

SPATIAL AND TEMPORAL NUTRIENT LOADING DYNAMICS IN THE SPRAGUE RIVER BASIN, OR, WATER YEARS 2002 – 2020



Prepared for

Klamath Tribes Natural Resources Department

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EXECUTIVE SUMMARY

Restoration of the Sprague River basin is an essential element of the overall restoration and ecological health of the entire Klamath basin. The Sprague River is a major tributary to Upper Klamath Lake (UKL) and discharges a significant portion of the total phosphorus (TP) loading to the lake, which is a major driver of cyanobacteria blooms that lead to severe water quality impairments. The Sprague River also provides important habitat for endemic fish species and will provide spawning and rearing habitat for anadromous salmonids once downstream barriers to fish migration are removed.

The goal of this study was to evaluate the streamflow and nutrient dynamics of the Sprague River basin over water years (WYs)¹ 2002 – 2020 using biweekly flow and nutrient measurements collected by Klamath Tribes at eight sampling stations across the basin (Figure ES1)². Continuous daily timeseries of flows, loads, and concentrations were computed using methodologies similar to a recent hydrologic and nutrient mass balance study for the entire UKL basin (Walker and Kann, 2022). These daily timeseries were used as a basis to investigate the spatial and temporal dynamics of nutrient concentrations and loads, estimate relative amounts of background and anthropogenic loading, assess the potential impacts of the Klamath Tribes' water rights calls on instream flow and water quality in recent years, and evaluate long-term trends at each sampling station within the Sprague River basin. These analyses led to the following major findings:



Figure ES1: Map showing location of Sprague River sampling stations.

¹ A water year is defined as the 12-month period from October through September. For example, WY 2020 spans from October 1, 2019 through September 30, 2020.

² Two stations on the lower North Fork (NF_Ivory) and South Fork (SF_Ivory) were added later in the sampling program in WY 2010

- Over WY 2010 – 2020, the long-term average TP concentration at each station ranged from 44 ppb at the upper South Fork station (SF) to 75 ppb at the downstream-most station at Power near the Sprague River outlet (Table ES1, Figure ES2). Runoff (flow per unit area) and TP export (load per unit area) rates ranged from 6.3 cm/yr and 3.2 kg/km²/yr at Sycan to 41.2 cm/yr and 19.9 kg/km²/yr at the upper NF station, which were substantially higher than any other station likely due to high spring/seep discharge and snowmelt. TP concentrations increased by approx. 50% from 44 – 50 ppb at the relatively unimpacted sub-basins (Sycan, NF, SF) to 71 – 75 ppb at the downstream mainstem stations (Lone Pine and Power).

Table ES1: Mean annual flows, loads, and FWM concentrations for TP, TN and TSS by station, WY 2010 – 2020.

Sampling Station	Drainage Area (km ²)	Flow (hm ³ /yr)	Runoff (cm/yr)	Load (mt/yr)			Export (kg/km ² /yr)			FWM Conc		
				TP	TN	TSS*	TP	TN	TSS*	TP (ppb)	TN (ppb)	TSS* (ppm)
Power	4,123	404.7	9.8	30.5	142.2	5,350	7.4	34.5	1,300	75.3	351	12.8
Lone_Pine	3,693	394.1	10.7	28.0	140.0	4,970	7.6	37.9	1,350	71.0	355	12.2
Godowa	1,470	267.5	18.2	17.0	59.6	3,170	11.6	40.6	2,160	63.6	223	11.6
Sycan	1,441	91.3	6.3	4.6	42.5	740	3.2	29.5	510	50.1	466	7.7
SF_Ivory	753	75.8	10.1	5.0	26.5	1,590	6.7	35.2	2,110	66.6	350	20.2
SF	280	45.7	16.4	2.0	8.2	380	7.2	29.4	1,350	44.2	180	8.1
NF_Ivory	535	103.7	19.4	6.2	18.4	1,340	11.6	34.3	2,510	60.1	177	12.5
NF	187	77.0	41.2	3.7	10.0	270	19.9	53.4	1,430	48.3	130	3.4

* TSS results based on WY 2011 – 2020

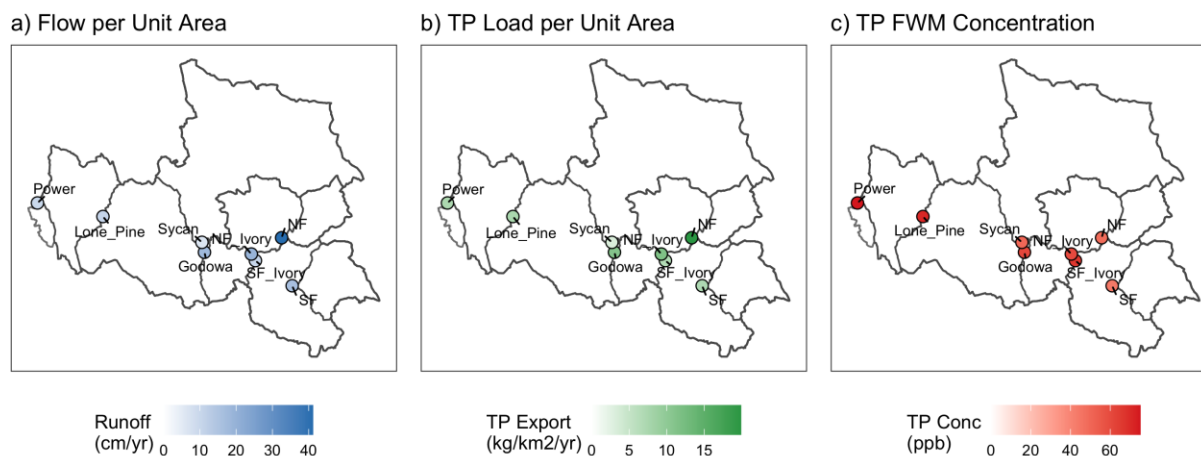


Figure ES2: Maps of flow per unit area (runoff), TP load per unit area (export), and TP FWM concentration at each station, WY 2010 – 2020.

2. The highest net change in flows and TP loads per unit area (runoff and TP export) occurred within the upper Sprague sub-basin between the Godowa and lower North and South Fork stations at Ivory Rd likely due to relatively high groundwater discharge (Table ES2, Figure ES3). However, the highest net increase in TP concentrations occurred in the lower South Fork sub-basin (SF_Ivory to SF), followed by the lower North Fork (NF_Ivory to NF) and middle Sprague (Lone_Pine to Godowa and Sycan). An analysis of the seasonal changes in concentration (Section 4.5.1) showed that a large fraction of the annual TP increases from background concentrations in the headwater basins (between the upper NF/SF and corresponding lower NF_Ivory/SF_Ivory stations) occurred during the fall and winter, and were driven by sharply increasing concentrations of particulate P (PP) and TSS.

Table ES2: Summary of annual net changes in flows, loads, and FWM concentration for TP, TN and TSS by sub-basin, WY 2010 – 2020.

Incremental Sub-basin	Drainage Area (km ²)	Net Change in Flow (hm ³ /yr)	Net Change in Runoff (cm/yr)	Net Change in Load (mt/yr)			Net Change in Export (kg/ km ² /yr)			Net Change in FWM Conc		
				TP	TN	TSS*	TP	TN	TSS*	TP (ppb)	TN (ppb)	TSS* (ppm)
Lower Sprague	430	10.7	2.5	2.5	2.2	381	5.8	5	887	4.3	-3.9	0.6
Middle Sprague	782	35.2	4.5	6.4	37.9	1,063	8.2	48	1,360	10.8	70.7	1.3
Upper Sprague	182	88.1	48.5	5.7	14.7	240	31.5	81	1,321	0.7	-27.3	-4.7
Sycan	1,441	91.3	6.3	4.6	42.5	736	3.2	30	511	--	--	--
Lower South Fork	474	30.0	6.3	3.0	18.3	1,210	6.4	39	2,554	22.5	170.5	12.2
Upper South Fork	280	45.7	16.4	2.0	8.2	377	7.2	29	1,349	--	--	--
Lower North Fork	348	26.7	7.7	2.5	8.4	1,074	7.2	24	3,082	11.8	47.5	9.1
Upper North Fork	187	77.0	41.2	3.7	10.0	267	19.9	53	1,431	--	--	--

* TSS results based on WY 2011 – 2020

Note: Net change in concentration not shown for Sycan, Upper South Fork and Upper North Fork since these are headwater basins and there is no upstream station from which to calculate a net change.

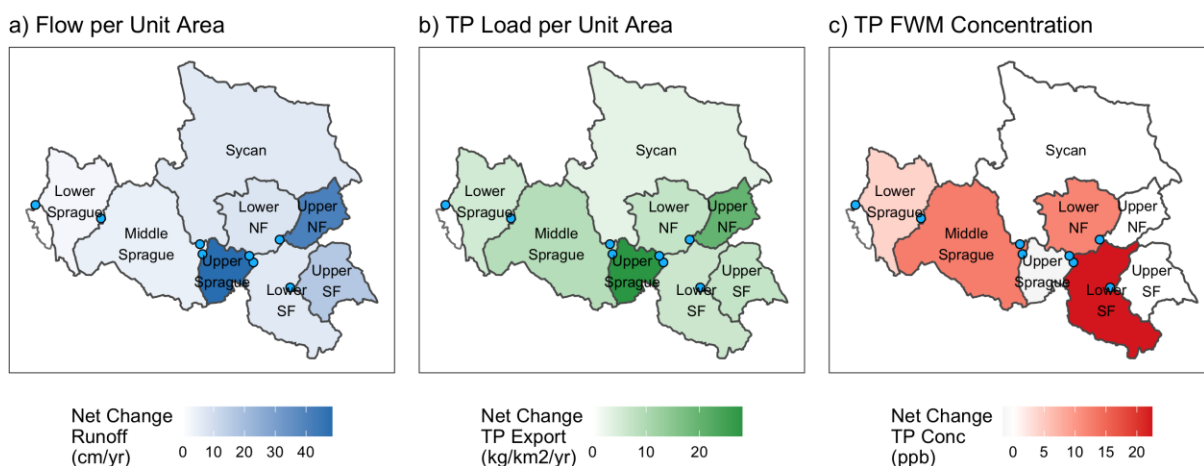


Figure ES3: Maps of net changes in flow per unit area (runoff), TP load per unit area (export), and TP FWM concentration by local sub-basin, WY 2010 – 2020.

Note: Net change in concentration not shown for Sycan, Upper South Fork and Upper North Fork since these are headwater basins and there is no upstream station from which to calculate a net change.

3. Long-term (WY 2010 – 2020) average annual flow-weighted mean (FWM) concentrations of total phosphorus (TP), particulate phosphorus (PP), and total suspended solids (TSS) had significant ($p < 0.1$) positive correlations with herbaceous and planted/cultivated land use and negative correlations with forest cover (Figure ES4a). Dissolved P (PO₄) was not correlated with any land use except planted/cultivated. This suggests that agricultural land uses are major drivers of increases in both dissolved and particulate P likely due to return flows and bank erosion. Concentrations of TP, PP, and TSS are also significantly correlated with the fraction of lower valley area as a designed place of use (POU) for water withdrawals³ within each basin and within almost all seasons (Figure ES4b). The significant winter and spring correlations between TSS (also PP) and fraction POU indicates erosional sources associated with storm related runoff across agricultural dominated floodplain surfaces⁴. Furthermore, correlations between PO₄ and fraction POU area were not significant in any season suggesting agricultural land use may primarily impact in-stream phosphorus levels through increases in particulate P.

Positive relationships between flow and TP, PP, and TSS, along with positive relationships between TSS and both TP and PP during the higher flow winter and spring periods (Section 4.7) further indicate that erosion associated with bank, streambed, and conveyance of sediment entrained from flood-plain surfaces and irrigation channels were, in part, a major source of TP in the Sprague River basin. Additionally, a relatively high fraction of particulate P under low flows at SF_Ivory compared to the other stations suggests that even under low flows there was a major source of particulate phosphorus loading to the lower South Fork reach between SF and SF_Ivory.

³ Fraction of lower valley as POU is an indicator of agricultural land use.

⁴ In addition, the slopes for the TSS, PP, and TP relationships are steeper in winter indicating agricultural areas export proportionally more sediment and P for a given POU fraction during the wetter winter period than during other seasons.

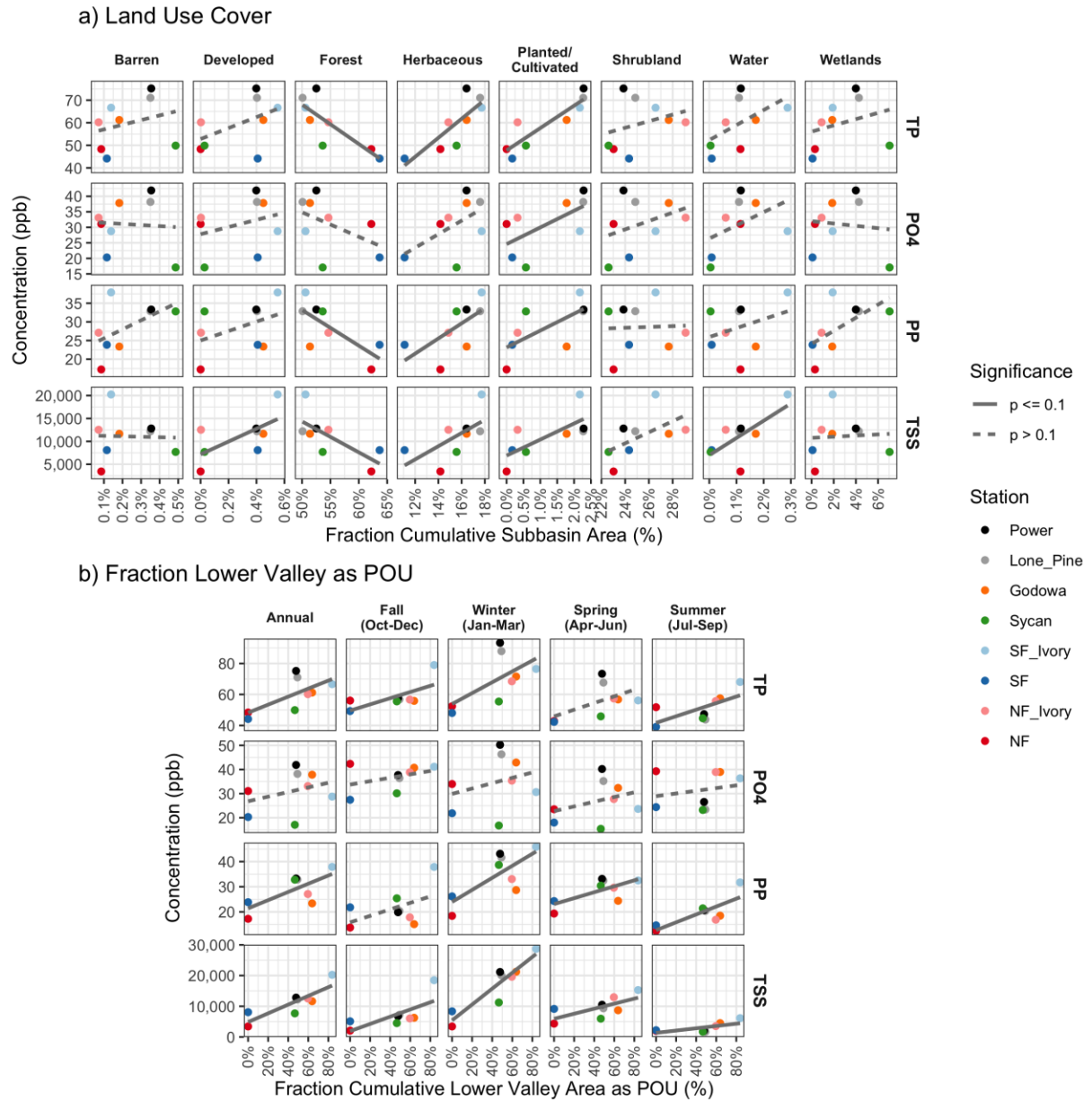


Figure ES4: Relationships between phosphorus/sediment concentrations and a) land use cover and b) fraction of lower valley area as Place of Use (POU), WY 2010 – 2020.

4. The TP loads associated with background and anthropogenic sources were estimated at each station based on assumed groundwater discharge flows and concentrations, and estimated background runoff concentrations computed using the relatively un-impacted SF and NF stations. Over WY 2010 – 2020, anthropogenic TP loads were estimated to be between 32 – 38 % of total loads at the two downstream stations (Power, Lone_Pine), and at the Sycan and SF_Ivory stations (Figure ES5). At Godowa, the estimated fraction of total TP load from anthropogenic sources was about half as much (16%) due to the high groundwater inflows in that portion of the Sprague River. The NF_Ivory station also had a relatively small anthropogenic load (12%), and there were minimal or no anthropogenic loads estimated for the upper SF and NF stations.

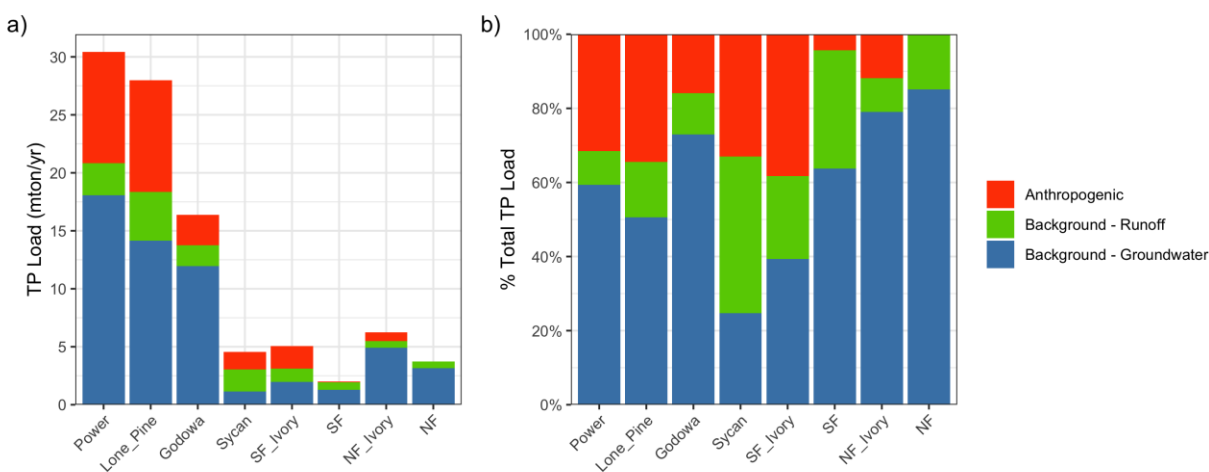


Figure ES5: Mean annual background (runoff and groundwater) and anthropogenic TP loads by station, WY 2010 – 2020.

5. Potential impacts of the Klamath Tribes' water rights calls were assessed by comparing seasonal variations in flows, loads, and concentrations between the years before (WY 2002 – 2012) and during (WY 2013 – 2020) the water use restrictions. The largest changes between these periods included higher summer flows (by as much as approx. 50 cfs in August) during the latter regulation period along the mainstem (Power, Lone_Pine, and Godowa) as well as at the lower NF station (NF_Ivory) (Figure ES6). Comparisons of the net change in flow within each sub-basin suggested the majority of these summer flows increases occurred between the NF_Ivory and NF stations (Figure ES7; 2nd row, 3rd column) possibly due to changes in the operation of the North Fork Ditch diversion structure, which normally transfers large quantities of water to the South Fork. Further comparison of flows with those from a streamflow gauge in the neighboring Chewaucan River (Section 4.9.2)⁵ indicated that the higher Sprague River flows during the regulation in July – September were not likely due to background climatic/hydrologic conditions and confirmed Sprague River flows were as much as 50 cfs higher for a given Chewaucan River flow during the regulation period as compared to prior years (see Figures 61 and 62, Section 4.9.2). No major differences were found between the pre-regulation and regulation periods for water quality.

⁵ Because the Chewaucan River gauge is located upstream from irrigated areas, inter-annual variation in discharge is due primarily to climate (e.g., snowpack and precipitation) and not water withdrawal.

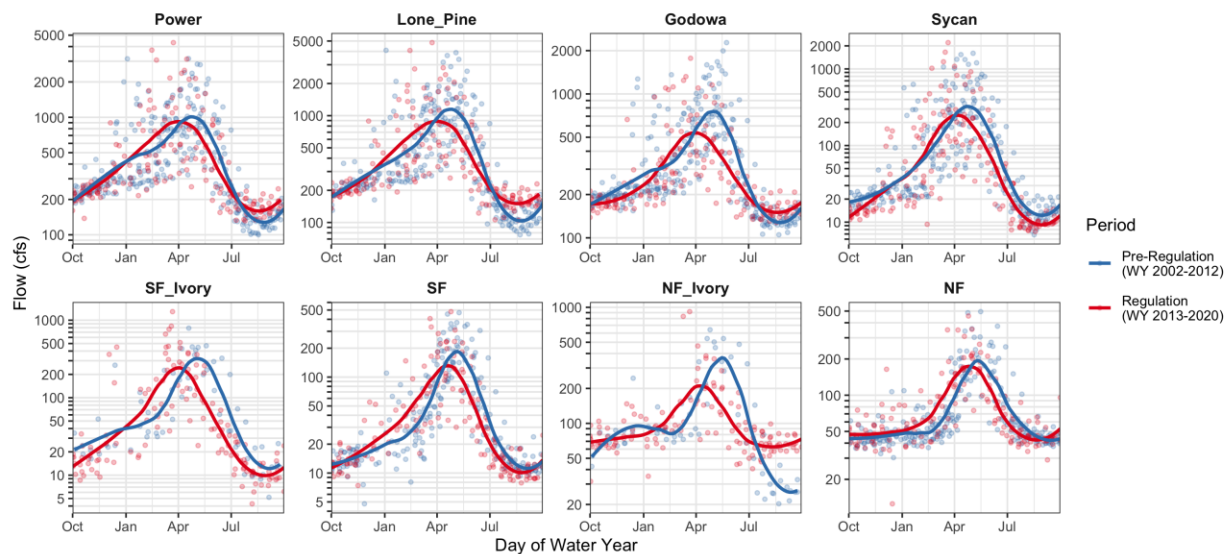


Figure ES6: Seasonal variations in flow before and during the water rights regulation period.

Lines show LOESS smooth of data points for each period. SF_Ivory and NF_Ivory only include data during WY 2010-2012 in Pre-Regulation period.

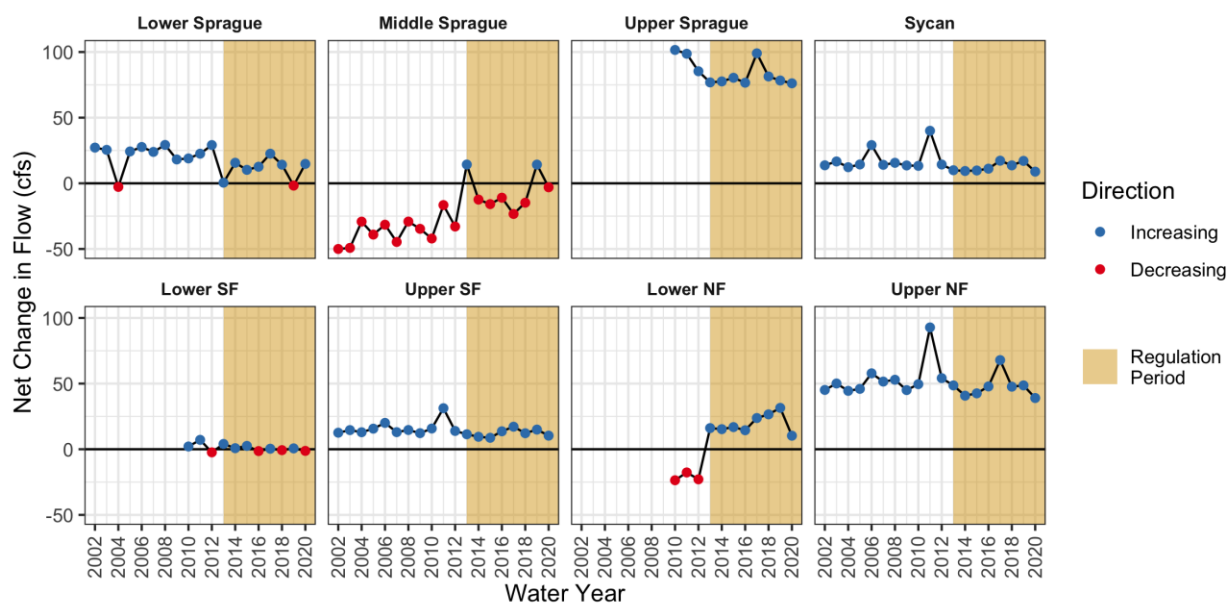


Figure ES7: Net change in mean summer (Jul-Sep) flow within each incremental sub-basin, WY 2002 – 2020.

See Figure ES3 for sub-basin boundaries.

6. Trend analyses showed significant decreasing trends in flow at Sycan and SF_Ivory over the last 11 years in the period of record (WY 2010 – 2020) (Figure ES8). There were also significant increasing trends in flow at NF_Ivory as well as Power and Lone_Pine in summer, which is consistent with the assessment of water rights impacts described above (summer flows were higher along the mainstem and in the lower NF sub-basin during the regulation period compared to earlier years). Furthermore, there were small, but significant decreasing trends in TP concentration at all three mainstem stations as well as the Sycan and SF_Ivory stations, which were primarily driven by decreasing trends in fall and summer. Conversely, there were small increasing trends in TP concentrations at the relatively un-impacted SF and NF stations, primarily in summer (also fall at SF).

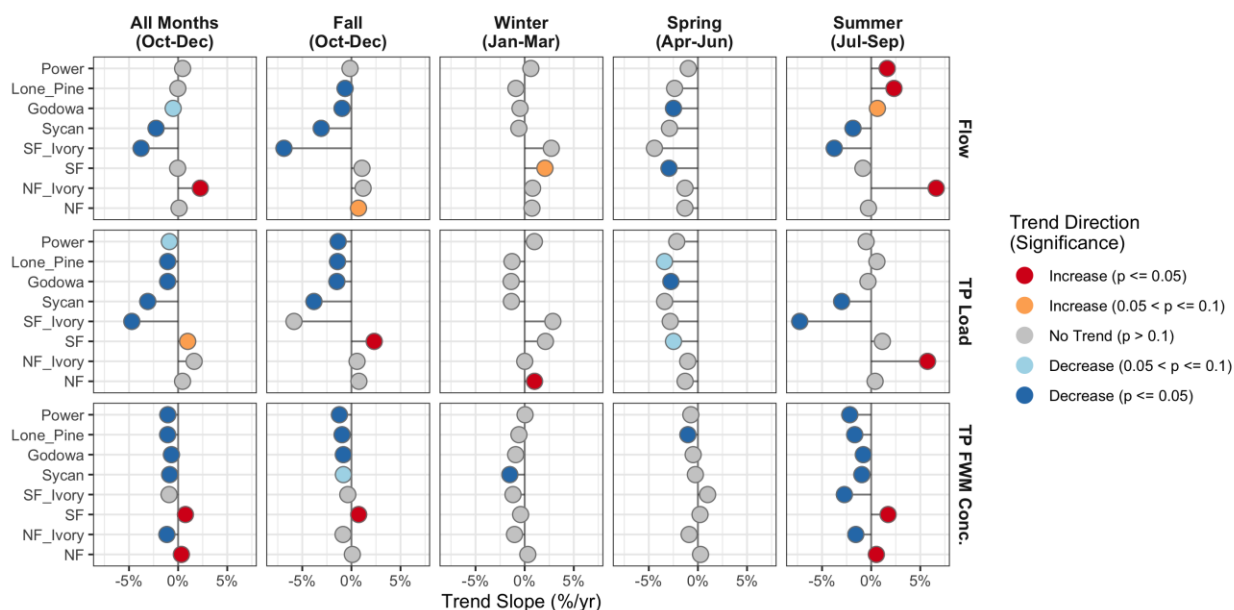


Figure ES8: Trend slopes and significance for flows, TP loads, and TP FWM concentrations for all months and individual seasons, WY 2010 – 2020.

Note: trends assessed using seasonal Kendall test on monthly values.

CONCLUSIONS

Overall, the results of this study indicate that some progress is being made towards reducing phosphorus levels within the Sprague River, likely as a result of recent and ongoing restoration activities. However, roughly a third of the total TP loads at the Sprague River outlet were estimated as having originated from anthropogenic sources, which indicates more restoration is still needed. In light of recent research showing that sediment phosphorus release during summer in Upper Klamath Lake, which is a major driver of algal blooms and subsequent poor water quality, is closely tied to external watershed P loading occurring during the previous winter (Walker and Kann 2022), the results of this study highlight the need for continued watershed restoration to further reduce sources of particulate P and TSS in order to reduce water quality impairments in UKL. Specifically, the need for further watershed restoration is based analyses showing 1) positive relationships between TP, PP, and TSS with

both fraction agricultural land use and fraction POU, and 2) increasing particulate P and TSS occurring during higher flow winter and spring periods.

The water use restrictions imposed over the eight years of the study period (WY 2013 – 2020) due to the Klamath Tribes' water rights calls appeared to have an impact on instream flows resulting in summer flows that have been as much as 50 cfs higher than years prior to these restrictions (WY 2002 – 2012). However, the majority of these differences appear to have originated solely within the lower North Fork basin. The lack of additional gains between sequential stations along the mainstem of the Sprague River (i.e., between Power and the confluence of the North and South Forks) suggests groundwater and/or illegal surface withdrawals may have prevented the greater accumulation of flows within those downstream basins during the regulation period. Furthermore, the water rights calls did not appear to have a significant impact on water quality. However, a full accounting of the sources and sinks of both water and nutrients within each reach and sub-basin is needed to accurately attribute these changes to specific activities due to the multiple, and sometimes confounding, impacts of climate change, water withdrawals, and watershed restoration.

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1 INTRODUCTION

Restoration of the Sprague River basin is an essential element of the overall restoration and ecological health of the entire Klamath basin. The Sprague River is a major tributary to Upper Klamath Lake (UKL) and provides important habitat for endemic fish species. The Sprague River and its tributaries will also provide important spawning and rearing habitat for anadromous salmonids once downstream barriers to fish migration are removed⁶. A series of restoration plans outline the need for remediation of the Sprague River basin to address issues related to the degradation of riparian habitat and stream channels, presence of fish passage barriers, water diversions resulting in fish entrainment, adverse water quality and hydraulic conditions, and fluctuating water levels (UKBWAPT, 2021; ESSA, 2022).

Water quality in the Sprague River is of concern both from an instream perspective (ODEQ, 2002)⁷ and as it relates to nutrient loading to UKL (Kann and Walker, 1999; Kann and Walker, 2020; ODEQ, 2002). Reducing nutrient loads to UKL (particularly for phosphorus, P) has been identified as an important means for improving water quality affecting native fishes in UKL⁸, as well as reducing export of organic matter and nutrients downstream to the Klamath River⁹. Phosphorus is a key element promoting the initial summer *Aphanizomenon* bloom (Kann, 2019a; Hoilman et al., 2008). Furthermore, Eldridge et al. (2013) indicate that *Aphanizomenon* and microcystin toxin¹⁰ are ultimately dependent on phosphorus to regulate growth and decline.

The dependence of UKL bloom-formers (primarily *Aphanizomenon* and secondarily hepatotoxin producing *Microcystis*) and subsequent poor water quality on nutrients (primarily phosphorus) that are both externally derived and internally recycled (Walker and Kann, 2020) led to the development of a

⁶ The Sprague River and its tributaries currently provide native fish habitat for redband trout, bull trout, and endangered shortnose and Lost River suckers (among others), and historically provided habitat for chinook salmon and steelhead. Decommissioning of four downstream dams (currently part of PacifiCorp's Klamath Hydroelectric Project) is expected in 2023 and would allow anadromous chinook salmon and steelhead to regain access to historical habitat on the Sprague River as well as other tributaries (ODFW & Klamath Tribes 2021). ODFW & Klamath Tribes (2021) estimate that the Sprague River and its tributaries contain 426 km of suitable rearing and spawning habitat.

⁷ In addition to habitat modification, the Sprague River is listed as water quality impaired for temperature, pH, chlorophyll-a, and low dissolved oxygen (ODEQ, 1998).

⁸ Upper Klamath and Agency Lakes are hypereutrophic and are seasonally dominated by large blooms of the nitrogen-fixing cyanobacterium *Aphanizomenon flos-aquae* (Kann, 1998; Kann and Smith, 1999). Bloom-driven water quality degradation that includes extended periods of low dissolved oxygen, elevated pH, and toxic levels of un-ionized ammonia has been associated with the decline of native endangered fish populations, including the Federally Listed shortnose (*Chasmistes brevirostris*) and Lost River (*Deltistes luxatus*) suckers (Perkins et al., 2000; Kann and Walker, 2020). More specifically these conditions have been linked to large fish kills and redistribution of the endangered sucker species in UKL (Perkins et al., 2000; Kann and Welch, 2005; Wood et al., 2006; Banish et al., 2009).

⁹ Water quality degradation in the Link and Klamath Rivers below UKL is associated with phytoplankton derived organic matter exported from UKL (e.g., Sullivan et al., 2013)

¹⁰ N-fixation by *Aphanizomenon* during the early summer appears to supply nitrogen for growth of toxigenic *Microcystis aeruginosa* later in the summer, and these secondary *M. aeruginosa* occurrences are responsible for production of the hepatotoxin microcystin in UKL (Jacoby and Kann, 2007, Eldridge et al., 2012).

Total Maximum Daily Load (TMDL) calling for reduction of external anthropogenic P loads¹¹ (Walker, 2001; ODEQ, 2002). The TMDL model found that a reduction in external P load of 40% relative to the historical baseline would be required to achieve a target long-term average TP loading rate of 109 metric tons/year.

Previous nutrient balances using data collected between 1992 and 1998 (Kann and Walker, 1999) formed the basis for the original TMDL (ODEQ, 2002) as well as a more recent update to the TMDL model (Wood et al., 2013). Wood et al. (2013) provided additional uncertainty analyses¹² for the 2002 TMDL model and showed that although predicted UKL P and algal biomass (chlorophyll) were somewhat higher than earlier predictions, a 40% reduction in external P load was predicted to decrease in-lake P and chlorophyll by ~40% (the average reduction based on various model runs).

Using water and nutrient balances for UKL updated through WY¹³ 2010 (Walker et al., 2012), Wherry et al. (2015) recalibrated the TMDL model and predicted that the TMDL target watershed phosphorus reduction of 40% would achieve steady-state concentrations for water column total P and chlorophyll of 74 ppb and 27 ppb, respectively, and would reduce the overall magnitude and frequency of algal (cyanobacterial) blooms¹⁴.

Sources of phosphorus in the UKL watershed have been related to erosional inputs occurring during the past century, including timber harvest, drainage of wetlands, agricultural activities associated with livestock grazing and irrigated cropland, and hydrologic modifications such as water diversions and channelization (Snyder and Morace, 1997; ODEQ, 2002; Bradbury et al., 2004; Eilers et al., 2004)¹⁵.

1.1 ROLE OF THE SPRAGUE RIVER IN NUTRIENT EXPORT

The primary land cover types in the Sprague River basin include forestlands (mostly on hillslopes and ridges), rangelands, irrigated pasture, grass, hay, open water, and wetlands (Connelly and Lyons, 2007). Much of the riverside woodlands, riparian zones, and wetlands that existed prior to settlement of this basin were modified through diking, draining, herbicide application, land-clearing, and grazing. A high correlation between flow and phosphorus load in the Sprague River indicates that sediment transport during high flow events is an important contributor to high phosphorus concentrations in the upper sub-basins (headwaters) of the Sprague River (ODEQ, 2002). Sources of the sediment inputs within the Sprague River drainage include agriculture, livestock grazing, forestry activities, and road-related erosion (ODEQ, 2002; Connelly and Lyons, 2007; Rabe and Calonje, 2009).

¹¹ ODEQ determined that reducing P loads linked to watershed development would be the most effective means of improving water quality conditions in the lake.

¹² Model uncertainty was evaluated based upon alternate chlorophyll models, P recycle mechanisms, phosphorus and light limitation coefficients, and updated initial sediment P concentration.

¹³ Water Year = October 1 – September 30 (e.g., WY 2020 = October 1, 2019 – September 30, 2020)

¹⁴ Modelling indicated that the time required to achieve steady state was 19 years. In addition, further steps were recommended to reduce model uncertainty (Wherry et al., 2015).

