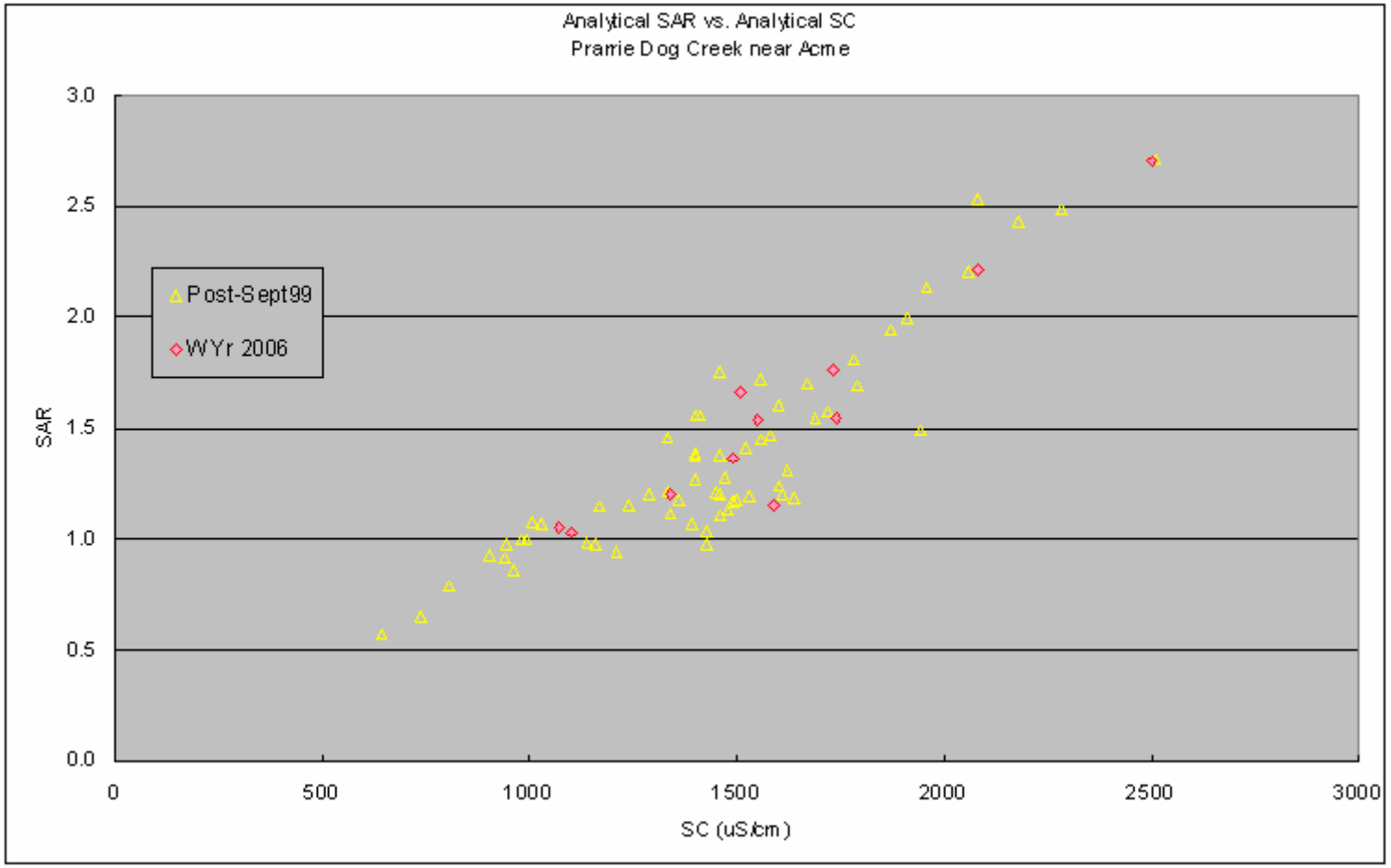


Figure 56 shows analytical SAR vs. analytical SC data for water year 2006 for Prairie Dog Creek near Acme, WY. Historical SAR vs. SC data are also shown to place the data in context.

Figure 57: Hanging Woman Creek near Birney, MT

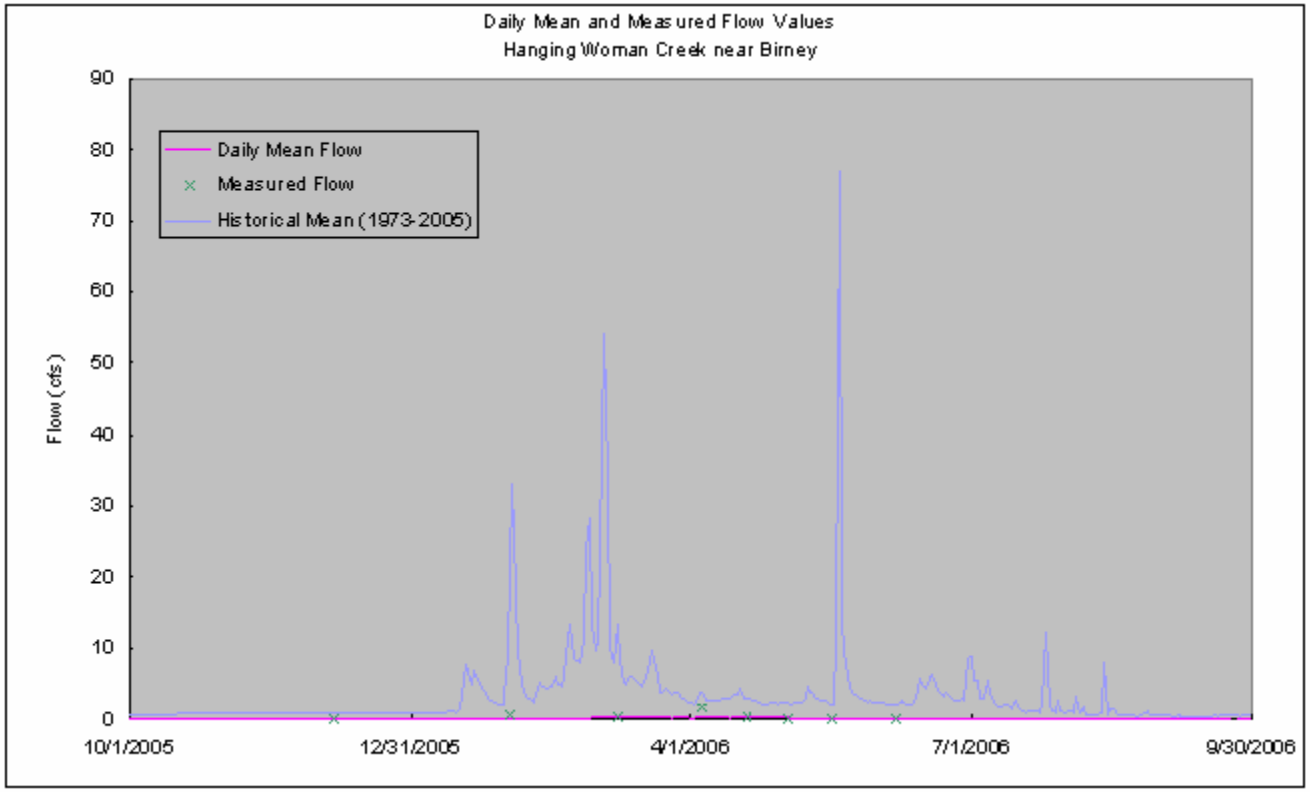
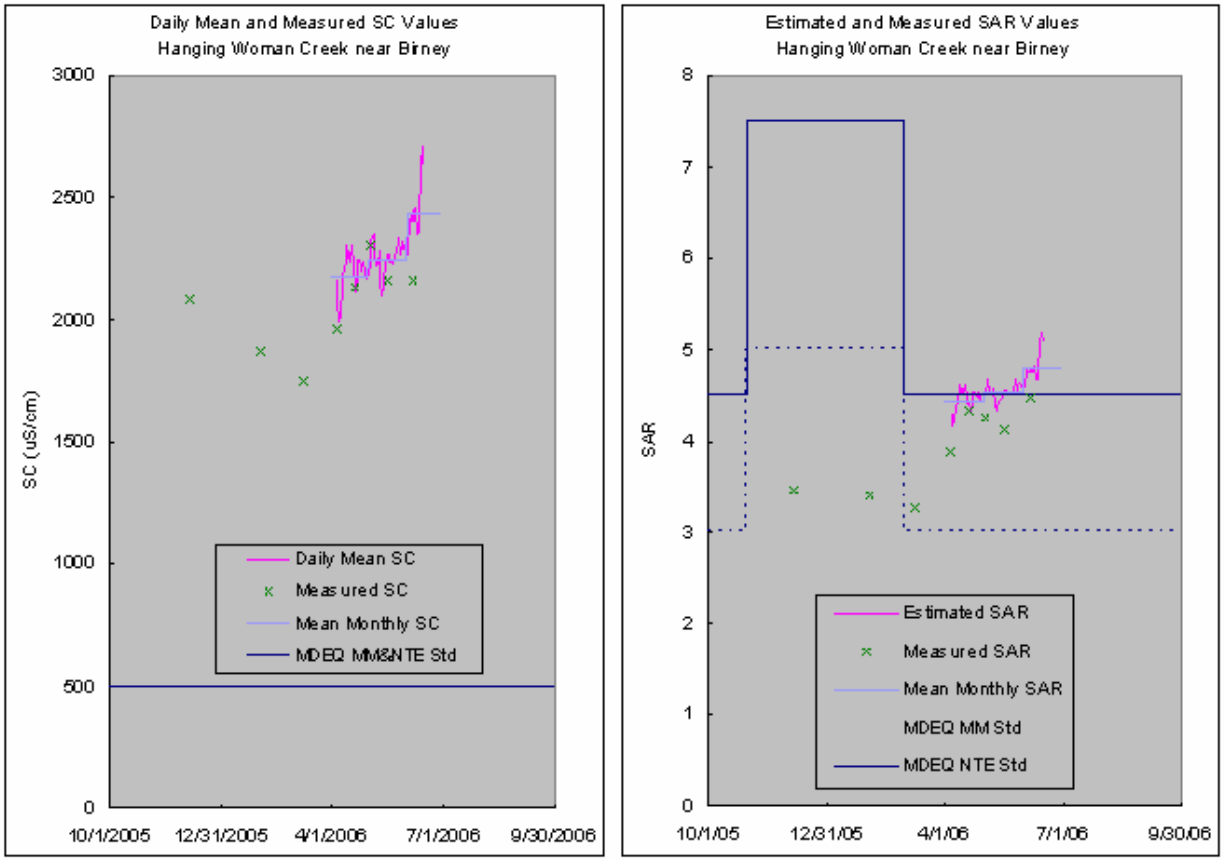


Figure 57 shows daily mean and field measurements of flow in a time series plot for water year 2006 for Hanging Woman Creek near Birney, MT. The historical average daily mean flow values are also shown. Daily mean flow values during 2006 ranged from 0 to 0.4 cfs. Flow throughout the entire year was substantially less than average.

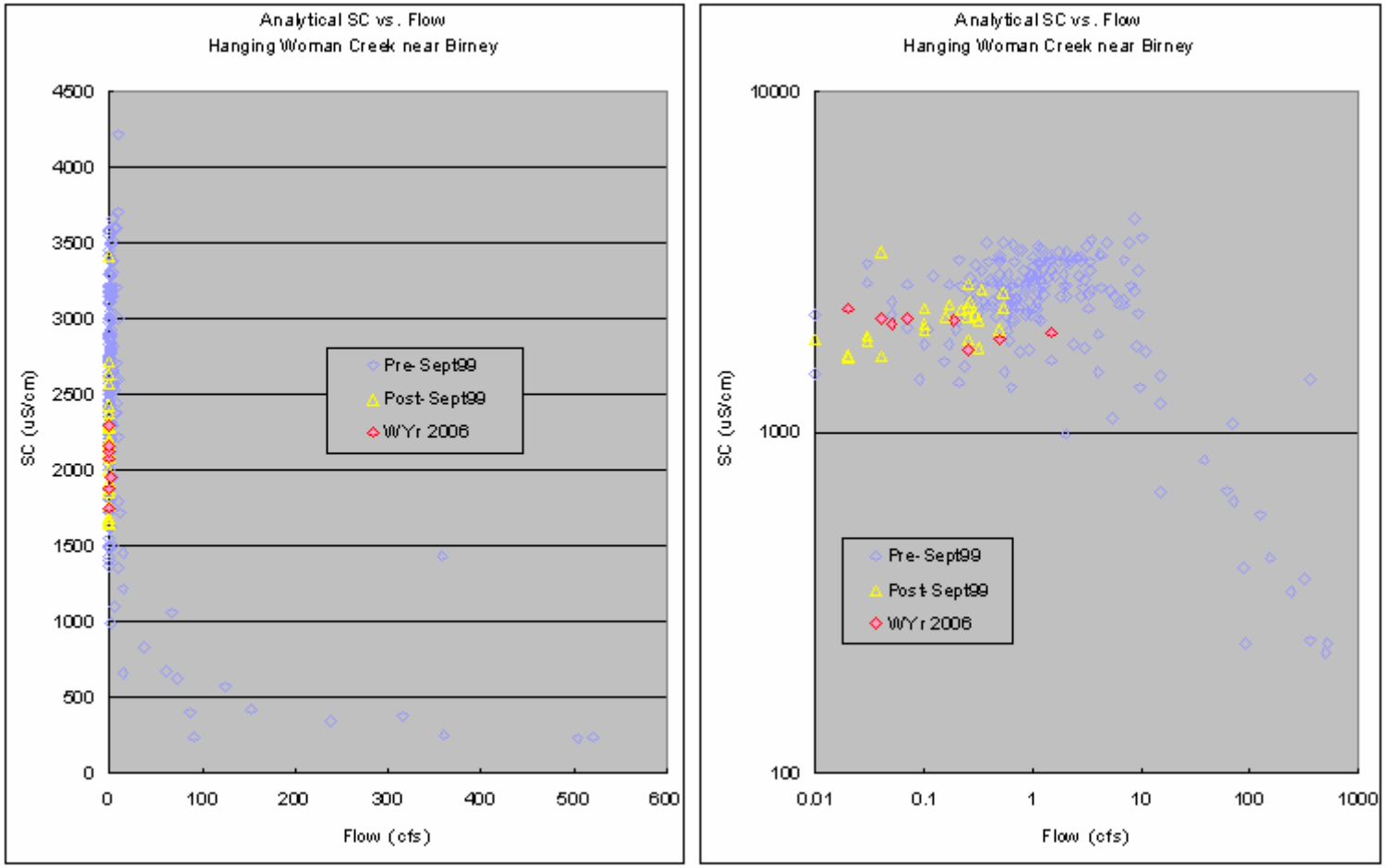
Figure 58: Hanging Woman Creek near Birney, MT



A **B**

Figure 58 shows analytical and daily mean SC values (A) and analytical and daily mean estimated SAR values (B) in time series plots for water year 2006 for Hanging Woman Creek near Birney, MT. Monthly mean SC and SAR values are also shown. SC values ranged from 1750 to 2710 uS/cm. SAR values ranged from 3.3 to 5.2. These values are compared to the instantaneous maximum and monthly mean standards developed by the MDEQ. SC values were in excess of the EC standards for the entire year. SAR values were often above the standards.