¹⁵ Paleolimnological and coring studies in particular showed increases in various indicators (e.g. Ti, Al, tephra, and charcoal) of watershed erosional inputs to UKL in the 20th century (Bradbury et al., 2004; Eilers et al., 2004; Simon et al., 2009)

Over a 27-year period (WY 1992 – 2018), the Sprague River contributed 31% of the tributary TP load and 44% of the tributary TN load to UKL on average (Table 1; Walker and Kann, 2022). Although watershed export (load per unit area) was relatively low compared to the Sevenmile Creek and Wood River systems (Table 1)¹⁶, much of the human activities in the Sprague River basin occur in a relatively small portion of the basin, primarily in the valley floor and riparian areas. These disturbed areas, which generally lack healthy riparian zones, are prone to enhanced transport of nutrients during agricultural activities and high flow events.

Table 1: Mean annual flows, nutrient loads, and concentrations for UKL tributaries, WY 1992 – 2018.

System	Flows	Nutrient Loads		Percent of Tributary Inflow to Upper Klamath Lake			FWM Nutrient Concentration		Drainage Area	Runoff	P Export	N Export
	hm ³ /yr	TP mt/y	TN mt/y	Flow	TP	TN	TP ppb	TN ppb	km ²	m/yr	kg/km ² /yr	kg/km ² /yr
Wood River	324.7	36.2	57.9	26%	30%	15%	111	178	394	0.82	92	147
7-Mile Creek	101.4	14.3	47.2	8%	12%	12%	141	466	96	1.06	149	494
Sprague River	481.3	36.2	170.2	39%	30%	45%	76	354	4,171	0.12	9	41
Williamson River ¹	338.0	34.8	107.6	27%	29%	28%	103	318	3,702	0.09	9	29
Total Tributary Inflow	1,245.3	121.2	380.0	100%	100%	100%	97	305	8,362	0.15	14	45

¹ excluding Sprague River

source: Walker and Kann, 2022

During high flow events in late-winter to spring, the Sprague River can contribute upwards of 50% of the total tributary TP load to UKL (e.g., Kann and Walker, 2020) and the export per unit area (kg/km²-yr) of TP can be much higher than its long-term average. Records et al. (2014) noted that the majority of agriculture in the Sprague River valley is flood-irrigated pasture concentrated in valleys of the South Fork and mainstem of the Sprague River, and that higher TP export occurred in valley bottoms.

In addition, Walker et al. (2012) showed a sharp increase in flow-weighted mean (FWM) TP and TN concentrations longitudinally¹⁷ from relatively un-impacted headwater stations on the upper North and South Forks of the Sprague River to stations representing agricultural areas on the lower South/North Forks and Sprague River mainstem (Figure 1; Figure 2). Such increases reflect the cumulative impacts of loads from anthropogenic sources and potential spatial variations in local inflows related to geology and other unknown factors (Walker et al., 2012). GMA (2007) found substantial increases in suspended sediment loads between stations at the upstream end of alluvial reaches and those near the confluence with the mainstem in both the North Fork and South Fork drainages. Previous Sprague River watershed assessments also noted that channelization and wetland/riparian area conversions were linked to increased erosion and particulate phosphorus transport (Rabe and Calonje, 2009).

A comprehensive analysis of the geomorphology and flood-plain vegetation of the Sprague and lower Sycan Rivers showed that while most of the important physical processes continue to function in the

¹⁶ Sprague River TP export was 9 kg/km²/yr compared to 92 and 149 kg/km²/yr for the Wood and Sevenmile systems, respectively.

¹⁷ FWM TP increased ~2x and FWM TN ~3x from the headwater sub-basins to the outlet of the Sprague River

Sprague River, systematic trends in channel and floodplain conditions indicate broadscale human influence such as declining sinuosity, increased channel slope, decreased migration rates, local channel incision, and diminished short woody near-channel vegetation (O'Connor et al., 2013)¹⁸. In addition, O'Connor et al. (2013) concluded that entrainment of sediment was high on the South Fork and mainstem of the Sprague River during high flow events primarily due to channel and bank erosion in these reaches and across flood-plain surfaces. Historically, these channels were less constrained, had lower gradients, and provided greater lateral floodplain connectivity, sediment storage, and riparian vegetation. Restoration of these functions would thus likely lead to decreased erosion and sediment transport via greater deposition and sediment capture.

¹⁸ O'Connor et al. (2013) further note that channel confinement by levees and other built features is probably the single most important factor contributing to these changes, but the direct and indirect consequences of other manipulations, such as local flow diversion and concentration, grazing, vegetation removal, and beaver eradication, have also been important, particularly at the valley-segment scale.

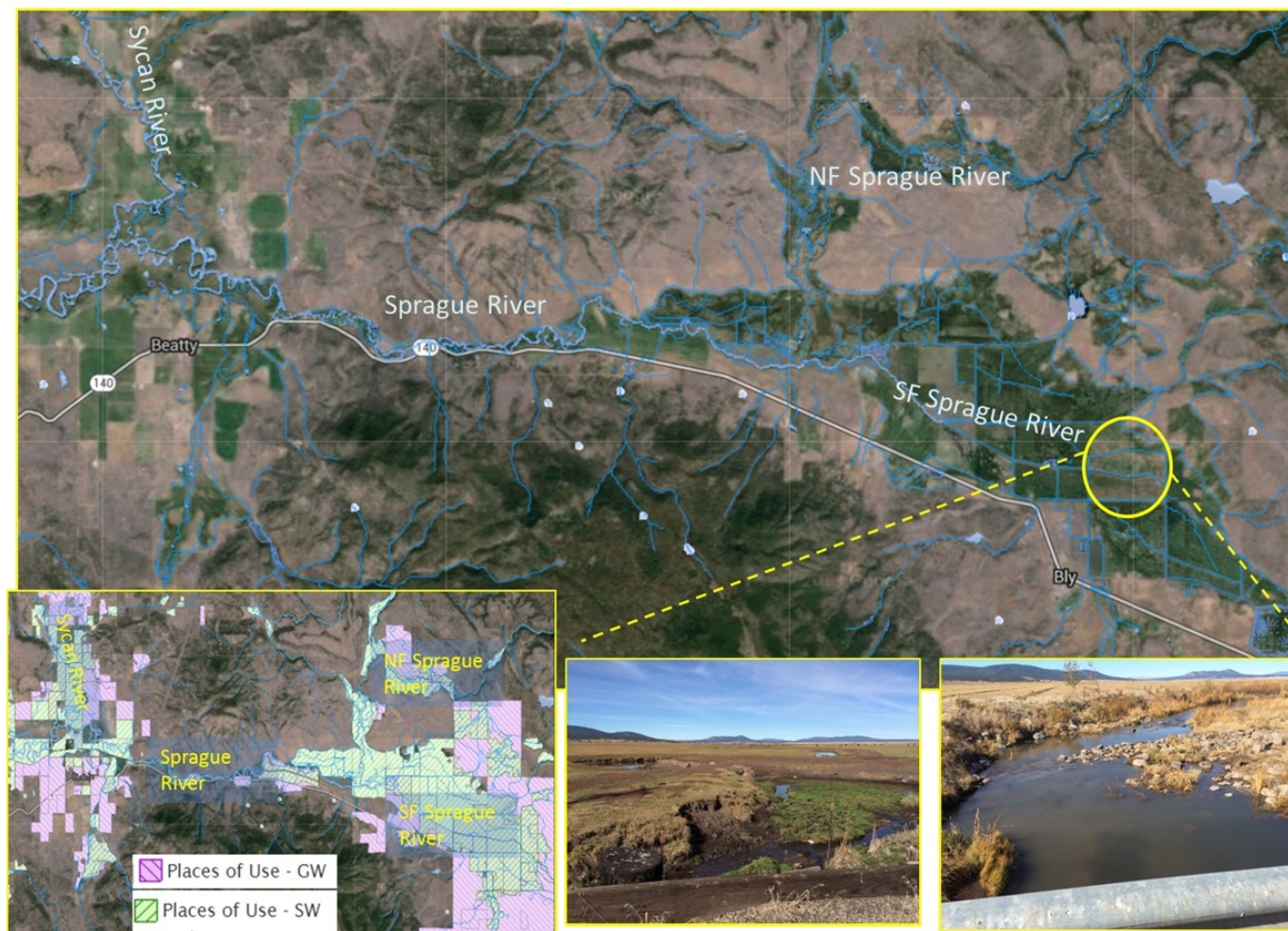


Figure 1: Aerial imagery of agricultural areas in the upper sub-basins of the Sprague River.

Green areas (mainly in valley bottoms) show irrigated areas. Inset map shows places of use for surface water (SW) and groundwater (GW) diversions.

Inset photos show erosional areas in the SF Sprague.

Map Source: OWRD (2022c)

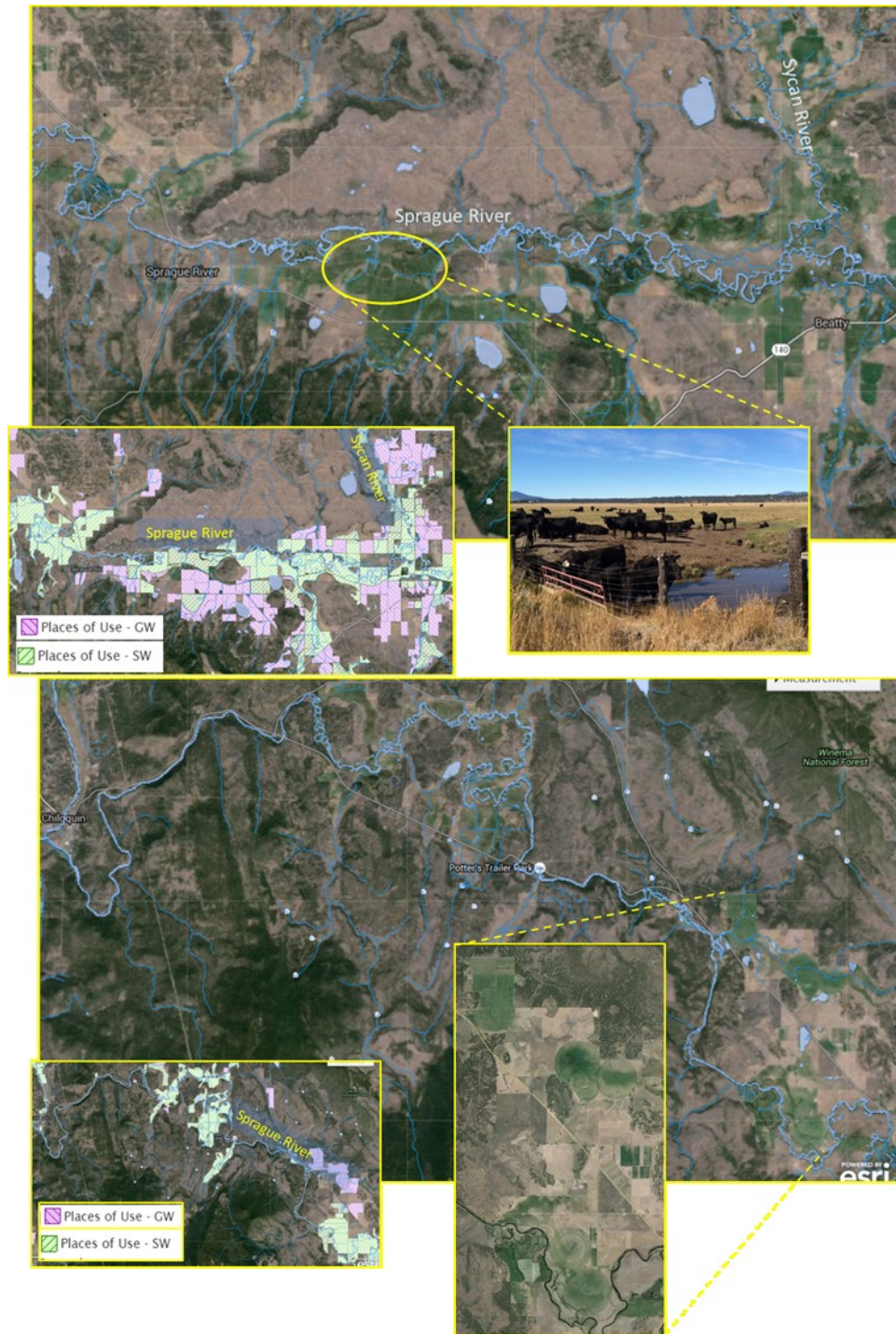


Figure 2: Aerial imagery of agricultural areas on the middle and lower sections of the Sprague River.

Green areas (mainly in valley bottoms) show irrigated areas. Top panel shows middle Sprague River; bottom panel shows lower Sprague River.

Inset maps show places of use for surface water (SW) and groundwater (GW) diversions.

Map Source: OWRD (2022c)

1.2 RESTORATION EFFORTS

Since the early-to-mid-1990s, numerous stream restoration projects have been implemented in the Sprague River basin including fencing, wetland creation, floodplain reconnection, levee breaching, meander-bend cutoff plugging, riparian planting, channel realignment, fish screens, irrigation water management, spring reconnection, and wetland connection (USDA, 2009; Newfields and Kondolf, 2012; Stillwater Sciences et al., 2013). The types of restoration activities and their performance were evaluated by Newfields and Kondolf (2012), who developed a post-restoration project appraisal (PPA) framework to guide analysis and conceptual models to further understanding of the Sprague River Basin. In a subset of ten restoration projects that they evaluated, the performance of 70% of the projects satisfied some success criteria but not others and did not consider all critical processes. Only 30% of those projects satisfied most or all success criteria.

Although many of these restoration projects have been beneficial, O'Connor et al. (2013) indicated that channel structure and function, and riparian vegetation were still compromised. As a result, they recommended restoration activities intended to promote a more natural channel and flood-plain geometry as well as channel aggradation to the extent that overbank flow can become more common¹⁹. Geomorphological activities such as these relate directly to sediment and nutrient transport dynamics. Other water quality-specific restoration recommendations included: (a) investigating the feasibility of constructing tailwater re-use systems and treatment wetland ponds for irrigation returns, (b) increasing shade and stream depth by restoring riparian corridors to their proper functioning, (c) implementing livestock grazing practices (e.g., rotation grazing and seasonal grazing) to limit stream access during critical growing seasons for riparian vegetation, and (d) managing for robust riparian communities (Connolly and Lyons, 2007).

Based in part on pasture-level monitoring studies showing that first-flush irrigation and storm events have the potential to export large quantities of phosphorus from irrigated grazing land in the Upper Klamath Lake basin (Ciotti et al., 2010), a network of diffuse source treatment wetlands (DSTWs) were proposed for the Sprague and Wood River valleys to decrease external loading of phosphorus and nitrogen to Upper Klamath and Agency Lakes (Stillwater Sciences et al., 2013). Due to short retention times (high inflow volume relative to DSTW volume) these have not been shown to be effective in the Wood River Valley and have not yet been tested in the Sprague River system.

As noted below, one important objective of the current study is to perform trend analyses to evaluate whether existing restoration effects have led to any potential downward trends in nutrient export from the Sprague River basin.

¹⁹ These include restoration of natural channel migration processes, maintenance and enhancement of the frequency and extent of overbank flooding and lateral connectivity between channels and flood plains, and promotion of vegetation succession and disturbance processes conducive to reversing historical losses of short woody vegetation cover types.

1.3 WATER RESTRICTIONS

The Klamath Tribes senior in-stream water rights for the Sprague River and its tributaries were confirmed in 2013 by the Oregon Department of Water Resources (OWRD) per the Final Order of Determination in the Klamath River Basin Adjudication (ACFFOD, 2014). These water rights specified minimum in-stream flows for each month. In a subsequent settlement called the Upper Klamath Basin Comprehensive Agreement (UKBCA), the Klamath Tribes agreed to regulatory thresholds (Specified In-stream Flow (SIF) thresholds) that change based on the relative wetness or dryness of near-term hydrologic conditions in exchange for permanent riparian restoration²⁰ and reductions in agricultural water use, among other things (UKBCA, 2014). Beginning with dry conditions in both 2013 and 2014 (2014 had particularly low rainfall/snowpack conditions, see Section 4.1 below), there have been calls for regulating irrigation water in the Sprague River basin based on the SIF thresholds as well as on water rights associated with the Klamath Reclamation Project. Because this was the first time that water rights regulations were imposed in the Sprague River basin, hydrologic conditions in 2013 and 2014 were different from those of previous drought years, especially during the irrigation season (e.g., Hess and Stonewall, 2014). SIF thresholds were also utilized in 2015 and 2016 to regulate irrigation withdrawal. Due to dissolution of the Comprehensive Agreement (UKBCA), calls for regulating withdrawals from 2017 through 2020 were based on the ACFFOD thresholds and were not based on near-term hydrologic conditions.

1.4 CURRENT ANALYSIS EFFORT

For over three decades, the Klamath Tribes have maintained a long-term tributary and lake monitoring program (1990 – present)²¹ to understand nutrient and water quality dynamics and to inform management and restoration activities. These datasets were the basis for the initial computation of water and nutrient mass balances for UKL (Kann and Walker, 1999) as well as the TMDL referenced above (ODEQ 2002). The initial UKL water and nutrient balances were subsequently updated and extended by Walker et al. (2012) to cover the period WY 1992 – 2010, and more recently by Walker and Kann (2022) for WY 1992 – 2018. In addition, long-term trend analyses for total phosphorus (TP) and total nitrogen (TN) were computed for the major long-term stations analyzed in Walker and Kann (2022). For the Sprague River, Walker and Kann (2022) used the lower-most station located above the Williamson River confluence (Sprague at Kircher's which is just downstream from Sprague @ Power; Figure 4), and additional data summaries and trends for that station have also been provided annually (e.g., Kann, 2019b).

In response to the need for better understanding nutrient and sediment dynamics relative to land use practices and recommended restoration activities, the Klamath Tribes expanded their monitoring program in 2002, and again in 2009, to include a network of additional stations on the mainstem Sprague River and tributaries (Figure 4). As part of the detailed analysis of the lower-most Sprague River station, Walker et al. (2012) also provided a preliminary assessment of these expanded watershed

²⁰ Implementation of Riparian Management Agreements with willing landowners that specify grazing management and nutrient reduction measures.

²¹ The Klamath Tribes sampling programs were temporarily suspended during 2019 for most stations (excluding the Sprague River basin) due to lack of funding

stations using data collected through WY 2010. However, the preliminary analysis only included computation of flow-weighted-mean (FWM) concentrations using the biweekly samples for the WY 2002 – 2010 period and did not include computation of daily nutrient concentrations and loads that would be necessary to determine seasonal trends and refinement of specific watershed loading estimates. In addition, trend analyses were not performed for these expanded stations. Walker and Kann (2022) did not update the analyses of the Sprague River stations that were provided in Walker et al. (2012) as these analyses have been incorporated in this study instead.

Records et al. (2014) also estimated and analyzed nutrient loads of the expanded stations but only for years 2001 – 2010 and did not include data for the North and South Forks above the confluence with the mainstem of the Sprague River (data collection for these stations, NF @ Ivory Pine Rd and SF @ Ivory Pine Rd, began in 2009).

Following the preliminary analysis of the Sprague River stations by Walker et al. (2012), Walker et al. (2015) performed a more detailed analysis of spatial and temporal dynamics of flows, nutrient and sediment loads, and concentrations within the Sprague River basin over the period WY 2002 – 2014. The current study is an update of Walker et al. (2015) and includes an additional six years of data (WY 2015 – 2020). The results from the previous study (Walker et al., 2015) should be considered superseded by those presented here.

1.5 STUDY AREA

The Sprague River basin is located in the upper Klamath River basin in south-central Oregon and has a drainage area of approximately 4,124 km². There are three major tributaries to the Sprague River including the Sycan River, and the North and South Forks of the Sprague River (Figure 4). Within the Sprague River basin, elevations range from 1,268 m at the Williamson River confluence to 2,549 m above sea level at Gearhart Mountain. The basin has a high semi-arid climate due to the rain-shadow casted east of the Cascade Mountain Range. As a result, mean annual precipitation ranges from less than 40 cm on the valley floors to 120 cm in high elevation margins (Figure 3; O'Connor et al., 2013; PRISM Climate Group, 2014). The majority of precipitation falls between October and March with about 30 – 47% falling as snow in the lower valleys and 50 – 64% as snow in the uplands (O'Connor et al., 2013, Records et al., 2014).

Despite significant groundwater and spring discharges (Gannett et al., 2007), Sprague River flows are highly responsive to winter precipitation (Mayer and Naiman, 2011). Mayer and Naiman (2011) also concluded that warmer winter temperatures and snowpack reductions have caused significantly earlier runoff peaks in both snowmelt and groundwater basins in the region, including the Sprague River.

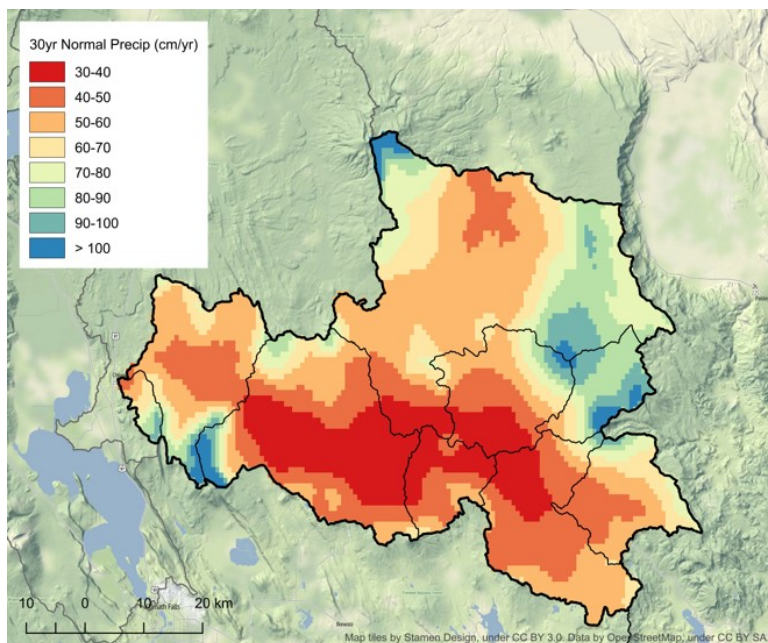


Figure 3: Spatial variability of the 30-year normal annual precipitation across the Sprague River basin.

Source: PRISM Climate Group (2004)

As noted by O'Connor et al. (2013), an upper reach of the Sycan River is designated as a Wild and Scenic River, and upper tributaries of the NF and SF of the Sprague River include portions of the Gearhart Mountain Wilderness Area. Lower reaches of the tributaries as well as the mainstem of the Sprague River historically meandered through broad alluvial valleys and currently support agriculture and livestock grazing²². The Sprague River serves as a major tributary to the Williamson River²³, which drains directly into Upper Klamath Lake, the outflow of which forms the Klamath River²⁴ that ultimately discharges to the Pacific Ocean in northern California.

Over the period WY 1992 – 2018, the Sprague River contributed on average 39% of the total flow and 30% and 45% of the total TP and TN loads from the primary tributaries to UKL (Table 1). Within the Sprague River Basin, the three main tributaries (Sycan River, North Fork, and South Fork) contribute 23%, 26%, and 19% of the mean annual flow to the Sprague River outlet, 15%, 20%, and 16% of the TP load, and 30%, 13%, and 19% of the TN Load, respectively, over WY 2010 – 2020 (Table 8 in Section 4.3 below).

²² O'Connor et al. (2013) provides detailed descriptions of the Sprague River basin geography and geology.

²³ The Sprague River contributed 59% of the total mean annual flow discharged from the Williamson River to UKL over WY 1992 – 2018 (Table 1).

²⁴ The outflow from UKL is named the Link River which drains into Lake Ewuana before being renamed as the Klamath River.



Figure 4: Map and photos of Sprague River basin and water quality sampling stations.

1.6 STUDY OBJECTIVES

The overall goal of this study was to update the previous study of hydrologic and nutrient loading dynamics in the Sprague River Basin (Walker et al., 2015) using an additional 6 years of data collected by the Klamath Tribes through WY 2020 (September 30, 2020). The specific study objectives are as follows:

1. Evaluate seasonal patterns in flows, loads, and concentrations for major nutrient and sediment parameters including total phosphorus (TP), phosphate-phosphorus (PO_4), particulate phosphorus (PP), total nitrogen (TN), nitrate/nitrite nitrogen ($\text{NO}_3+\text{NO}_2\text{-N}$), ammonia-nitrogen ($\text{NH}_4\text{-N}$), and total suspended solids (TSS)²⁵ at Sprague River stations shown in Figure 4.
2. Estimate sub-watershed loading and unit area export (e.g., $\text{kg}/\text{km}^2\text{-yr}$) rates to determine areas of concentrated loading in specific reaches occurring on both a seasonal and annual basis, and use these calculations to inform reach-specific restoration priorities.
3. Refine estimates of background loading from relatively un-impacted headwaters to inform estimates of loading attributed to land-use practices.
4. Evaluate long-term trends in flows, nutrient and sediment loads, and concentrations at each sampling stations over the period of record (WY 2002 – 2020).
5. Interpret year-to-year variations and long-term trends relative to variations in climate as well as due to the effects of water rights calls during recent years (2013 – 2020).

²⁵ Abbreviated as TP, PO_4 , PP, TN, NO_3 , NH_4 , and TSS in the report.

2 DATASET COMPILATION

2.1 DATA SOURCES

Table 2 summarizes the various datasets used in this study with further details provided in following sections.

Table 2: Summary of data sources.

Dataset	Source	URL
Hydrology		
Precipitation	PRISM	http://www.prism.oregonstate.edu/
Snowpack	NRCS SNOTEL	http://www.wcc.nrcs.usda.gov/snow/
Streamflow	USGS	http://waterdata.usgs.gov/nwis
	OWRD	http://apps.wrd.state.or.us/apps/sw/hydro_report/
	Klamath Tribes	Provided as Excel Spreadsheet
Water Quality		
Biweekly Samples of Nutrients/Sediment	Klamath Tribes	Provided as Excel Spreadsheet
GIS Data		
Hydrography	NHDPlus v2	https://nhdplus.com/NHDPlus/NHDPlusV2_home.php
Land Use	NLCD v2011	https://www.mrlc.gov/data/nlcd-2011-land-cover-conus
Water Rights	OWRD WRIS	https://www.oregon.gov/OWRD/programs/WaterRights/WRIS
Geomorphology	USGS	http://or.water.usgs.gov/proj/Sprague/

2.2 HYDROLOGIC DATA

2.2.1 PRECIPITATION

Historical monthly precipitation data were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (PRISM Climate Group, 2004). The PRISM dataset includes monthly precipitation and air temperatures for WY 1982 – 2020. The dataset is provided as a series of gridded raster layers (one layer per month) at 30-second spatial resolution (approximately 3.5 x 4.5 km grid cells). For each sub-basin and month, the mean precipitation was computed by intersecting the precipitation raster layer with the sub-basin boundary polygons (see Section 2.4.1) and then calculating the mean value across each sub-basin. The result was a monthly precipitation timeseries for each sampling station sub-basin. Precipitation records were generated for each individual sub-basin in order to capture the spatial variability across the sub-basins (see Figure 3 above). Figures A1 and A2 in Appendix A show the monthly and annual precipitation, respectively, for each sub-basin over the study period, WY 2002 – 2020.

2.2.2 SNOWPACK

Historical snowpack records were obtained from the Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) network (NRCS, 2015). Three SNOTEL stations were identified in the Sprague River basin that included snowpack records over the study period (WY 2002 – 2020) (Figure 5; Table A2 in Appendix A). The amount of snowpack is represented by measurements of snow water equivalent (SWE), which is the depth of water contained in snowpack and reflects the amount of water available for conversion to runoff during spring snowmelt. Because snowmelt is a major source of streamflow in the

Sprague River, the snowpack records were used as context for interpreting year-to-year variations in the basin's hydrology.

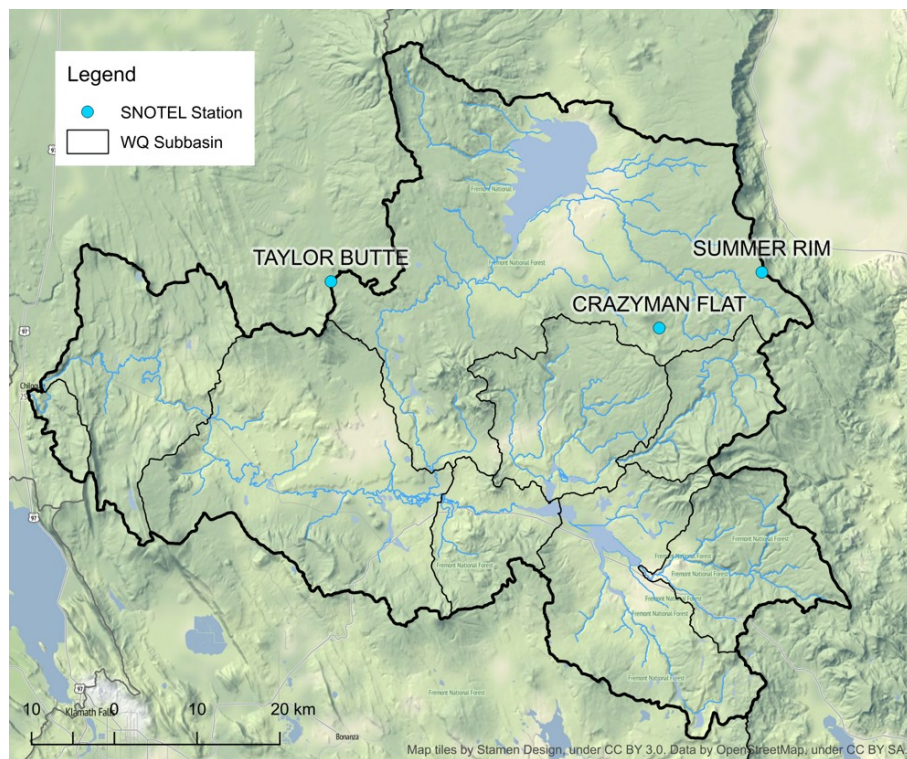


Figure 5: Map of SNOTEL monitoring stations.

2.2.3 STREAMFLOW

Continuous daily streamflow data were obtained from the U.S. Geological Survey (USGS, 2022) and Oregon Department of Water Resources (OWRD, 2022a). Figure 6 shows the locations of the continuous streamflow monitoring stations used in this study. Three of these stations were used to estimate daily streamflow at each water quality station; the remaining stations were used for comparison to the biweekly (measured every two weeks) flows measured by Klamath Tribes as part of the water quality sampling program (Section 3.1 below describes which streamflow station was used to estimate flows for each water quality station). Details about each streamflow station including the latitude/longitude and period of record are provided in Table A1 of Appendix A.

Instantaneous streamflow measurements²⁶ were also provided by Klamath Tribes at each water quality station. Flows were measured at each station during the time of nutrient sampling yielding paired flows and concentrations at approximately biweekly intervals. These biweekly flow measurements were related to the USGS and OWRD daily streamflow datasets to generate a continuous daily flow timeseries for each station. Details of this process are described below in Section 3.1.

²⁶ Specific discharge measurement methodology is contained in the Sprague River Water Quality Lab (SRWQL) SOP manual (Klamath Tribes, 2013a)

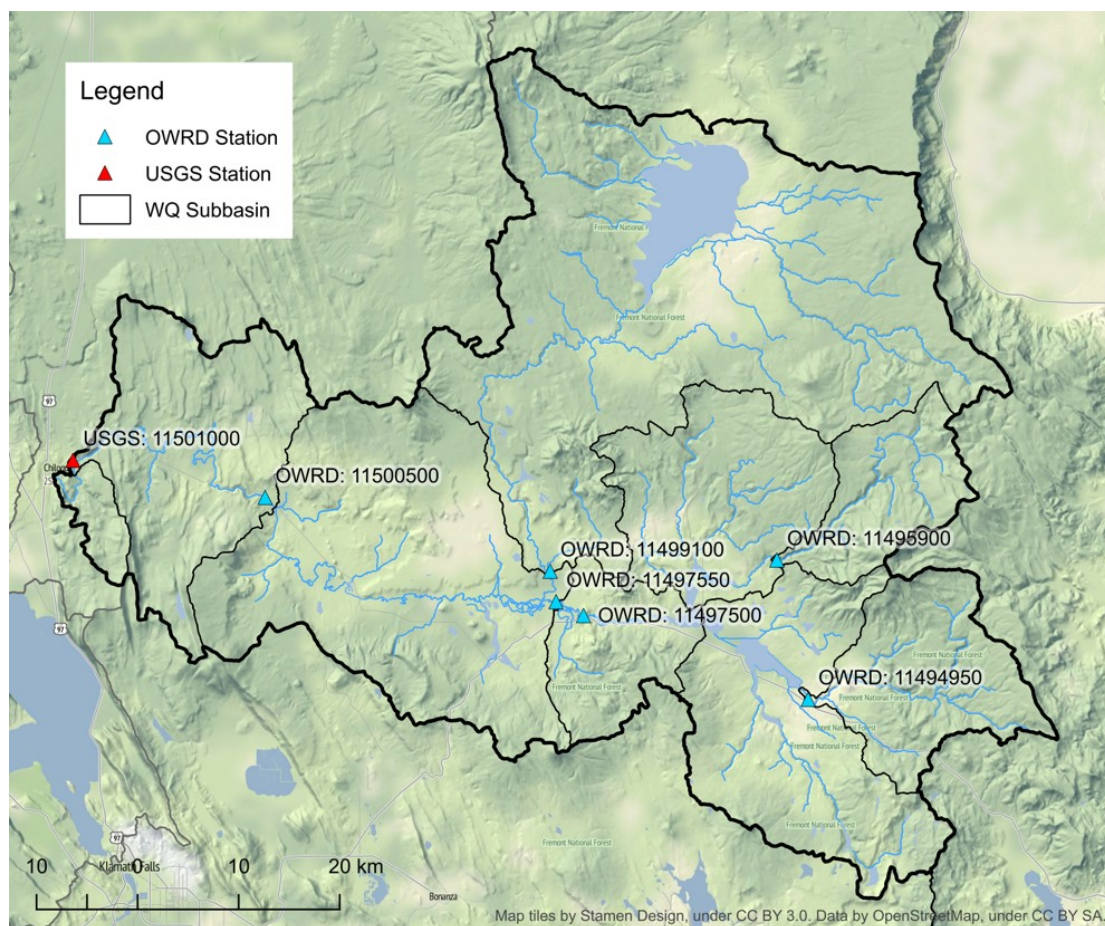


Figure 6: Map of continuous streamflow monitoring stations.

2.3 WATER QUALITY DATA

Water quality samples of nutrient (nitrogen and phosphorus) concentrations were collected by the Klamath Tribes at six long-term monitoring stations (red symbols in Figure 4) within the Sprague River basin over WY 2002 – 2020 at approximately biweekly intervals²⁷. Two stations (SF_Ivory, NF_Ivory) were added as routine sampling locations in August 2009 near the outlets of the North and South Forks at Ivory Pine Rd (orange symbols in Figure 4). Although samples were also collected in 2005 and 2006 at the North Fork station at Ivory Pine Rd, these values were removed from the dataset due to a lack of flow measurements and a gap in sampling during 2007 – 2009. Total suspended solids (TSS) measurements were added to the sampling program as a routine parameter in September 2010 (WY 2011) at all stations.

Table 3 lists the water quality stations including their locations, drainage areas, and periods of record. Figure 4 shows the locations and sub-basin drainage areas of these stations. The delineation of these sub-basins is described in Section 2.4.1 below. An exploratory data analysis of the water quality data

²⁷ Specific nutrient methodology and field collection protocol are contained in the Sprague River Water Quality Lab (SRWQL) Standard Operating Procedure (SOP) (Klamath Tribes, 2013a) and Quality Assurance Protection Plan (QAPP)r (Klamath Tribes, 2013b).

including timeseries of the sampled concentrations, comparisons between water quality parameters and flow at each station, and comparisons between the stations is provided in Appendix B.

Table 3: Water quality station locations, drainage areas, and sampling periods.

ID	Name	Description	Latitude	Longitude	Drainage Area (km ²)	Sampling Period
SR0090	Power	Sprague R @ Power Plant	42.5846	-121.8419	4,123	4/2001 – 9/2020
SR0080	Lone_Pine	Sprague R @ Lone Pine	42.5505	-121.6176	3,693	3/2001 – 9/2020
SR0060	Godowa	Sprague R @ Godowa Rd	42.4604	-121.2699	1,470	3/2001 – 9/2020
SR0070	Sycan	Sycan R @ Drews Rd	42.4855	-121.2785	1,441	3/2001 – 9/2020
SR0150	SF_Ivory	SF Sprague @ Ivory Pine	42.4394	-121.0954	753	8/2009 – 9/2020
SR0050	SF	SF Sprague @ Picnic Area	42.3761	-120.9694	280	3/2001 – 9/2020
SR0140	NF_Ivory	N. Fork Sprague R @ Ivory Pine	42.4560	-121.1094	535	8/2009 – 9/2020
SR0040	NF	NF Sprague @ 3411 Rd	42.4970	-121.0056	187	3/2001 – 9/2020

2.3.1 DATA QUALITY REVIEW

An extensive review of the water quality dataset was performed prior to the analyses in order to identify erroneous or abnormal data points. This review included:

1. Identifying samples that were abnormally low and thought to be the result of incorrectly labeled blank samples,
2. Removing negative concentrations (TSS only),
3. Removing concentrations of dissolved nutrient species that greatly exceeded total nutrient concentrations (i.e. if PO₄ > TP, then the PO₄ value was excluded from the dataset but the TP value was retained), and
4. Performing pairwise comparisons between related variables and stations to identify outliers that did not fit general trends or relationships in the dataset.

Table 4 lists the number of samples for each site and water quality parameter that were removed from the dataset after the data quality review. Further details of this review are provided in Appendix B.

Table 4: Number of water quality samples removed by station and parameter.

Station	TP	PO ₄	TN	NH ₄	NO ₃	TSS
Power	3	0	1	0	0	0
Lone_Pine	2	0	1	0	0	2
Godowa	4	0	0	0	0	0
Sycan	1	1	1	2	1	1
SF_Ivory	1	1	1	0	0	0
SF	1	3	2	1	1	1
NF_Ivory	3	1	1	0	0	0
NF	0	4	0	0	0	1
Total Samples Removed	15	10	7	3	2	5
Total Samples Collected	3,226	3,226	3,226	3,225	3,225	1,759
% Samples Removed	0.5%	0.3%	0.2%	0.1%	0.1%	0.3%

2.3.2 CHANGES IN DETECTION LIMITS

A review of the water quality dataset revealed changes in detection limits for the three nitrogen species (TN, NH₄, NO₃) that occurred in April 2008. Table 5 summarizes the detection limits of all parameters before and after these changes. Note that there were no changes to the detection limits of the phosphorus species, and TSS samples were only collected after 2008.

Table 5: Detection limits of water quality parameters.

Parameter	Higher Limits (mg/L) 3/2001 – 3/2008	Lower Limits (mg/L) 4/2008 – 9/2020
TP	0.018	0.018
PO ₄	0.003	0.003
TN	0.1	0.03
NH ₄	0.01	0.006
NO ₃	0.01	0.008
TSS	N/A	1

In order to ensure that the dataset was consistent across the period of record, all concentrations were constrained to be no less than the higher detection limits used prior to April 2008. The effect of this constraint on the results of this study was evaluated by re-running the analyses for the nitrogen species using only the later years and constraining the concentrations to the lower detection limits. These results were then compared to the results using the higher detection limits and showed relatively small differences in the annual FWM concentration of each station and nitrogen species (Appendix D; Figure D2).

2.4 GEOSPATIAL DATA

2.4.1 CUMULATIVE SUB-BASIN DELINEATION

In this report, the term “cumulative sub-basin” refers to the total drainage area associated with each water quality station. These areas were delineated using the National Hydrograph Dataset (NHD) Plus v2 catchment delineation (McKay et al., 2012). Figure 4 above shows the delineations and Table 3 provides the drainage areas of these cumulative sub-basins. Note that the cumulative sub-basins are nested meaning upstream sub-basin areas are included within the downstream sub-basins since each sub-basin covers the entire drainage area for each station.

2.4.2 INCREMENTAL SUB-BASIN DELINEATION

The term “incremental sub-basin” refers to the drainage area *between* consecutive water quality stations along the river reach network. Table 6 lists the names, upstream and downstream stations, and drainage areas of the incremental sub-basins, which are shown in Figure 7. Note that the Upper Sprague + Lower SF/NF sub-basin (which excludes the SF_Ivory and NF_Ivory stations that were added in 2009), is only used when presenting results over the entire period of record (WY 2002 – 2020).

Table 6: Summary of incremental basin stations and drainage areas.

Incremental Basin Name	Downstream Station	Upstream Station(s)	Drainage Area (km ²)
Lower Sprague	Power	Lone_Pine	430
Middle Sprague	Lone_Pine	Godowa + Sycan	782
Upper Sprague	Godowa	SF_Ivory + NF_Ivory	182
Upper Sprague + Lower SF/NF*	Godowa	SF + NF	1,004
Sycan	Sycan	--	1,441
Lower SF	SF_Ivory	SF	474
Upper SF	SF	--	280
Lower NF	NF_Ivory	NF	348
Upper NF	NF	--	187

* Only used when presenting results over the period of record (WY 2002 – 2020) and is the combination of the Upper Sprague, Lower SF, and Lower NF incremental sub-basins

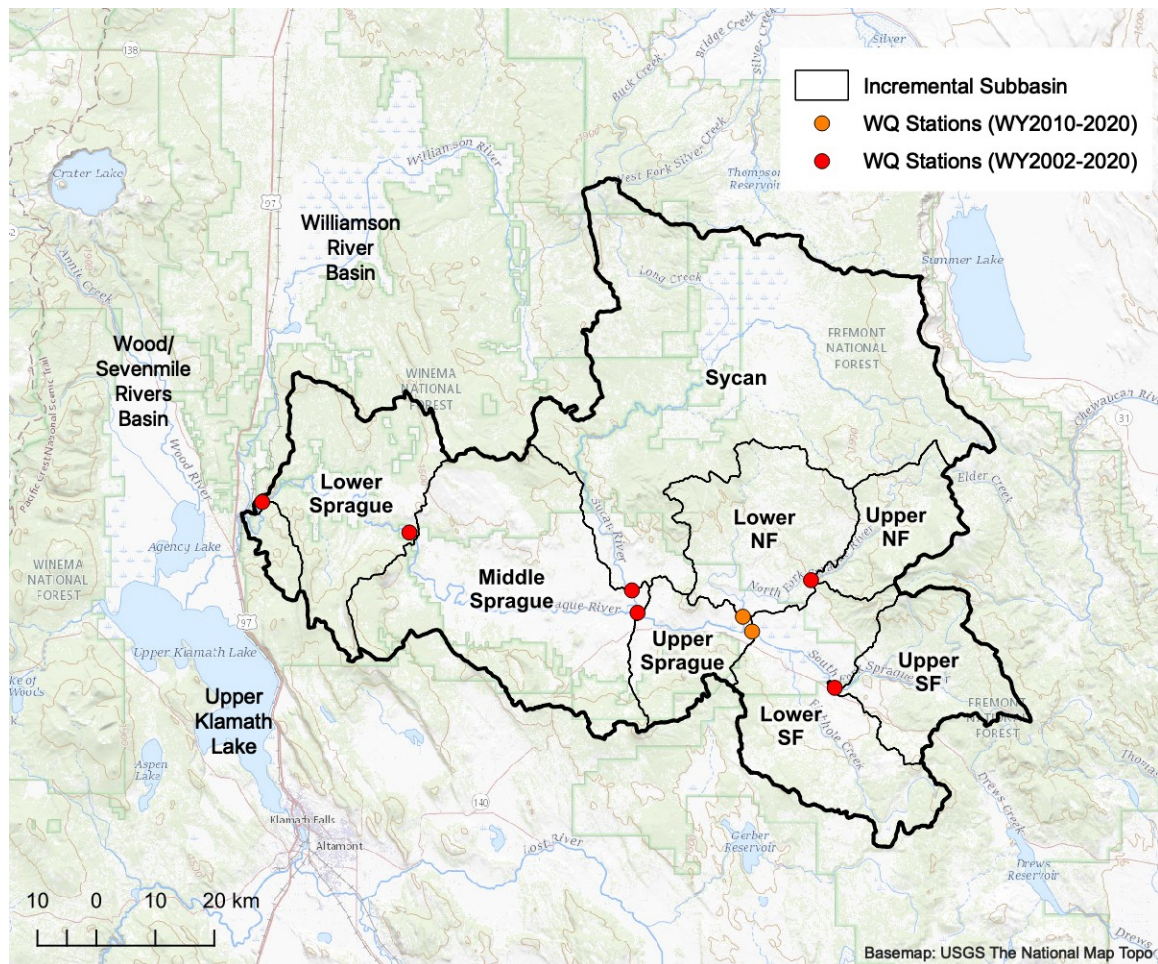


Figure 7: Map of incremental sub-basins.

2.4.3 LOWER VALLEY DELINEATION

A geomorphologic delineation of the lower valley of the Sprague River basin was used to characterize the land use composition of areas that have the greatest degree of human impact and thus expected to have the greatest effect on water quality²⁸. The delineation of the lower valley was obtained from O’Conner et al. (2013) who performed this delineation using remote sensing data and field surveys. The lower valley region encompasses the floodplain and main alluvial valleys of the Sprague River and its major tributaries (Sycan River, North Fork, and South Fork). Figure 8 shows the extent of the lower valley.

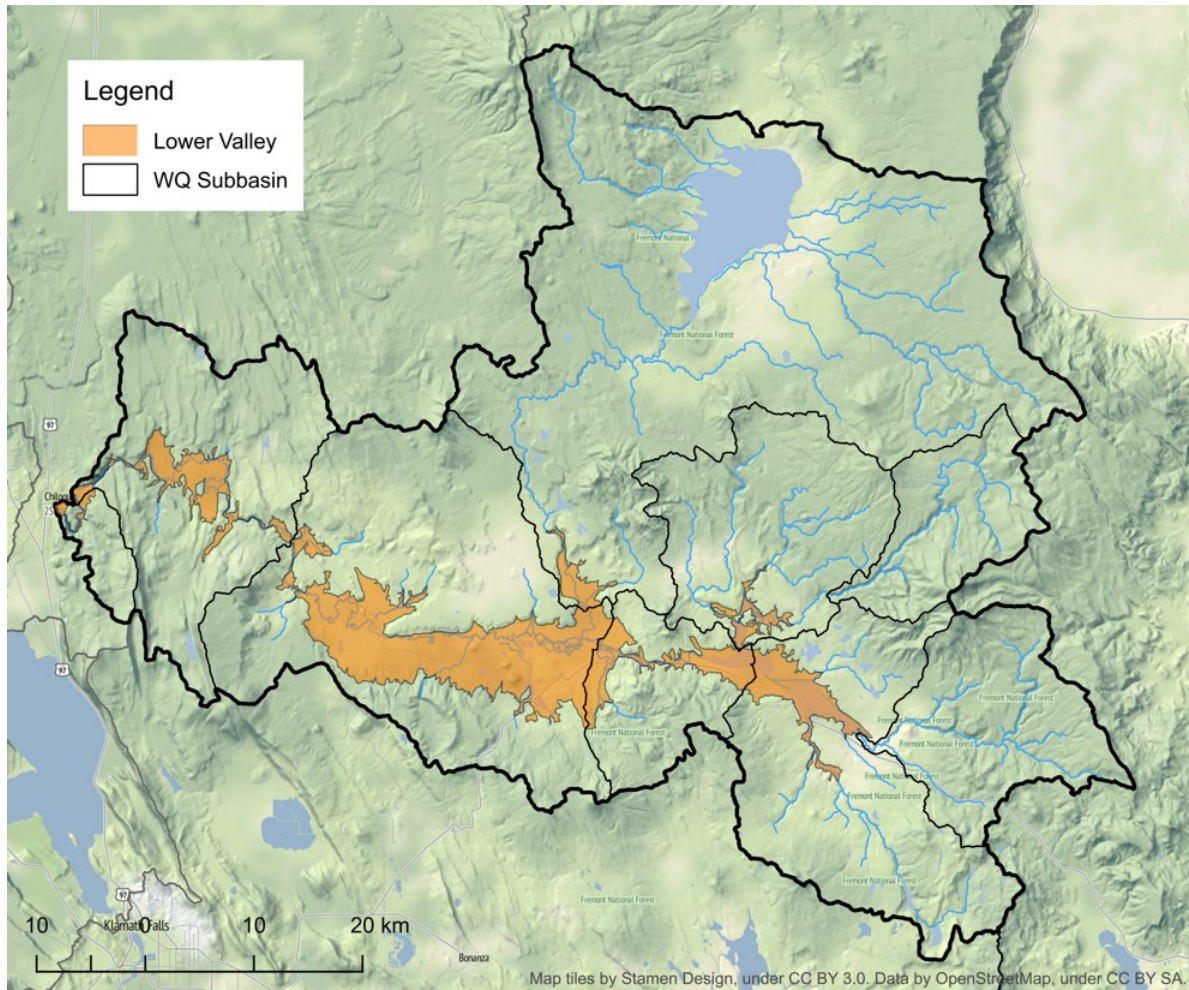


Figure 8: Geomorphological delineation of Sprague River valley.

Source: O’Conner et al. (2013)

2.4.4 LAND USE

Figure 9 presents the land use composition of the Sprague River basin based on the National Land Cover Dataset (NLCD) v2011 dataset (Homer et al., 2015).

²⁸ As discussed above, Records et al. (2014) note that the majority of agriculture in the Sprague River valley is flood-irrigated pastureland concentrated in the lower valleys.

The land use composition of each sub-basin (i.e., % area of each land use category) was determined by performing a spatial intersection between the NLCD land cover raster layer and the sub-basin polygons, and then tabulating the percent area of each sub-basin for each land use type using zonal statistics. The land use composition was similarly determined for the lower valley of each sub-basin by first clipping the land use raster to the lower valley delineation (see Figure 8).

The percent land-use composition of each sub-basin is shown in Figure 10 for both the lower valley and total area of each cumulative sub-basin. Note that the NLCD land use categories shown in Figure 10 were aggregated from the sub-categories shown in Figure 9 to higher level categories for the purpose of this study (e.g., Forest includes Deciduous Forest, Evergreen Forest, and Mixed Forest). Also note that because the lower valley delineation does not extend above the upper SF and NF water quality stations (see Figure 8; upper SF and NF watersheds), the lower valley land use composition is not shown for these sub-basins in Figure 10.

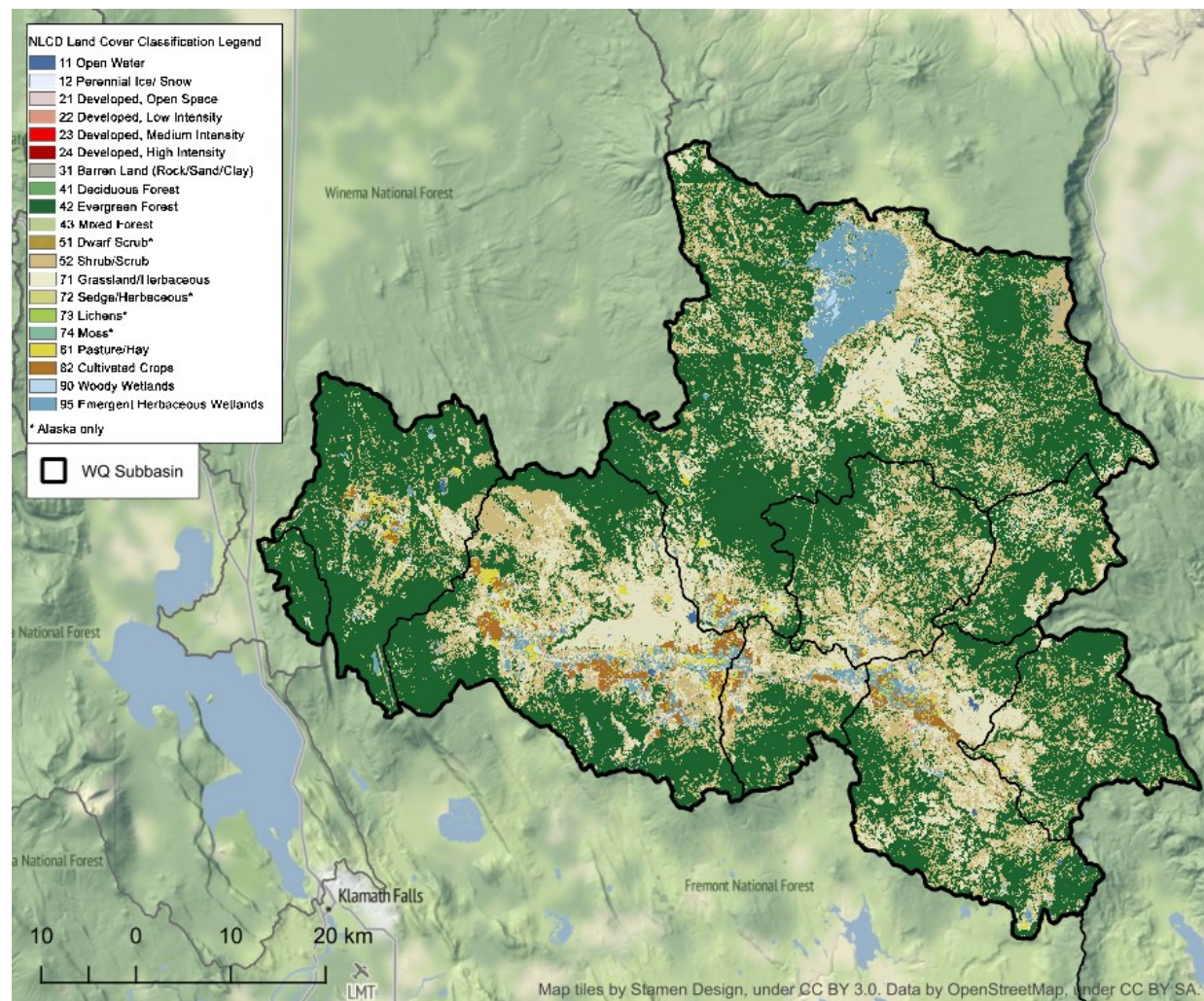


Figure 9: Map of NLCD land use composition.

Source: NLCD v2011 (Homer et al., 2015)

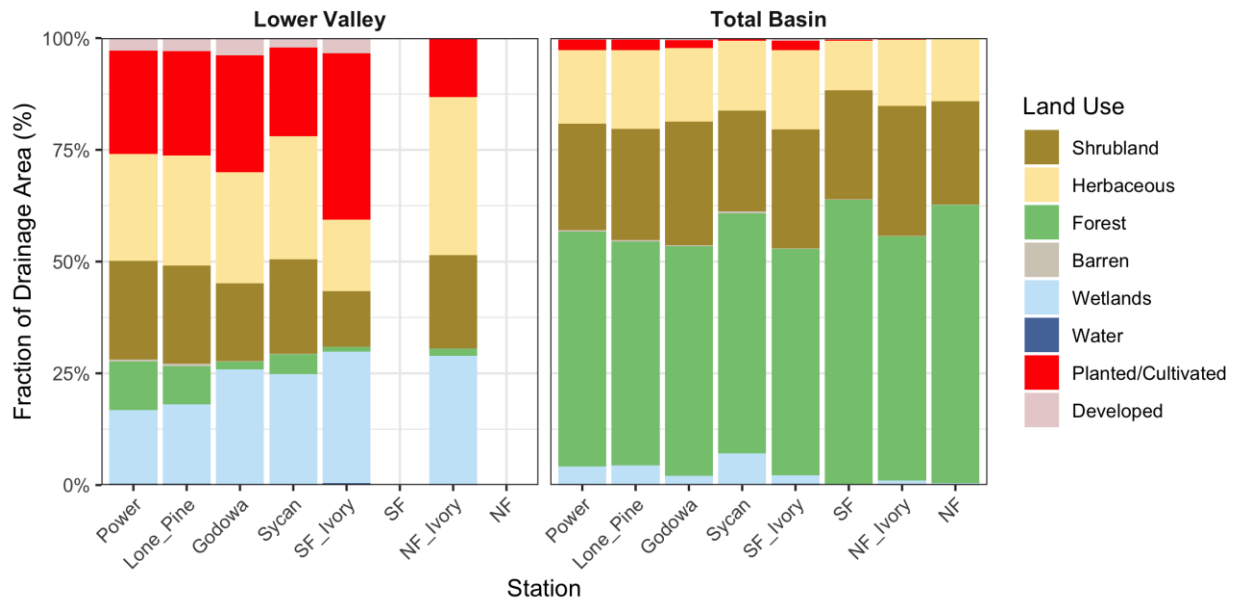


Figure 10: NLCD land use composition by water quality station in lower valley and total sub-basins.

Comparison of the left and right panels in Figure 10 reveals differences in the land use composition within the lower valley relative to the total sub-basin areas. In general, the lower valley contains greater fractions of developed and planted/cultivated land use whereas the basin-wide areas are more than 50% forested. The fraction of wetlands is also much greater in the lower valley than across the entire sub-basin areas. However, this classification does not distinguish between natural and human-made wetlands caused by irrigation or other hydrologic modifications. A review of aerial imagery and ground photos revealed that many of the areas classified as wetlands are actually used for grazing and other agricultural uses. Similarly, some areas classified as herbaceous or shrubland are used for agricultural purposes. Therefore, there are limitations in using the NLCD dataset for differentiating between areas that are “natural” and those that are impacted by human activities.

2.4.5 WATER RIGHTS PLACE OF USE (POU)

Because of the limitations in the NCLD dataset for differentiating between natural and anthropogenic land uses, an alternative representation of agricultural land use was derived from the OWRD water rights database (OWRD, 2022b). This database classifies water rights by use types, which include not only consumptive uses (e.g., domestic water supply or irrigation) but also environmental uses such as minimum in-stream flows. For this study, the dataset was limited to surface water rights classified for irrigation use, which comprise the majority of water rights in the basin. For each registered water right, a delineation of the land parcel associated with that water right is also available in the database; these areas are referred to as Place of Use (POU). Although POUs may not always accurately delineate irrigated areas²⁹, they provide an alternative means of relating agricultural land use to spatial variations in water quality.

²⁹ For example, only a portion of a POU may be irrigated in a given year and areas without POU’s shown in Figure 11 may have also been irrigated.

The POU areas associated with irrigation surface water rights were extracted from the database and used to represent land areas associated with agricultural land use. Figure 11 shows the POU irrigation areas and the associated water withdrawal locations referred to as points of diversion (POD). Figure 12 shows the percent of the cumulative drainage area as POU irrigation area for each water quality station within both the entire sub-basin drainage area and within only the lower valley. The percent POU areas in the lower valley are much greater than those for the total drainage areas indicating that most agricultural activities occur in the lower valley. The exception is the Sycan Marsh in the upper Sycan River basin, which is managed by The Nature Conservancy in cooperation with local ranchers for restoration and grazing (Connelly et al., 2007). The highest percent POU area in the lower valley occurs at SF_Ivory in the lower South Fork with over 80% of the lower valley upstream of this station being associated with POU irrigation areas. Above the Power station near the Sprague River outlet, POU areas account for 48% of the lower valley across the entire basin.

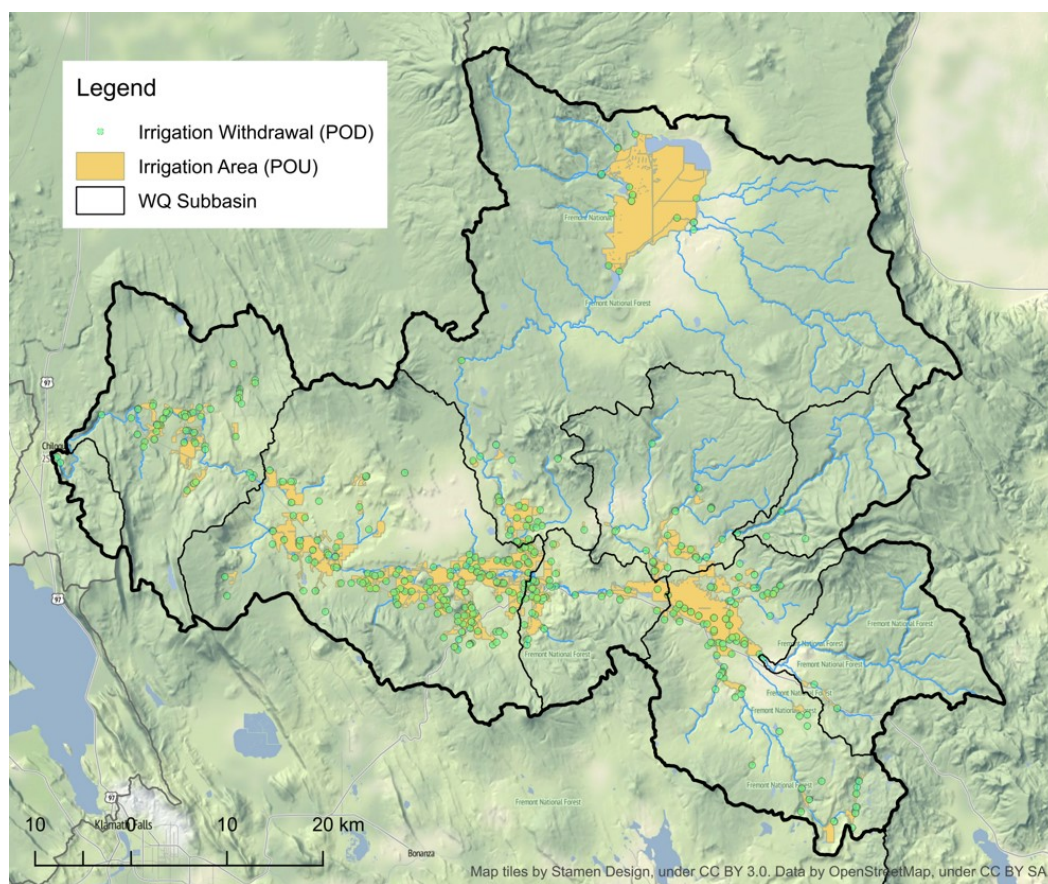


Figure 11: Map of Place of Use (POU) and Points of Diversion (POD) for irrigation water rights.

Source: OWRD (2022b)

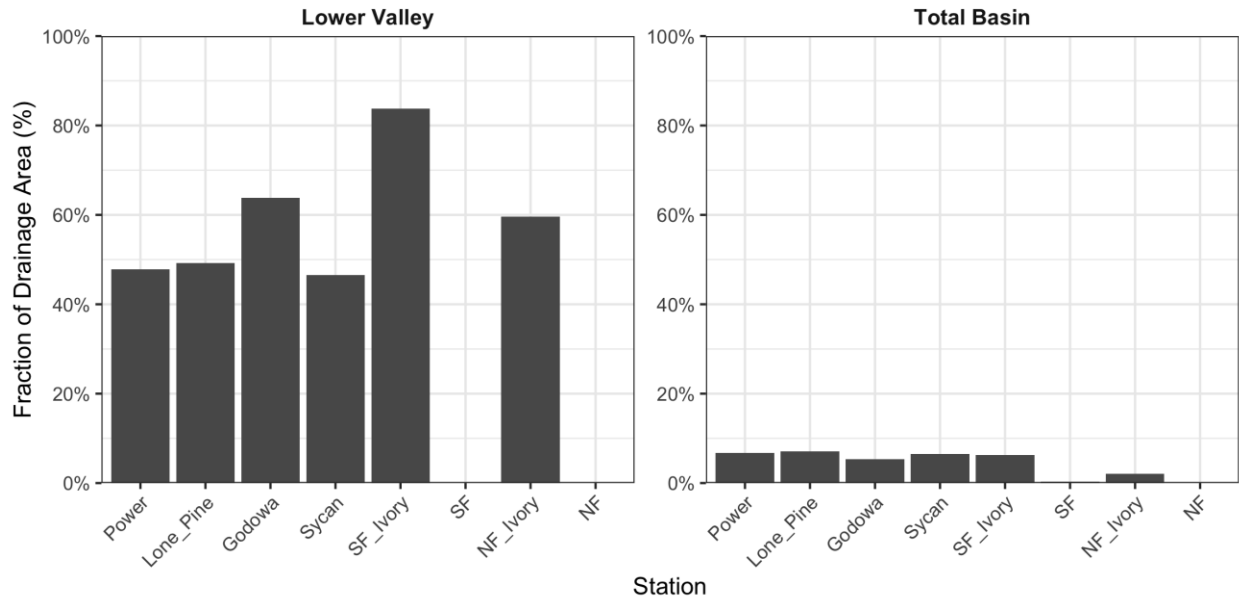


Figure 12: Fraction of drainage area as POU irrigation area in lower valley and total basin above each station.

3 METHODOLOGY

Daily timeseries of flows, loads, and concentrations were generated for each water quality station and parameter using the methodology in Walker and Kann (2022). Daily flows were generated from the biweekly flows measured by Klamath Tribes using daily streamflow records from three long-term, continuous streamflow gages in the basin. Similarly, daily concentrations were generated from the measured biweekly concentrations using predictions from a linear regression model that includes independent variables representing flow, time, and seasonality. Daily loads were computed by multiplying daily flows and concentrations. These daily timeseries were aggregated to various monthly, seasonal, and annual timescales by computing the sum of flows and loads. Flow-weighted mean (FWM) concentrations were then computed by dividing the total load by corresponding total flow.

Throughout this report, water years are used in place of calendar years to reflect the dynamics associated with the hydrologic cycle. Each water year begins on October 1 of the previous calendar year and ends the following September 30. For example, WY 2002 refers to the period October 1, 2001 to September 30, 2002. This report also aggregates results to seasonal increments based on 3-month intervals: Fall (October – December), Winter (January – March), Spring (April – June), and Summer (July – September).

Finally, many of the results presented in this report are based on mean annual values computed over multi-year periods for each station and sub-basin (e.g., mean annual flow, load, and FWM concentration). Because two of the stations (NF_Ivory, SF_Ivory) were added at the start of WY 2010, the mean annual results were primarily computed over the last 11 years of the study period, WY 2010 – 2020, in order to use consistent time periods across all stations. Mean annual results computed over the entire study period (WY 2002 – 2020) are provided in the appendices and exclude the two stations in the North and South Forks at Ivory Pine Rd.

3.1 STREAMFLOW MODEL

For each water quality station, a continuous timeseries of daily flows was generated based on the biweekly flow measurements collected by Klamath Tribes. Each water quality station was paired with a long-term continuous streamflow station maintained by USGS or OWRD, which are referred to as the reference³⁰ stations (Figure 13). Although there are other active streamflow gages in the basin (see Figure 6), only the three long-term stations with continuous data over the entire period of record (WY 2002 – 2020) were used as reference stations. The other four continuous streamflow stations are also located near the Klamath Tribes' water quality stations, but have shorter periods of record beginning in 2008 or 2009 and thus could not be used to compute daily flows over the entire study period. Daily flows measured at these other continuous stations were instead used for comparison purposes to evaluate amounts of bias and error in the computed daily flows at the coinciding water quality stations.

The two stations in the lower basin (Power and Lone_Pine) were both paired with the USGS station 11501000, which is located near the water quality station on the Sprague River at Power. The Sycan station was paired with OWRD station 11499100, both of which are located at the outlet of the Sycan River. The remaining stations at Godowa and on the North and South Forks were paired with the OWRD 11497500 station, which is located a few river miles upstream of the Godowa station in Beatty, OR.

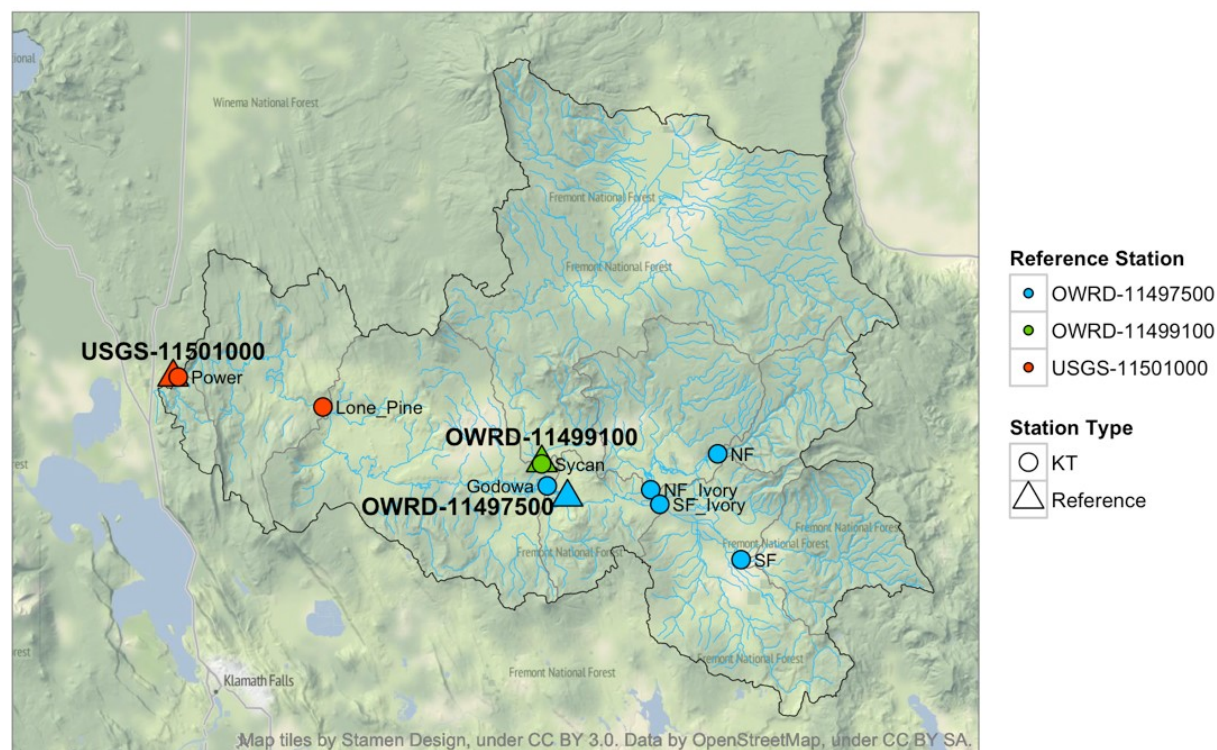


Figure 13: Map of reference streamflow gauge stations for estimating daily flows.

³⁰ Note that the term “reference” here does not imply that these stations represent background or un-impacted conditions as sometimes used in other studies, but rather that these stations are used as a reference for estimating the daily flows at nearby water quality stations.

Using these paired reference stations, the continuous daily flow records for each water quality station were generated using the following algorithm:

1. For each month of the year (Jan, Feb, ...), compute the mean flow over the period of record for the water quality station using the biweekly flows measured by Klamath Tribes, and for the corresponding reference station using only flows measured on water quality sampling dates (i.e., using the same dates as the biweekly flows).
2. For each month, divide the mean of the biweekly flows at the water quality station by the mean flow from the reference station to yield a mean flow ratio for that month.
3. Multiply the mean monthly flow ratios by the complete streamflow record from the reference station to generate an estimated daily flow record for each water quality station.
4. Compute log-transformed residual flows by dividing the estimated daily flow for each station by the biweekly flow measured by Klamath Tribes on each sampling date and taking the logarithm of this ratio.
5. Perform a linear interpolation of the log-transformed residuals to generate a continuous timeseries of daily log-residuals.
6. Multiply the interpolated daily log-residuals by the estimated daily flows generated in step 3.

By using the interpolated residuals of the estimated daily flows based on the monthly flow ratios, the end result is a continuous daily flow record for each water quality station that preserves the flows measured by Klamath Tribes on dates when water quality samples were collected. Between water quality sampling dates, the daily flows were computed using the log-residuals of the estimated daily flows computed from the monthly flow ratios. This process thus preserved the biweekly flows measured by Klamath Tribes and used the continuous reference streamflow datasets to fill in estimated daily flows between these biweekly flows via the algorithm described above.

3.2 WATER QUALITY MODEL

Continuous daily timeseries of concentrations and loads for each water quality parameter and station were generated using the same method that has been used previously for the nutrient mass balances of the entire UKL basin (Walker et al., 2012; Walker and Kann, 2022). This method uses predictions from a multiple linear regression model that relates the logarithm of concentration to various time and flow related terms to interpolate between the biweekly measured concentrations.