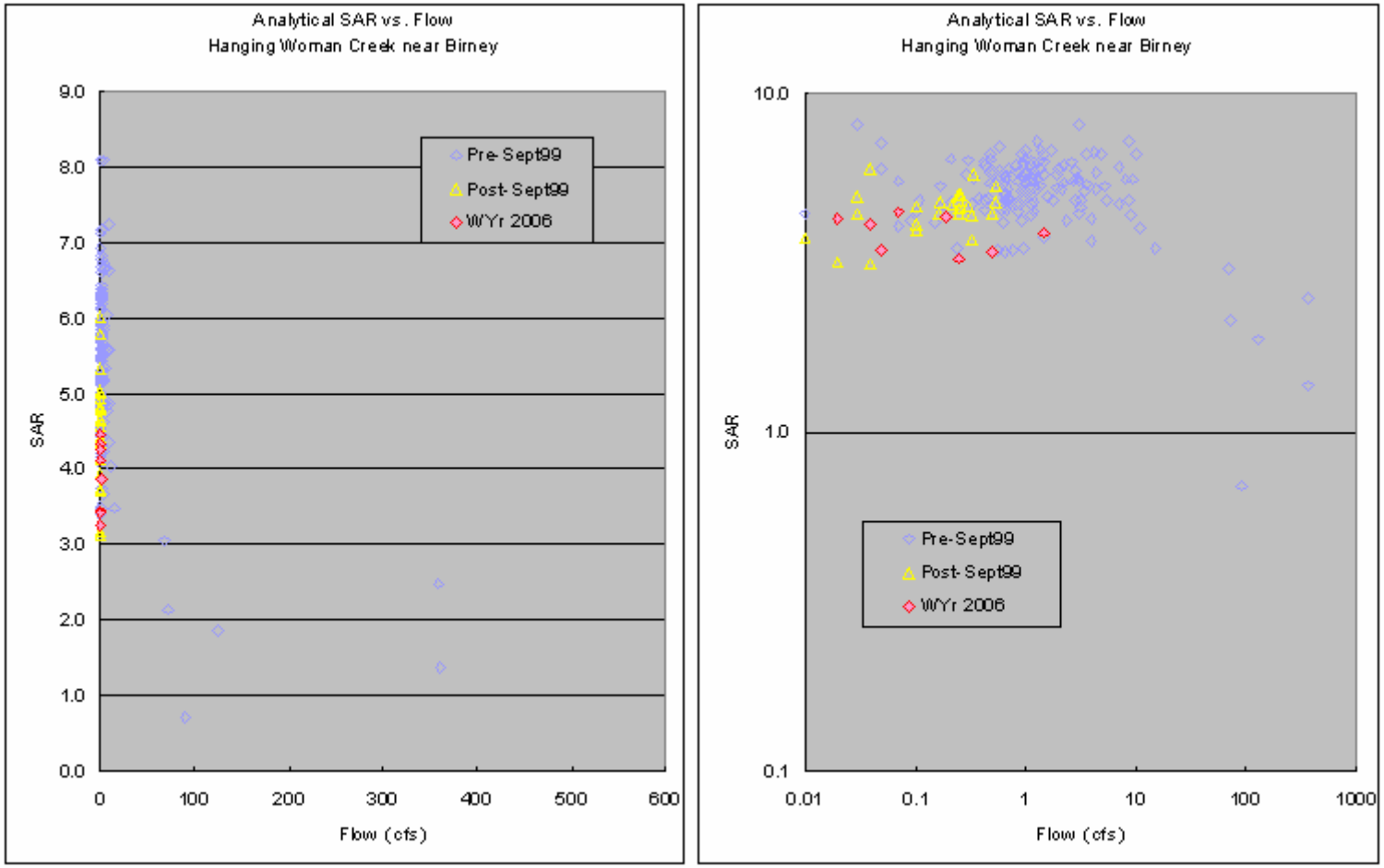
Figure 59: Hanging Woman Creek near Birney, MT



A **B**

Figure 59 shows analytical SC vs. Flow data for water year 2006 for Hanging Woman Creek near Birney, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 60: Hanging Woman Creek near Birney, MT



A **B**

Figure 60 shows analytical SAR vs. Flow data for water year 2006 for Hanging Woman Creek near Birney, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 61: Hanging Woman Creek near Birney, MT

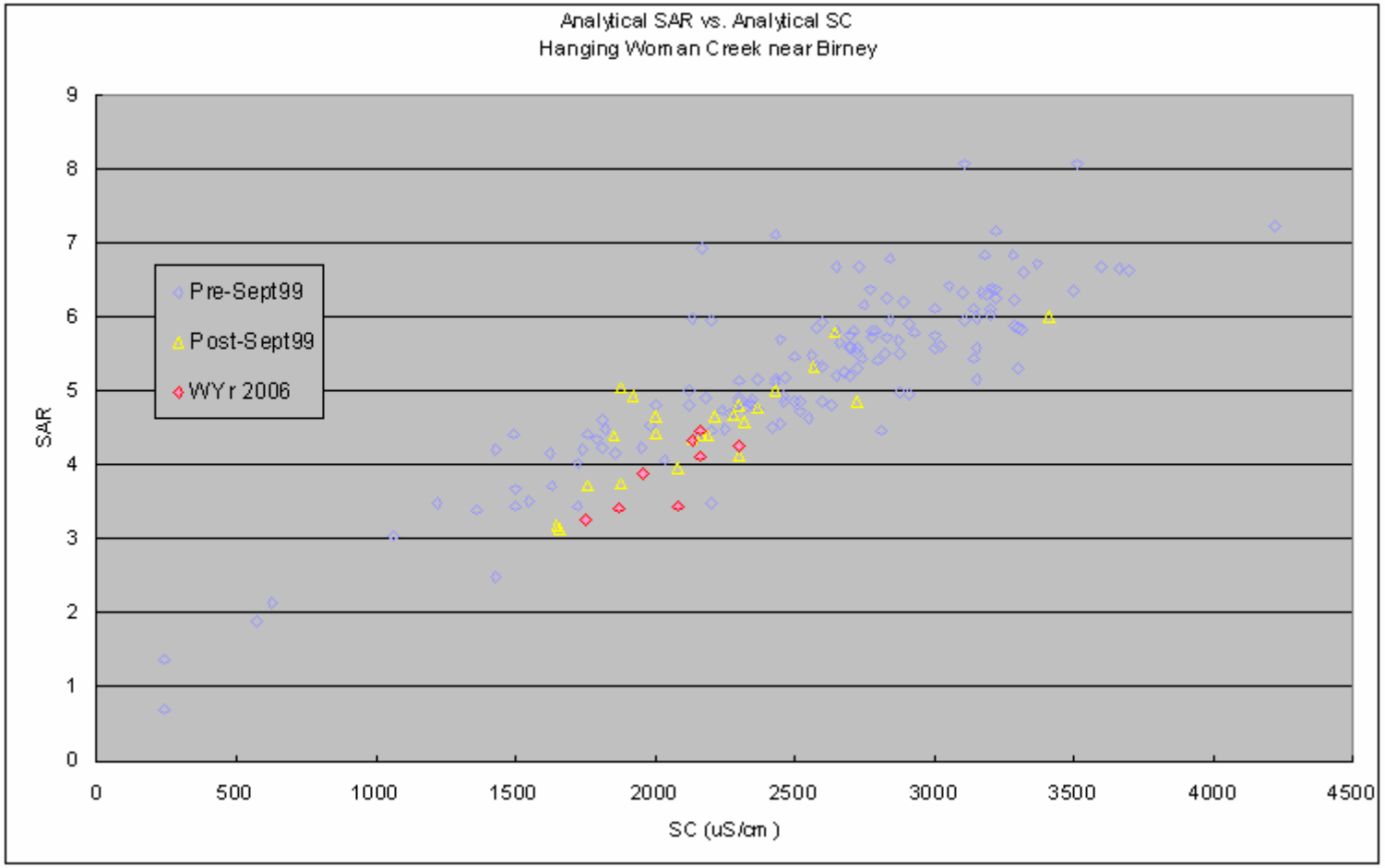


Figure 61 shows analytical SAR vs. analytical SC data for water year 2006 for Hanging Woman Creek near Birney, MT. Historical SAR vs. SC data are also shown to place the data in context.

Figure 62: Otter Creek at Ashland, MT

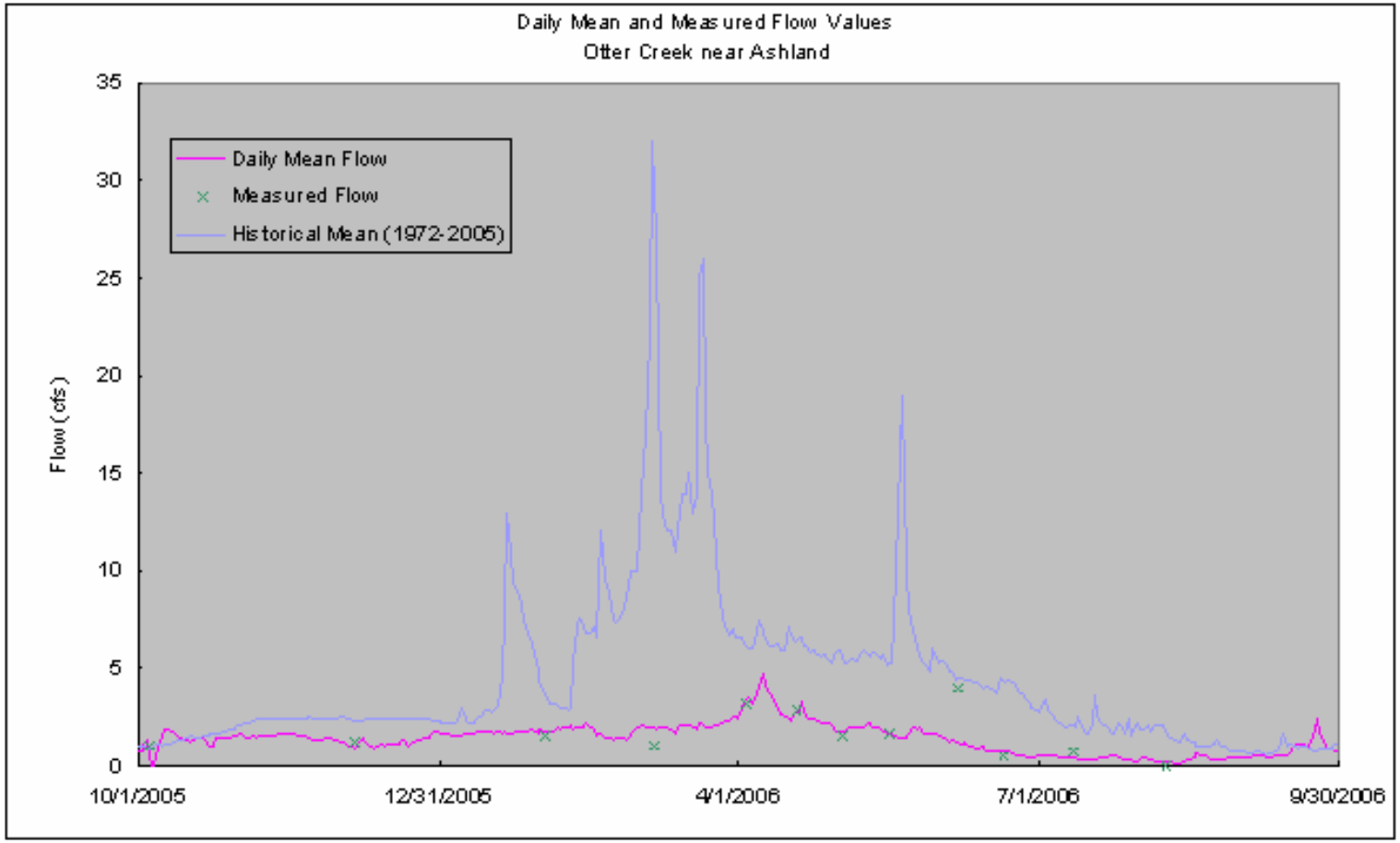
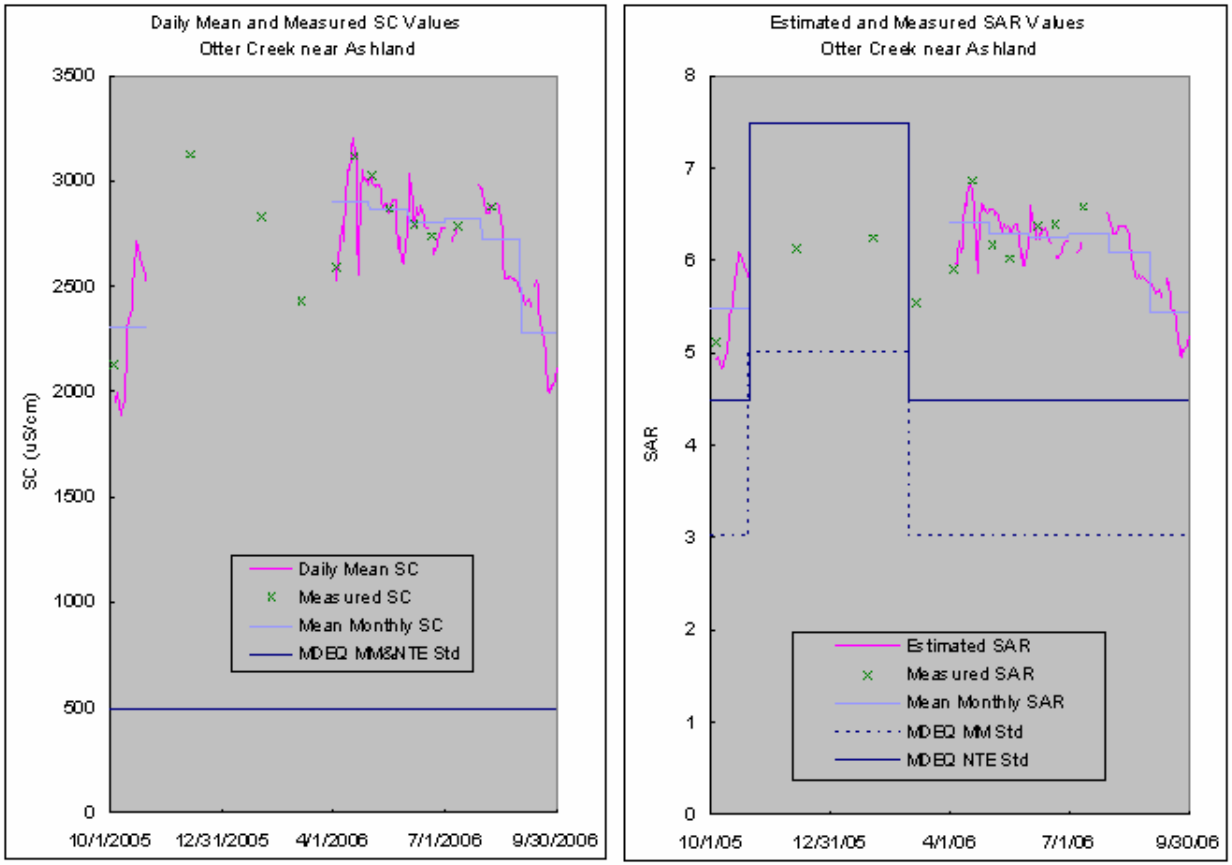


Figure 62 shows daily mean and field measurements of flow in a time series plot for water year 2006 for Otter Creek near Ashland, MT. The historical average daily mean flow values are also shown. Daily mean flow values during 2006 ranged from 0.1 to 4.7 cfs. Flows during 2006 were less than average for most of the year.

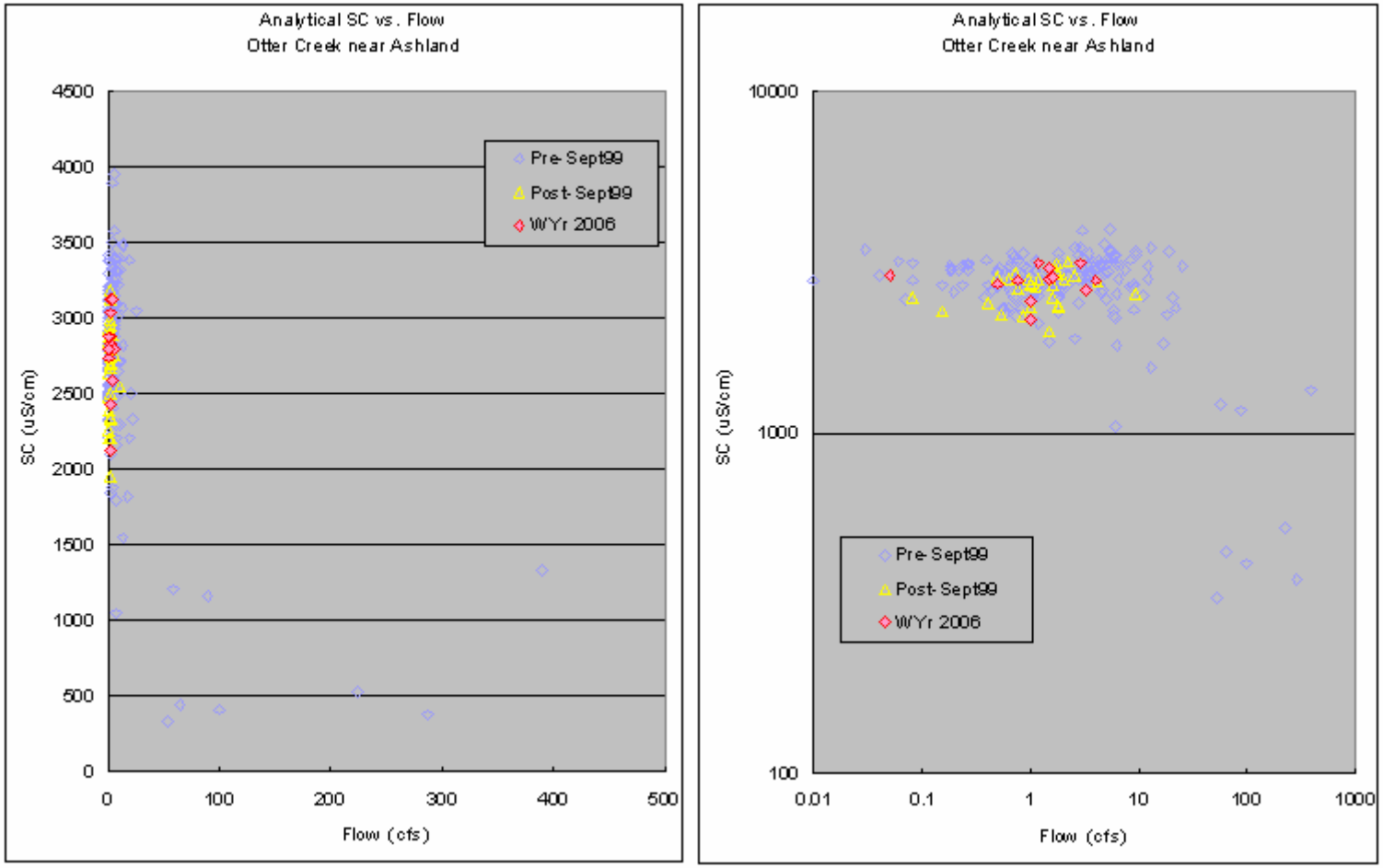
Figure 63: Otter Creek at Ashland, MT



A **B**

Figure 63 shows analytical and daily mean SC (A) and analytical and daily mean estimated SAR (B) values in time series plots for water year 2006 for Otter Creek at Ashland, MT. Monthly mean SC and SAR values are also shown. SC values ranged from 1890 to 3130 uS/cm. SAR values ranged from 4.8 to 6.9. These values are compared to the instantaneous maximum and monthly mean standards developed by the MDEQ. SC values were in excess of the EC standards for the entire year. Recorded SAR values were above the SAR standards for most of the year.

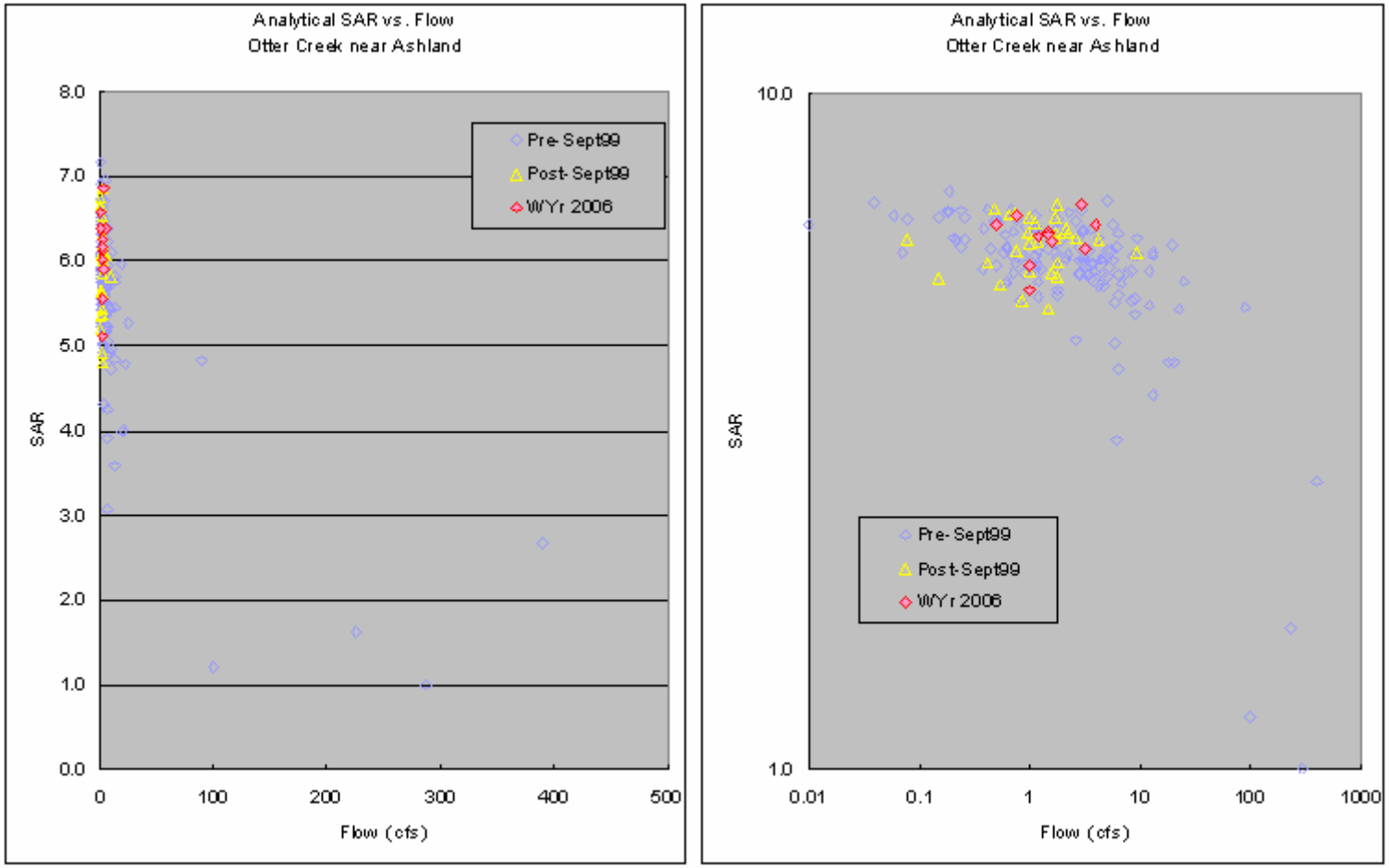
Figure 64: Otter Creek at Ashland, MT



A **B**

Figure 64 shows analytical SC vs. Flow data for water year 2006 for Otter Creek at Ashland, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 65: Otter Creek at Ashland, MT



A **B**

Figure 65 shows analytical SAR vs. Flow data for water year 2006 for Otter Creek at Ashland, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 66: Otter Creek at Ashland, MT

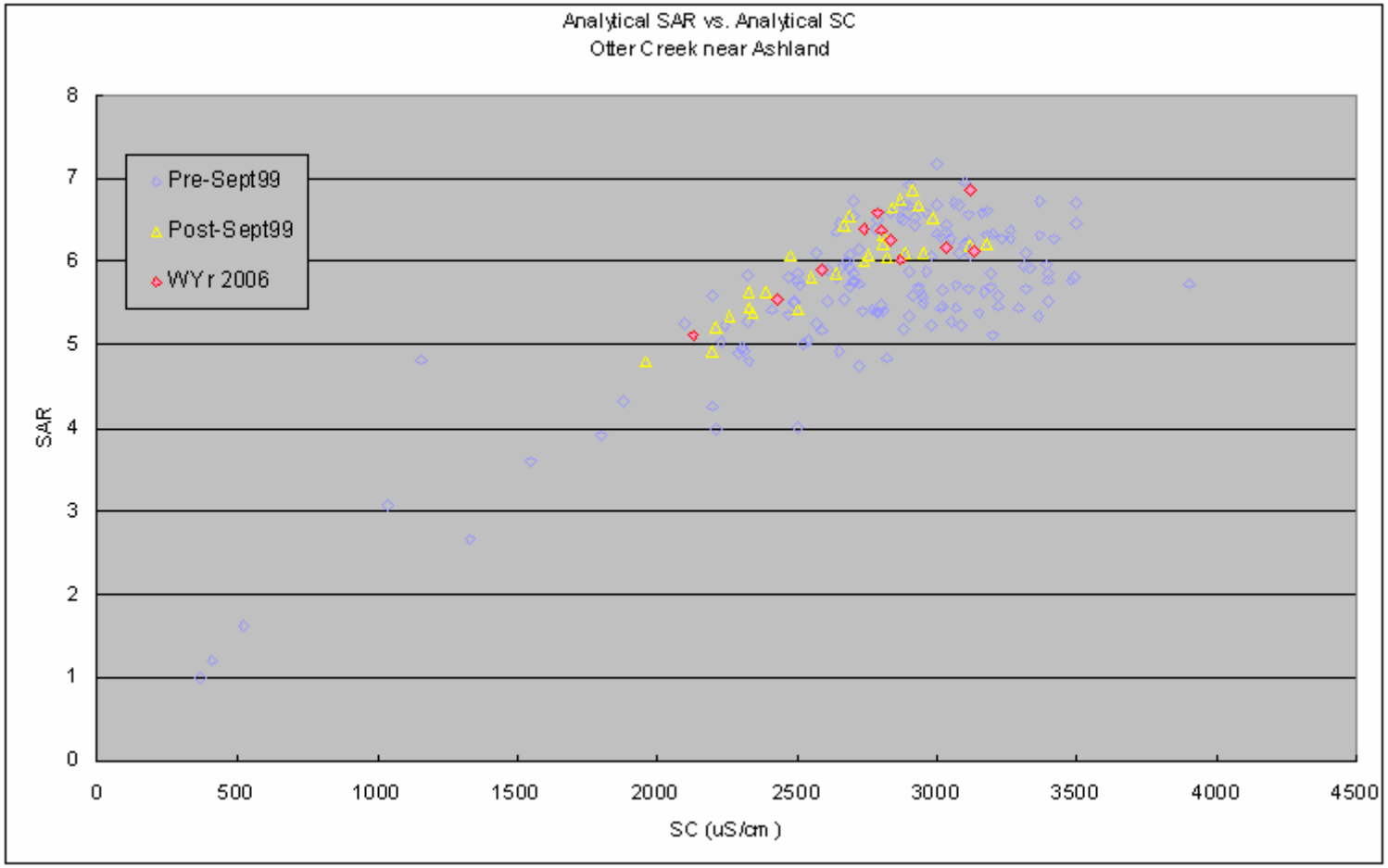


Figure 66 shows analytical SAR vs. analytical SC data for water year 2006 for Otter Creek near Ashland, MT. Historical SAR vs. SC data are also shown to place the data in context.

Figure 67: Pumpkin Creek near Miles City, MT

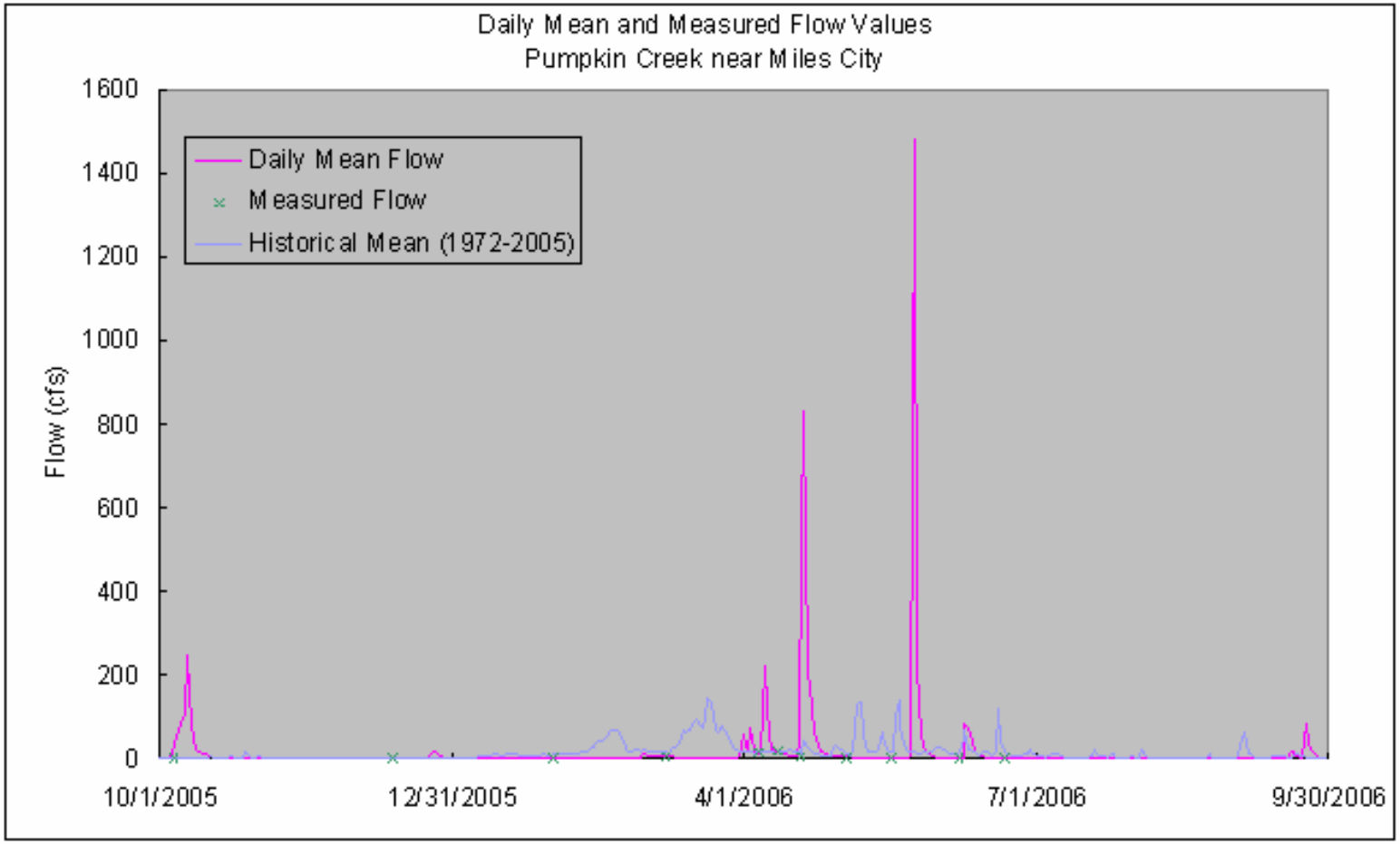
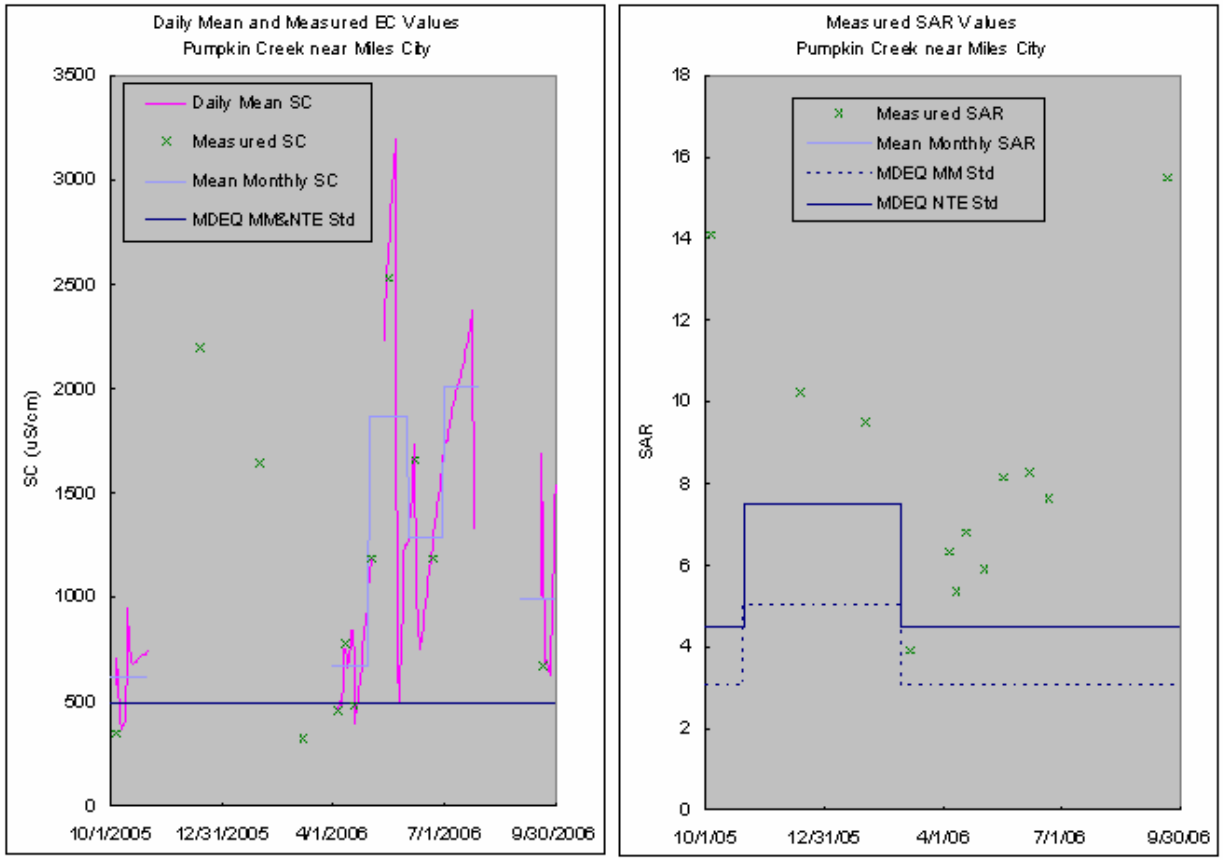


Figure 67 shows daily mean and field measurements of flow in a time series plot for water year 2006 for Pumpkin Creek near Miles City, MT. The historical average daily mean flow values are also shown. Daily mean flow values during 2006 ranged from 0 to 1480 cfs. Flows during 2006 were roughly comparable to average; however this is a highly variable system.