3.2.1 MODEL DESCRIPTION

The linear regression model is defined by the following equation:

$$\ln(C_t) = \beta_0 + \beta_1 \ln(Q_t) + \beta_2 [\ln(Q_t)]^2 + \beta_3 [\ln(Q_t)]^3 + \beta_4 \ln\left(\frac{Q_t}{Q_{t-1}}\right) + \beta_5 t + \beta_6 t^2 + \beta_7 \cos\left(2\left(\frac{2\pi j}{365.25}\right)\right) + \beta_8 \sin\left(2\left(\frac{2\pi j}{365.25}\right)\right) + \beta_9 \cos\left(\frac{2\pi j}{365.25}\right) + \beta_{10} \sin\left(\frac{2\pi j}{365.25}\right)$$

where C_t is concentration on date t , Q_t is the flow on date t , t is the date (in decimal years), and j is the Julian day of the year (e.g. Jan 1 = 1). This equation includes 11 coefficients and incorporates the effects of flow, rate of change in flow, date, and time of the year (or seasonality) on daily concentrations.

For each water quality station and parameter, this equation was fitted to the sampled concentrations using ordinary least squares regression. Note that all terms in this model were retained for each station and water quality parameter regardless of the significance of each coefficient in order to maintain consistency across all stations and parameters. The regression models were then used to generate a continuous timeseries of predicted daily concentrations, which were adjusted to correct for re-transformation bias from log space back to original concentrations units. Similar to the streamflow model described above, the log-residuals of the predicted daily concentrations were used to fill in estimated concentrations between sampling dates and thus generate continuous daily concentrations that preserve the measured values on dates when samples were collected. The resulting continuous daily concentration timeseries were then multiplied by the corresponding daily flow timeseries to generate daily loads for each station and parameter. More details about this algorithm as well as an illustrative example can be found in Figure D1 (Appendix D).

3.2.2 PARTICULATE PHOSPHORUS

The daily concentration timeseries for TP and PO₄ were used to estimate a daily concentration timeseries of particulate phosphorus (PP) at each station by difference ($PP = TP - PO_4$)³¹. Due to measurement uncertainty and other sources of error, this calculation yielded some negative PP concentrations where $TP < PO_4$. In these cases, the PP concentration was set to 1 ppb.

3.2.3 UNIT AREA RUNOFF AND NUTRIENT/SEDIMENT EXPORT BY CUMULATIVE SUB-BASIN

Unit area flows and loads (i.e., runoff and export rates) were computed for each cumulative sub-basin by dividing the flows and loads by the corresponding drainage area. These quantities represent the total unit area flow and load across the entire drainage area for each water quality station. In addition, flow-weighted-mean (FWM) nutrient concentrations were calculated by dividing load by flow for various time periods and watershed areas.

3.2.4 NET CHANGES IN FLOWS, LOADS AND CONCENTRATIONS BY INCREMENTAL SUB-BASIN

For each incremental sub-basin (see Figure 7, Section 2.4.2), the net changes in flows and loads were computed by subtracting the flows and loads at the downstream station from the sum of flows and loads at upstream stations. These differences in flows and loads represent the **net** changes between sampling stations and incorporate both sources (e.g., runoff, agricultural return flows, groundwater discharge) and sinks (e.g., biological uptake³², settling, water withdrawals) along the corresponding river reach. The net change in FWM concentration was also computed by difference for each incremental sub-basin. The change in FWM concentration indicates whether the concentrations increased or decreased over each river reach and by how much. Note that the changes in concentrations are not direct estimates of the concentration associated with direct loading to the reaches because these

³¹ For the Sevenmile system on the west side of the Upper Klamath Basin these estimates have been shown to overestimate the amount of particulate P due to the presence of dissolved P fractions in the TP measurement. However, those systems are dominated by wetlands and wetland soils, and the difference between $TP - PO_4$ is expected to better approximate particulate P in the Sprague basin.

³² The Sprague River and tributaries are known for areas of extensive aquatic plant growth and attached algae (ODEQ, 2002). Although biological uptake occurs, it usually reflects a temporary sink as plant and algal material often detaches and is transported downstream. For example, dead plant material is often observed in the water column in the downstream most reaches of the Sprague and Williamson Rivers prior to entering UKL.

changes incorporate both sources and sinks and are affected by in-stream water quality processes. The net changes in flows and loads per unit area were also computed by dividing the net flows and loads by the incremental sub-basin drainage areas.

Because the net changes in flows, loads, and concentrations were computed by difference, these terms can result in negative values if the sum of the upstream stations is greater than the value at the downstream station. These negative values thus indicate a net decrease in flow, load, or concentration between the upstream and downstream stations.

3.3 TREND ANALYSIS

Trend analyses were performed on the continuous timeseries of flows, loads and concentrations at each long-term water quality station and water quality parameter as well as on precipitation to determine whether conditions have significantly changed over the entire study period due to either natural or anthropogenic activities. The daily timeseries of each term was first aggregated to monthly time steps by computing the mean monthly flow and load, and then computing the monthly FWM concentration by dividing monthly load by flow. Trends were computed over two primary periods: 1) the complete period of record, WY 2002 – 2020, which excludes the NF and SF Ivory Rd stations as well as TSS, 2) the last 11 years, WY 2010 – 2020, in order to include the NF and SF Ivory Rd stations for comparison against the other stations, and 3) the last 10 years, WY 2011 – 2020, for TSS at all stations since sampling of TSS did not begin until WY 2011.

Trends were evaluated using both non-parametric and parametric statistical tests. The primary trend test was based on the non-parametric seasonal Kendall test, which is commonly used to evaluate trends in hydrologic timeseries exhibiting seasonal patterns and is more robust than parametric methods that require assumptions regarding the distributions of the data (Helsel et al., 2020). The seasonal Kendall test was applied to the entire timeseries of each term, as well as monthly and seasonal subsets to determine whether trends occurred primarily during one or more seasons. In addition to the seasonal Kendall test, trends in annual mean precipitation, flows, loads, and FWM concentrations were evaluated using the non-parametric Mann-Kendall test and a simple linear regression, which is a parametric test.

For all trend tests of flows, loads, and concentrations, the values were first transformed to a \log_{10} scale (precipitation values were not transformed due to some months having zero precipitation). The significance of each trend test was evaluated by comparing the p-value to critical thresholds of $\alpha = 0.05$ ($p \leq 0.05$ indicating high significance) and $\alpha = 0.10$ ($0.05 < p \leq 0.10$ indicating moderate significance). The slope and intercept of each trend were estimated using the Sen slope estimator for the non-parametric methods (Helsel et al., 2020). The estimated slopes for flows, loads and concentrations were converted from log-transformed units (e.g. $\log(\text{hm}^3/\text{d})$, $\log(\text{kg}/\text{d})$, $\log(\text{ppb})$) per year to percent per year by:

$$[\text{Slope in \%}/\text{yr}] = 10^{[\text{Slope in log(units)}/\text{yr}]} - 1$$

For precipitation, which was not based on a log-scale, the slope in percent per year was computed by dividing the slope in original units by the mean value over the study period.

A sensitivity analysis was also performed to evaluate the impact of varying the starting year of the trend analysis period. The primary trend test (seasonal Kendall test using all months) was recomputed over rolling periods with the first year varying from the first year of the period of record (WY 2002 for most stations, WY 2010 for the NF/SF Ivory Rd Stations, and WY 2011 for TSS) to WY 2015 and the last year always ending in WY 2020. These rolling trend periods thus ranged from 19 to 6 years in duration.

4 RESULTS AND DISCUSSION

The following sections present and discuss key results with respect to:

- 4.1 Climate Conditions
- 4.2 Streamflow Model Results
- 4.3 Water Quality Model Results
- 4.4 Seasonal Patterns of Monthly Flows, Loads, and Concentrations
- 4.5 Spatial Patterns of Mean Flows, Loads, and Concentrations
- 4.6 Relationships between Concentrations and Land Use
- 4.7 Phosphorus, Sediment, and Nitrogen Dynamics Related to Flow and Season
- 4.8 Background vs Anthropogenic Loading
- 4.9 Impacts of Water Rights Calls
- 4.10 Trend Analyses

Additional results and diagnostic plots are provided in the following appendices:

- A Data Sources
- B Exploratory Data Analysis and Review of Water Quality Data
- C Streamflow Model Results and Diagnostics
- D Water Quality Model Results and Diagnostics
- E Reach Network Plots of Flows, Loads, and Concentrations
- F Spatial Maps of Flows, Loads, and Concentrations
- G Trend Analysis Results and Diagnostics

4.1 CLIMATE CONDITIONS

Using the precipitation and snowpack datasets (see Sections 2.2.1 and 2.2.2), this section provides the hydrologic context for interpreting year-to-year and seasonal patterns in the streamflow and water quality results.

4.1.1 PRECIPITATION

Figure 14 shows the annual precipitation by water year for the Sprague River basin over a 39-year period (WY 1982 – 2020). During the study period (WY 2002 – 2020; highlighted in yellow), annual precipitation was less than the long-term (WY 1982 – 2020) mean of 56.8 cm/yr in all but five years (WYs 2006, 2011, 2016, 2017, 2019). In one of the study period years (WY 2020), annual precipitation was 34.1 cm, which was only 1.5 cm higher than the lowest annual precipitation over this period (32.6 cm in WY 1994).

Figure 15 shows the total precipitation in the Sprague River basin for each 3-month season by water year over the study period (WY 2002 – 2020). Precipitation was generally highest in fall and winter, followed by spring, and the lowest precipitation occurred in summer. The majority of precipitation in the fall and winter seasons occurred in the form of snowfall, although temperatures can vary widely during these seasons across elevations resulting in rain and rain-on-snow events.

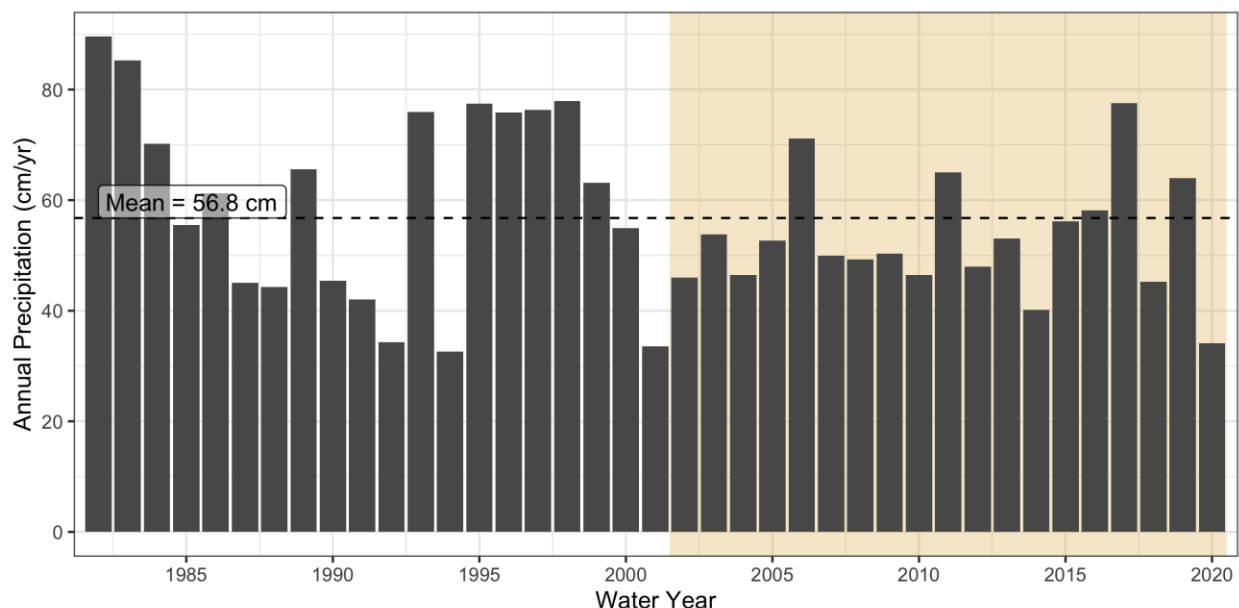


Figure 14: Annual precipitation in Sprague River basin, WY 1982 – 2020.

Shaded area indicates study period, WY 2002 – 2020.

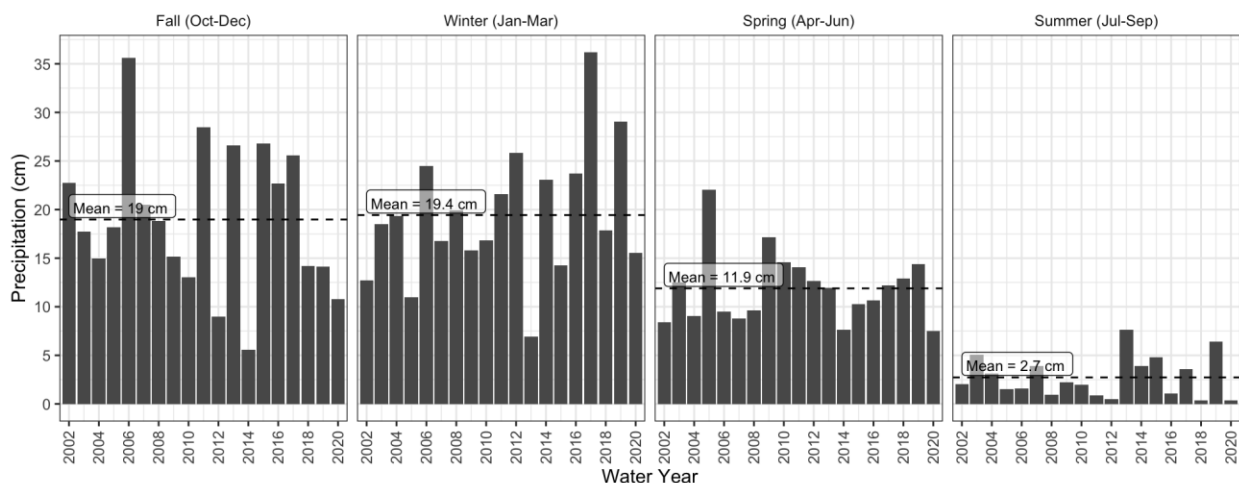


Figure 15: Seasonal precipitation by water year, WY 2002 – 2020.

4.1.2 SNOWPACK

Figure 16 shows the daily snow water equivalent (SWE) for each of the three SNOTEL stations over WY 1979 – 2020 (see location map in Figure 5). The largest snowpack occurred in WY 2006 and the smallest snowpacks occurred in WYs 2014, 2015, and 2018.

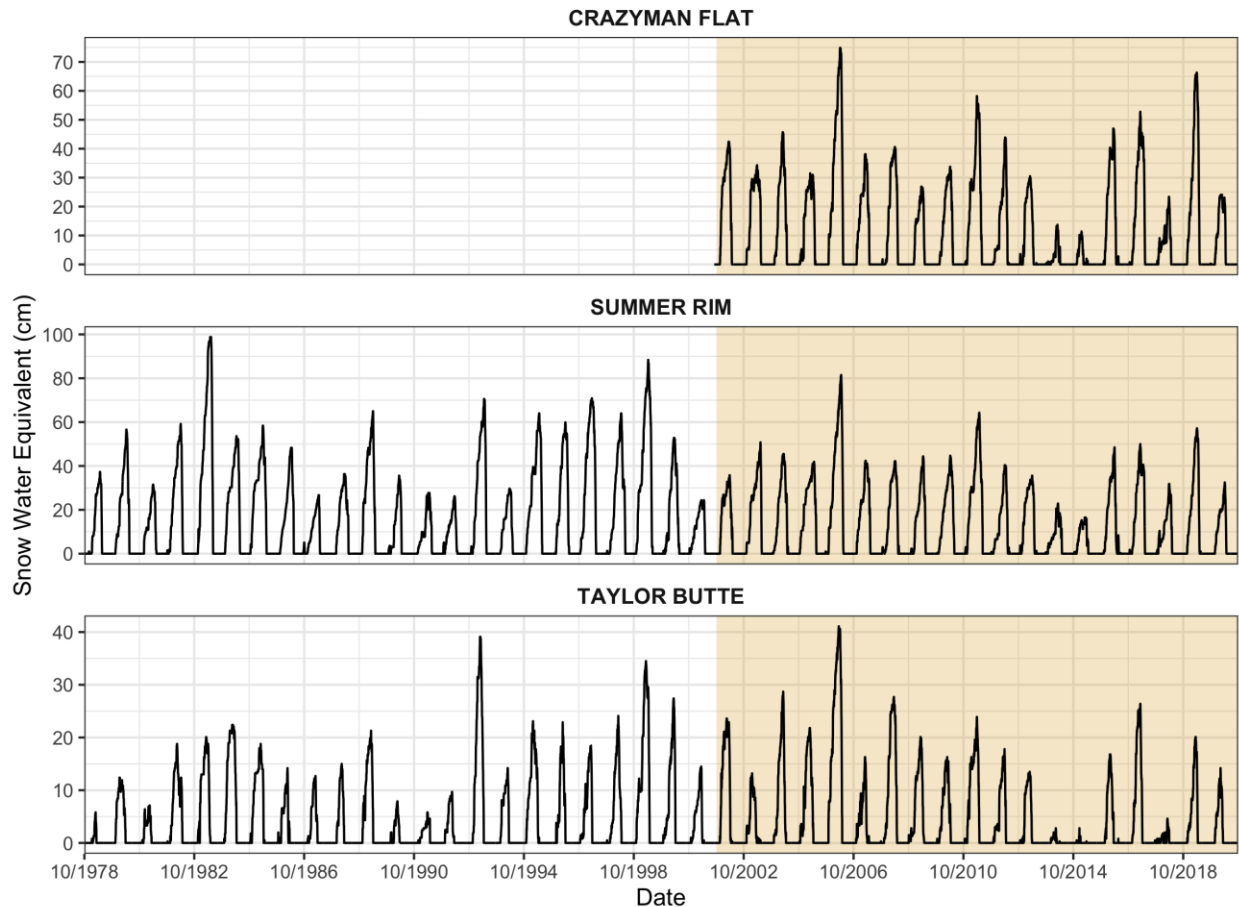


Figure 16: Historical daily snow water equivalent, WY 1979 – 2020.

Shaded area indicates study period, WY 2002 – 2020.

Figure 17 shows the daily SWE by day of the year (starting at beginning of the water year on Oct 1) in order to compare the magnitude and timing of snowpack formation and melting across different years. Snowpack generally begins forming between mid-October and early-December, and melts in April or May depending on the year and location. During the last 8 water years (WY 2013 – 2020, highlighted in red in Figure 17) during which the Tribes' water rights were in effect, the snowpack tended to be smaller and also melted earlier than in the first 11 years (WY 2002 – 2012, gray in Figure 17). These declining trends are also reflected in the annual maximum SWE, April 1 SWE, and the last day of each year when the SWE fell below 1 cm (Figure 18). These declines in snowpack and snowmelt timing are consistent with Mayer and Naman (2011) who concluded that warmer winter temperatures and snowpack reductions have caused significantly earlier runoff peaks in the Klamath Basin based on long-term streamflow analysis.

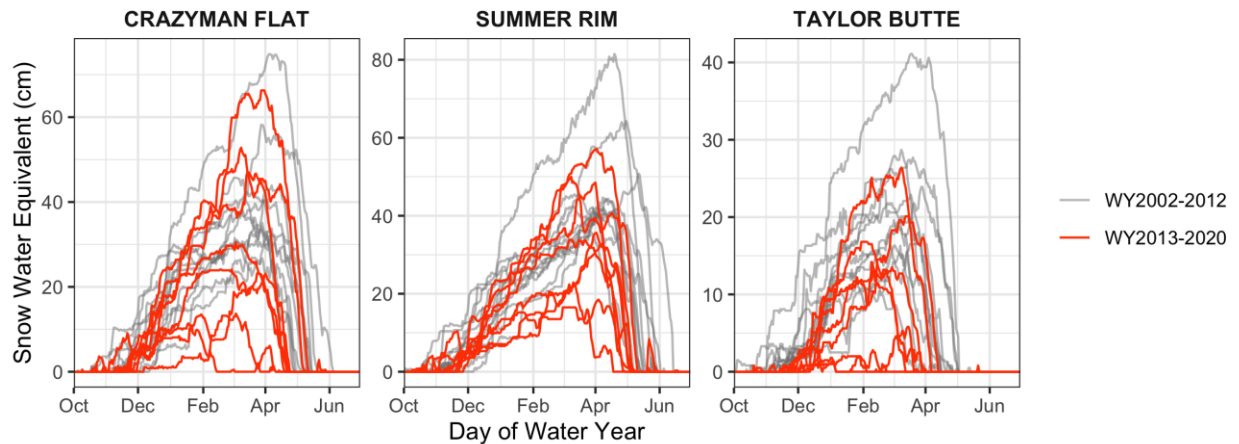


Figure 17: Seasonal variations in daily snow water equivalent, WY 2002 – 2020.

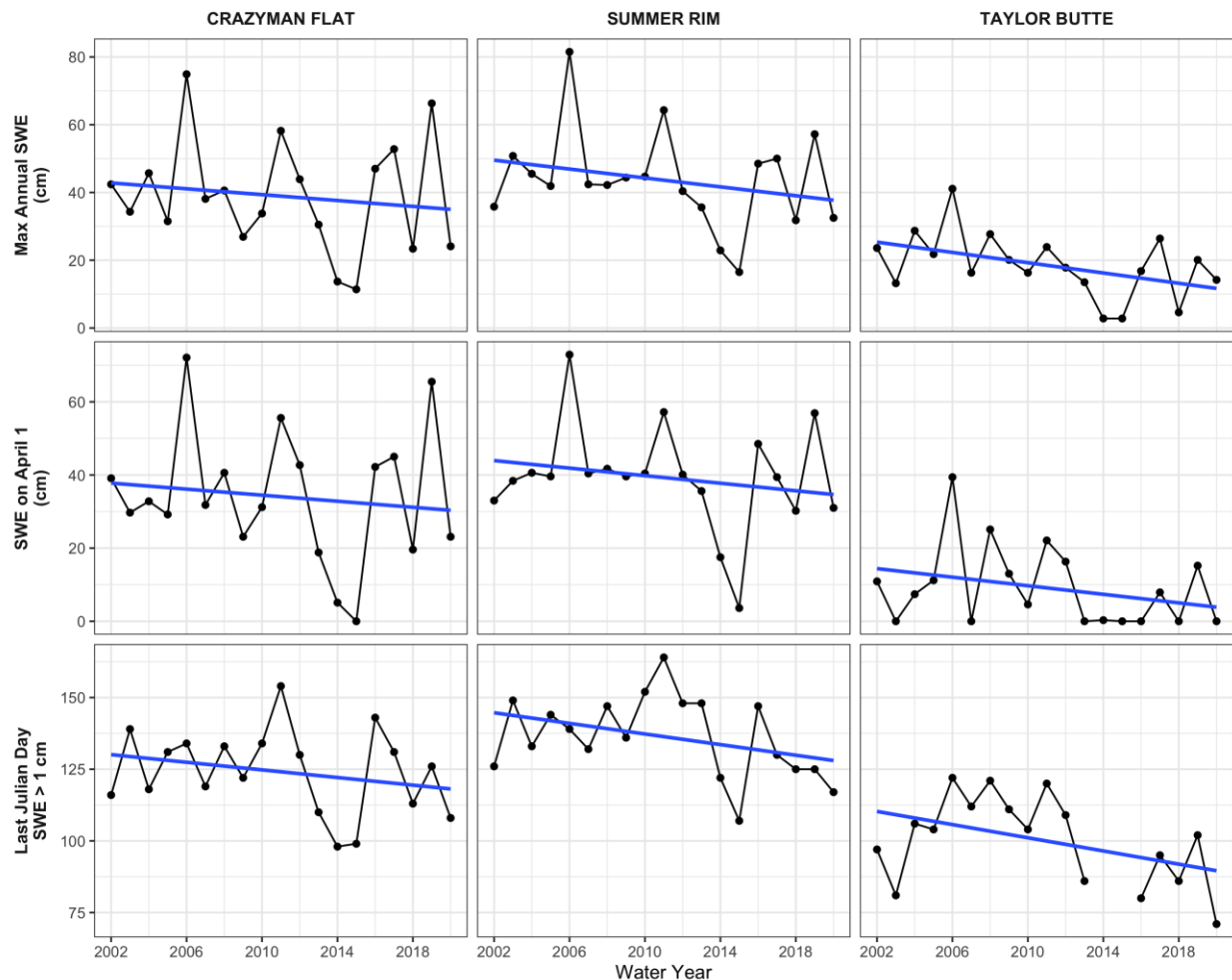


Figure 18: Annual variations in maximum and April 1 SWE, and snowmelt timing of each year, WY 2002 – 2020.

Bottom row shows the last Julian day (y-value) of each water year when the snowpack fell below 1 cm (Julian Day of 100 = April 10, 150 = May 30). Gaps at Taylor Butte in WYs 2014 and 2015 due to no significant snowpack in those years. Blue lines show linear regression trendlines.

4.2 STREAMFLOW MODEL RESULTS

4.2.1 RESULTS AND DIAGNOSTICS

For each water quality station, the daily streamflow model results are summarized by a diagnostic display containing the following charts:

- Timeseries of the continuous daily flows at the reference station, biweekly flows measured by Klamath Tribes, and final computed daily flows for the water quality station.
- Scatterplot comparison between the biweekly measured flows and the corresponding continuous daily flows measured at the reference site.
- Distributions and mean values of the monthly flow ratios used to scale the daily reference flows.
- Timeseries of the flow residuals.
- Scatterplot comparison of the flow residuals against the measured biweekly flows to show any potential bias under low or high flows.

Figure 19 provides an example of the streamflow model diagnostics for the Power water quality station on the Sprague River. The residuals timeseries plot in this figure (bottom-center panel) shows greater variability in the first half of the period (before 2008) compared to the second half (after 2008). This change indicates greater differences between the biweekly flows measured by Klamath Tribes and the continuous measurements made by USGS at the nearby reference station. This pattern could be caused by changes in the rating curves at one or both of these stations, or a change in the river hydraulics caused by removal of the Chiloquin Dam in mid-2008, which was located a few miles downstream of these stations. Results and diagnostics for the other stations are provided in Figure C1 (Appendix C), as well as comparisons between computed daily flows at the Lone_Pine, Godowa, SF, and NF stations and the corresponding continuous streamflow gages mentioned in Section 3.1 that were not used as reference stations (Figures C2 – C5, Appendix C).

Streamflow Model Diagnostics

Site: Power | Reference Site: USGS:11501000

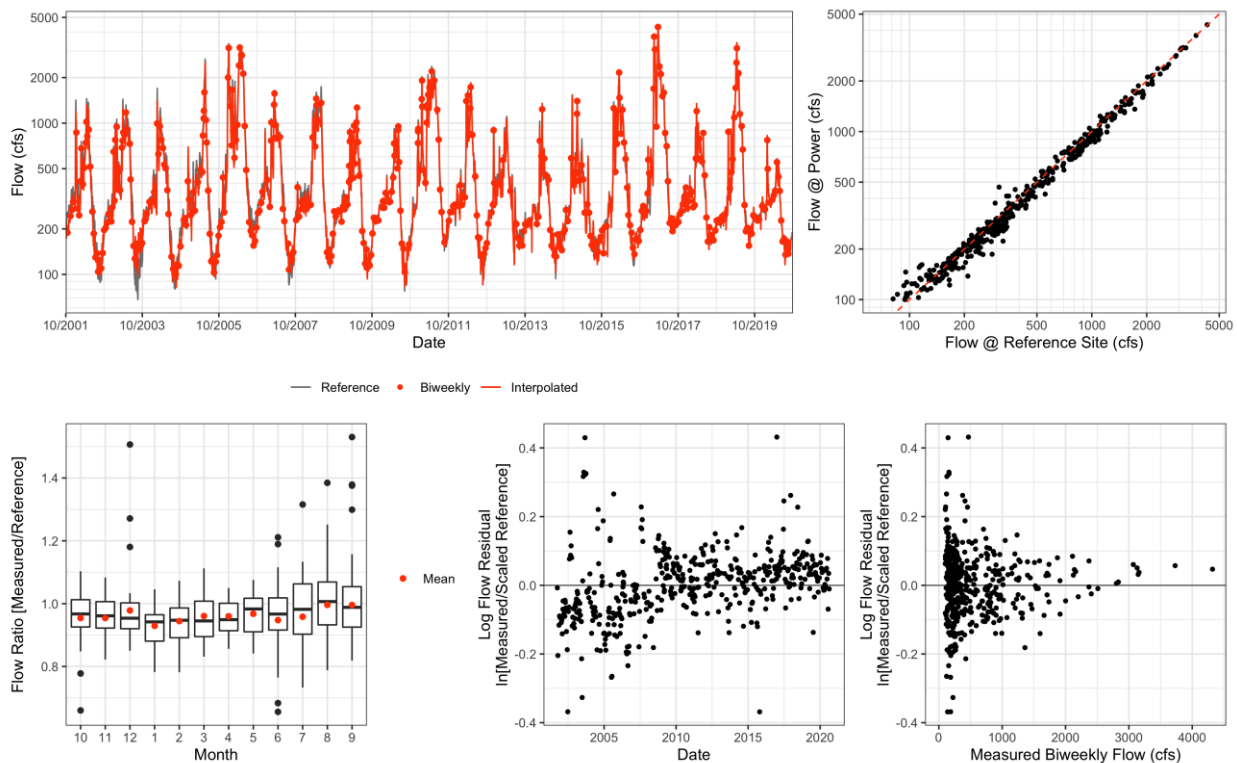


Figure 19: Streamflow model diagnostics for Power station.

4.2.2 ANNUAL AND SEASONAL STREAMFLOW

Figure 20 shows the mean annual and seasonal flows at each water quality station over the last 11 years of the study period (WY 2010 – 2020)³³. This figure also includes the total flow for two pairs of combined stations: Godowa+Sycan representing the combined flow at the confluence of the Sprague and Sycan Rivers just downstream of the Godowa station, and SF_Ivory+NF_Ivory representing the combined flows from the South Fork and North Fork at the start of the upper Sprague River mainstem. As expected, the highest flows occur in spring due to snowmelt and the lowest flows occur in summer when there is little precipitation. Also in summer, there is relatively little change in flow along the lower Sprague River from Godowa to Power despite numerous springs and tributaries discharging between these stations (see Section 4.2.3 below).

³³ Only the last 11 years of the study period are shown in order to include the SF_Ivory and NF_Ivory stations

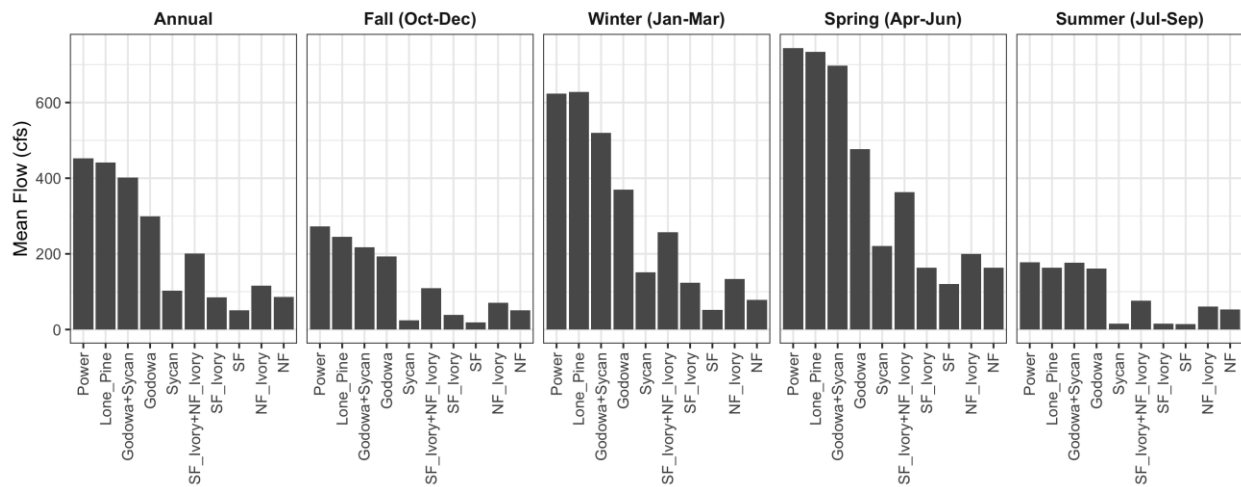


Figure 20: Mean annual and seasonal flows at each station, WY 2010 – 2020.

Figure 21 shows the net changes in mean annual and seasonal flow for each incremental sub-basin over WY 2010 – 2020. The net change in mean annual flow showed a relatively small increase (+12 cfs) in the lower Sprague River between Lone_Pine and Power despite an increase in drainage area of 420 km² (10% of the total basin area). Furthermore, there was a small decrease of 4 cfs between these stations under high flow conditions during the winter.

Among the other sub-basins, flow also decreased by 13 cfs in the middle Sprague River (Godowa to Lone_Pine) during summer. Similarly, summer flows only increased by 1 cfs in the lower South Fork, which is heavily modified by canals and irrigation ditches. In the upper Sprague River, there was a consistent increase in flow both annually and across all seasons ranging from 84 to 114 cfs. The relatively low variability across seasons suggests that flow gains in this reach were primarily from groundwater discharge, which is discussed further in Section 4.2.3 below.

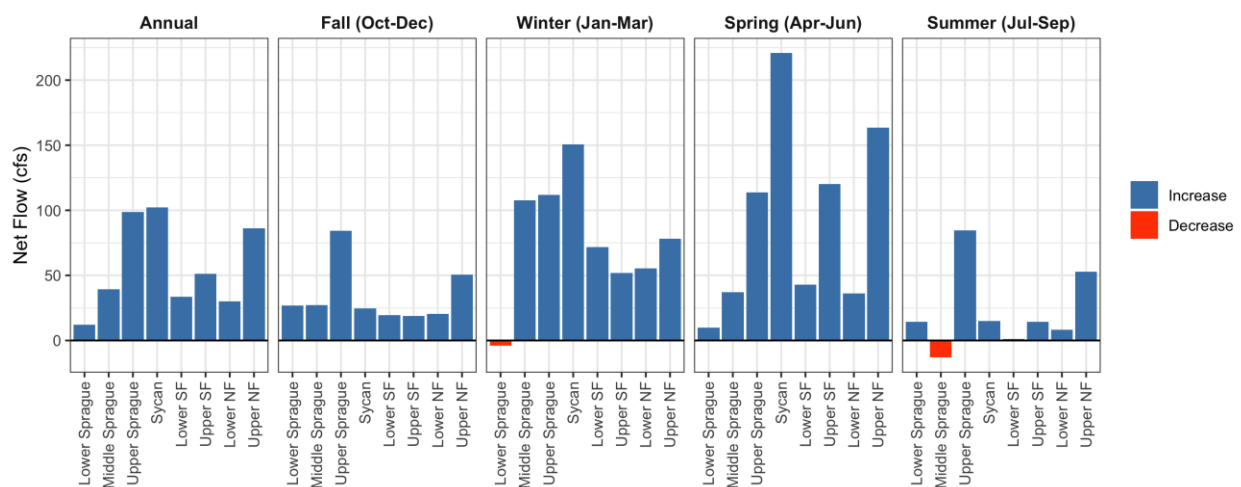


Figure 21: Net changes in mean annual and seasonal flows of each incremental sub-basin, WY 2010 – 2020.

4.2.3 GROUNDWATER DISCHARGE

In order to better understand the changes in flow along the Sprague River as well as the potential for nutrient loading from groundwater, the net changes in mean summer flow were compared to estimates of groundwater discharge reported by Gannett et al. (2007). Gannett et al. (2007) used synoptic flow measurements to estimate groundwater discharge rates from springs and seeps along discrete reaches of the Sprague River and its tributaries. In order to compare their estimates to the results of this study, the reaches defined by Gannett et al. (2007) (see Table 6 of their report) were aggregated to the reaches coinciding with incremental sub-basins based on the Klamath Tribes' water quality stations. Most of the reaches defined in Gannett et al. (2007) use start and end points that are located at or near the Klamath Tribes water quality stations, with one exception: Reach 10, which extends from the South Fork Sprague at Picnic Area (RM 10.2), where the Tribes' SF station is located, to Sprague at Cinder Pit (RM 77.5), which is about 6 miles upstream of the Godowa station. Because about half of Reach 10 extends above the outlet of the South Fork at the SF_Ivory station, the total groundwater discharge from this reach was split evenly between the Upper Sprague and Lower South Fork sub-basins. Also, note that the total spring discharge for the Sycan River only includes the reaches below the Sycan Marsh, which Gannett et al. (2007) report as a net sink of groundwater at a rate between -10 to -20 cfs.

Table 7 lists the total groundwater discharge and the associated reaches from Gannett et al. (2007) for each incremental sub-basin and compares these values to the net change in mean summer flow over the period WY 2010 – 2020. The mean flows during summer were used due to the relatively little precipitation that occurs during this season, and thus most flow is expected to originate from groundwater seeps and springs. Figure 22 provides a comparison of the total groundwater discharges and the net change in summer flows.

Table 7: Spring/seep discharge from Gannett et al. (2007) and mean net summer flows by incremental sub-basin, WY 2010 – 2020.

Incremental Sub-basin	Gannett et al. (2007)		WY 2010 – 2020
	Reaches*	Total Flow (cfs)	Net Summer Flow (cfs)
Lower Sprague	19-22	73	14
Middle Sprague	15-18	20	-13
Upper Sprague	10**-14	94	85
Sycan	27-31	21	15
Lower SF	10**	13	1
Upper SF	1-4	24	14
Lower NF	7-9	33	8
Upper NF	5-6	59	53

* Reach numbers referenced from Table 6 of Gannett et al. (2007)

** Reach 10 split evenly between Upper Sprague and Lower SF

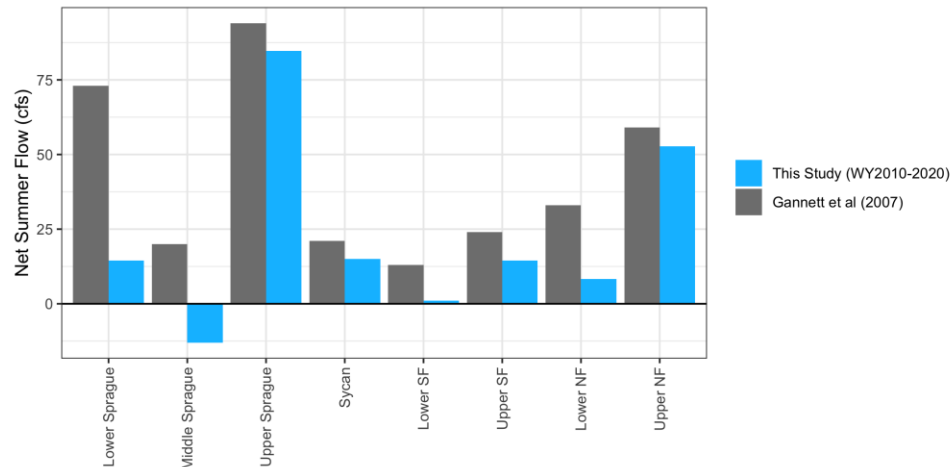


Figure 22: Spring/seep discharge from Gannett et al. (2007) and mean net summer flows by incremental sub-basin, WY 2010 – 2020.

Table 7 and Figure 22 show close agreement between the total groundwater discharge from Gannett et al. (2007) and the estimated net summer flow in some reaches, but not others. In the three headwater basins (upper North Fork, upper South Fork, and the Sycan River), net summer flows were slightly less than the total groundwater discharge, which is expected because the net flows incorporate losses due to, for example, evaporation and water withdrawals. Among the other incremental sub-basins, the large increase in net summer flow of 85 cfs in the upper Sprague River closely matched the total groundwater discharge of 94 cfs. As mentioned above in Section 4.2.2, the net increase in flow for this reach was fairly consistent across seasons. Therefore, this comparison provides further evidence that a large source of the flow gain in the upper Sprague River upstream of the Godowa station originates from groundwater discharge.

However, for the other incremental basins, there are greater differences between the net summer flow and total groundwater discharge. The largest difference was in the lower Sprague River between Lone_Pine and Power, which received an estimated 73 cfs of groundwater discharge, but had a net flow increase of only 14 cfs. In the middle section of the Sprague River between Lone_Pine and Godowa+Sycan, the total groundwater discharge was 20 cfs, but the net change in summer flow was -13 cfs. Because these differences were greater for areas with higher levels of human activity, this comparison suggests that human activity (e.g., irrigation withdrawal) has a significant impact on the flows in the river during summer. However, detailed quantification of the total sources (e.g., runoff, groundwater pumping, return flows) and sinks (e.g., evapotranspiration, consumption) in each reach is needed to determine the causes of these changes in flows and the differences relative to the total groundwater discharge estimates from Gannett et al. (2007).

4.3 WATER QUALITY MODEL RESULTS

4.3.1 DIAGNOSTIC AND SUMMARY DATA DISPLAYS

Similar to the streamflow model results, the water quality model results are summarized by a series of data displays providing daily, annual, and monthly results as well as various diagnostic summary

statistics and comparison charts. These summary and diagnostic displays are provided in Figure D3 (Appendix D).

For each station and water quality parameter, a series of three data displays were generated. Figure 23 – Figure 25 show examples for the results of TP at the Power water quality station located near the outlet of the Sprague River. The first set of charts (Figure 23) shows the estimated daily and annual concentrations, flows, and loads. The next set of charts (Figure 24) shows monthly timeseries and distributions of mean values by month of the year to illustrate the seasonality in each term. Finally, the last set of charts (Figure 25) shows diagnostic plots of the model residuals and comparisons between the observed and predicted concentrations and loads, as well as summary tables of the model performance and estimated coefficients. Similar sets of charts for the other stations and parameters are provided in Figure D3 (Appendix D).

Daily and Annual Flows, Loads, and Concentrations

Station: Power | Parameter: TP

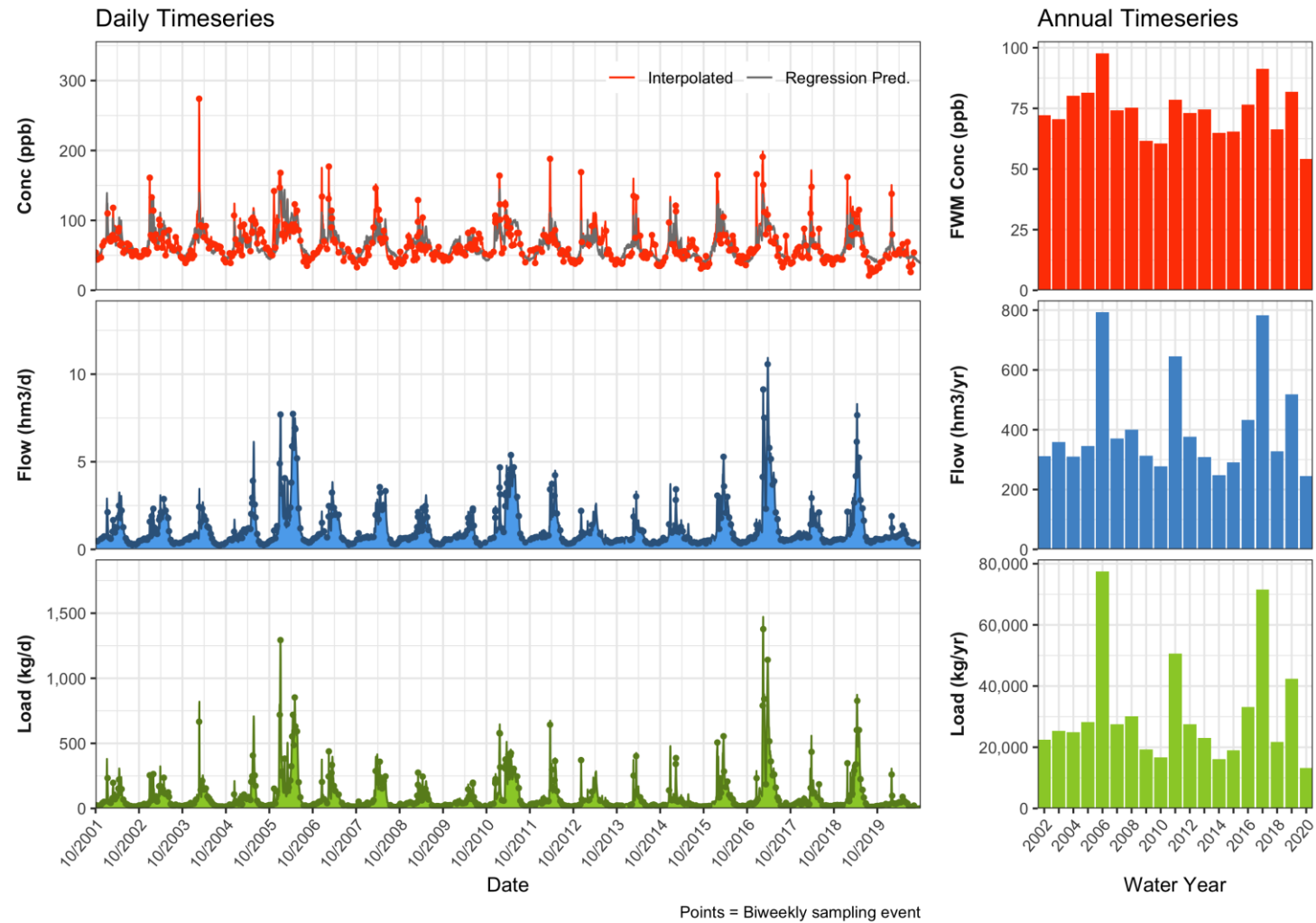


Figure 23: Example of daily and annual water quality model diagnostics for TP at Power station.

Monthly Flows, Loads, and Concentrations

Station: Power | Parameter: TP

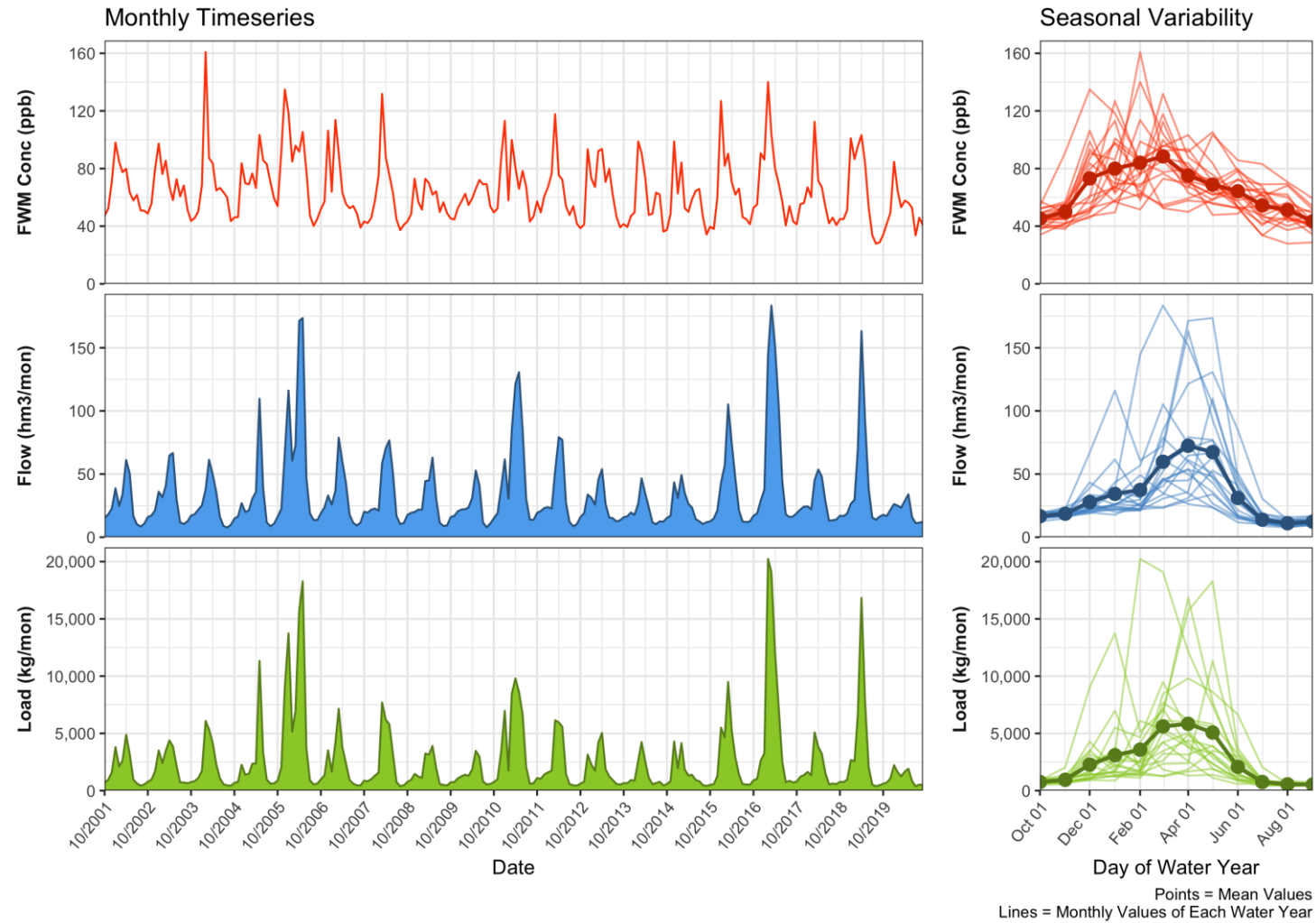


Figure 24: Example of monthly water quality model diagnostics of monthly results for TP at Power station.

Regression Model Diagnostics

Station: Power | Parameter: TP

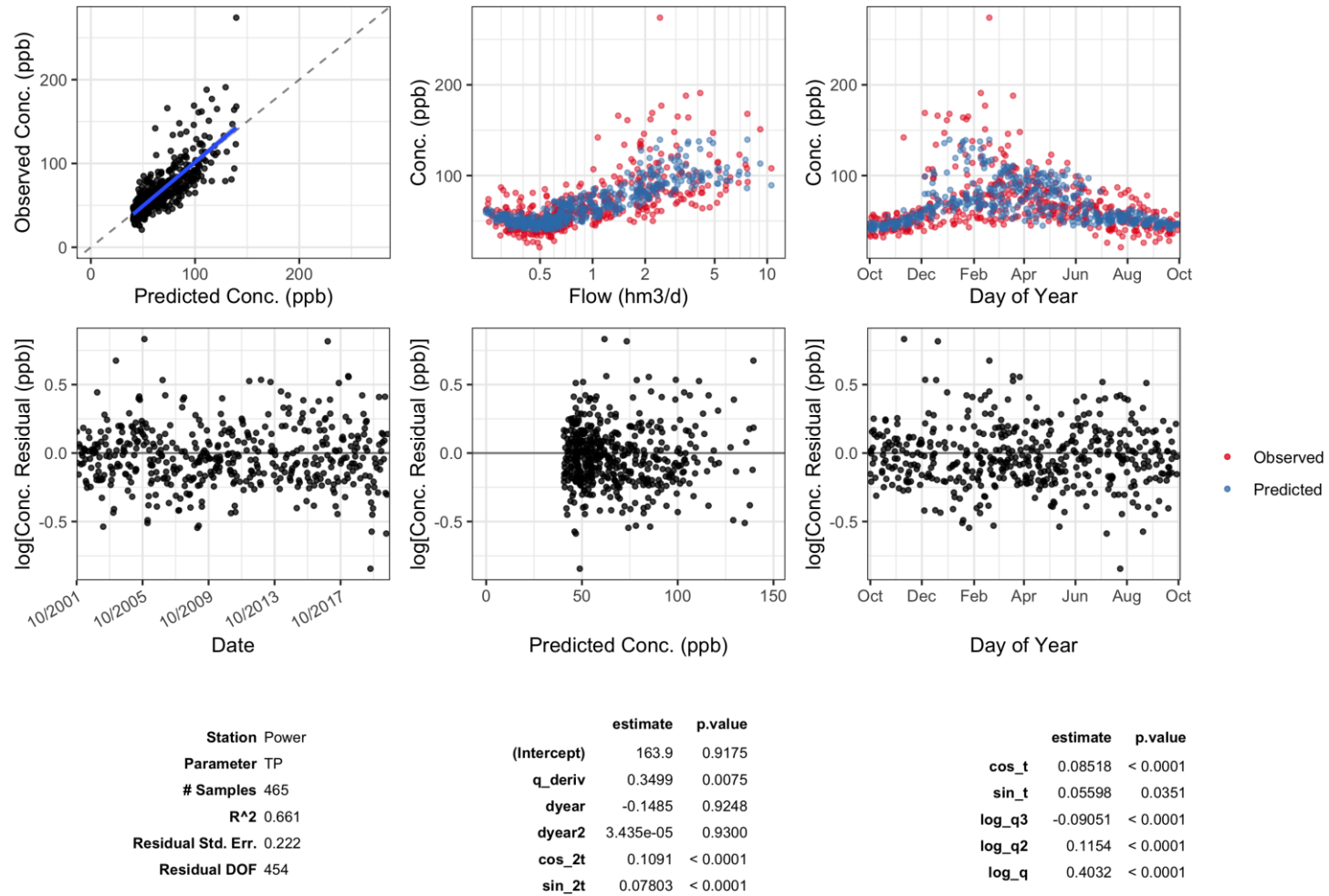


Figure 25: Example of water quality model residuals diagnostics for TP at Power station.

4.3.2 MONTHLY FLOWS, LOADS AND CONCENTRATIONS

The daily timeseries of flows, loads, and concentrations were aggregated to monthly time steps by computing the monthly mean flow and load at each station. The monthly flow-weighted mean (FWM) concentrations were then computed by dividing the monthly load by corresponding flow. Figure 26 shows the monthly flow, TP and TN load, and TP and TN FWM concentration for each station over the study period (WY 2002 – 2020). Note that the results for SF_Ivory and NF_Ivory begin in October 2010 due to the limited sampling period at these stations. This figure illustrates the strong seasonality of flows and loads due to high snowmelt-driven flows in the winter and spring, and low summer flows originating primarily from groundwater. This figure also shows the higher flows and loads at Lone_Pine relative to Power during high flow seasons. Both TP and TN concentrations also exhibit some seasonality with higher concentrations occurring in the winter and spring when flows are higher. Peak TP concentrations at high flow tended to occur at the lower and middle Sprague stations and SF_Ivory, while peak TN concentrations occurred at the Sycan station as well as these stations. Further interpretation of the seasonal and spatial patterns of these results are provided in Sections 4.4 and 4.5 below.

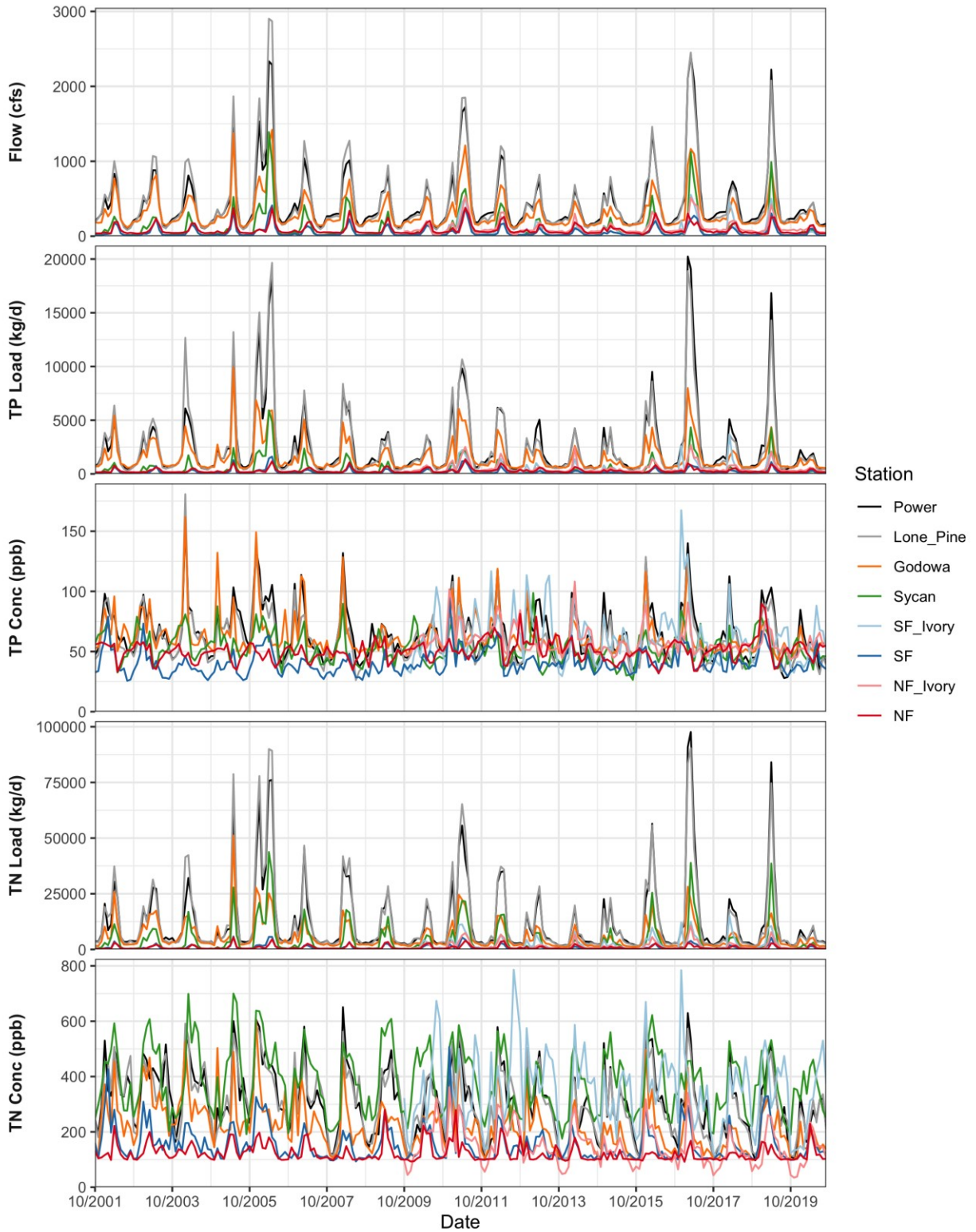


Figure 26: Monthly flow, TP and TN loads, and FWM concentrations, WY2002 – 2020.

4.3.3 LONG-TERM MEAN AND ANNUAL FLOWS, LOADS AND CONCENTRATIONS

The long-term mean annual flows, loads and FWM concentrations for TP, TN, and TSS over the period WY 2010 – 2020 are summarized in Table 8. Only the last eleven years of the study period were used in order to maintain consistency across all the stations since the results for SF_Ivory and NF_Ivory began in WY 2010. The net flows, loads and changes in FWM concentrations for the incremental sub-basins over this same period are listed in Table 9. Note that the net change in FWM concentration for the headwater incremental sub-basins (Sycan, upper South Fork, upper North Fork) could not be computed because there are no upstream stations for these sub-basins³⁴. Negative net changes in concentration occurred on a few occasions (TN in the Lower and Upper Sprague sub-basins) when downstream concentrations were lower than those upstream. Interpretations of these mean annual summary results are discussed using reach network plots in Section 4.5 below.

Figure 27 shows the annual flow, runoff (flow per unit area), TP and TN load, export (load per unit area), and FWM concentration for each station by water year. Note that results are not shown for SF_Ivory and NF_Ivory in years prior to WY 2010 when these stations added to the routine sampling program. Figure 28 shows the annual FWM concentration of each water quality parameter and station.

³⁴ For the Sycan, SF, and NF, the net change in flow and load is equal to the long-term average annual values because there are no upstream basins from these, so the net change is effectively computed relative to zero flow or load, indicating how much flow/load accumulates within a sub-basin. However, for concentration it would be misleading to compute the net change relative to zero.

Table 8: Mean annual flows, loads, and FWM concentrations for TP, TN and TSS by station, WY 2010 – 2020.

Sampling Station	Drainage Area (km ²)	Flow (hm ³ /yr)	Runoff (cm/yr)	Load (mt/yr)			Export (kg/km ² /yr)			FWM Conc		
				TP	TN	TSS*	TP	TN	TSS*	TP (ppb)	TN (ppb)	TSS* (ppm)
Power	4,123	404.7	9.8	30.5	142.2	5,350	7.4	34.5	1,300	75.3	351	12.8
Lone_Pine	3,693	394.1	10.7	28.0	140.0	4,970	7.6	37.9	1,350	71.0	355	12.2
Godowa	1,470	267.5	18.2	17.0	59.6	3,170	11.6	40.6	2,160	63.6	223	11.6
Sycan	1,441	91.3	6.3	4.6	42.5	740	3.2	29.5	510	50.1	466	7.7
SF_Ivory	753	75.8	10.1	5.0	26.5	1,590	6.7	35.2	2,110	66.6	350	20.2
SF	280	45.7	16.4	2.0	8.2	380	7.2	29.4	1,350	44.2	180	8.1
NF_Ivory	535	103.7	19.4	6.2	18.4	1,340	11.6	34.3	2,510	60.1	177	12.5
NF	187	77.0	41.2	3.7	10.0	270	19.9	53.4	1,430	48.3	130	3.4

* TSS results based on WY 2011 – 2020

Table 9: Summary of annual net changes in flows, loads, and FWM concentration for TP, TN and TSS by incremental sub-basin, WY 2010 – 2020.

Incremental Sub-basin	Drainage Area (km ²)	Net Change in Flow (hm ³ /yr)	Net Change in Runoff (cm/yr)	Net Change in Load (mt/yr)			Net Change in Export (kg/ km ² /yr)			Net Change in FWM Conc		
				TP	TN	TSS*	TP	TN	TSS*	TP (ppb)	TN (ppb)	TSS* (ppm)
Lower Sprague	430	10.7	2.5	2.5	2.2	381	5.8	5	887	4.3	-3.9	0.6
Middle Sprague	782	35.2	4.5	6.4	37.9	1,063	8.2	48	1,360	10.8	70.7	1.3
Upper Sprague	182	88.1	48.5	5.7	14.7	240	31.5	81	1,321	0.7	-27.3	-4.7
Sycan	1,441	91.3	6.3	4.6	42.5	736	3.2	30	511	--	--	--
Lower South Fork	474	30.0	6.3	3.0	18.3	1,210	6.4	39	2,554	22.5	170.5	12.2
Upper South Fork	280	45.7	16.4	2.0	8.2	377	7.2	29	1,349	--	--	--
Lower North Fork	348	26.7	7.7	2.5	8.4	1,074	7.2	24	3,082	11.8	47.5	9.1
Upper North Fork	187	77.0	41.2	3.7	10.0	267	19.9	53	1,431	--	--	--

* TSS results based on WY 2011 – 2020

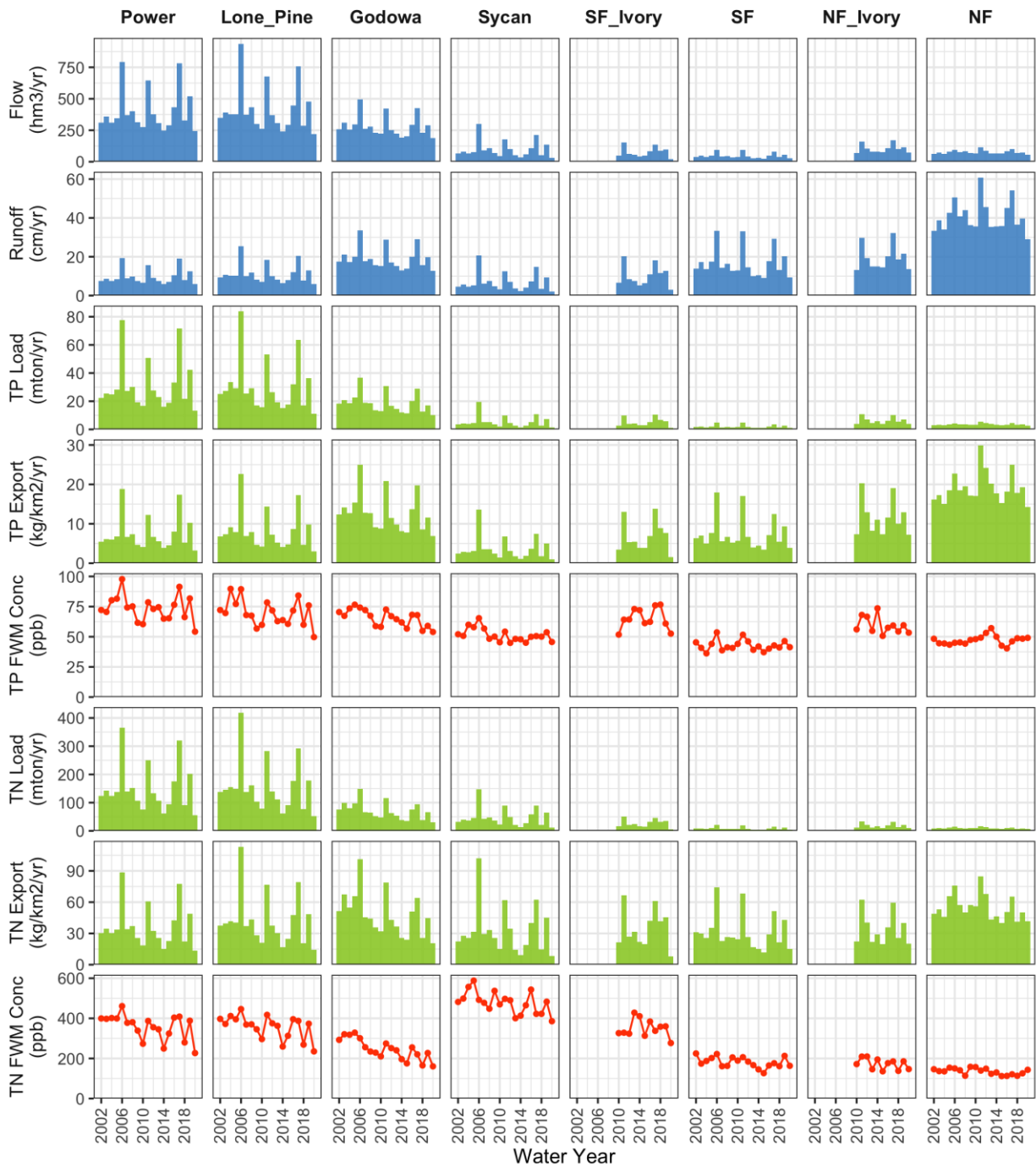


Figure 27: Annual flow, runoff, TP and TN load, export, and FWM concentrations by station.

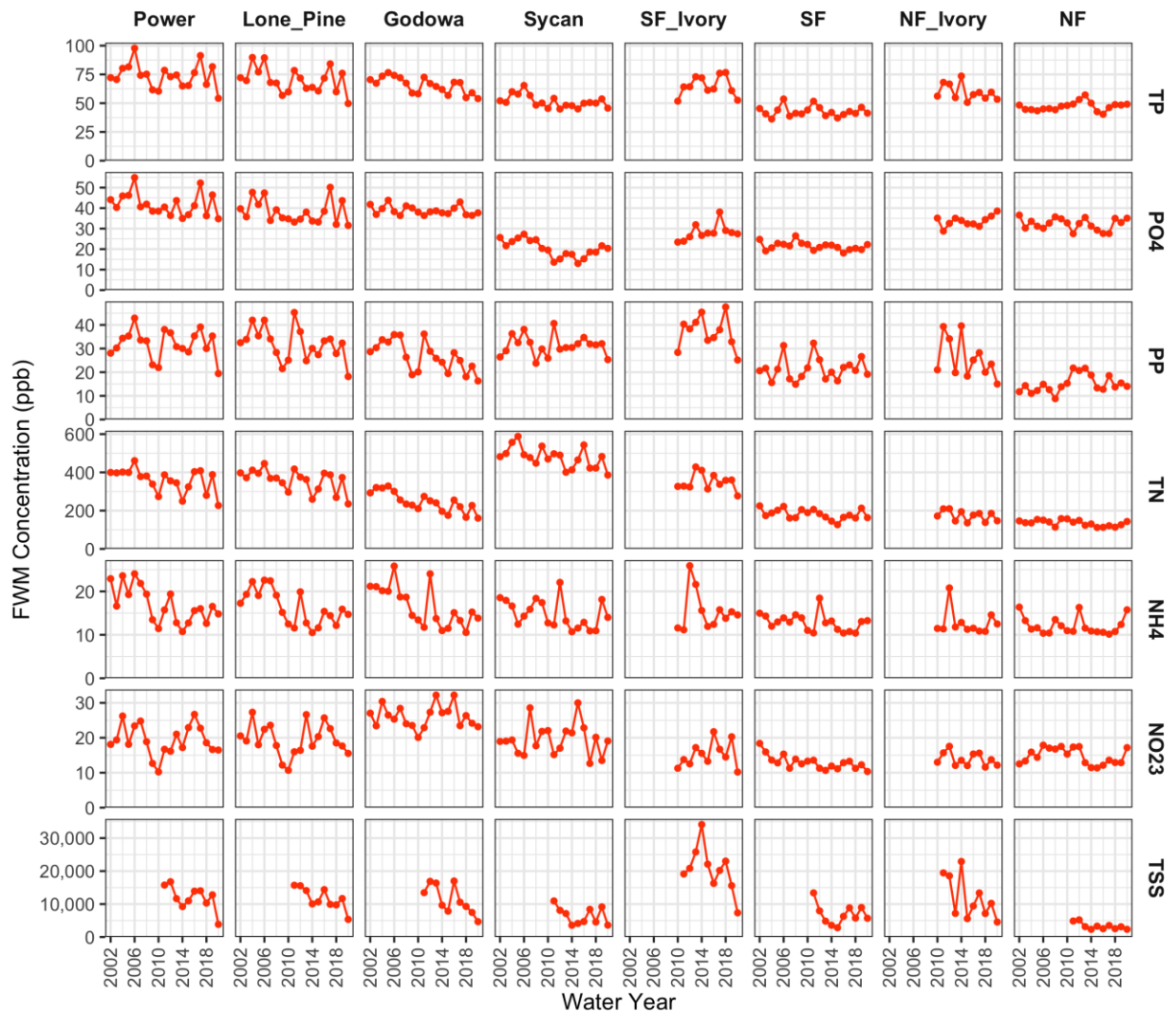


Figure 28: Annual FWM concentration of each nutrient and sediment species by station.

On an inter-annual basis, TP and TN loads and unit-area export rates were related to flow and water runoff at most stations, with highest values occurring in WYs 2006, 2011, and 2017 (Figure 27). For the lower Sprague station at Power, both TP and TN concentrations were also relatively high in those, but at other stations the concentration pattern appeared to be less tied to annual flow (Figure 28). For example, Lone_Pine showed higher TP concentration in WY 2004 than in WY 2017 (Figure 28). Annual means for TN concentration were consistently higher at Sycan than other stations, and NO23 mean annual values were consistently higher at Godowa. Other inter-annual trends include consistently higher NH4 values in WY 2012³⁵ at all stations, and an apparent decline in TN over time at the Power, Lone_Pine, and Godowa stations (this and other timeseries trends are discussed further in Section 4.10, below).

³⁵ It is not clear whether the 2012 spike is a real event or possibly due to a data quality assurance issue.

4.4 SEASONAL PATTERNS OF MONTHLY FLOWS, LOADS, AND CONCENTRATIONS

The continuous daily timeseries of flows, loads, and concentrations provide a basis for more detailed analyses and interpretations related to the seasonal and spatial patterns in the watershed. A series of data visualizations were used to present these results in different contexts in order to facilitate comparisons between stations, seasons, years, and water quality parameters.

Seasonal patterns in flows and concentrations are shown using heatmaps in Figure 29. A heatmap is a visualization technique used to show large quantities of data in a condensed format. This type of chart consists of a set of tiles, with the color of each tile representing an individual value (in this case, monthly flow or FWM concentration). Because the range of values varies between flows and water quality concentrations, the data are standardized in order to use a consistent color scale across all parameters. The values for each parameter were first transformed to a logarithmic scale and then normalized by subtracting the mean and dividing by the standard deviation of all values for that parameter across the stations. The result is a set of standardized monthly values for each flow and water quality parameter which have roughly the same overall distribution (standard normal) and can thus be represented by a single color scale.

The top row of Figure 29 shows the monthly flows at each station. The highest values tended to occur between March and June as expected due to spring snowmelt. However, in some years (WYs 2006 and 2011, which were wet years in the study period) high flows also occurred in the winter between December and February at most stations.

The second row in Figure 29 show the seasonal patterns of monthly FWM concentrations for TP. These panels show that among the three mainstem stations (Power, Lone_Pine, Godowa) as well as the Sycan River station, the highest concentrations tended to occur in the winter (December-March), and lowest concentrations occurred in fall (September-November). The upper SF station showed relatively little seasonality compared to the other stations, and SF_Ivory showed high TP concentrations in summer (July – September) unlike the other stations. The upper NF station exhibited a different seasonal pattern with relatively constant TP concentrations in all months except in May and June when flows were highest and concentrations were lowest. This pattern is likely due to dilution of groundwater sources by spring snowmelt, which has relatively low phosphorus content.