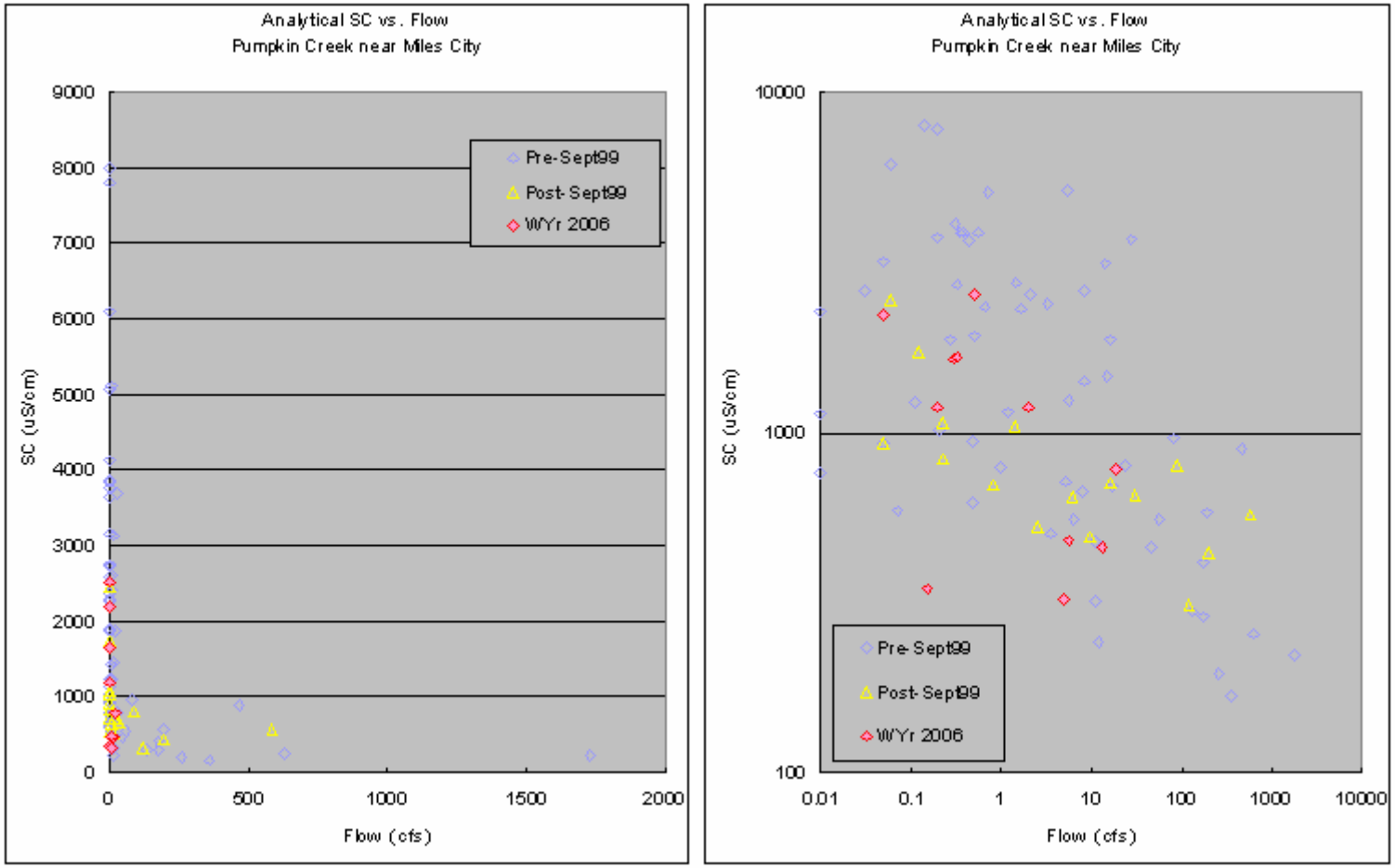
Figure 68: Pumpkin Creek near Miles City, MT



A **B**

Figure 68 shows analytical and daily mean SC (A) and analytical SAR (B) values in time series plots for water year 2006 for Pumpkin Creek near Miles City, MT. Monthly mean SC values are also shown. SC values ranged from 321 to 3190 uS/cm. SAR values ranged from 3.9 to 15.5. These values are compared to the instantaneous maximum and monthly mean standards developed by the MDEQ. SC values were above the EC standard for most of the year. SAR values were above the SAR standard for most of the year.

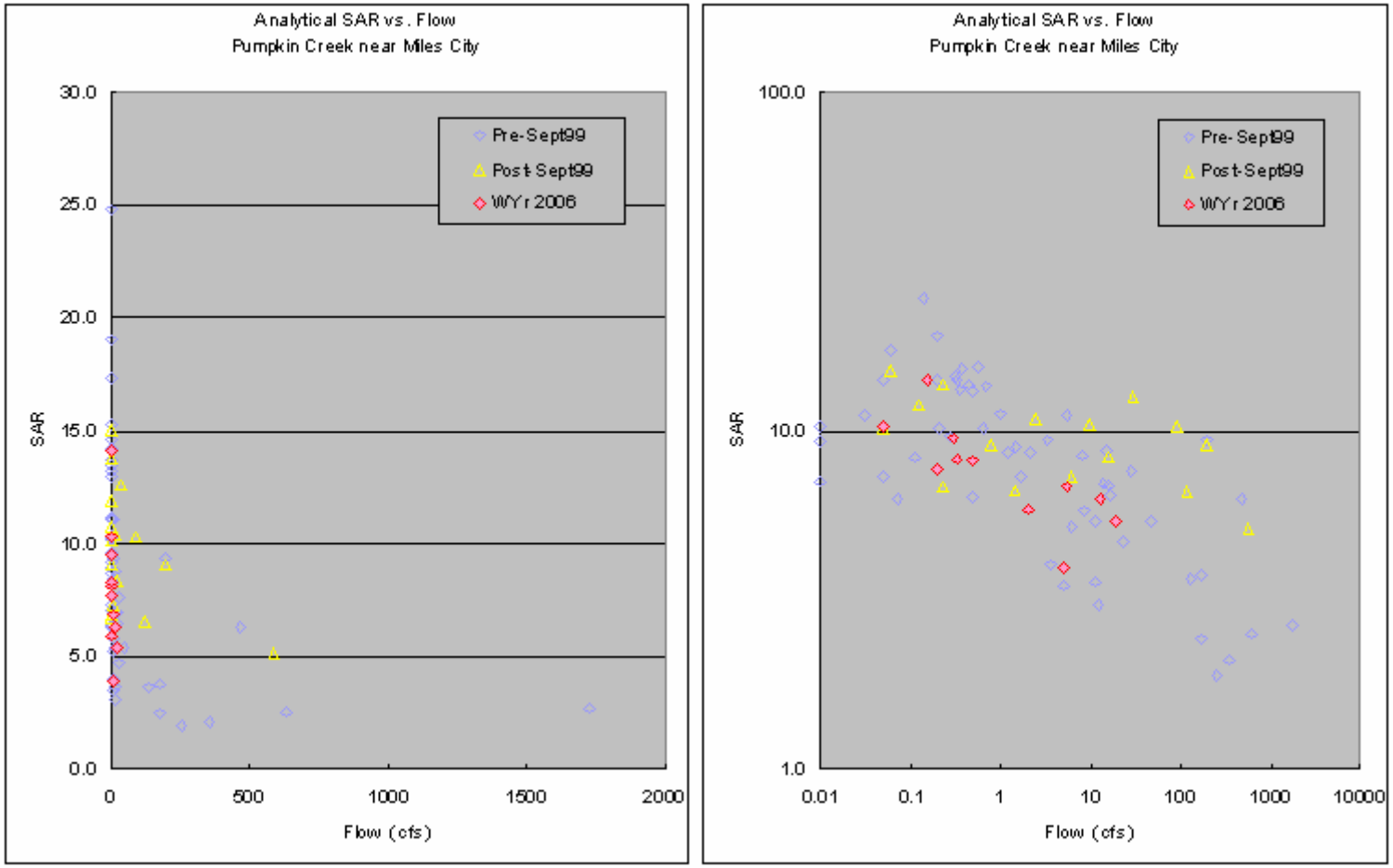
Figure 69: Pumpkin Creek near Miles City, MT



A **B**

Figure 69 shows analytical SC vs. Flow data for water year 2006 for Pumpkin Creek near Miles City, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SC vs. Flow data are also shown to place the data in context.

Figure 70: Pumpkin Creek near Miles City, MT



A **B**

Figure 70 shows analytical SAR vs. Flow data for water year 2006 for Pumpkin Creek near Miles City, MT. These data are charted on both linear (A) and logarithmic (B) scales. Historical SAR vs. Flow data are also shown to place the data in context.

Figure 71: Pumpkin Creek near Miles City, MT

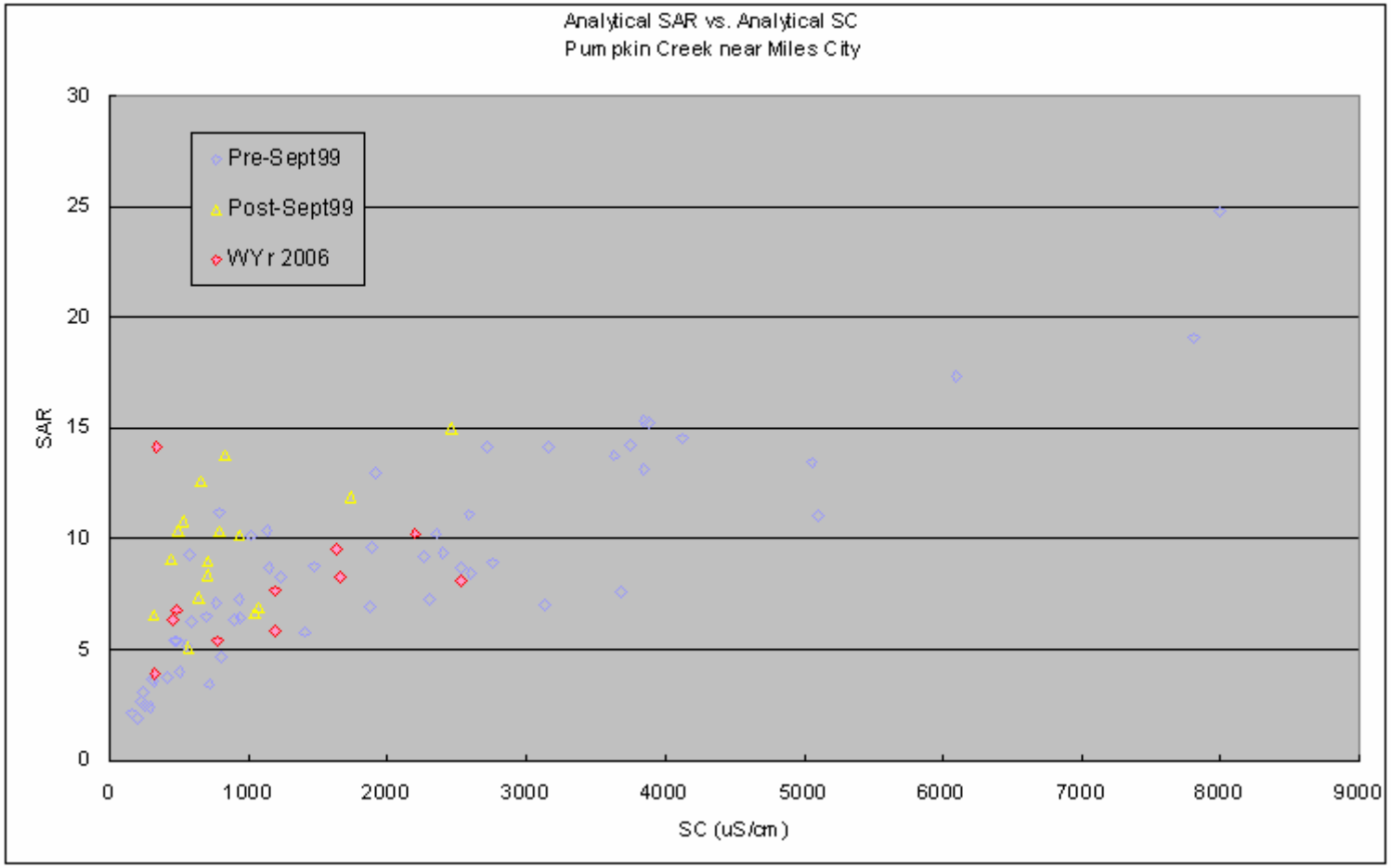


Figure 71 shows analytical SAR vs. analytical SC data for water year 2006 for Pumpkin Creek near Miles City. Historical SAR vs. EC data are also shown to place the data in context.

Appendix A

Trend Analysis
Water Years 1986-1999 vs. 2000-2006
Tongue River at State Line

The Sodium Adsorption Ratio (SAR) vs. Specific Conductance (SC) graphs in the figures section of this report indicate that there may be an increase in the relative proportion of sodium within the Tongue River since 1999. In particular the SAR appears to be increased relative to SC. If this change were due to CBNG influences it would be expected that the USGS's Tongue River at the State Line station (06306300) should be showing the greatest impacts, since most untreated discharges are occurring upstream of this station, and it does not have the benefit of the reservoir homogenizing water quality. Therefore this analysis looks at the data from the Tongue River at the State Line Station. It should be noted that this area has been in an extended drought over the 2000-2006 period (See figure A1).

SAR is a complex ratio of sodium (Na) to calcium (Ca) plus magnesium (Mg) and is defined as:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

where all constituents are in milliequivalants per liter (meq/L). SC is the ease with which a current will pass through a water sample at 25°C, and it is proportional to salinity. SC is typically expressed as microSiemens per centimeter (μS/cm). Since SAR is a ratio it is unitless.

The water in the Tongue River is the result of the mixing of groundwater inputs (including CBNG waters), overland flow, and irrigation return flows. The groundwater inputs have moderate SC values and are dominated by sodium cations. Overland flow inputs have variable SC values and are typically dominated by Ca and Mg cations. Irrigation return flow typically have higher SC values and are dominated by Ca and Mg cations. The relatively high Ca and Mg values observed in overland flow and irrigation return flows are a result of the dissolution of Ca-Mg sulfates, which are the dominate soluble salt in the shallow subsurface (Wheaton and Brown, 2005). The result of this system is that concentrations of dissolved constituents vary with flow due to changes in the relative proportion of inflows (i.e. groundwater inputs are relatively constant while overland flow varies greatly with snow melt and precipitation events) (See Figs A2-A4).

Although simple evaluation of constituents vs. time can be conducted (See Figs A5-A6) this is of limited value since it is known that all of these constituents vary with flow. Since this region has been in an extended drought it is expected that the absolute values will be higher than historical averages. More useful comparisons can be developed by using the flow corrected values. The values can be flow corrected by dividing the constituent by its flow dependent power curve. This will minimize the flow effects, and allow for comparison of the resulting values. For example, Figure A2 shows that through Water Year 1999:

$$SC = 6261.8Q^{-0.4296}$$

Where Q represents flow in cubic feet per second and SC is in μS/cm. This can be rearranged by dividing both sides by the power function, resulting in:

$$\frac{SC}{6261.8Q^{-0.4296}} = 1$$

Thus when all SC values are divided by the power function using the applicable flow, the result will be equal to 1 if it falls precisely on the best fit line. Values greater than 1 indicate that the SC for that sample is higher than would be predicted by the best fit line, while values lower than 1 indicate that it is lower.

Using this technique the values become comparable, and thus the values can be charted vs. time to give an indication of if changes in the system are occurring (See Figs A7-A12).

Flow correction can also allow statistical analysis to be used. A parametric analysis can be used if there is a normal distribution of the data. The flow corrected data for SC, SAR, Na, Ca, Mg, and SO_4 all approximate normal distributions, with frequency diagrams approximating Gaussian distributions, and Quantile Plots showing linier relationships (r^2 values ranging from 0.93 to 0.99) (See Figs A13-A18).

The "true" mean value can be particularly useful, since it gives an indication of if the overall system is changing. While the true mean can never be determined through measurements, we can determine with a set degree of certainty a range that it will be in. For this analysis a 90% confidence interval is used. This range is determined using a Student's t analysis (Harris, 1995). Following this method:

$$\mu = x \pm \frac{t\sigma}{\sqrt{n}}$$

Where: μ = true mean
x = observed mean
t = Student's t value (tabulated based on the degrees of freedom)
σ = observed standard deviation
n = number of observations

The Student's t analysis results in ranges in which we can be 90% confident that the true mean is within. These ranges are shown on Figures A11-A16.

This analysis shows that when flow corrected values from October 1985 to September 1999 (Water Years 1986-1999) are compared to data collected from October 1999 to September 2006 (Water Years 2000-2006) the following results:

- SC decreases (the true mean range is lower and there is no overlap in the ranges)
- SAR increases (the true mean range is higher and there is no overlap in the ranges)
- Na is unchanged (there is significant overlap in the true mean ranges)
- Ca decreases (the true mean range is lower and there is no overlap in the ranges)
- Mg decreases(the true mean range is lower and there is no overlap in the ranges)
- SO_4 decreases (the true mean range is lower and there is no overlap in the ranges)

These results have also been examined in a simple trend analysis. The 90% true mean range from the 1986-1999 data is treated as base line. Values collected from water year 2000-2006 are assigned a +1 value if they are above this range and a -1 value if they are below this range. The results are then summed, and the net value must be greater than 0.25n (25% of the total) for a trend to be assigned. The results of this analysis are shown on Table A1 below.

Table A1: Tongue River at the State Line; Flow Adjusted Values

	Water Years 1986-1999					Water Years 2000-2006					
				Range (90%)							
	Mean	σ	n_1	Lower Limit	Upper Limit	n_2	# Lower	# Higher	Net Score	Test ($\pm 0.25n_2$)	Trend
SC	1.03	0.24	115	0.99	1.06	111	94	8	-86	28	down
SAR	1.02	0.18	25	0.96	1.08	99	19	64	45	25	up
Ca	0.99	0.14	25	0.94	1.03	99	70	14	-56	25	down
Mg	1.01	0.21	25	0.94	1.08	99	70	11	-59	25	down
Na	1.00	0.24	25	0.92	1.09	99	30	37	7	25	NA
SO_4	1.04	0.24	25	0.96	1.13	99	76	8	-68	25	down

A Trend is defined as:
up: Score>$0.25n_2$
down: Score<$-0.25n_2$
Not Apparent (NA): $-0.25n_2$<Score<$0.25n_2$

These two approaches both indicate that flow corrected SC is decreased and flow corrected SAR is increased due to the decrease Ca and Mg (since SAR is a ratio). As expected, SO_4 decreases similar to Ca and Mg.

The decrease in flow corrected Ca and Mg values is likely attributable to the extended drought, which results in less overland flow, and from changes in irrigation practices, where center pivots and side rolls are being used more extensively, resulting in less irrigation return flows.

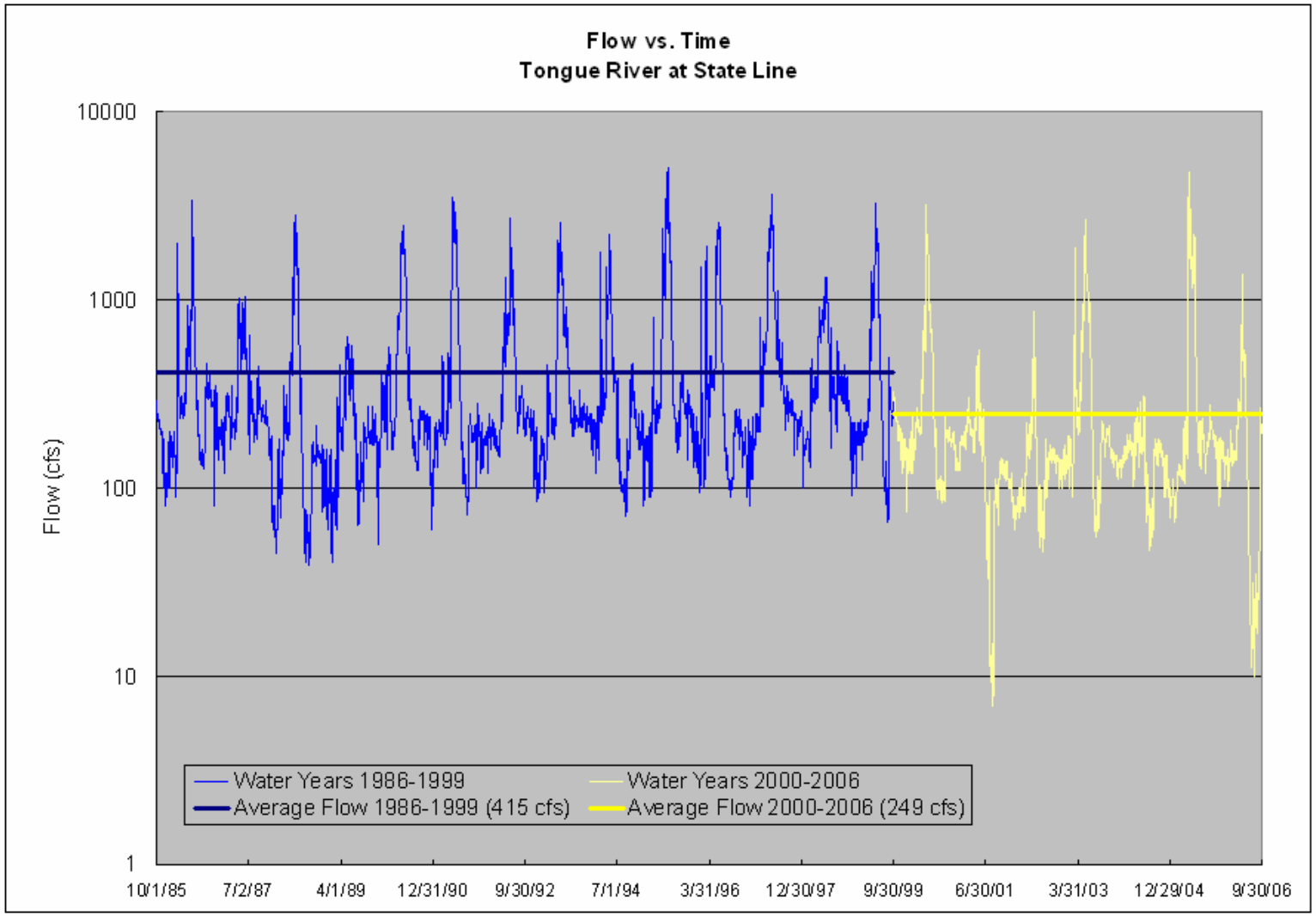


Figure A1: Flow vs. Time. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The flows are less from 2000-2006 due to the extended drought. Average flows are 415 cfs from 1986-1999 and 249 cfs from 2000-2006.

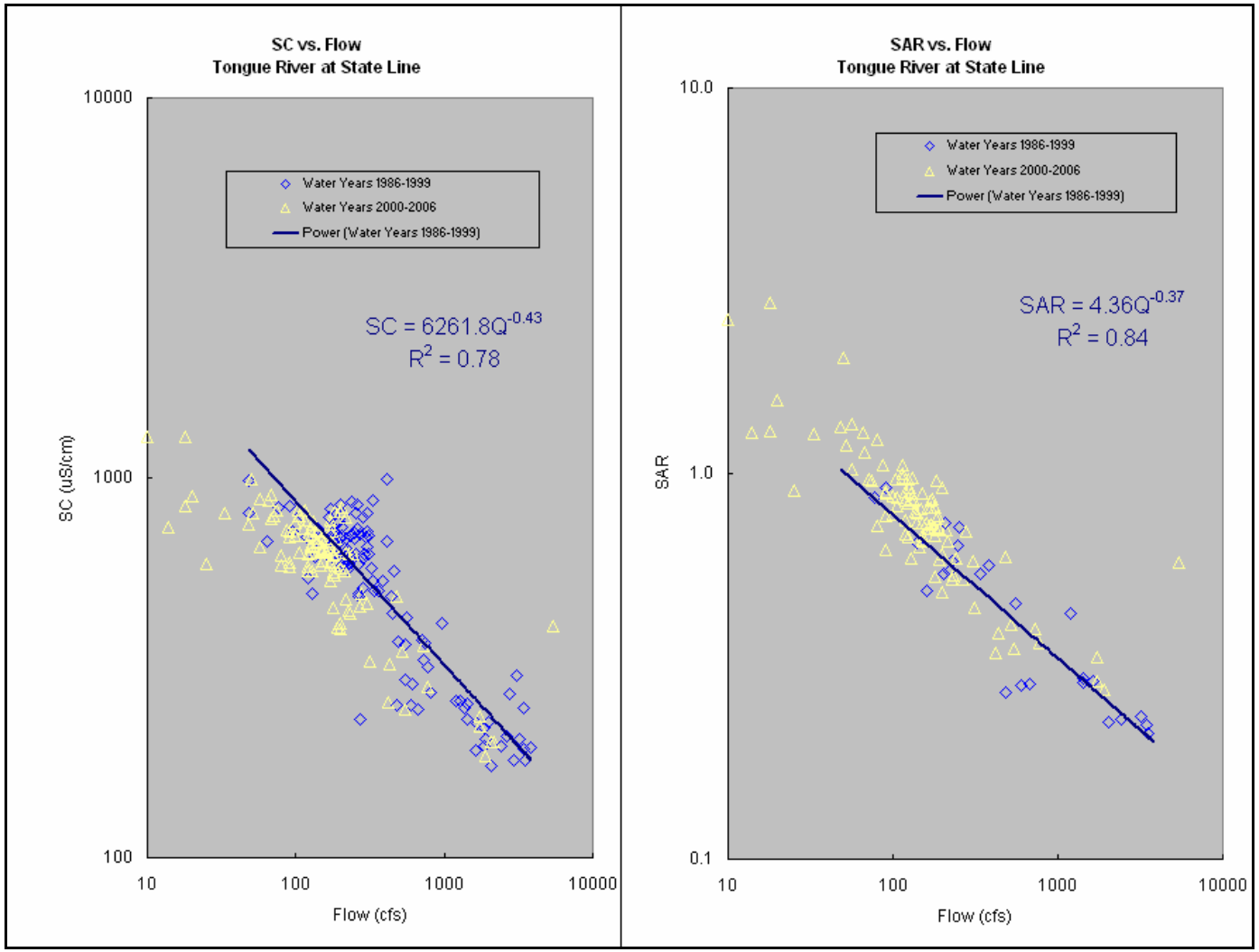


Figure A2: SC vs. Flow and SAR vs. Flow. SC and SAR decrease with increased flow. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The SC values recorded from 2000-2006 fall somewhat below the 1986-1999 values. The SAR values recorded from 2000-2006 fall somewhat above the 1986-1999 values.

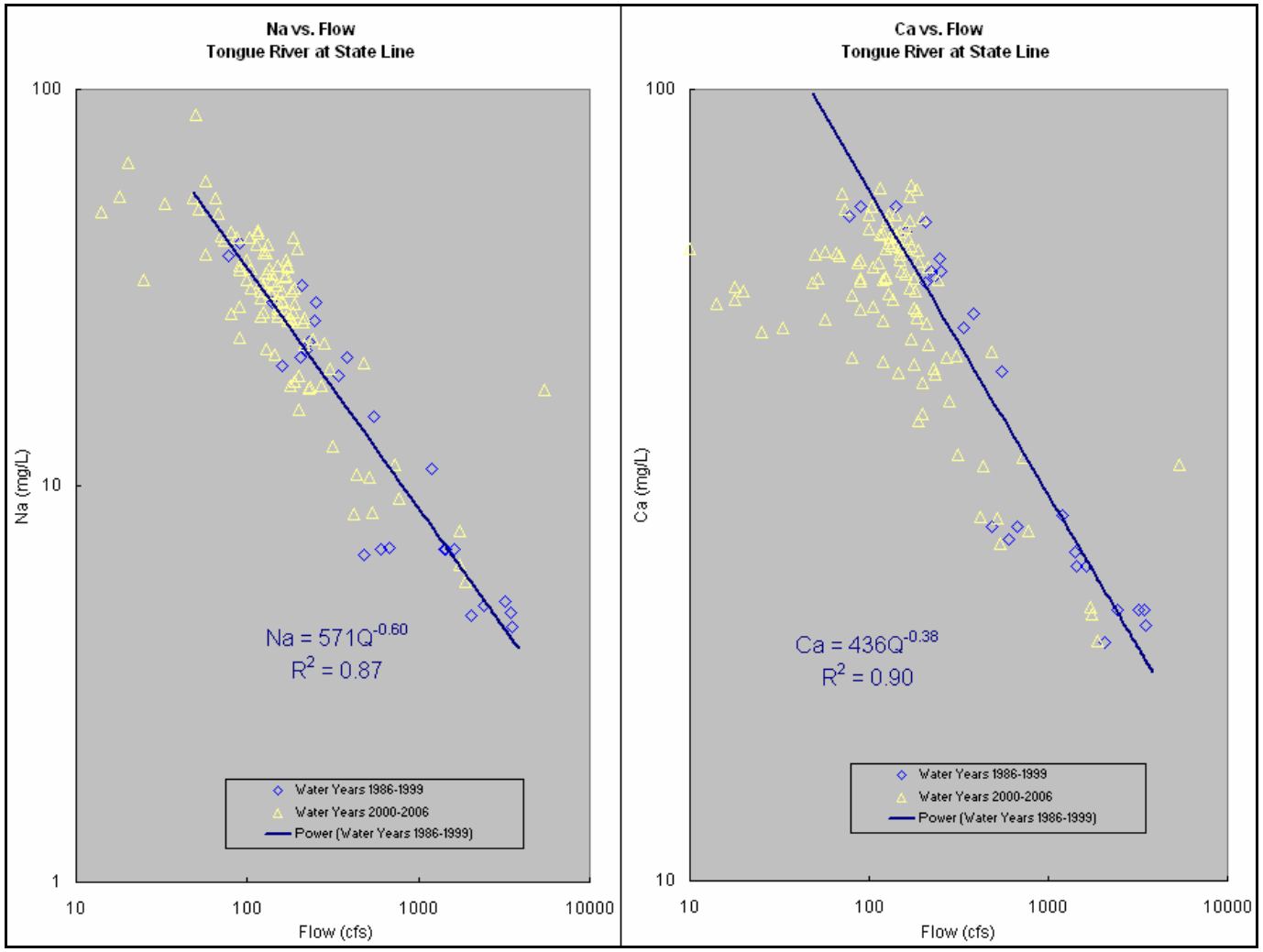


Figure A3: Na vs. Flow and Ca vs. Flow. Na and Ca decrease with increased flow. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The Na values recorded from 2000-2006 fall in line with the 1986-1999 values. The Ca values recorded from 2000-2006 fall somewhat below the 1986-1999 values.

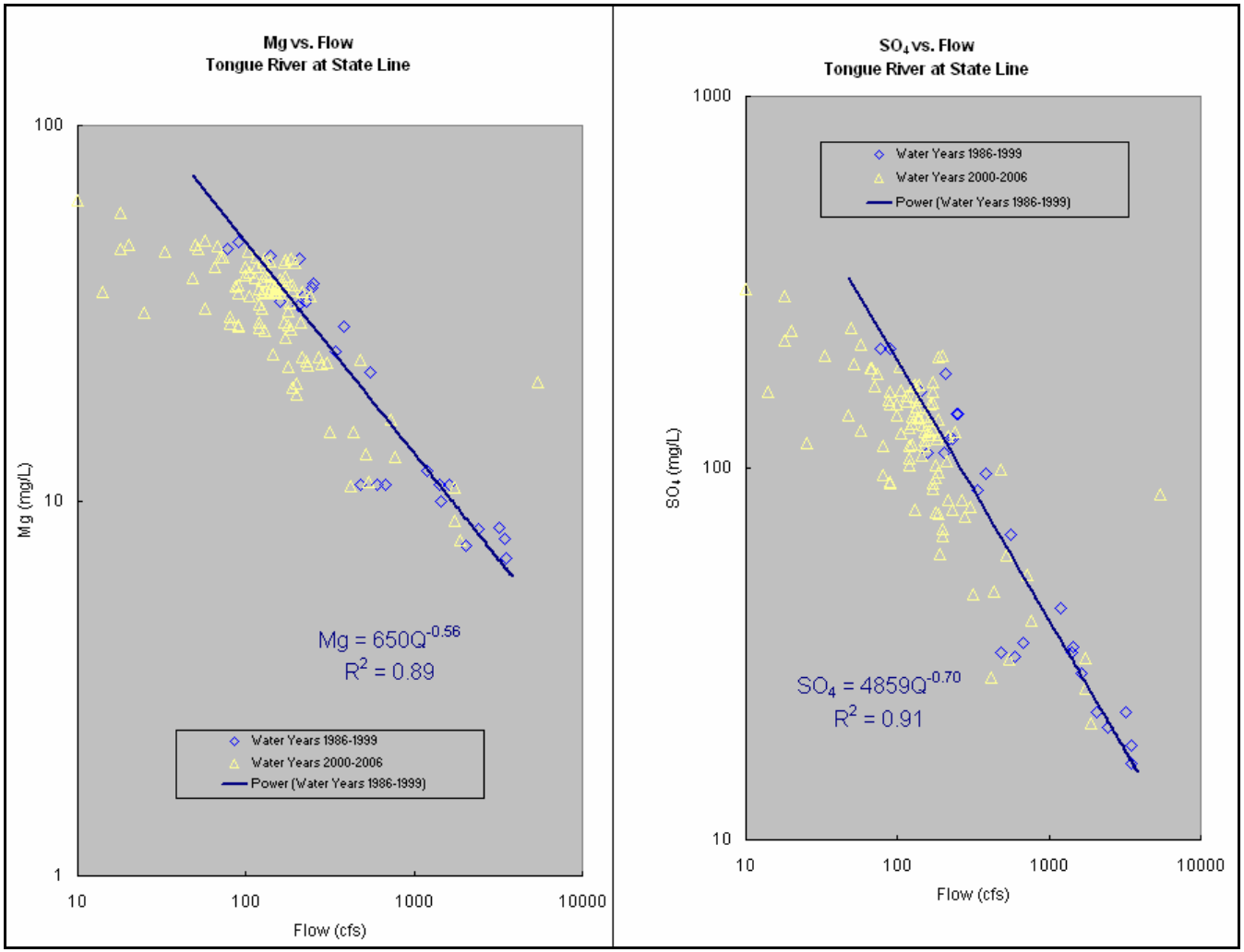


Figure A4: Mg vs. Flow and SO_4 vs. Flow. Mg and SO_4 decrease with increased flow. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The Mg values recorded from 2000-2006 fall somewhat below the 1986-1999 values. The SO_4 values recorded from 2000-2006 fall somewhat below the 1986-1999 values.

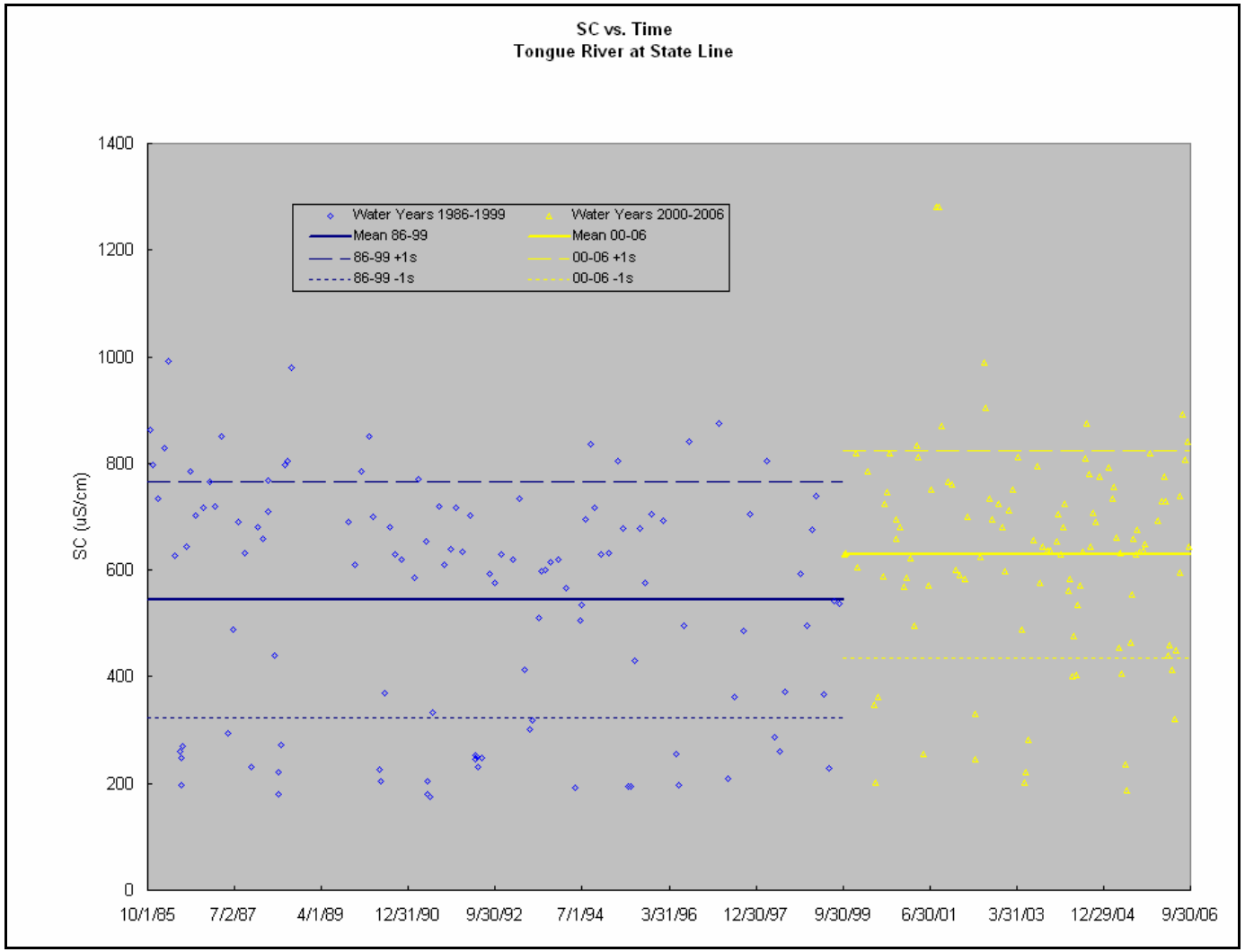


Figure A5: Absolute SC values vs. Time. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The absolute values recorded from 2000-2006 are somewhat greater; however this is not unexpected given the low flows. Mean and ± 1 standard deviation are shown.