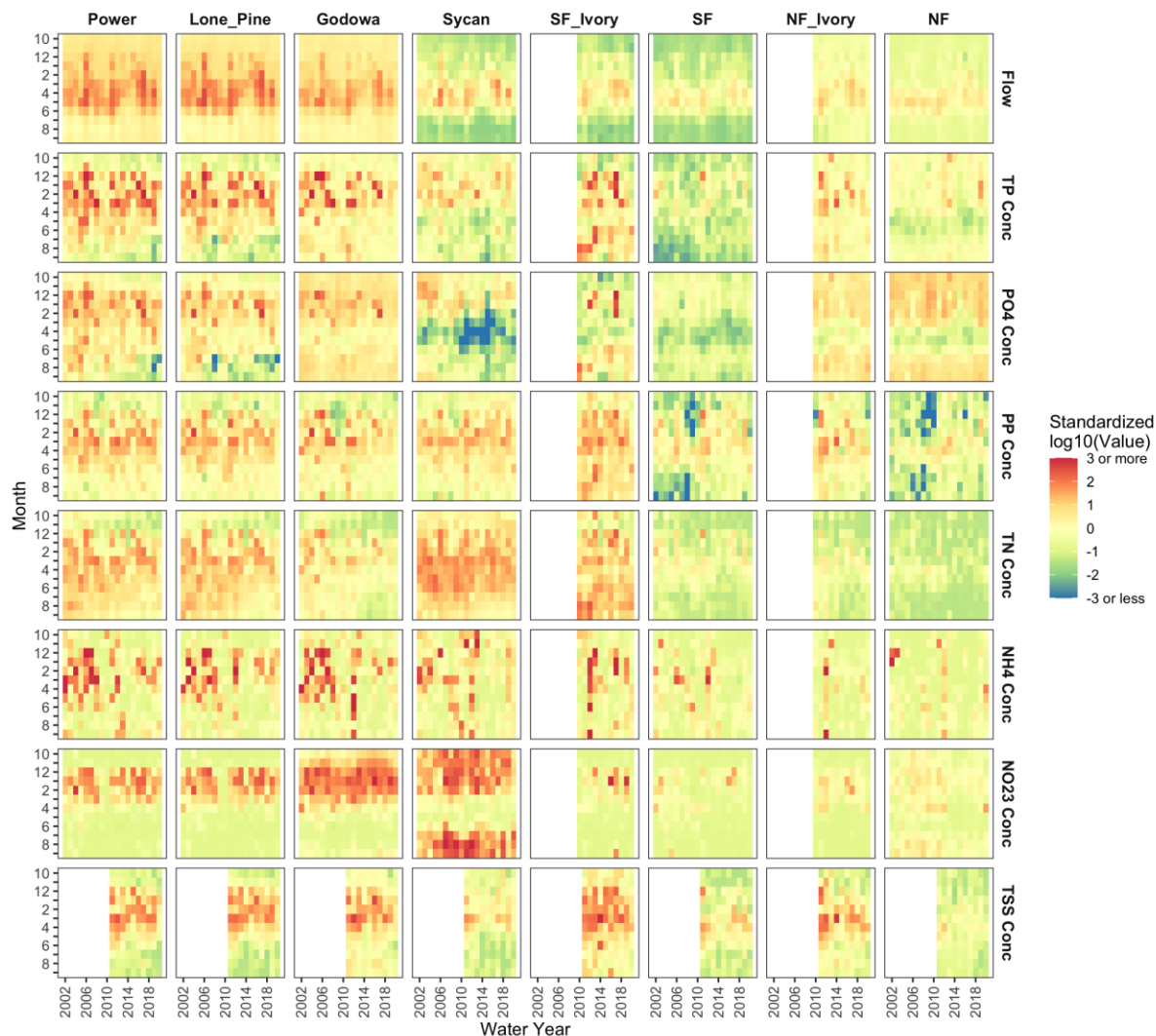


Figure 29: Heatmaps of monthly flows and FWM concentrations by station and parameter.

Although discussed in more detail relative to flow and season below, observations for the other water quality parameters include:

- For PO4, the Godowa, NF_Ivory and NF stations showed the highest concentrations across much of the year except during spring snowmelt between April and June. The SF station had the lowest concentrations year-round. Power and Lone_Pine both had higher concentrations during the winter (December – March) and lower concentrations in late summer and fall (August – November).
- For PP, concentrations tended to be highest during winter and spring likely due to high flows in these seasons. At SF_Ivory and NF_Ivory, concentrations also remained relatively high in summer between June – September. The upper SF and NF stations had the lowest overall concentrations and exhibited less seasonality than at the other stations.
- For TN, highest concentrations occurred at most stations between February – September and lowest concentrations occurred in the fall between October – December. One exception is SF_Ivory which had highest concentrations in August and September. TN concentrations were

lowest in October and November at all stations before increasing substantially in December. The NF and SF stations showed relatively constant low concentrations with some increase during spring months of April – June. The Sycan station had the overall highest concentrations year-round.

- For NH₄, concentrations exhibited less seasonality than for the other parameters across all stations. The mainstem stations at Power, Lone_Pine and Godowa showed elevated concentrations in winter (December – May) in some years, but not as often in later years (2009 – 2020). The Sycan showed higher fall NH₄ concentrations, while NH₄ was lowest in summer and fall at Power, Lone-Pine, and Godowa. Note that a significant number of NH₄ measurements were reported below the detection limit and thus the lack of seasonality may simply reflect the inability to accurately measure these low concentrations.
- For NO₃, Power and Lone_Pine generally showed high concentrations in winter (December-March) in most years except 2009 and 2010. Sycan showed a different pattern with concentrations highest in the summer and fall/early-winter, and with lowest concentrations occurring during spring (April – June). Godowa showed a longer period of high concentrations (November – April) relative to other stations and values increased beginning in the fall. SF and SF_Ivory both had relatively low and constant concentrations year-round. Concentrations at the upper NF station were also relatively constant but somewhat elevated, and higher than all other stations except Sycan in the summer.
- For TSS, most stations had high concentrations during the winter and spring likely due to erosion during high flows, except for NF which had relatively low concentrations year-round.

4.5 SPATIAL PATTERNS OF MEAN FLOWS, LOADS, AND CONCENTRATIONS

4.5.1 REACH NETWORK PLOTS

Reach network plots show how flows and concentrations change longitudinally along the Sprague River and its tributaries from the headwaters to the outlet. In these plots, the flows, loads, and FWM concentrations are plotted against cumulative drainage area such that the upstream stations appear on the left-hand side and downstream stations on the right-hand side of each panel. The stations are connected by line segments to show the network of reaches between stations. The thicker lines represent the mainstem reaches of the Sprague River, and the thinner lines represent the tributary reaches. The slope of these line segments reflect the change in flow, load, and concentration per unit change in drainage area. Line segments with large positive slopes indicate a large increase per unit area, and large negative slopes indicate a large decrease. These plots also include two additional points representing the confluence of two pairs of stations (Godowa+Sycan and NF_Ivory+SF_Ivory). Note that the flows, loads and concentrations at these points are computed by mass balance, as opposed to from direct measurements as done for the individual stations. For flows and loads, the values at these confluences are simply the sum of the flows and loads for the corresponding pair of stations. The FWM concentration is computed by dividing the sum of the loads by the sum of the flows.

Figure 30 shows reach network plots of the annual and seasonal flow, TP and TN load and FWM TP and TN concentration over the period WY 2010 – 2020. The seasonal mean values for each station and variable were computed by first calculating the mean value within each season and water year, and then

computing the mean across all water years. This figure shows only mean values computed over the last eleven years in order to include the two stations added in WY 2010 (SF_Ivory and NF_Ivory). Similar figures for the other water quality parameters and using only the long-term stations over the period of record (WY 2002 – 2020) are provided in Appendix E.

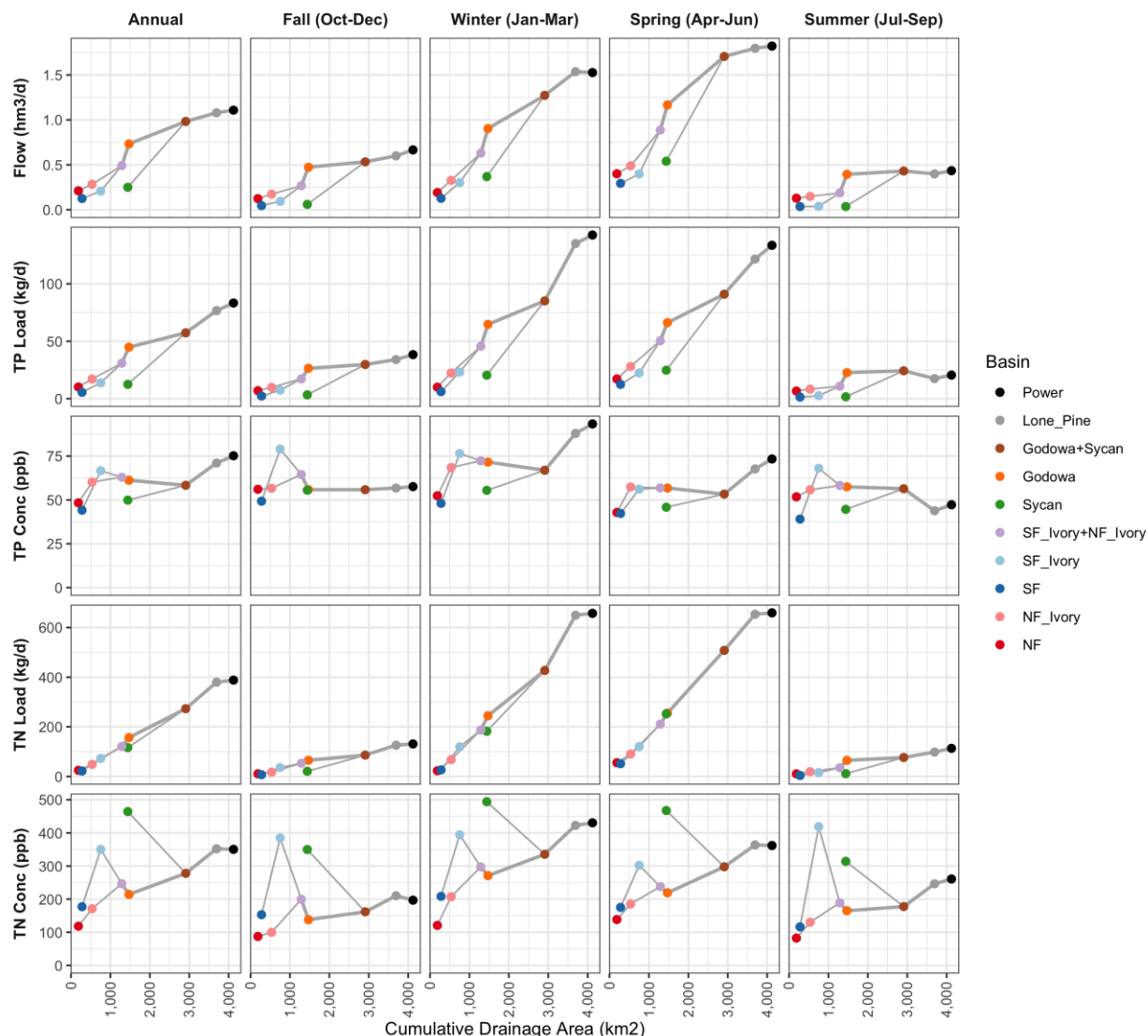


Figure 30: Reach network plots of mean annual and seasonal flow, TP and TN load, and FWM concentrations, WY 2010 – 2020.

Values for Godowa+Sycan and SF_Ivory+NF_Ivory represent the confluence of two stations and are computed by mass balance.

The reach network plots show how flows, loads, and FWM concentrations changed from the headwaters to the outlet of the Sprague River (Figure 30 and Figure 31). For example, annual flows (top left panel) showed a steep increase between the confluence of SF_Ivory+NF_Ivory and Godowa, and relatively small change in the lower Sprague River between Lone_Pine and Power (Figure 30). The seasonal mean flows showed that the largest increase in flow occurred in spring, and to a lesser extent in winter. During summer, there was almost no change in flow along the mainstem from Godowa to Power. As expected due to the greater variability of flow relative to concentration, mean annual and seasonal TP loads

showed very similar patterns as those for flow. Longitudinal patterns in TN loads were also related to flow but to a lesser extent and tended to show a more linear upstream to downstream pattern than did TP load (i.e., for TP load the slopes between stations were more variable compared to those for TN; Figure 30).

The mean annual FWM TP concentration of each station showed a large increase from 48 and 44 ppb at the relatively un-impacted NF and SF stations to 60 and 67 ppb at the NF_Ivory and SF_Ivory stations near the confluence of the North and South Forks (Figure 31). From this confluence at the start of the upper Sprague River mainstem to the Godowa station the concentration reached 61 ppb (Figure 31) despite the large increase in flow (Figure 30; top left panel). The Sycan river station also had a relatively low concentration of 50 ppb. The confluence of Godowa+Sycan had an estimated combined annual FWM concentration of 58 ppb, which then increased to 71 ppb at Lone_Pine. Finally, there was a small increase from 71 to 75 ppb at the Power station near the Sprague River outlet. In short, this figure indicates that a large fraction of the increase from background concentrations in the headwater basins occurred between the upper NF/SF and corresponding lower NF_Ivory/SF_Ivory stations, with some additional increase from the confluence of the Sycan and Sprague Rivers near Godowa down to Lone_Pine.

On a seasonal basis FWM TP concentrations showed large variations in these patterns. For example, in the fall there was relatively little change in the concentration along the entire river with a slight decrease from an estimated 64 ppb at the confluence of the South and North Forks (SF_Ivory+NF_Ivory) to 58 ppb at Power near the Sprague River outlet. During winter, the greatest increases in concentration occurred, primarily between SF/NF and SF_Ivory/NF_Ivory in the lower South and North Forks. In summer, there was a decrease in concentration of 11 ppb from 58 ppb at the confluence of the North and South Forks to 47 ppb at Power. This decrease, which primarily occurred between Godowa+Sycan and Lone_Pine, may reflect biological uptake by aquatic vegetation and algae. Eilers and Eilers (2006) noted that these Sprague River reaches can have high rates of primary production associated with macrophytes, attached algae, floating macrophytes and suspended algae. Others have noted the importance of periphyton as a temporary nutrient sink during summer growing seasons, with delayed downstream nutrient transport occurring during high energy flow events (Godwin et al., 2009).

Although there was only a small change in the annual FWM TP concentration between the SF_Ivory and NF_Ivory stations to Godowa, there was a large increase in PO₄ and a large decrease in PP (Figure 31). This pattern indicates a change in the relative fraction of dissolved vs. particular phosphorus, which is likely due to large groundwater discharges and springs just upstream of the Godowa station that contain high dissolved phosphorus content. The mean PO₄ and PP concentrations during the summer also showed that the majority of the decrease in TP between Godowa+Sycan and Lone_Pine was due to a decrease in PO₄, with only a slight increase in PP, again indicative of uptake by aquatic vegetation and algae. TSS showed a pattern similar to TP and PP where a large fraction of the increase from background concentrations in the headwater basins occurred between the upper NF/SF and corresponding lower NF_Ivory/SF_Ivory stations. These increases were most pronounced in fall and winter.

The mean annual and seasonal FWM TN concentration also showed a large increase between the relatively un-impacted SF station to the SF_Ivory station (particularly in summer), but a similar trend was

not seen for the NF stations (Figure 31). Despite higher TN concentrations for the Sycan during all seasons, TN only increased slightly for the Sprague stations downstream of the Sycan confluence. Spatial and seasonal patterns were more apparent for NH₄ and NO₂3, where NH₄ increased sharply between SF and SF_Ivory during the fall and winter (but particularly in the fall) with relatively little longitudinal change observed for remaining stations, even though NH₄ was substantially higher for the Sycan during the winter season³⁶. Spring and summer NH₄ and NO₂3 concentrations were low across all stations likely reflecting uptake (assimilation) by aquatic macrophytes and algae. NO₂3 increased sharply between SF_Ivory+NF_Ivory and the Godowa station on an annual basis and during the fall and winter, and NO₂3 at Sycan was relatively high in the summer and fall, although the high Sycan summer concentration did not have a large effect in terms of raising downstream concentrations. Although less likely than assimilation by primary producers, nitrification/denitrification dynamics may also play a role in certain seasons and reaches, but further analysis is outside the scope of this report. For further discussion of nitrogen seasonal dynamics see Section 4.7, below.

³⁶ The lack of longitudinal effect despite higher concentration inflows such as the Sycan reflects the relatively low overall concentrations and loads for these parameters (NH₄<20 ppb and NO₂3<50 ppb)

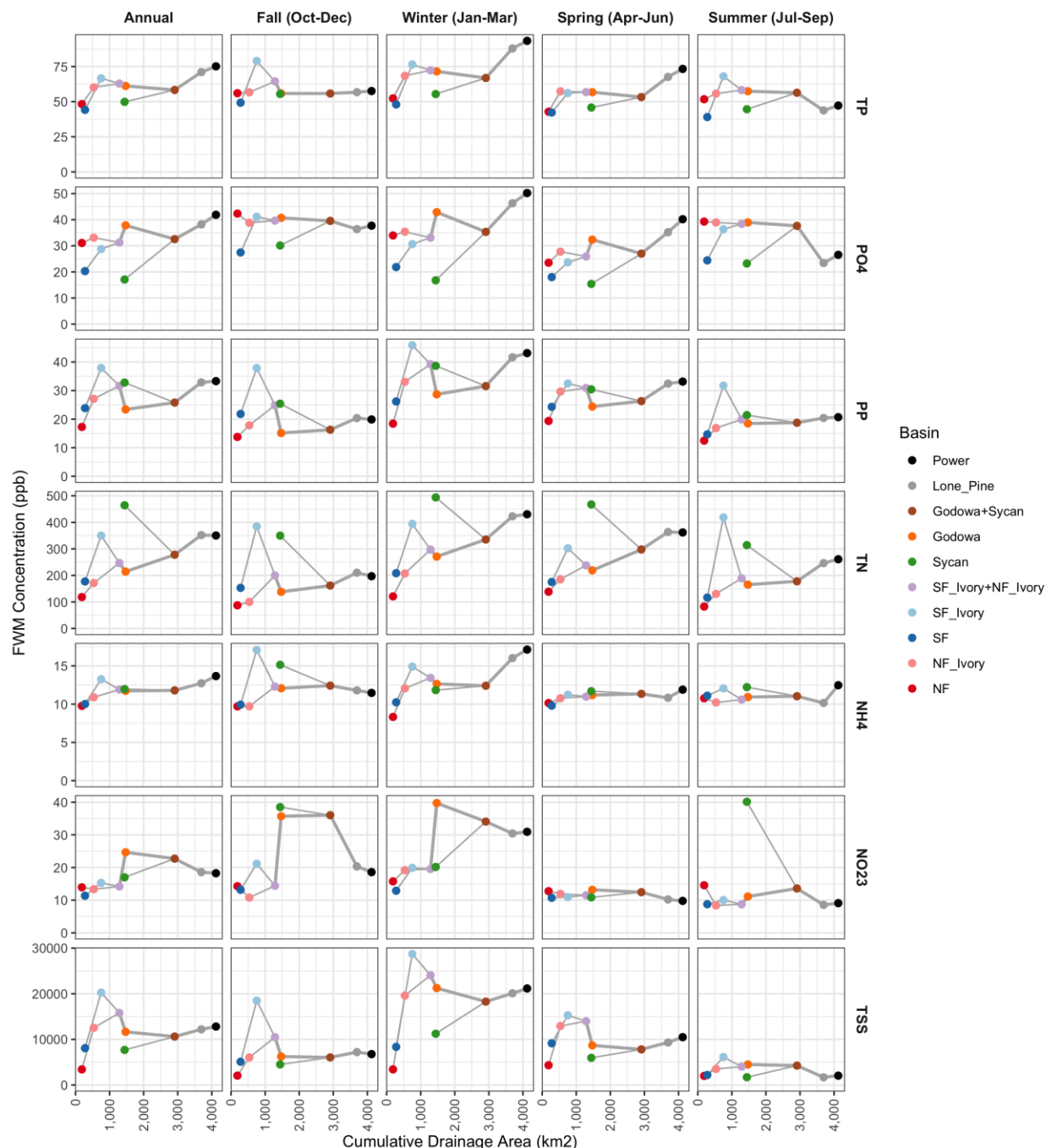


Figure 31: Reach network plots of mean annual and seasonal FWM concentrations, WY 2010 – 2020.

Values for Godowa+Sycan and SF_Ivory+NF_Ivory represent the confluence of two stations and are computed by mass balance

4.5.2 SUB-BASIN MAPS

In addition to the reach network plots, the streamflow and water quality results were also summarized by a series of map displays, which provide an alternative format for exploring the spatial patterns across the basin. Separate sets of maps were generated for both the cumulative and incremental sub-basins. The cumulative sub-basin maps show the mean annual flows, loads, and concentrations associated with the total drainage area of each station. The incremental sub-basin maps show the net changes in mean annual flows, loads, and concentrations for the drainage areas of each reach between sequential

stations. Both flows and loads are shown on a per unit area basis (i.e., runoff and export rates), in order to remove the effect of drainage area on the total flow volumes.

This section presents the map displays for runoff (flow per area), TP export (load per unit area), and TP FWM concentration over the period WY 2010 – 2020, which was chosen in order to include the sub-basins associated with the lower South and North Fork sub-basins associated with the SF_Ivory and NF_Ivory stations.

Appendix F provides similar map displays for other parameters and for the mean annual results over the entire study period, WY 2002 – 2020, in which the lower South and North Fork basins are combined with the upper Sprague River basin due to the limited period for the SF_Ivory and NF_Ivory stations.

4.5.2.1 Cumulative Sub-basin Maps

Figure 32 – Figure 34 show map displays of mean annual runoff, TP export, and TP FWM concentration for the cumulative sub-basins computed over the period WY 2010 – 2020. Each display includes a map (top) and bar chart (lower left) both showing the mean annual values for each sub-basin, and a heatmap (lower right) showing the individual values for each water year. A separate map is shown for each cumulative sub-basin because the values are associated with the entire drainage area for each station. Appendix F provides similar sets of plots for all water quality parameters based on WY 2002 – 2020 (Figure F1) and WY 2010 – 2020 (Figure F2).

The figures below show that the highest flow and TP load per unit area occurred in the upper NF sub-basin, which is primarily driven by spring seepage and snowmelt. The highest concentrations, however, occurred in the downstream mainstem stations (Power, Lone_Pine). The relatively unimpacted sub-basins (Sycan, NF, SF) had lower concentrations ranging between 44 to 50 ppb. The heatmaps of annual values show that the highest flows and loads occurred in the wettest years (WYs 2011 and 2017) at all stations. TP concentrations showed similar patterns as the flows and loads at the downstream stations (Power and Lone_Pine).

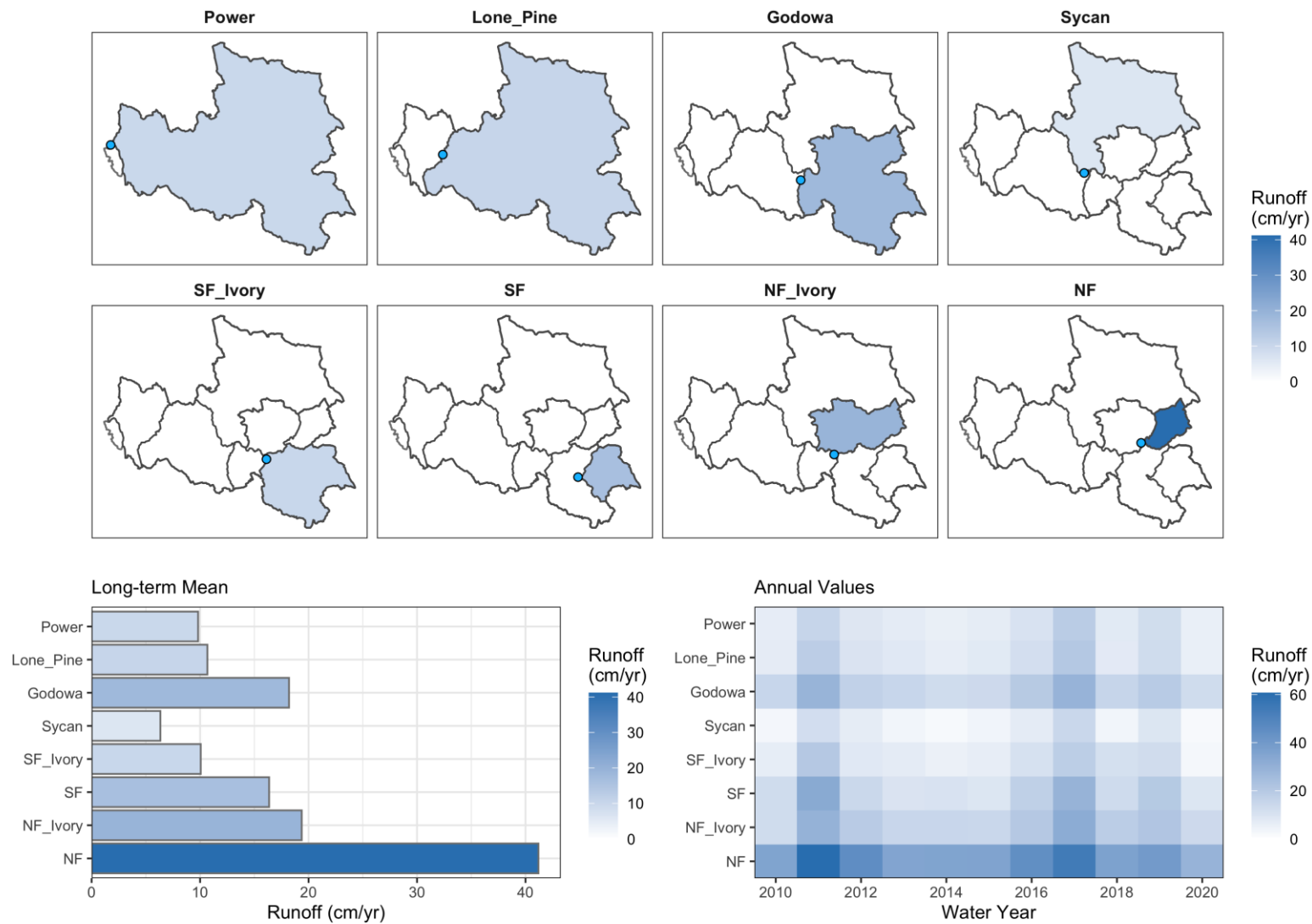


Figure 32: Cumulative sub-basin maps of mean annual flow per unit area, WY 2010 – 2020.

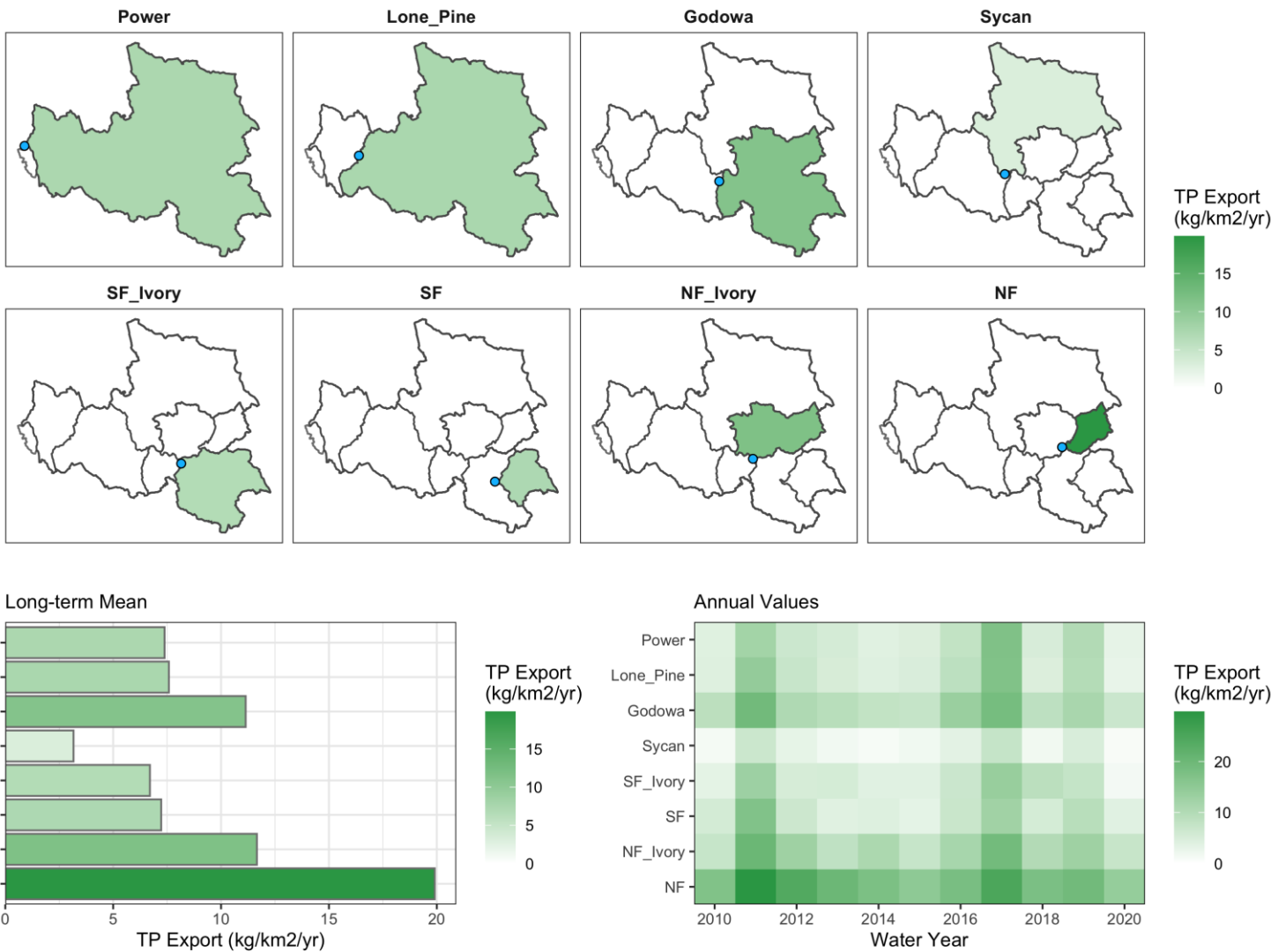


Figure 33: Cumulative sub-basin maps of mean annual TP export, WY 2010 – 2020.

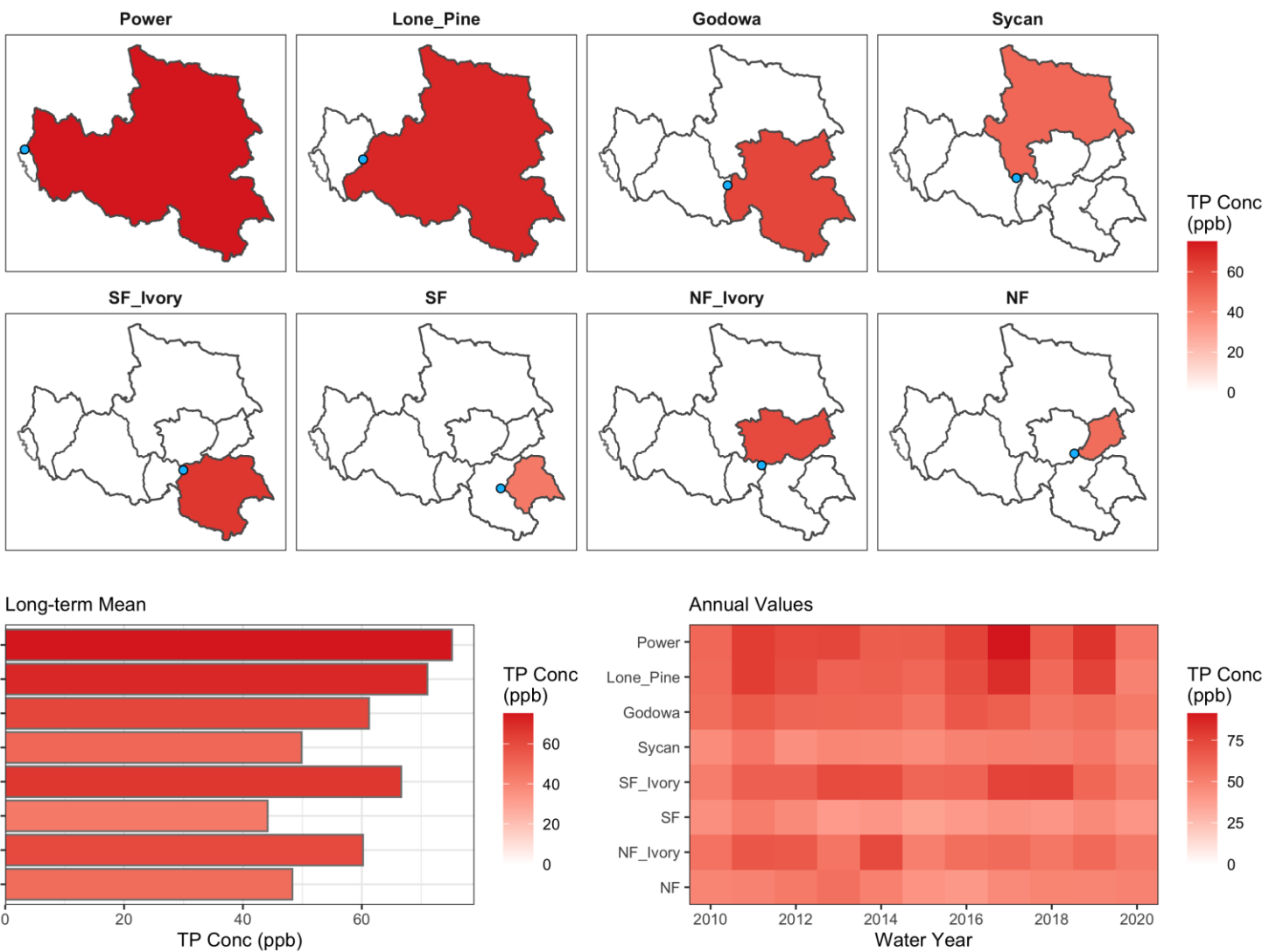


Figure 34: Cumulative sub-basin maps of mean annual TP FWM concentration, WY 2010 – 2020.

4.5.2.2 Incremental Sub-basin Maps

Figure 35 to Figure 37 show the net changes in mean annual runoff, TP export, and TP FWM concentration for each incremental sub-basin over the period WY 2010 – 2020. Each figure includes a map (top) and bar chart (lower left) that both show the net changes in mean annual values for each incremental sub-basin, and a heatmap (lower right) showing the net changes for each individual water year. The net changes in flow and load for each incremental sub-basin were computed by subtracting the sum of flows and loads at the upstream stations from those at the downstream station; the net change in FWM concentrations were computed by subtracting the combined FWM concentration of the upstream station(s) from the FWM concentration at the downstream station. Note that net changes in concentration cannot be computed for the three headwater sub-basins (Sycan, upper NF, upper SF) because there are no upstream stations, and thus no values are shown for these sub-basins in Figure 37. Appendix F provides similar sets of plots for all water quality parameters based on WY 2002 – 2020 (Figure F3) and WY 2010 – 2020 (Figure F4).

The figures below show that the largest increase in runoff and TP export rates occurred in the upper Sprague River sub-basin between Godowa and the SF_Ivory+NF_Ivory confluence. However, this incremental sub-basin also had the only negative net change in FWM TP concentration indicating a small decrease in concentration from the upstream stations (SF_Ivory and NF_Ivory) to the downstream station (Godowa). The largest increase in FWM concentration occurred in the lower South Fork sub-basin between the SF_Ivory and SF stations.

The incremental sub-basin map for the net change in TN export showed a somewhat similar pattern to the net change in TP export (Figure F4, Appendix F) except for the Sycan which had proportionally larger unit area loading compared to TP, and the lower Sprague which showed a relatively small net change in TN unit area load. The change in FWM TN concentration was highest in Lower SF, followed by the Middle Sprague and Lower NF, and the largest change in FWM TN for the Lower SF occurred in WYs 2013 and 2014 (Figure F4, Appendix F). Similar to FWM TN, the net change in FWM NH₄ was also highest in the Lower SF, and similar changes in NH₄ concentrations were found in the Lower NF and the mainstem of the Sprague (Figure F4, Appendix F). As noted above in the discussion of the reach network plots, the net change in FWM NO₃ was greatest in the Upper Sprague watershed area (Figure F4, Appendix F).