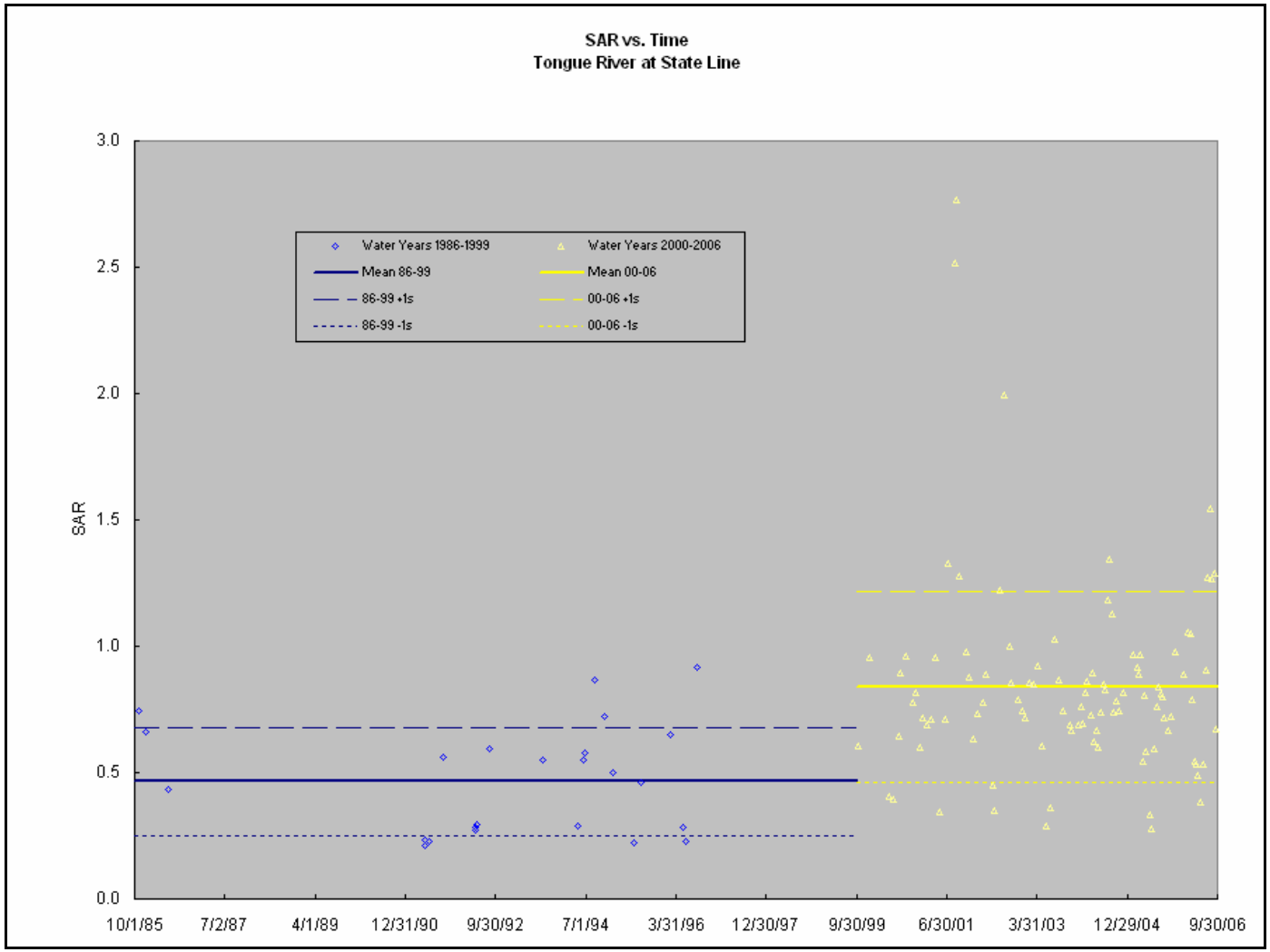


Figure A6: Absolute SAR values vs. Time. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The absolute values recorded from 2000-2006 are somewhat greater; however this is not unexpected given the low flows. Mean and ± 1 standard deviation are shown.

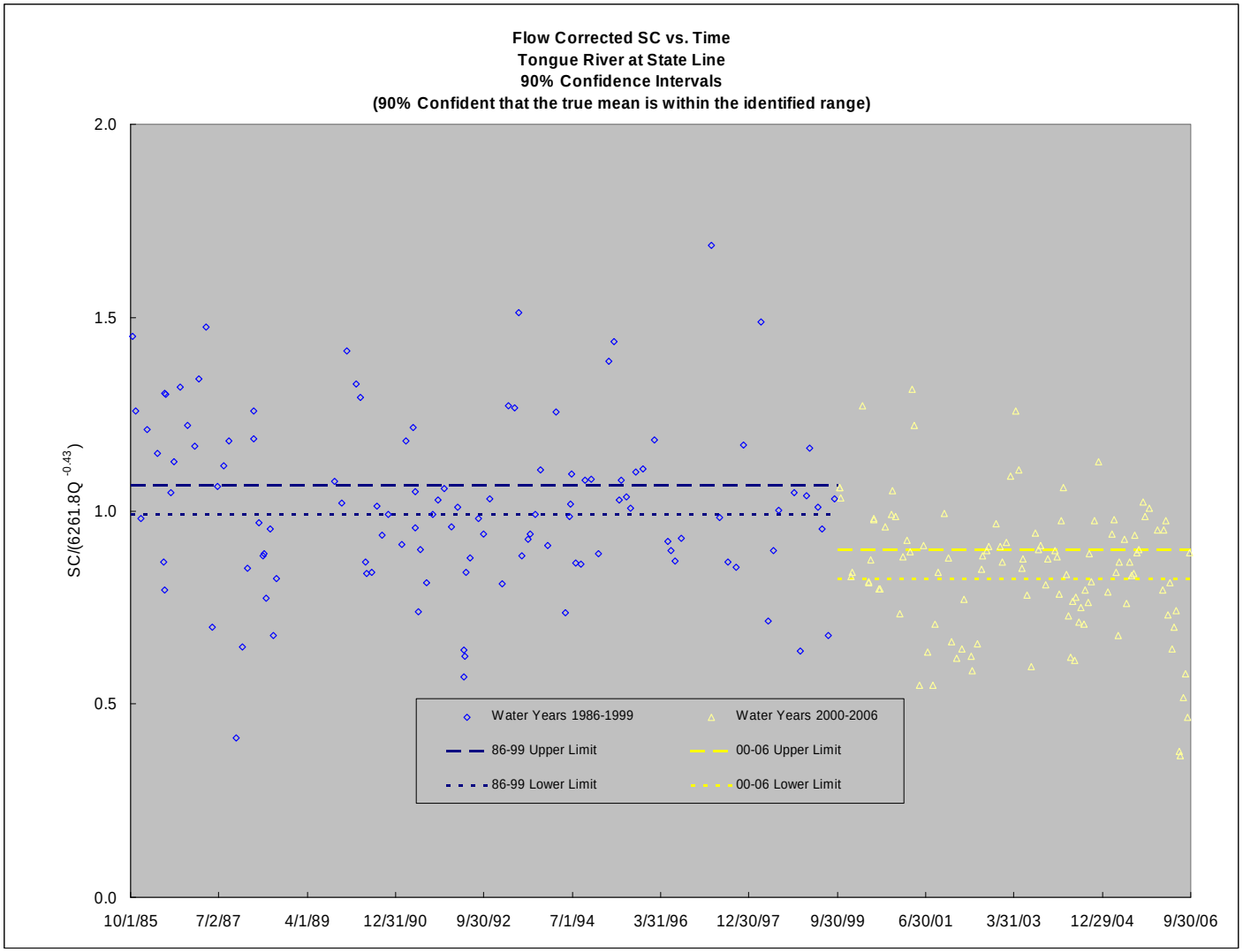


Figure A7: Flow corrected SC vs. Time. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The flow corrected values recorded from 2000-2006 are lower. The 90% confidence ranges for true means are also shown.

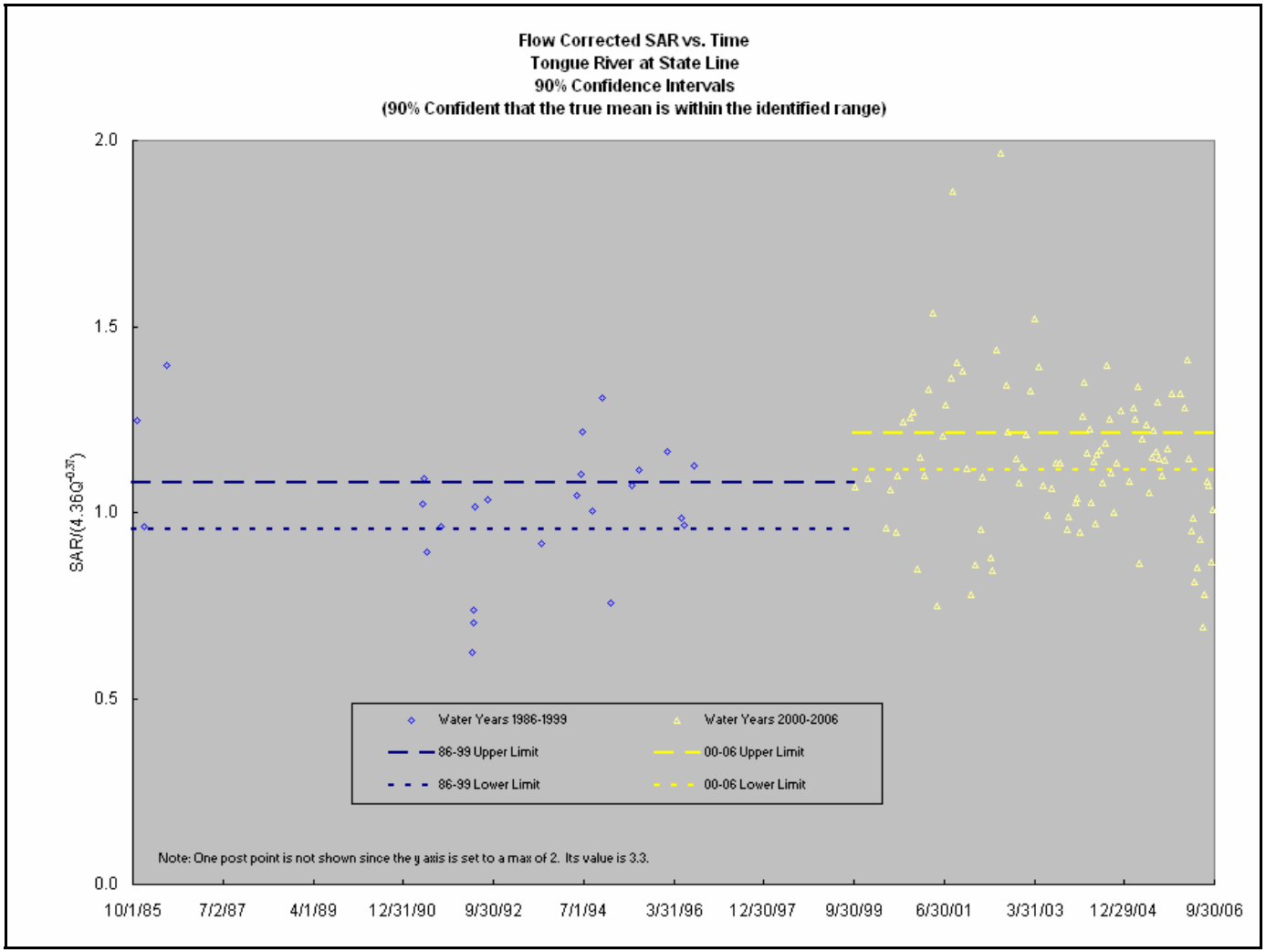


Figure A8: Flow corrected SAR vs. Time. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The flow corrected values recorded from 2000-2006 are higher. The 90% confidence ranges for true means are also shown.

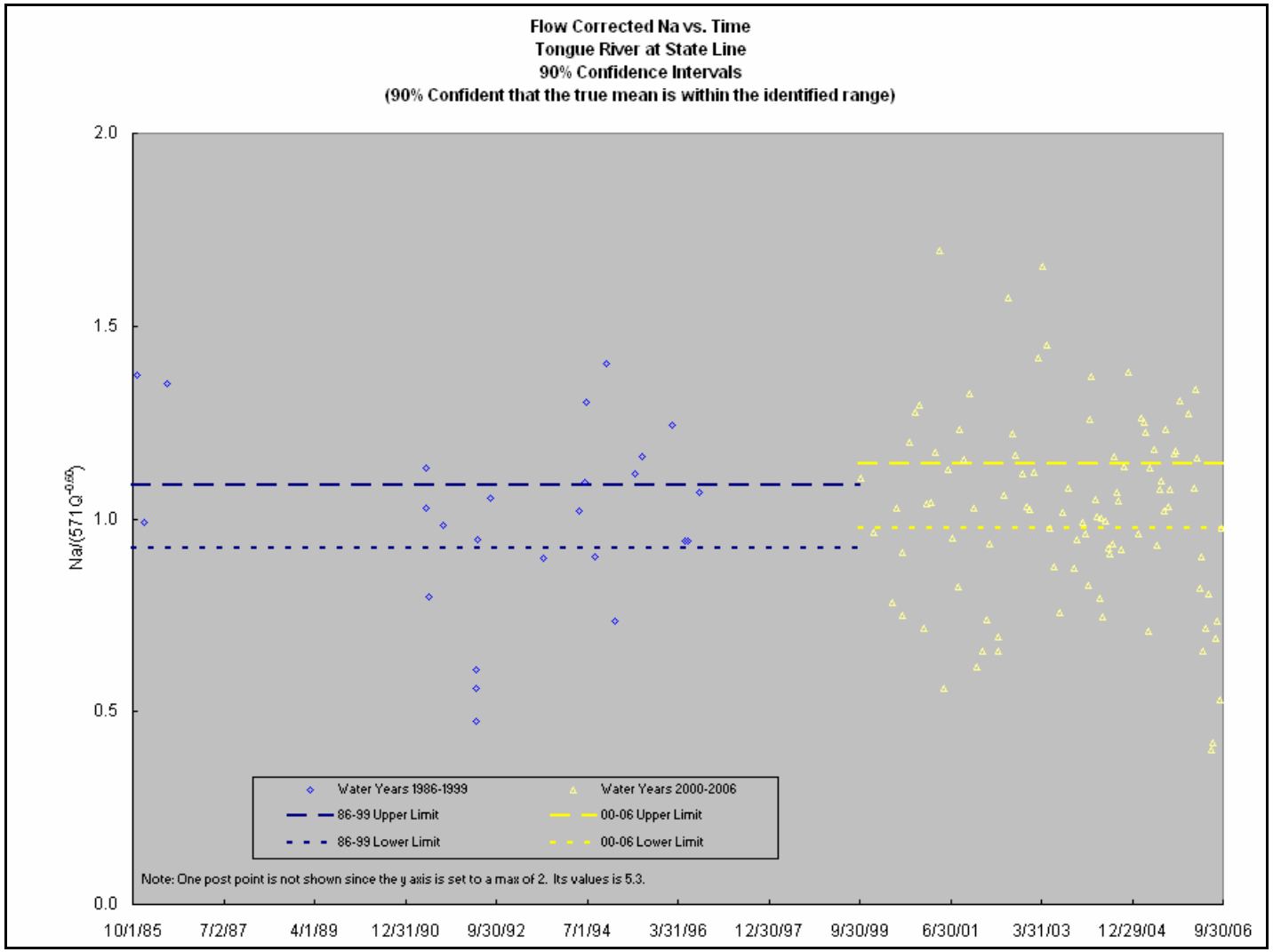


Figure A9: Flow corrected Na vs. Time. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The flow corrected values recorded from 2000-2006 not substantially different. The 90% confidence ranges for the true means are also shown.

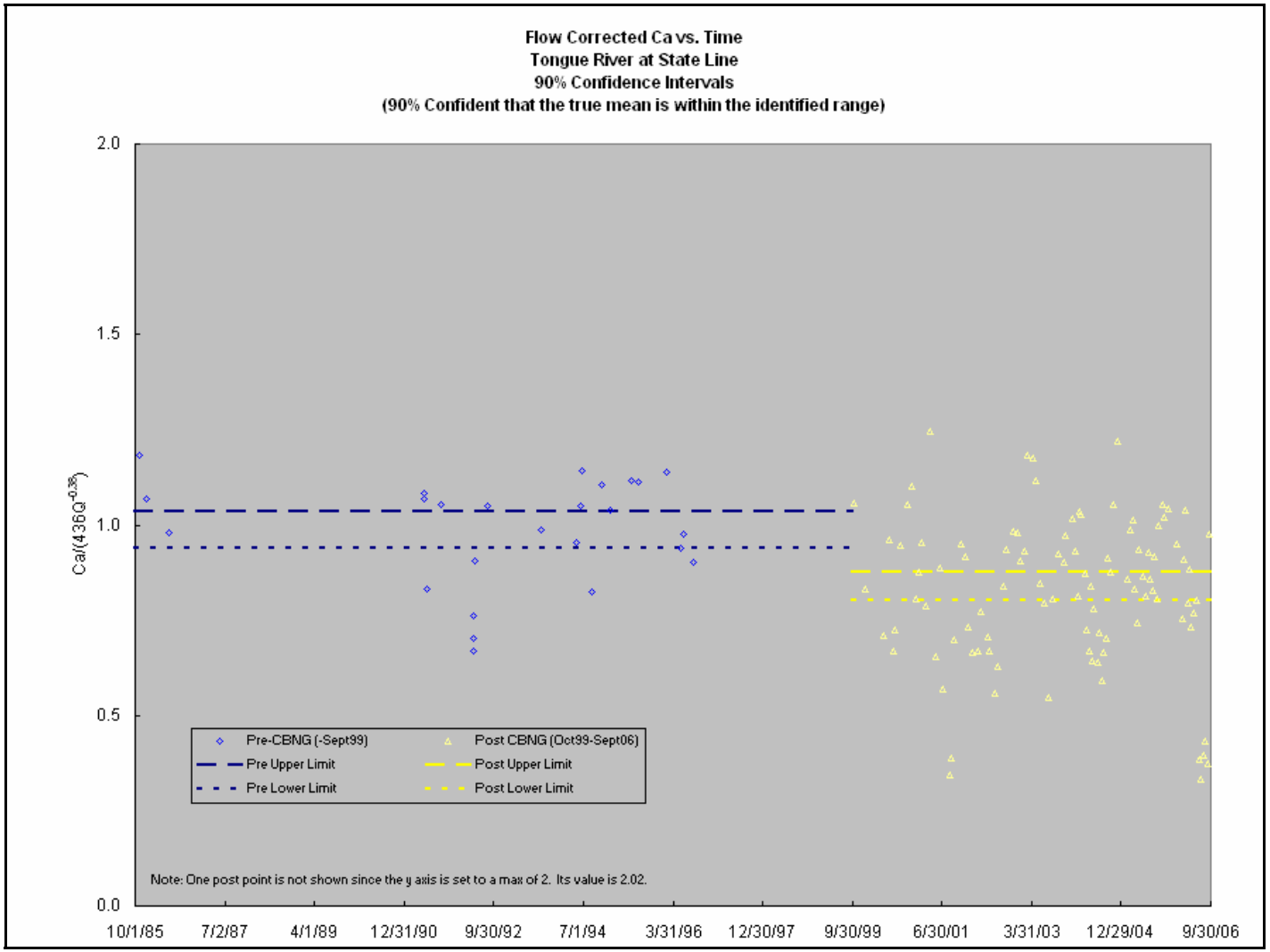


Figure A10: Flow corrected Ca vs. Time. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The flow corrected values recorded from 2000-2006 are lower. The 90% confidence ranges for the true means are also shown.

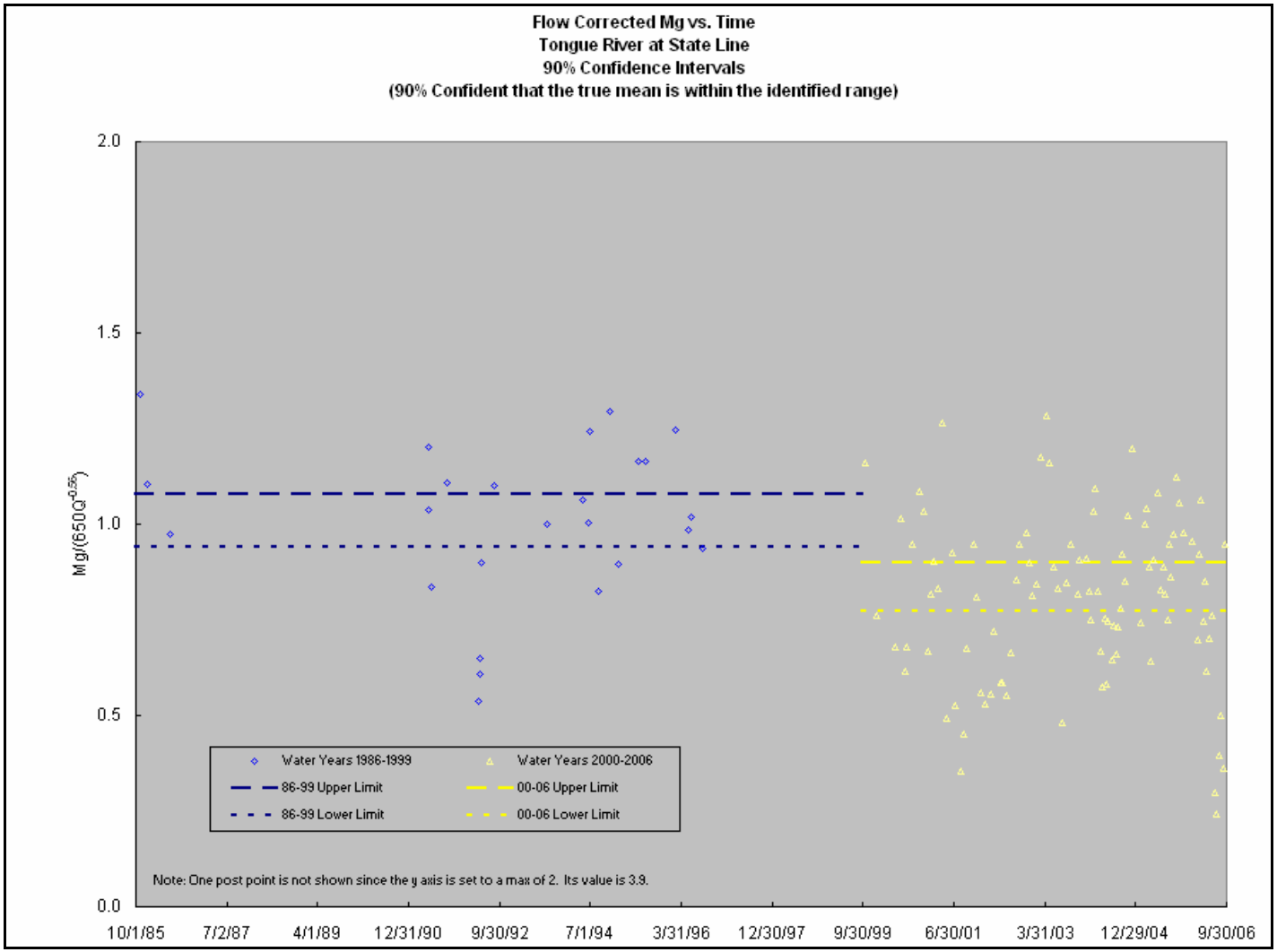


Figure A11: Flow corrected Mg vs. Time. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The flow corrected values recorded from 2000-2006 are lower. The 90% confidence ranges for the true means are also shown.

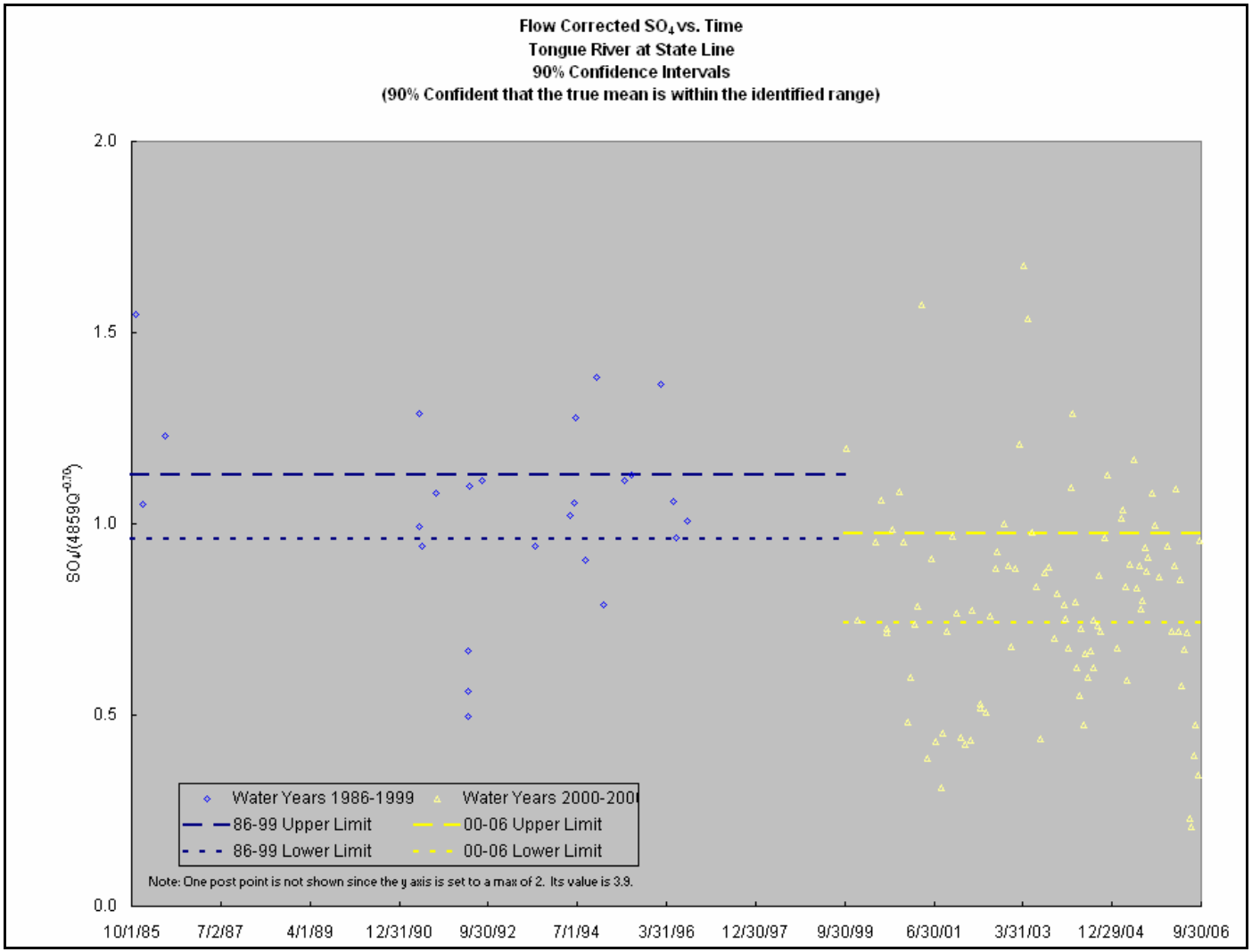


Figure A12: Flow corrected SO_4 vs. Time. A comparison is made between Water Years 1986-1999 and Water Years 2000-2006. The flow corrected values recorded from 2000-2006 are lower. The 90% confidence ranges for the true means are also shown.

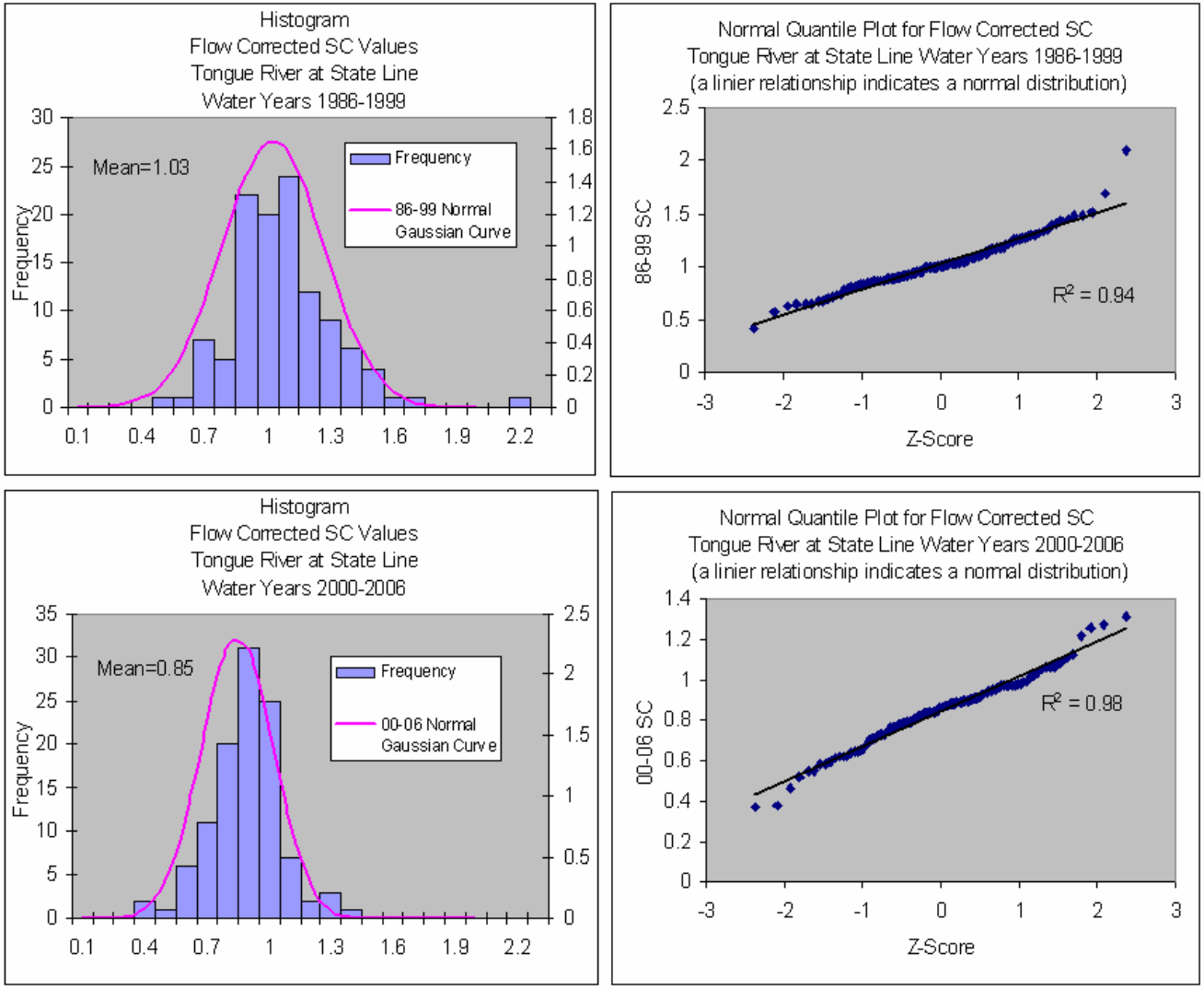


Figure A13: Evaluation of Normality for Flow Corrected SC Data. Assumption of normality appears to be valid since histograms approximate Gaussian curves, and Normal Quantile Plots approximate linearity.

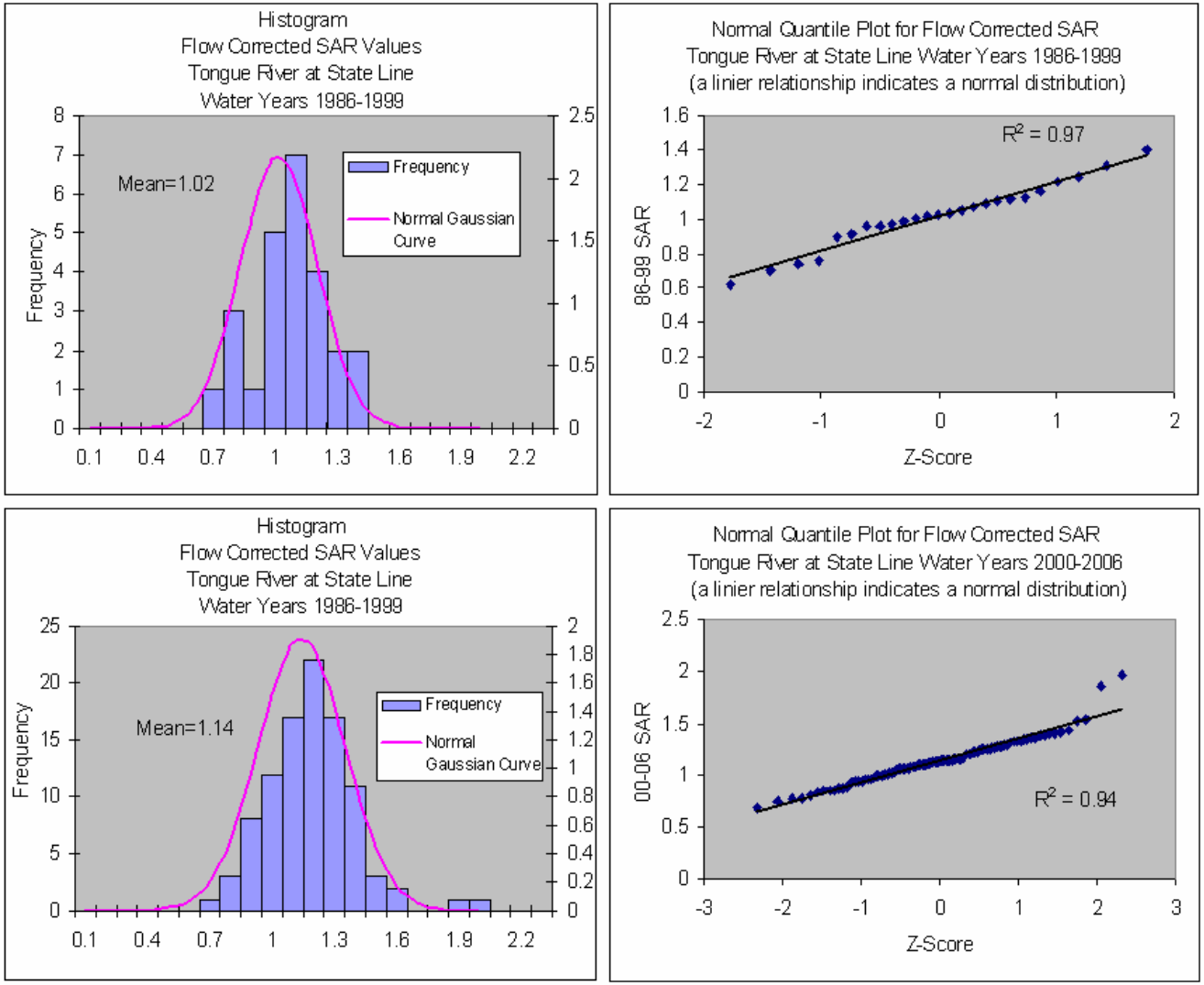


Figure A14: Evaluation of Normality for Flow Corrected SAR Data. Assumption of normality appears to be valid since histograms approximate Gaussian curves, and Normal Quantile Plots approximate linearity.