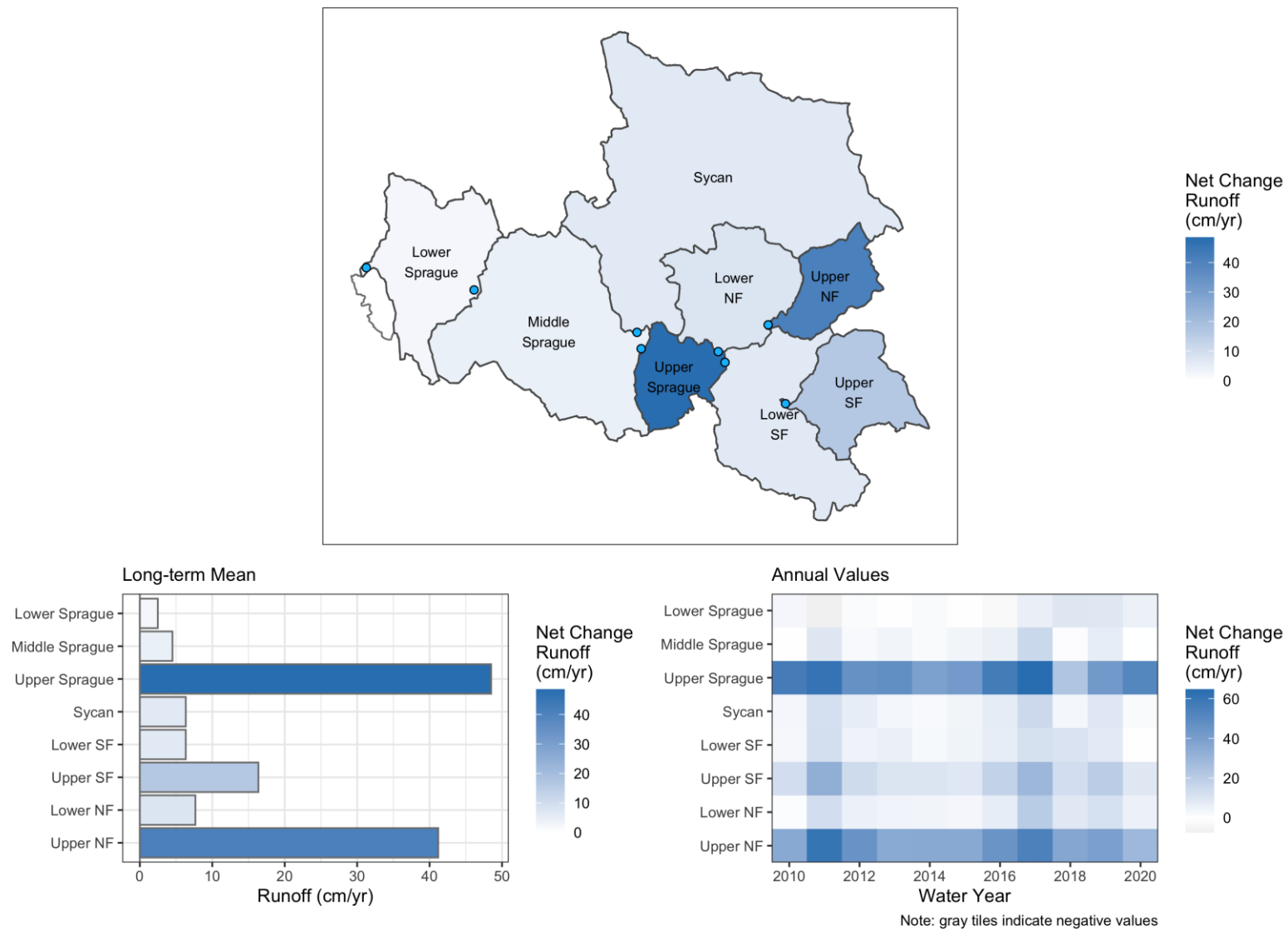


Figure 35: Map of runoff rates by incremental sub-basin, WY 2010 – 2020.

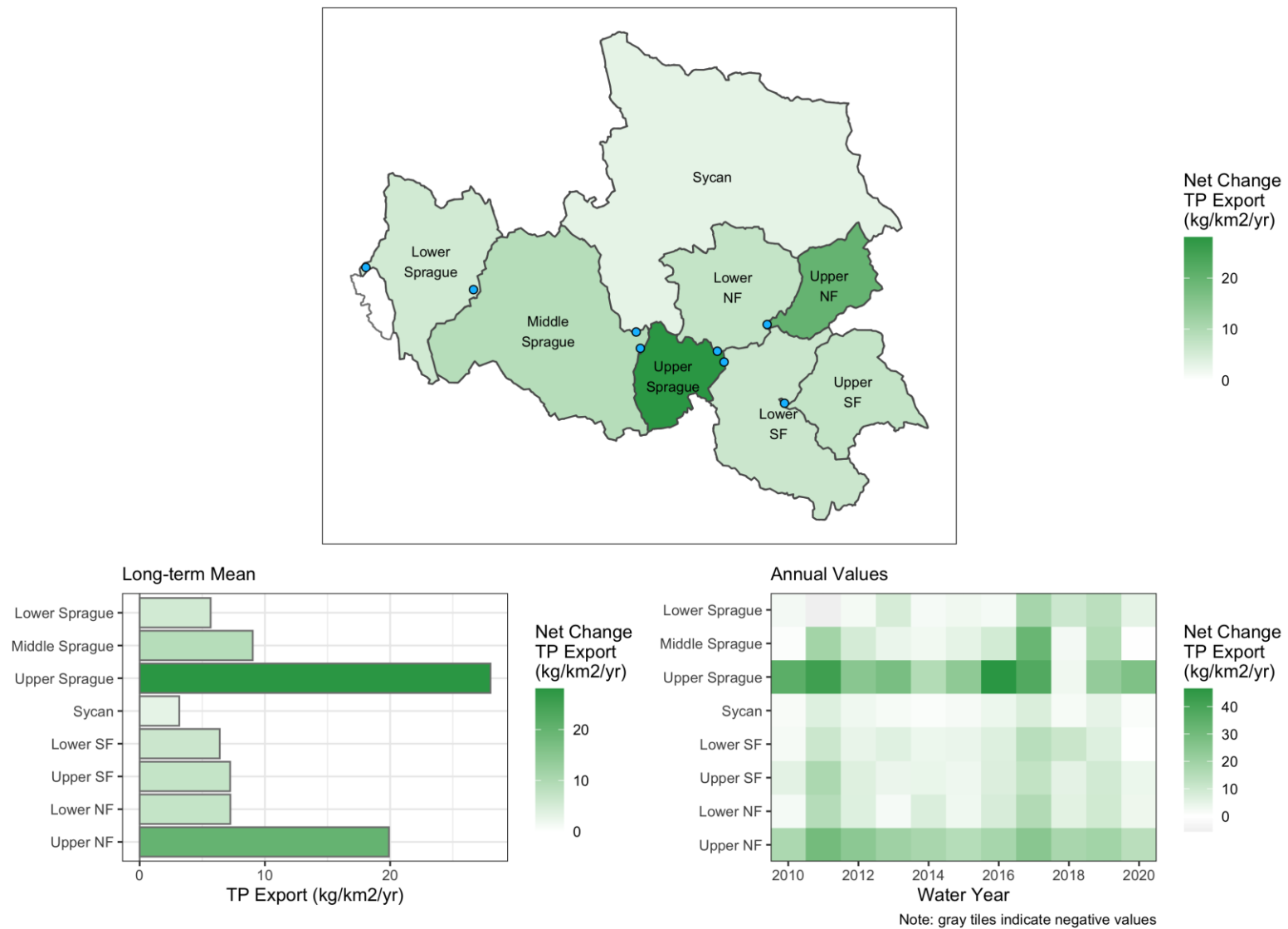


Figure 36: Map of TP export rates by incremental sub-basin, WY 2010 – 2020.

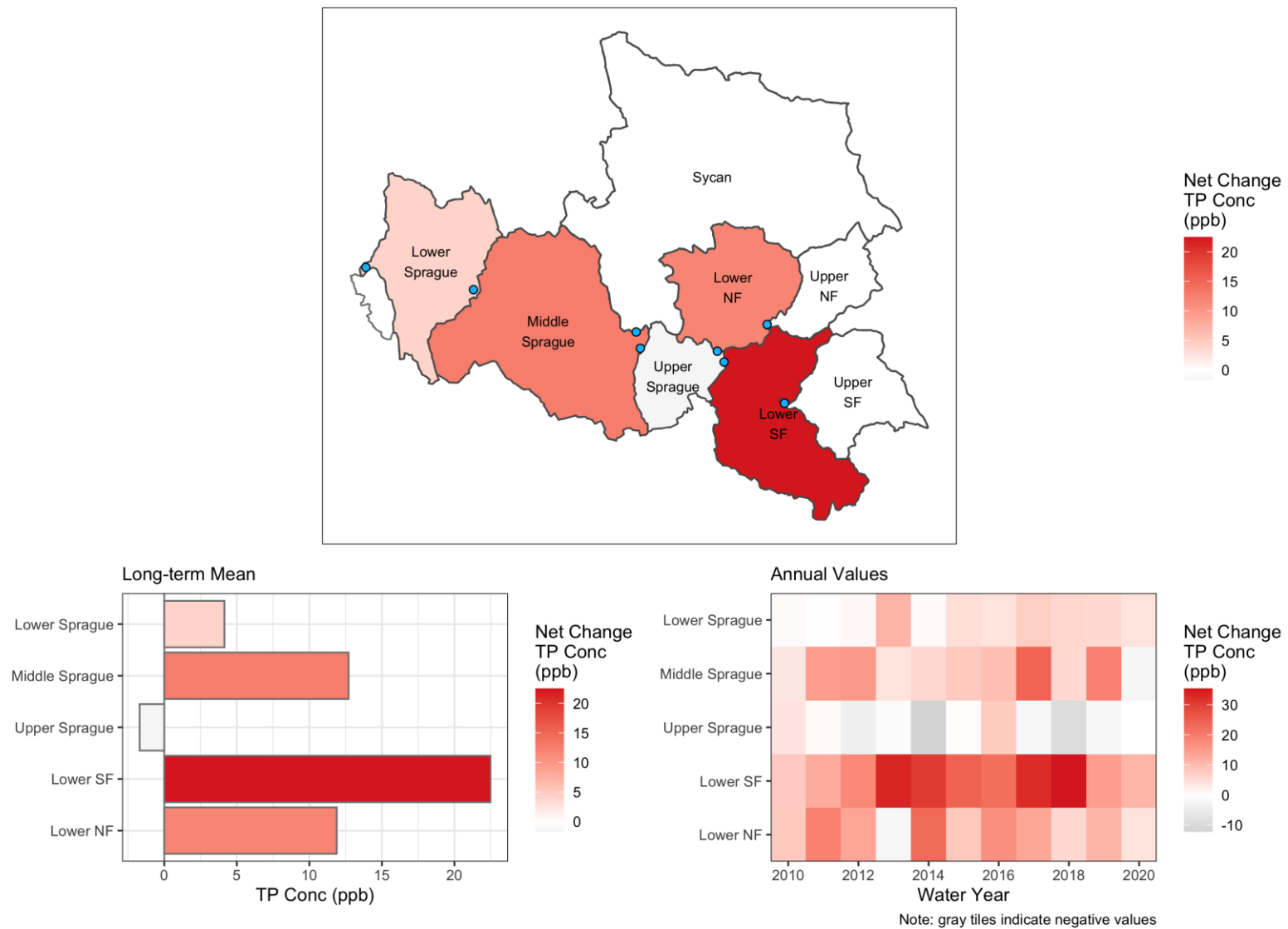


Figure 37: Map of FWM TP concentration by incremental sub-basin, WY 2010 – 2020.

4.6 RELATIONSHIPS BETWEEN CONCENTRATIONS AND LAND USE

Relationships between concentrations and land use composition were generated to investigate the effects of anthropogenic activities on water quality. It is important to note that these relationships are based on the in-stream water quality conditions, which reflect the cumulative effects of both sources (e.g., runoff, groundwater discharge, irrigation return flows) and sinks (e.g., settling, biological uptake) within each sub-basin. Although these relationships provide some indication of whether land use composition effects in-stream water quality, a more detailed nutrient budget that accounts for individual sources and sinks is recommended to more accurately represent the effect of land use composition on loads to the river.

4.6.1 NLCD LAND USE

Figure 38 shows the relationships between mean annual FWM concentration computed over WY 2010 – 2020 and land use composition for each water quality parameter. Land use composition is represented by the fraction of total cumulative drainage area for each land use type (see Figure 10, above). The black lines in each panel show linear regression trend lines. Solid lines indicate a significant correlation using the Pearson correlation coefficient with $p \leq 0.10$; dashed lines indicate that the correlation is not significant with $p > 0.10$.

For the annual TP concentrations shown in the top row, there were significant positive correlations against both planted/cultivated and herbaceous, and a significant negative correlation against forest cover. PP concentrations had similar significant relationships, however, PO₄ showed only a significant relationship against planted/cultivated. This suggests that land use has a greater effect on particulate phosphorus than on dissolved phosphorus likely due to channel modifications, destabilized riverbanks, and other anthropogenic changes along the river corridor. Among the different land use types, forest cover had significant negative correlations for all water quality parameters except PO₄. TN showed strong positive correlations with both barren and wetlands cover and NH₄ showed positive relationships for planted/cultivated and herbaceous.

As mentioned above in Section 2.4.4, the NLCD dataset was found to have limitations in its classification of land use types and for differentiating between un-impacted vs human-impacted conditions. In particular, many areas known to be used for grazing were classified as wetlands, herbaceous or shrubland. Therefore, these results should be interpreted with caution and may not accurately reflect the effects of anthropogenic activities on in-stream water quality concentrations.

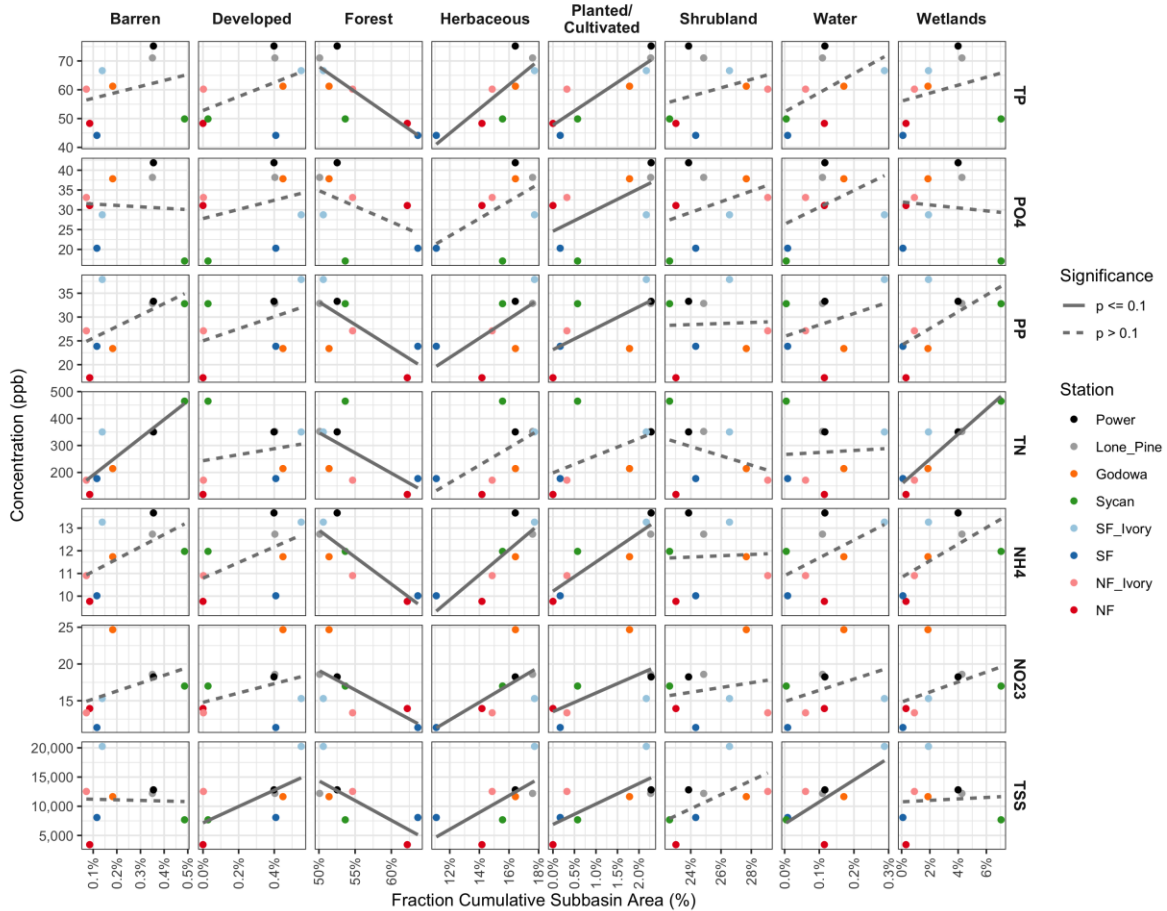


Figure 38: Relationships between annual FWM concentration and cumulative sub-basin land use composition, WY 2010 – 2020.

Note: TSS based on WY 2011 – 2020.

4.6.2 IRRIGATION WATER RIGHTS PLACE OF USE (POU)

The OWRD water rights database was used as another data source for characterizing agricultural land use based on the Place of Use (POU) areas associated with irrigation surface water rights (see Section 2.4.5 above). Figure 39 shows the relationship between annual and seasonal FWM concentrations computed over WY 2010 – 2020 versus the fraction of lower valley area used for irrigation (determined from POU area data; see Figure 12, above). The black lines in each panel show linear regression trend lines. Solid lines indicate a significant correlation using the Pearson correlation coefficient with $p \leq 0.10$; dashed lines indicate that the correlation is not significant with $p > 0.10$.

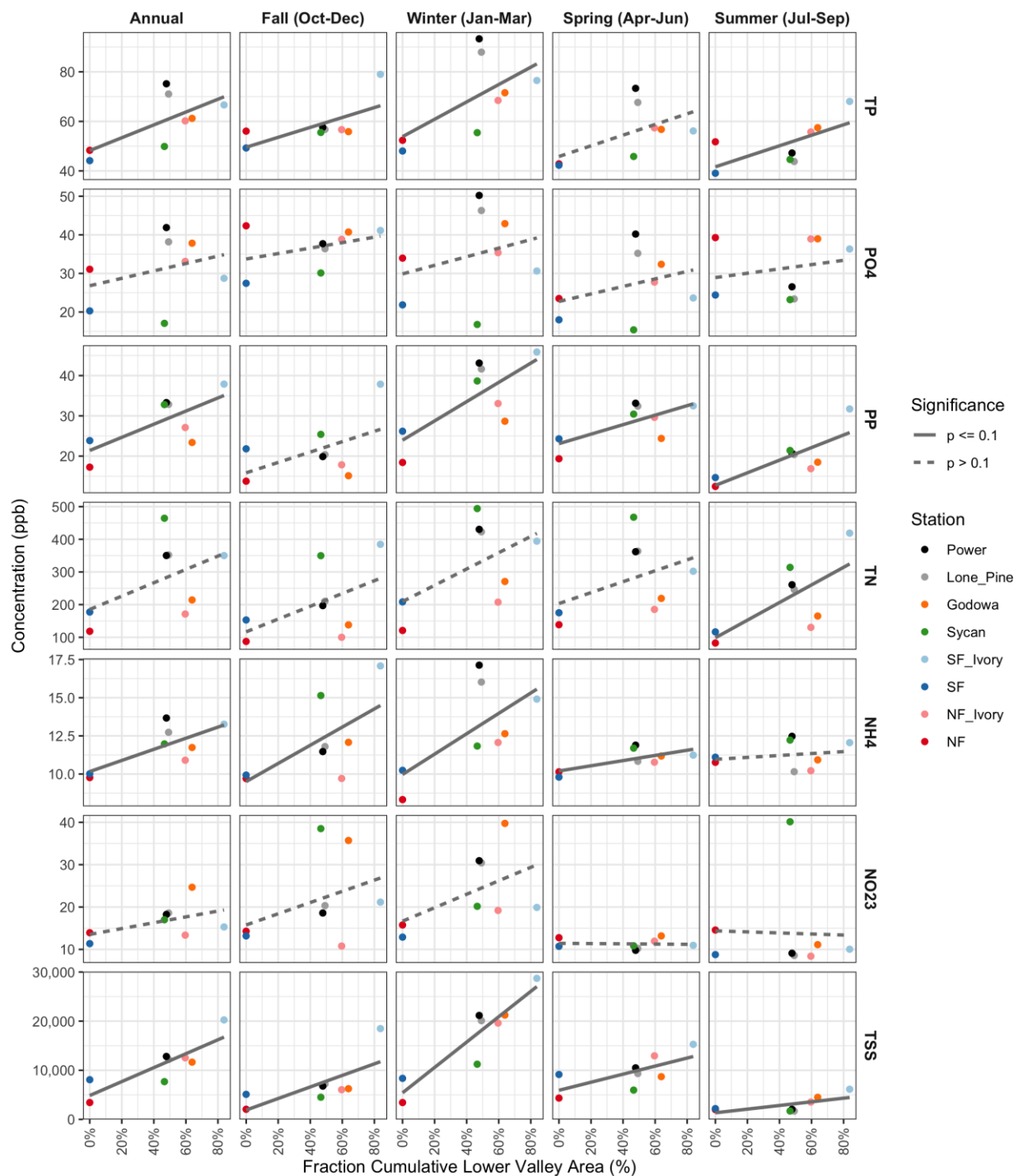


Figure 39: FWM concentration vs percent cumulative lower valley as POU irrigation area, WY 2010 – 2020.

Note: TSS based on WY 2011 – 2020.

The panels in the top row of Figure 39 show significant positive relationships for annual, fall, winter and summer mean TP concentration. In the spring season, the TP relationship was not significant possibly due to a dilution effect from snowmelt, which comprises a larger portion of flows in the spring relative to other seasons.

For PO₄, there were no significant relationships at the annual or any seasonal scale. This suggests that PO₄ concentrations are driven by non-anthropogenic factors, most likely groundwater discharge which has a relatively high concentration of dissolved phosphorus (see Section 4.8.1 below).

PP concentrations showed strong positive correlations based on annual and seasonal means in all seasons except fall, and TSS concentration relationships were significant in all seasons, with the winter season showing the highest slope. These strong correlations suggest that increasing agricultural land use tends to increase the amount of erosion, which thus increases particulate and total phosphorus concentrations. Further discussion on erosion potential across the basin is provided in Section 4.7 below.

Among the nitrogen species, there were significant correlations for TN only in summer, and significant correlations for NH₄ in all seasons except for summer. Conversely, there were no significant correlations for NO₃.

4.7 PHOSPHORUS, SEDIMENT, AND NITROGEN DYNAMICS RELATED TO FLOW AND SEASON

4.7.1 PARTICULATE PHOSPHORUS AND SEDIMENT DYNAMICS

The river network plots of annual FWM concentrations in Figure 31 above showed large increases in both PP and TSS concentrations in the lower North and South Fork sub-basins between NF and NF_Ivory, and between SF and SF_Ivory in all seasons, but especially during winter and spring under high flow conditions. These increases suggest sediment transport from disturbed channel and floodplain areas may be a significant source of phosphorus in the lower reaches of the North and South Forks. To further explore whether sediment³⁷ input is a major contributor of phosphorus loads in the various sub-basins, the following section presents the relationships between flow, TSS, TP, and the percent of TP as particulate phosphorus (% particulate P). Note that the figures in this section are based on the sampled biweekly concentrations and not the computed daily concentrations.

Figure 40 shows the relationship between TSS concentration and flow at each station with each symbol colored by season. The black lines are locally weighted scatterplot smoothing (LOWESS) trends used to indicate the general shape of the relationships (Helsel et al., 2020). This figure shows positive relationships between TSS concentrations and flow at all stations, with lower TSS concentrations and lower flows during summer, and higher concentrations and flows in winter and spring. It also shows that SF_Ivory, NF_Ivory, and Godowa tended to have higher TSS concentrations under low flow conditions than at the other stations suggesting that stream banks may be more unstable and vulnerable to erosion than in other reaches, or that there are other sources of particulates in the lower North and South Forks and upper Sprague sub-basins possibly related to irrigation return flows during summer low flows³⁸. There was also greater non-linearity in the relationships for the mainstem stations at Power, Lone_Pine,

³⁷ This does not include bedload sediment transport which was not measured as part of this study.

³⁸ The increased TSS suggests a dominant fine-grained fraction since the flows are very low during these periods, inferring that the summer sediment sources are due to riparian grazing, channel straightening, and related incision (see Figure 1 for stream channel example in the lower South Fork).

and Godowa with TSS concentrations decreasing at extreme high flows, which likely reflects floodplain deposition (e.g., settling of particulates as water distributes over the floodplain), possible dilution from snowmelt, or seasonal hysteresis whereby sediment transport occurs during early season flows but is then depleted during later season high flow events. TSS concentrations in winter tended to be greater than those during spring under high flow conditions (the red symbols are generally above the smoother lines and the blue symbols are below) indicating that first-flush events in the winter transport proportionally greater suspended material. TSS at lower stations Power and Lone_Pine tended to show greater variability with flow in the winter, and increased scatter in the relationship at the Godowa site likely reflects the large groundwater influences there.

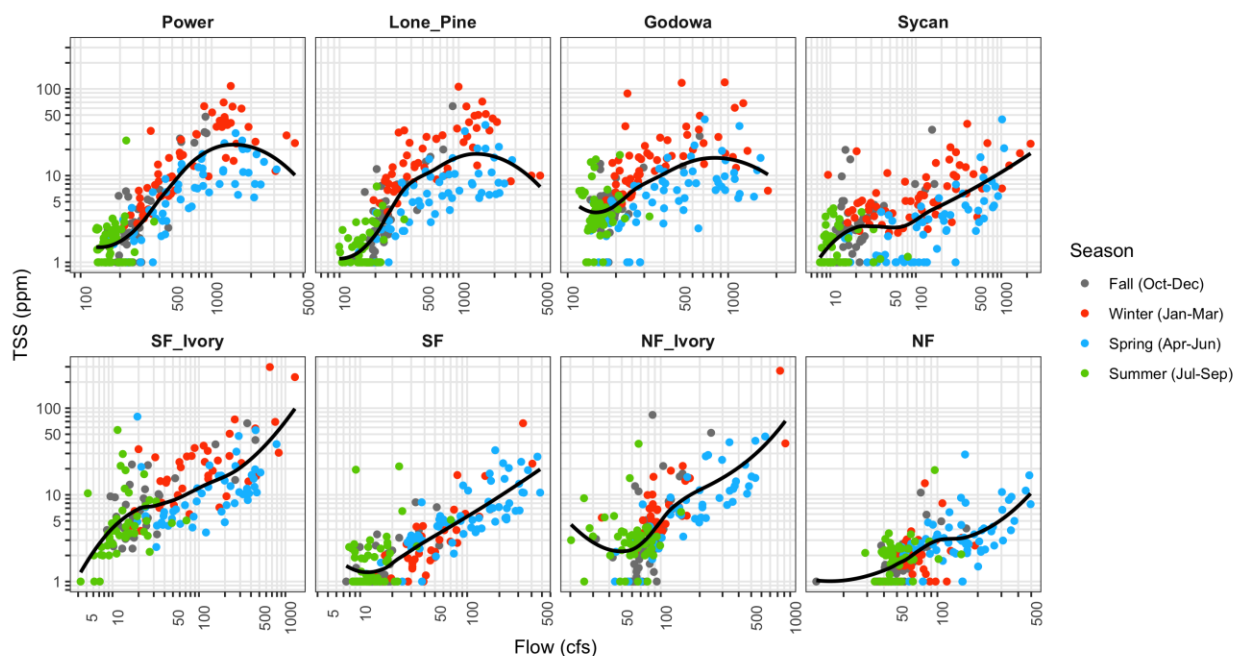


Figure 40: Relationships between biweekly TSS concentration and flow, WY 2011 – 2020.

To explore the relationships between TSS and phosphorus, the percent particulate P (% PP) was computed by dividing the PP concentration ($PP = TP - PO_4$) by the TP concentration. Figure 41 shows the distribution of % PP at each station. The highest % PP occurred at SF_Ivory with a median of 51%. The upper SF station, however, had a median of 36% indicating a significant increase in particulate phosphorus relative to dissolved phosphorus between these stations in the lower reach of the South Fork. Similarly, there was an increase in the median % PP in the lower North Fork reach from 21% at NF to 34% at NF_Ivory. The NF station had the lowest % PP indicating that dissolved phosphorus from groundwater is likely the primary source of phosphorus loading to the upper North Fork sub-basin.

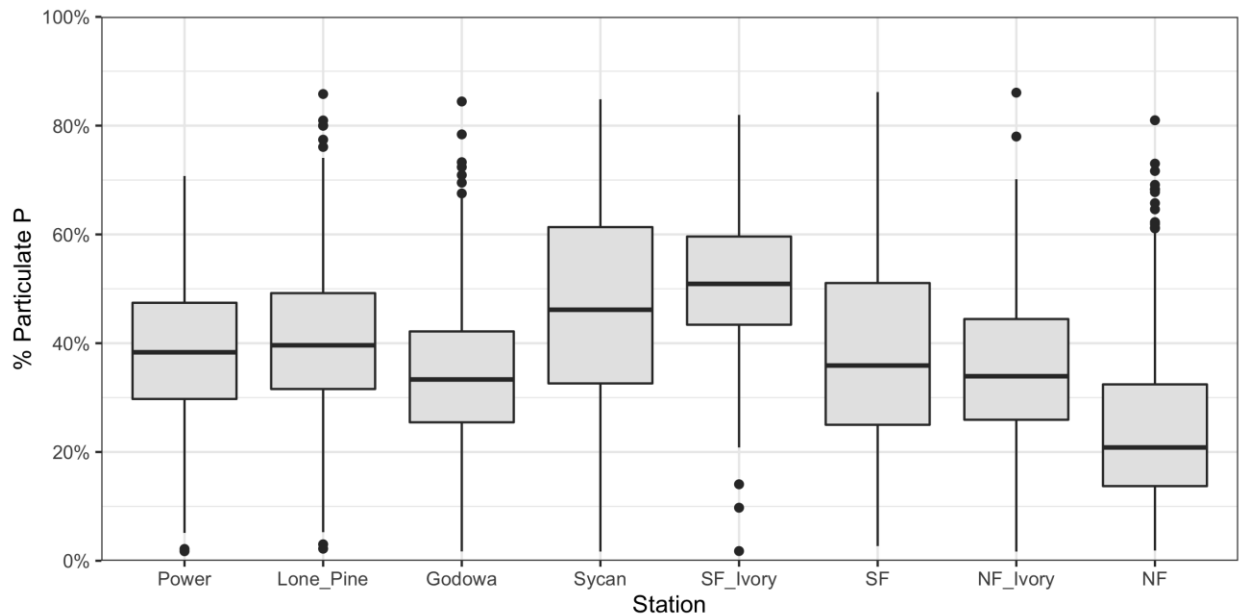


Figure 41: Distributions of percent particulate P by station, WY 2002 – 2020.

SF_Ivory and NF_Ivory based on WY 2010 – 2020.

*Middle line = median, lower and upper box hinges = 25th and 75th percentiles, lower and upper whiskers = 1.5 * IQR from box hinges or minimum/maximum value, whichever is smaller, points = values more than 1.5 * IQR from box hinges.*

Figure 42 shows the relationship between fraction particulate TP (% PP) and flow for each station with the symbols colored by season. The black lines again show LOWESS trends. The four stations in the North and South Forks (bottom row) all show relatively positive linear relationships between fraction particulate TP and flow. The other four stations (top row) show more non-linear relationships with the fraction particulate TP higher under lowest flows, decreasing under intermediate flows, and then increasing with flow before tending to level off and decline at highest flows. The relatively high % PP under low flows at these stations occurred primarily during summer and was likely caused by a combination of bio-uptake of dissolved phosphorus (PO₄) during the summer growing season, sloughing of algal and macrophyte material, and increased particulate phosphorus loading through irrigation or other agricultural practices such as cattle access to degraded riparian areas (e.g., see inset photos in Figure 1). The relatively high fraction of particulate P under low flows at SF_Ivory compared to the other stations again suggests that even under low flows there is a major source of particulate phosphorus loading to the lower South Fork reach between SF and SF_Ivory. Declines in the particulate fraction of TP at intermediate flows (occurring in late-fall to early winter) indicate initial dilution prior to an increase in higher energy flows associated with increased particulate P occurring in the winter.

Periphyton/macrophyte mediated cycling among dissolved, particulate, organic and inorganic nutrient forms is a well-documented phenomenon that influences temporal and longitudinal nutrient variation in river systems (e.g., Newbold et al., 1982; Mullholand et al., 1985; Anderson and Carpenter, 1998).

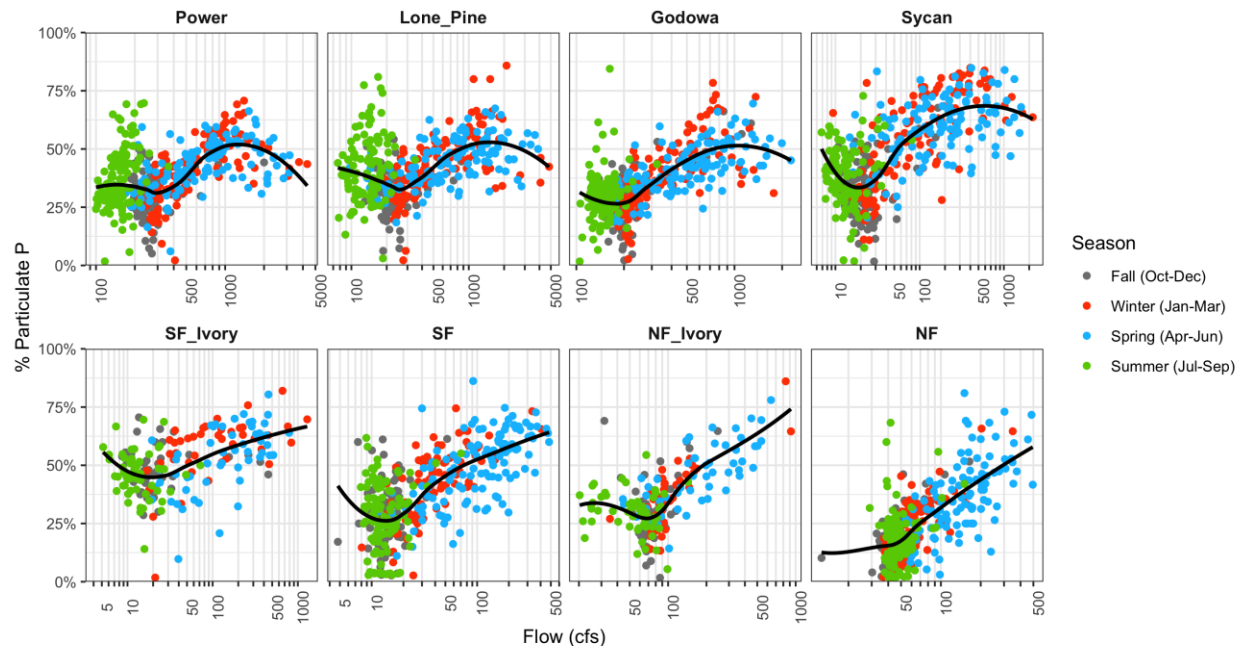


Figure 42: Relationships between biweekly percent particulate P and flow, WY 2002 – 2020.

SF_Ivory and NF_Ivory based on WY 2010 – 2020.

Figure 43 shows the relationships between TP and TSS concentrations, and Figure 44 shows the relationships between fraction particulate TP and TSS. Both TP concentrations and the fraction particulate TP (PP/TP) show positive relationships with TSS further confirming that erosion is a major source of TP in the Sprague system. These results are consistent with O'Connor et al. (2013), who in a review of the GMA (2007) sediment transport study, observed that significant sediment entrainment in the South Fork valley segment likely resulted from channel and bank erosion, including additional sources of sediment from eroding bank crevasses or cuts which facilitate conveyance of sediment entrained from flood-plain surfaces and irrigation channels.