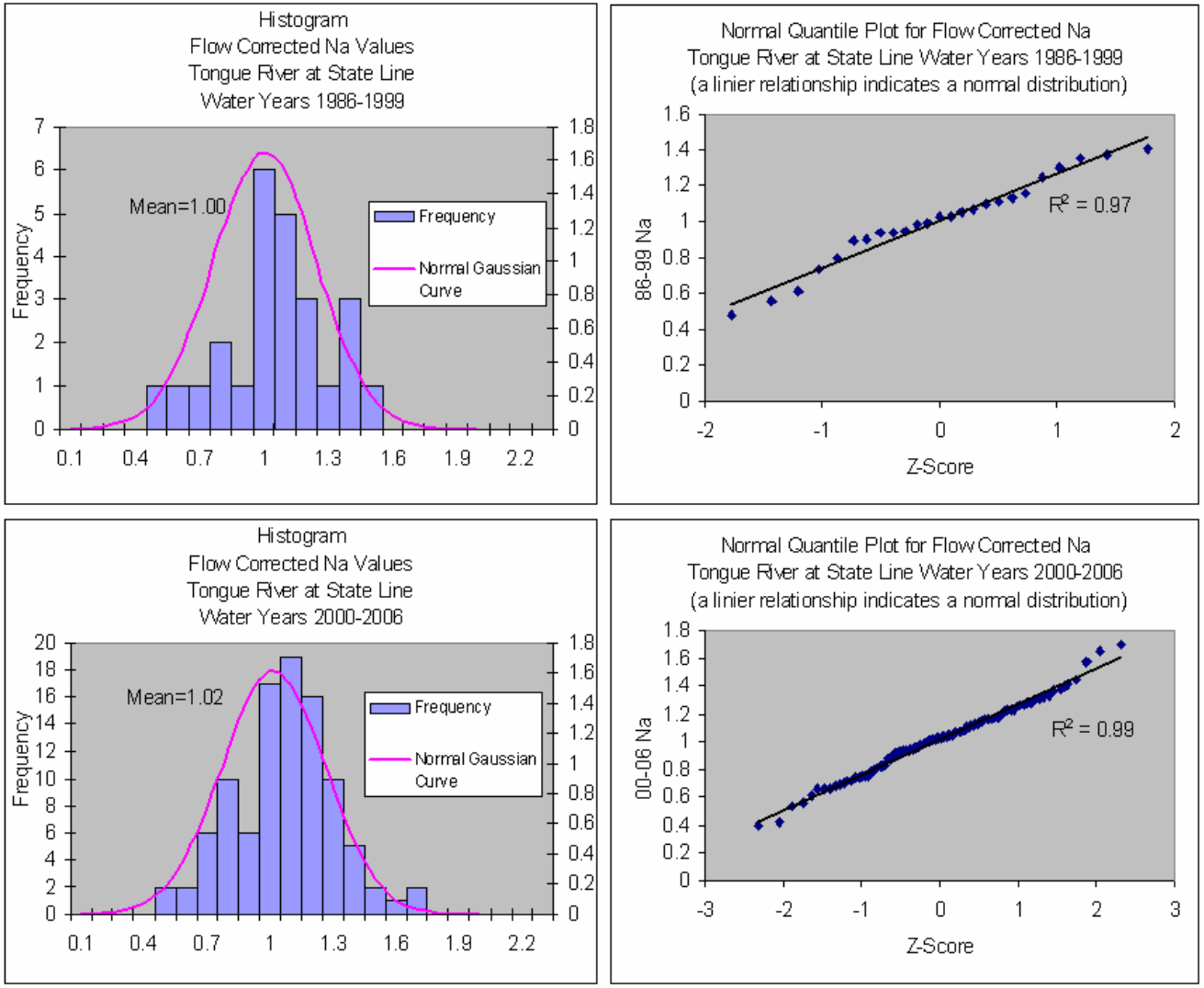


Figure A15: Evaluation of Normality for Flow Corrected Na Data. Assumption of normality appears to be valid since histograms approximate Gaussian curves, and Normal Quantile Plots approximate linearity.

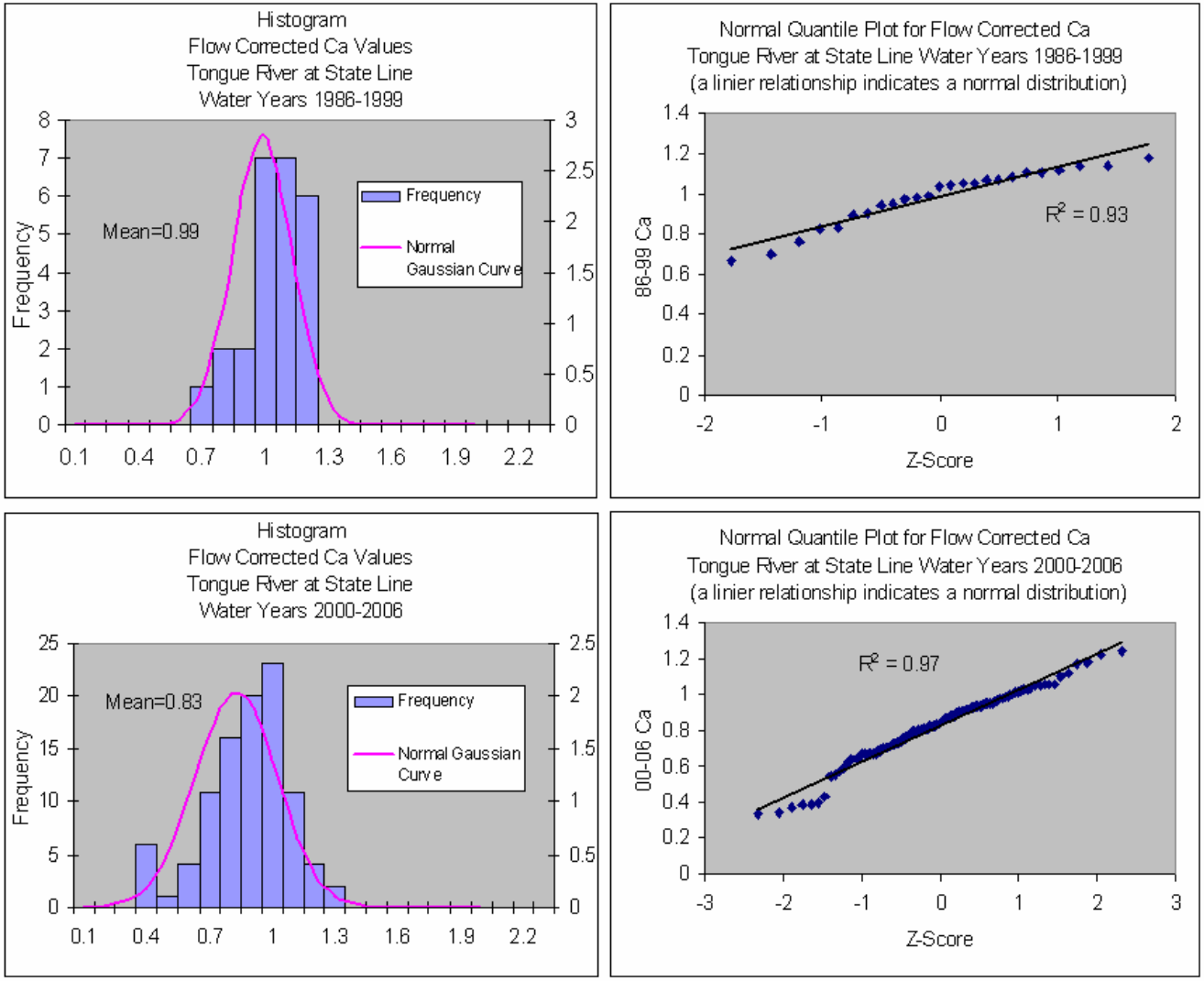


Figure A16: Evaluation of Normality for Flow Corrected Ca Data. Assumption of normality appears to be valid since histograms approximate Gaussian curves, and Normal Quantile Plots approximate linearity.

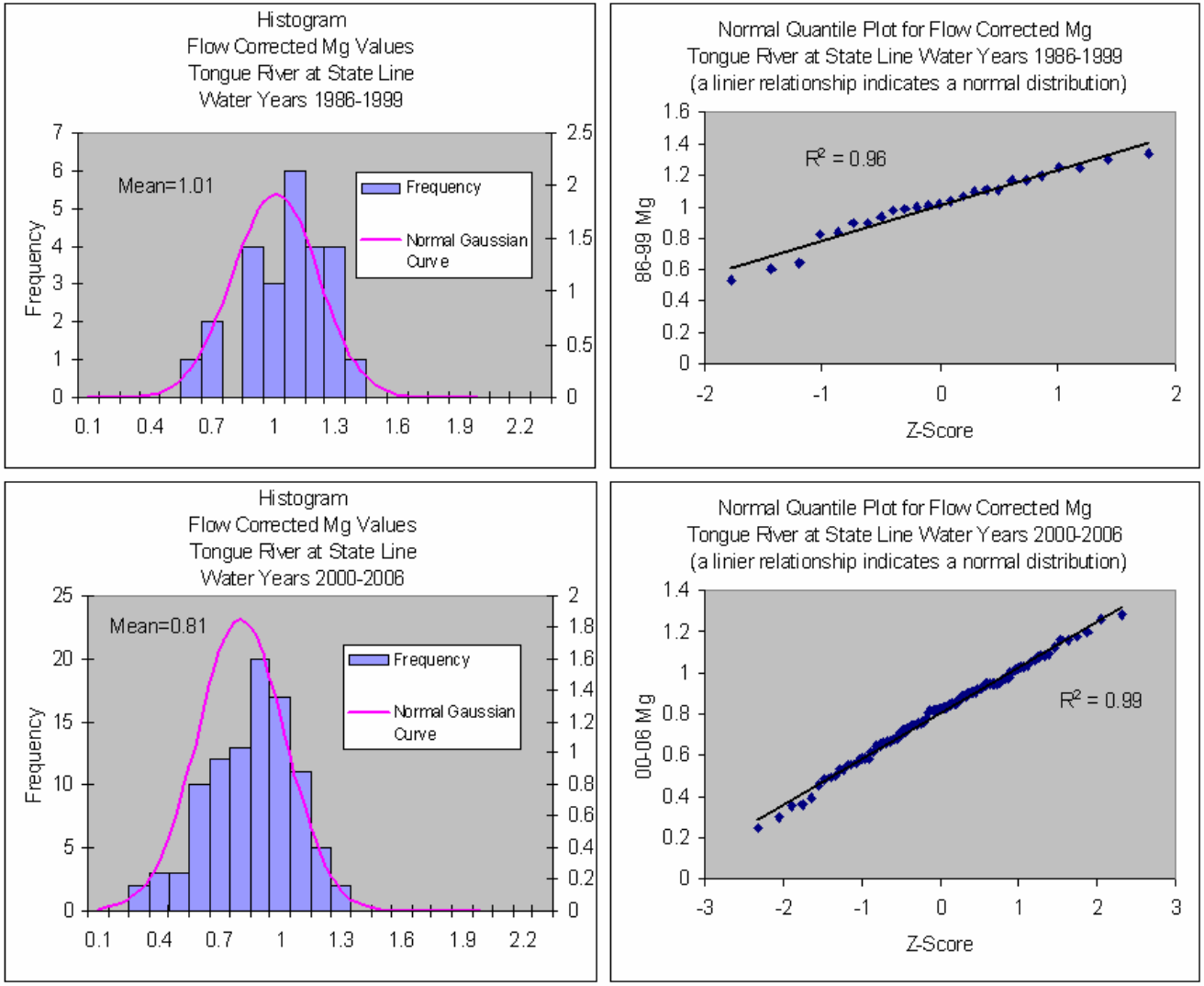


Figure A17: Evaluation of Normality for Flow Corrected Mg Data. Assumption of normality appears to be valid since histograms approximate Gaussian curves, and Normal Quantile Plots approximate linearity.

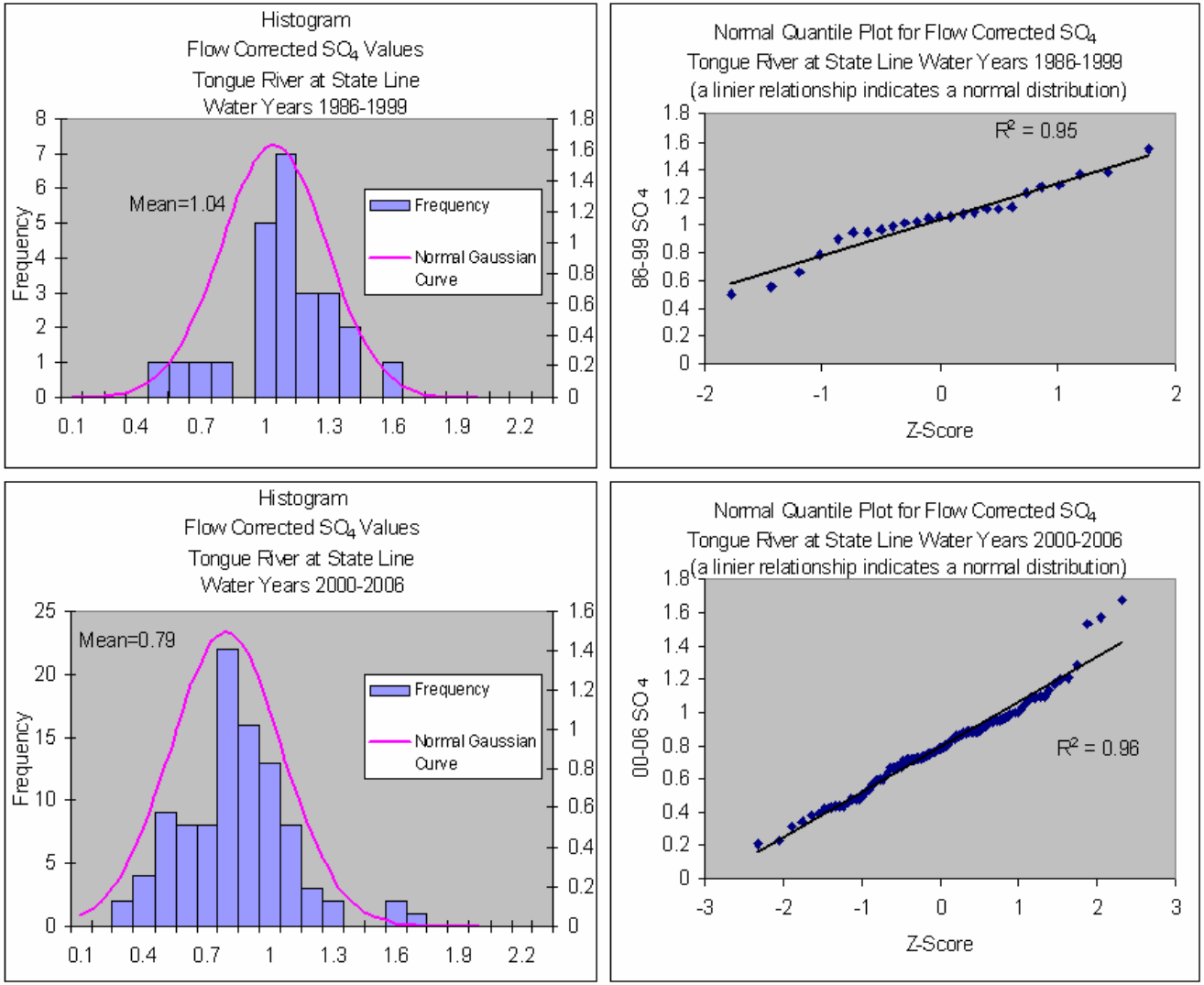


Figure A18: Evaluation of Normality for Flow Corrected SO_4 Data. Assumption of normality appears to be valid since histograms approximate Gaussian curves, and Normal Quantile Plots approximate linearity.