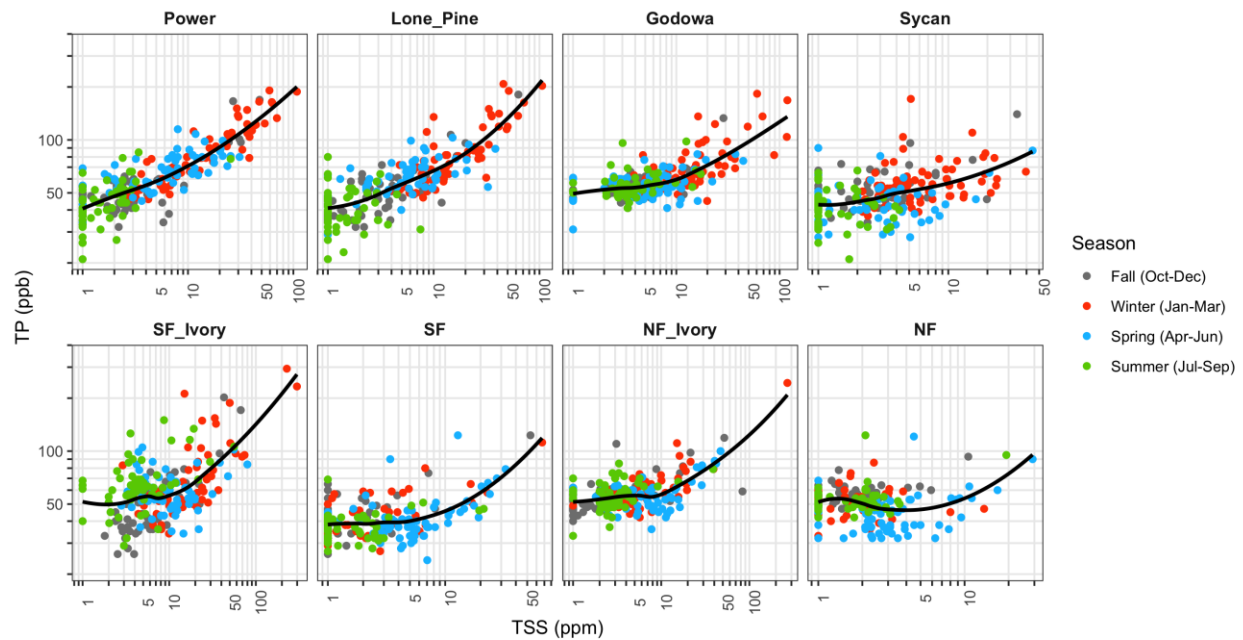


Figure 43: Relationships between biweekly TP and TSS concentrations, WY 2011 – 2020.

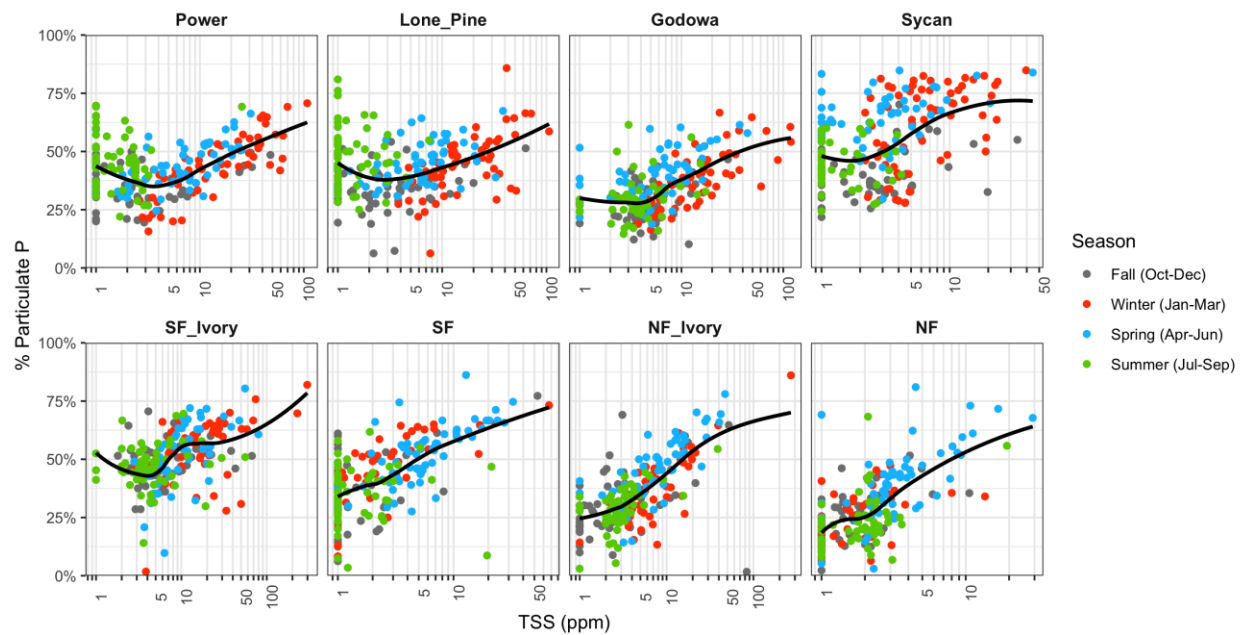


Figure 44: Relationships between biweekly percent particulate P and TSS concentrations, WY 2011 – 2020.

Finally, Figure 45 shows the relationships between particulate P concentrations and TSS, and Figure 46 shows particulate P versus flow. Again, all stations show positive relationships between particulate P and both TSS and flow, as expected. Similar to the relationships between TSS and flow shown in Figure 40, Figure 46 shows that under high flows, particulate P concentrations tended to be higher in winter than in spring at the mainstem stations.

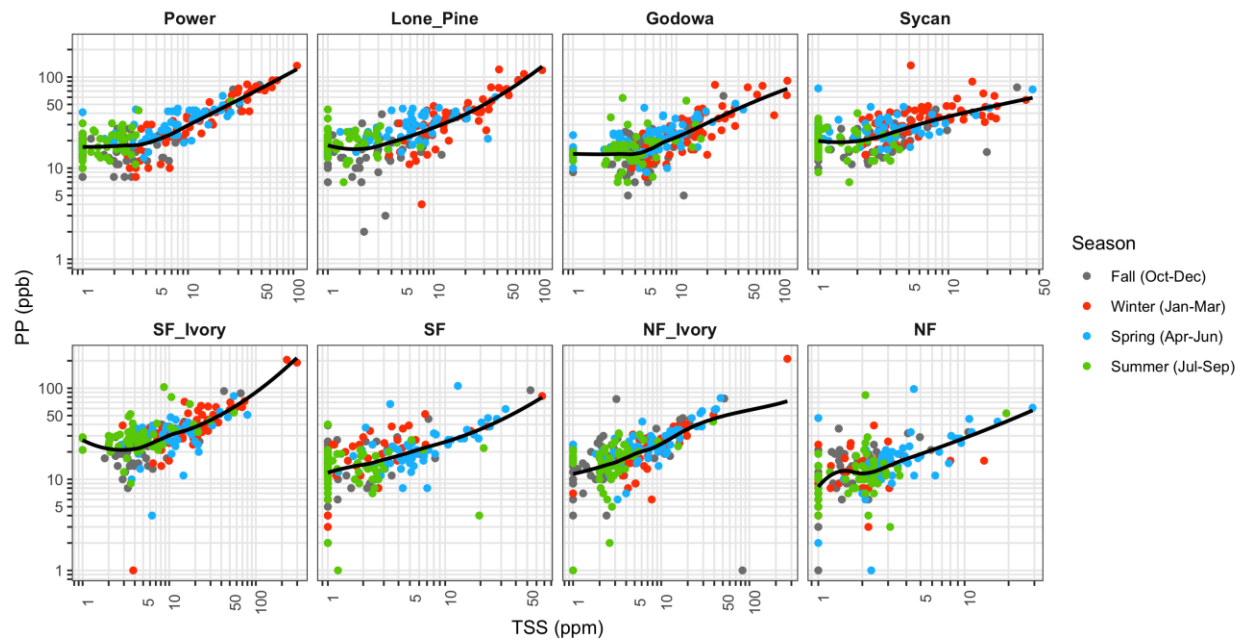


Figure 45: Relationships between biweekly PP and TSS concentrations, WY 2011 – 2020.

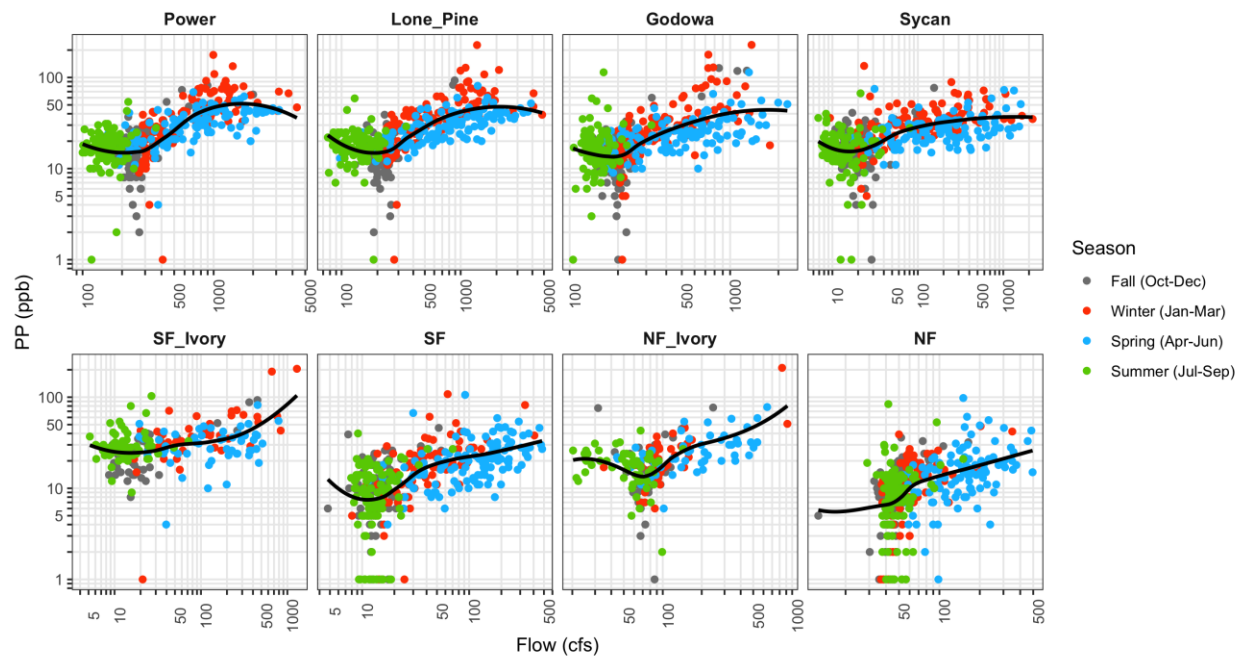


Figure 46: Relationships between biweekly PP concentration and flow, WY 2002 – 2020.

SF_Ivory and NF_Ivory based on WY 2010 – 2020.

4.7.2 NITROGEN DYNAMICS

Similar scatterplots were created for comparing various nitrogen parameters to flow and TSS at each station (including symbols colored by season and a LOWESS trend line). TN concentration was non-linearly related to flow at most stations, with relatively high values occurring during the summer low flow period, declining values in the fall and increasing values as flow increased in the winter and spring

(Figure 47). As with the phosphorus parameters, TN values tended to be higher in the winter than the spring during higher flows (Figure 47; blue symbols below the smoother, red symbols above), and similar to PP, TN values tended to level off or decline at the very highest flows. At several stations (Power, Lone_Pine, SF_Ivory and NF_Ivory) the low flow summer TN values were among the highest for any season and flow, and higher summer flows tended to be associated with lower TN concentration at Power, Lone_Pine, and NF_Ivory.

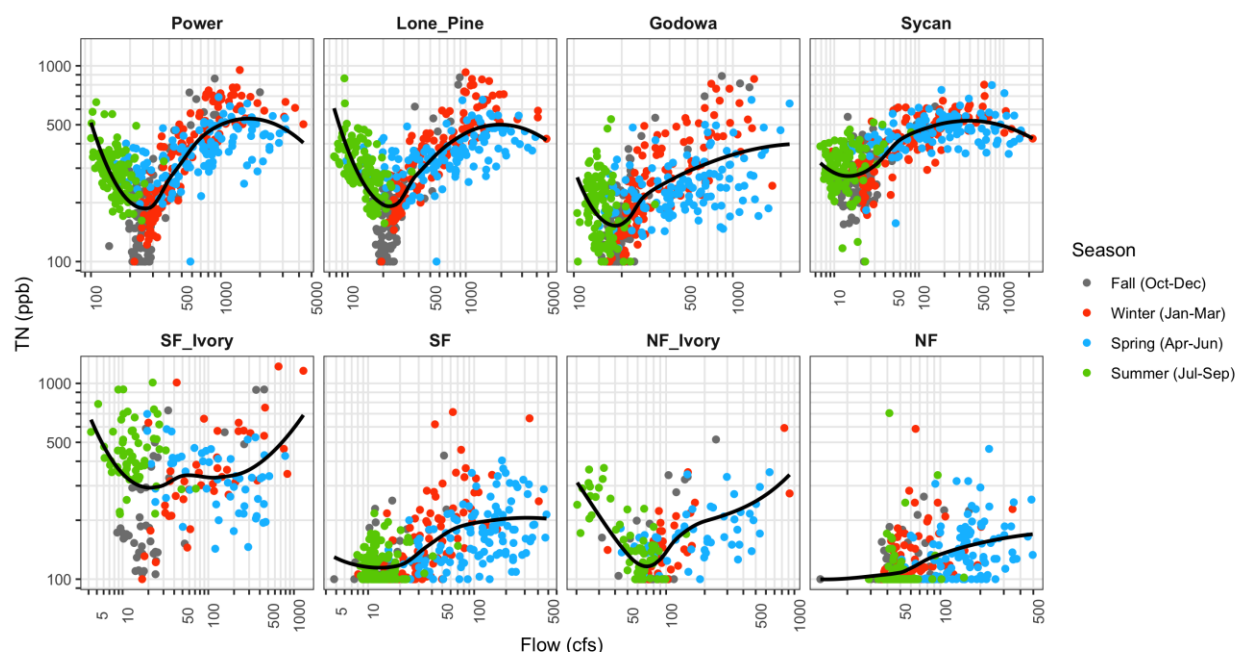


Figure 47: Relationships between biweekly TN concentration and flow, WY 2002 – 2020.

SF_Ivory and NF_Ivory based on WY 2010 – 2020.

With the exception of the Sycan and Godowa stations for NO₂₃, NH₄ and NO₂₃ showed only slight relationships with flow compared to those for TN (Figure 48 and Figure 49). In most cases, summer NH₄ values were as high as other seasons and the LOWESS trend line was relatively flat with only a slight increase at the highest flows for the Sprague mainstem stations (Figure 48). In contrast, summer NO₂₃ values tended to be lowest in summer for all stations except the Sycan and NF stations (Figure 49). The Sycan was unique in that NO₂₃ showed a strong negative relationship with flow, with summer and fall values highest and winter-spring high flow values lowest. Aldous (2009) also noted that NO₂₃ loads increased between the outlet of Sycan Marsh and the confluence with the Sprague River but was unsure of the NO₂₃ source. Since flows from the Sycan marsh upstream abate between mid-June and the end of October, fall/winter concentrations and load are driven by outflow from the marsh, but summer values are driven by the watershed below the marsh outfall, including spring inflow (e.g., Torrent Springs), tributaries, and agricultural activities.

The pattern at Godowa was also unique in that NO₂₃ increased with flow in the summer through early winter and then leveled off and declined in late winter and spring as flows increased further, although the cause of these dynamics is not clear. Low summer values at Power, Lone_Pine, SF_Ivory, NF_Ivory,

and SF likely reflect uptake by attached algae and macrophytes, dilution from spring inflow, and possible denitrification.

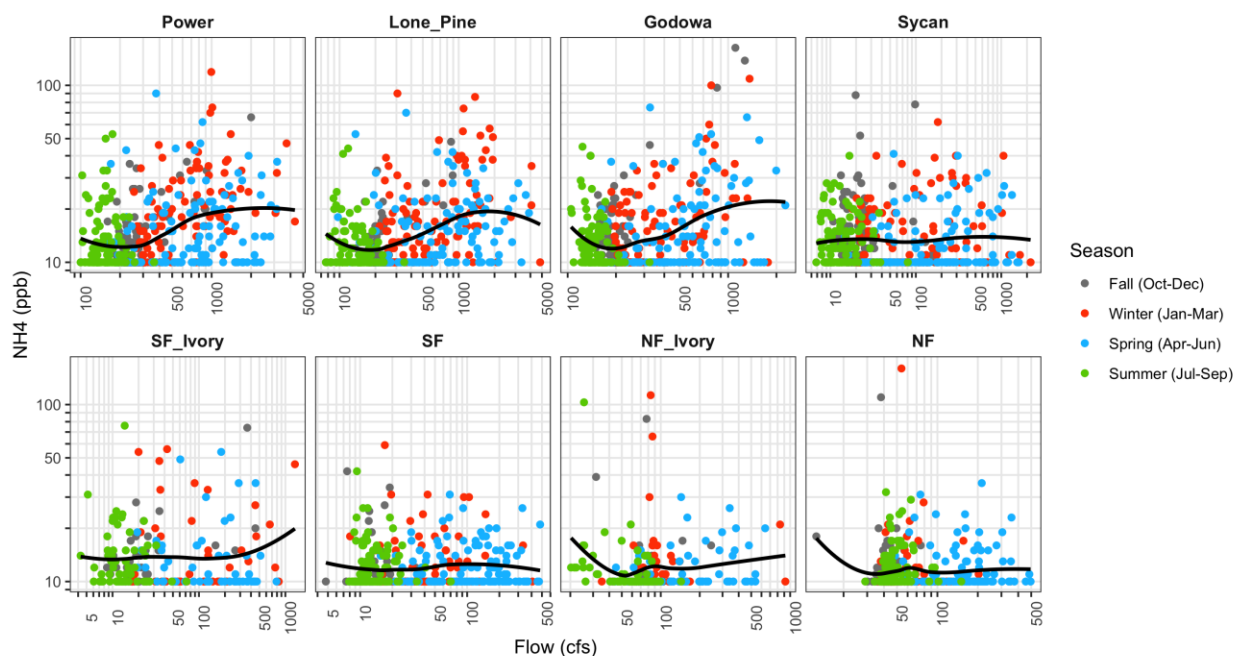


Figure 48: Relationships between biweekly $\text{NH}_4\text{-N}$ concentration and flow, WY 2002 – 2020.

SF_Ivory and NF_Ivory based on WY 2010 – 2020.

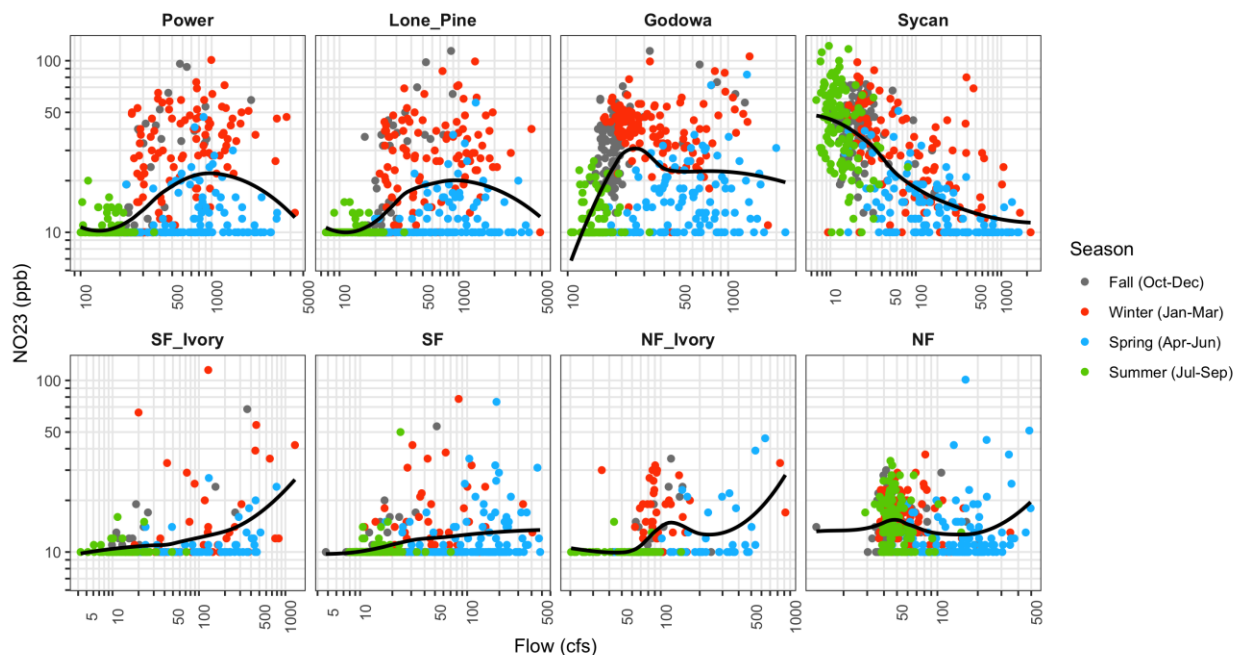


Figure 49: Relationships between biweekly $\text{NO}_{23}\text{-N}$ concentration and flow, WY 2002 – 2020.

SF_Ivory and NF_Ivory based on WY 2010 – 2020.

As expected given the generally low NH_4 and NO_{23} concentrations, the pattern in organic-N (computed as TN minus the sum of NH_4 and NO_{23}) was similar to that for TN on a seasonal basis (Figure 50). The

ratio of organic to inorganic-N generally followed the organic-N pattern (higher during summer low flow values, declining at intermediate flows in summer and fall, and increasing again in the winter and spring; Figure 51). One exception was for the Sycan which showed low summer-fall ratios due to the relatively high NO₂₃ values occurring at that time, before increasing as flows from the Sycan marsh commence in the late fall (Figure 51). In addition, ratio values at Godowa tended to be lower than those for Power and Lone-Pine overall (Figure 51), and the percent organic-N declined sharply at Godowa (data not shown) during the fall/early-winter period that coincided with an NO₂₃ increase.

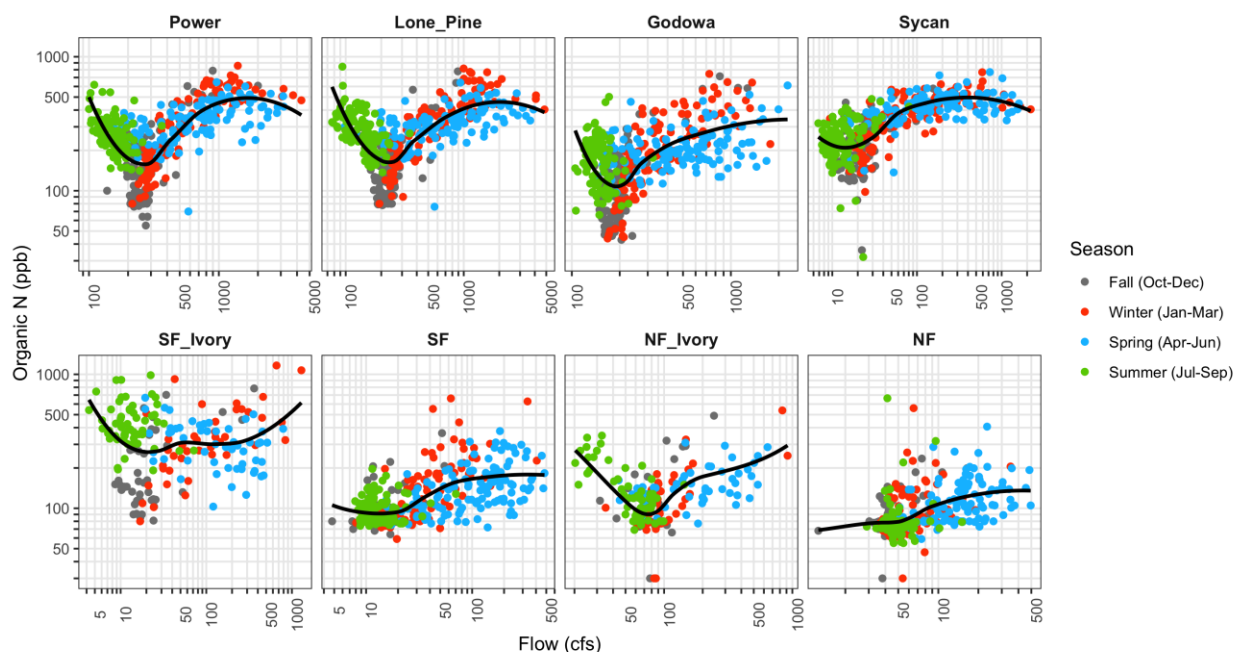


Figure 50: Relationships between biweekly Organic-N concentration and flow, WY 2002 – 2020.

SF_Ivory and NF_Ivory based on WY 2010 – 2020.

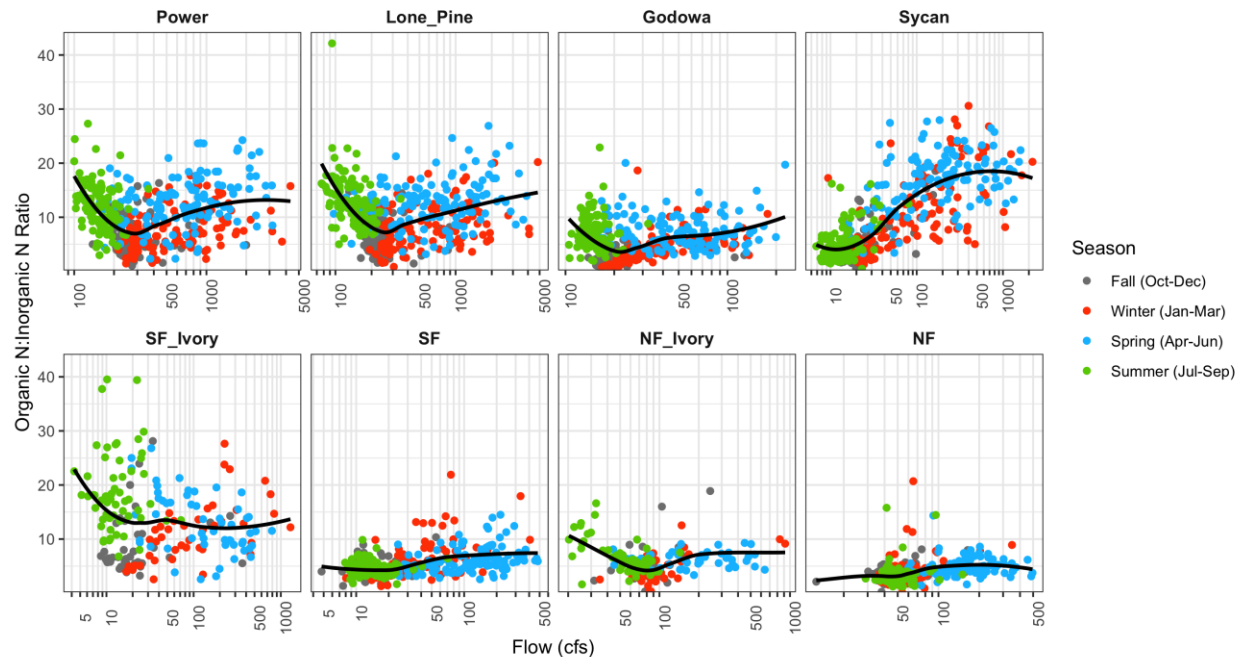


Figure 51: Relationships between biweekly Organic-N to Inorganic-N ratio and flow, WY 2002 – 2020.

SF_Ivory and NF_Ivory based on WY 2010 – 2020.

TN and organic-N (not shown since patterns were identical to TN) concentrations generally remained constant over a range of TSS concentrations during summer and fall low flow periods before increasing during winter and spring increases in TSS at most stations (Figure 52). One exception was for the SF_Ivory station which showed higher TN and organic-N values during the summer season and summer values were higher than fall-winter even at similar TSS concentrations (Figure 52). Unlike % PP which increased with increasing TSS (Figure 44) percent organic-N remained relatively constant with increasing TSS in most cases indicating a decoupling between the fractionation of organic- vs. inorganic-N and TSS (Figure 53).

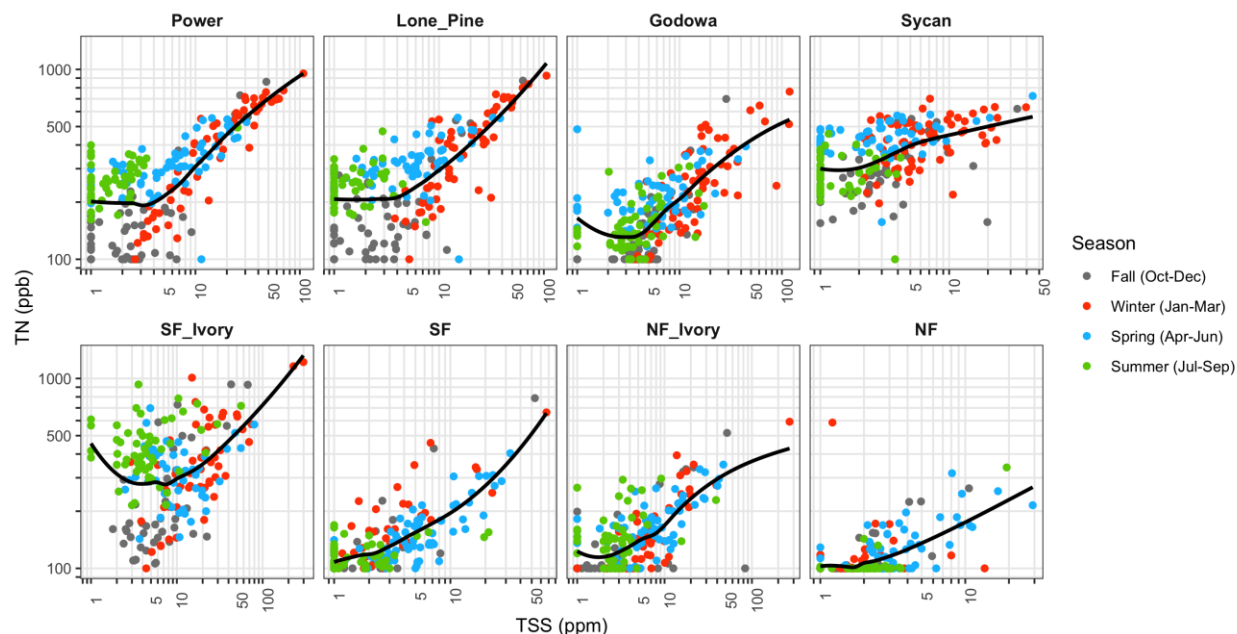


Figure 52: Relationships between biweekly TN and TSS concentrations, WY 2011 – 2020.

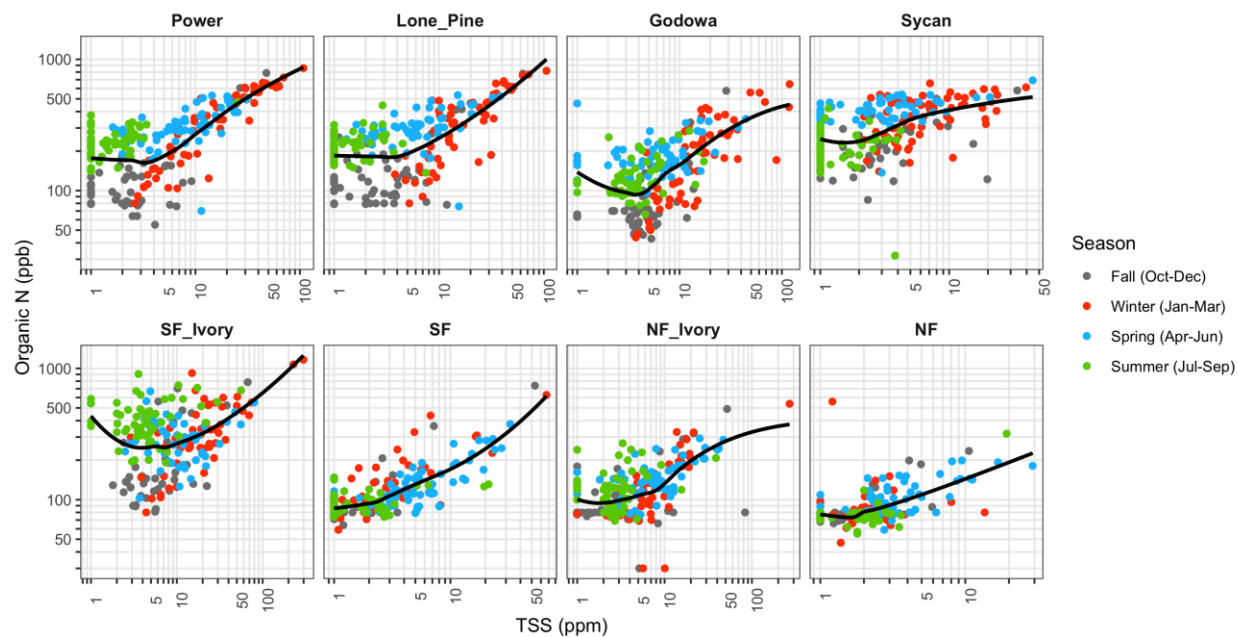


Figure 53: Relationships between biweekly percent Organic-N and TSS concentration, WY 2011 – 2020.

4.8 BACKGROUND VS ANTHROPOGENIC LOADING

As one of the study objectives, the water quality results were used to refine estimates of background TP loading from areas with minimal anthropogenic impacts, and to estimate the relative contributions of anthropogenic activities to the total TP loading in the Sprague River system. Walker et al. (2012) performed a similar analysis of background and anthropogenic loading for the entire Upper Klamath

Lake basin. Using a background TP concentration of 65 ppb, that study estimated that 31% of the total loads to UKL were associated with anthropogenic activities over the period WY 2008 – 2010 (see Table 4 of Walker et al., 2012). However, Walker et al. (2012) also noted that within the Sprague River Basin, the two relatively un-impacted sub-basins in the upper South and North Forks had observed FWM concentrations lower than the basin-wide background concentration (44 and 58 ppb, respectively, over WY 2010 – 2020 based on the results of this study, see Table 9). These lower concentrations suggested that background concentrations may be lower within the Sprague River system relative to other basins draining to Upper Klamath Lake. Walker and Kann (2022) subsequently updated portions of that analysis using an extended period over WY 1992 – 2018 but did not include the Sprague River sampling stations. The methodology used in Walker et al. (2012) and Walker and Kann (2022) was therefore modified to better reflect the lower concentrations observed in the relatively un-impacted upper South and North Forks.

For this study, background loading was divided into two components: 1) groundwater discharge from seeps and springs, and 2) runoff due to snowmelt, rainfall, and any other non-groundwater inputs. These two components will be referred to as “groundwater” and “runoff” in this report, although it is important to note that the latter includes all inputs not accounted for by the groundwater discharge estimates.

Using the estimates of groundwater discharge from Gannett et al. (2007) (see Section 4.2.3) the total flow at each station was partitioned into the separate groundwater and runoff components. The background concentration associated with groundwater discharge was estimated based on direct measurements collected from springs and creeks by the Klamath Tribes. The background concentration for runoff was then calculated from the total loads (L_{Total} as calculated and described above in Section 3.2.1) and FWM concentrations from the relatively un-impacted sub-basins (upper North Fork, upper South Fork). The difference between the total loads at each station and the total background loads, which includes both groundwater and runoff, were then computed to represent anthropogenic loads. These calculations are represented by the following equations:

$$L_{GW} = Q_{GW}C_{GW}$$

$$L_{Runoff} = (Q_{Total} - Q_{GW})C_{Runoff}$$

$$L_{Background} = L_{GW} + L_{Runoff}$$

$$L_{Anthropogenic} = L_{Total} - L_{Background}$$

$$C_{Anthropogenic} = \frac{L_{Anthropogenic}}{Q_{Total}}$$

Note that the concentration associated with anthropogenic loading represents the *increase* from background levels to the total observed concentration as opposed to the concentration associated with discharges originating from anthropogenic sources (e.g., irrigation return flows).

4.8.1 BACKGROUND CONCENTRATION FOR GROUNDWATER

The background concentration associated with groundwater discharge was estimated using water quality data collected by Klamath Tribes as part of a synoptic sampling program in the Sprague River Basin. The synoptic samples were collected on springs and creeks at locations that are not part of the routine biweekly sampling program. Because these samples were collected at different times of the year and with varying frequency, annual FWM concentrations could not be directly calculated as was done for the routine sampling locations. However, the synoptic data were primarily collected from groundwater-fed springs and thus expected to have relatively constant concentrations over time. The locations of the synoptic samples are shown in Figure 54. Figure 55 shows the sampled TP concentrations as well as the median of each location.

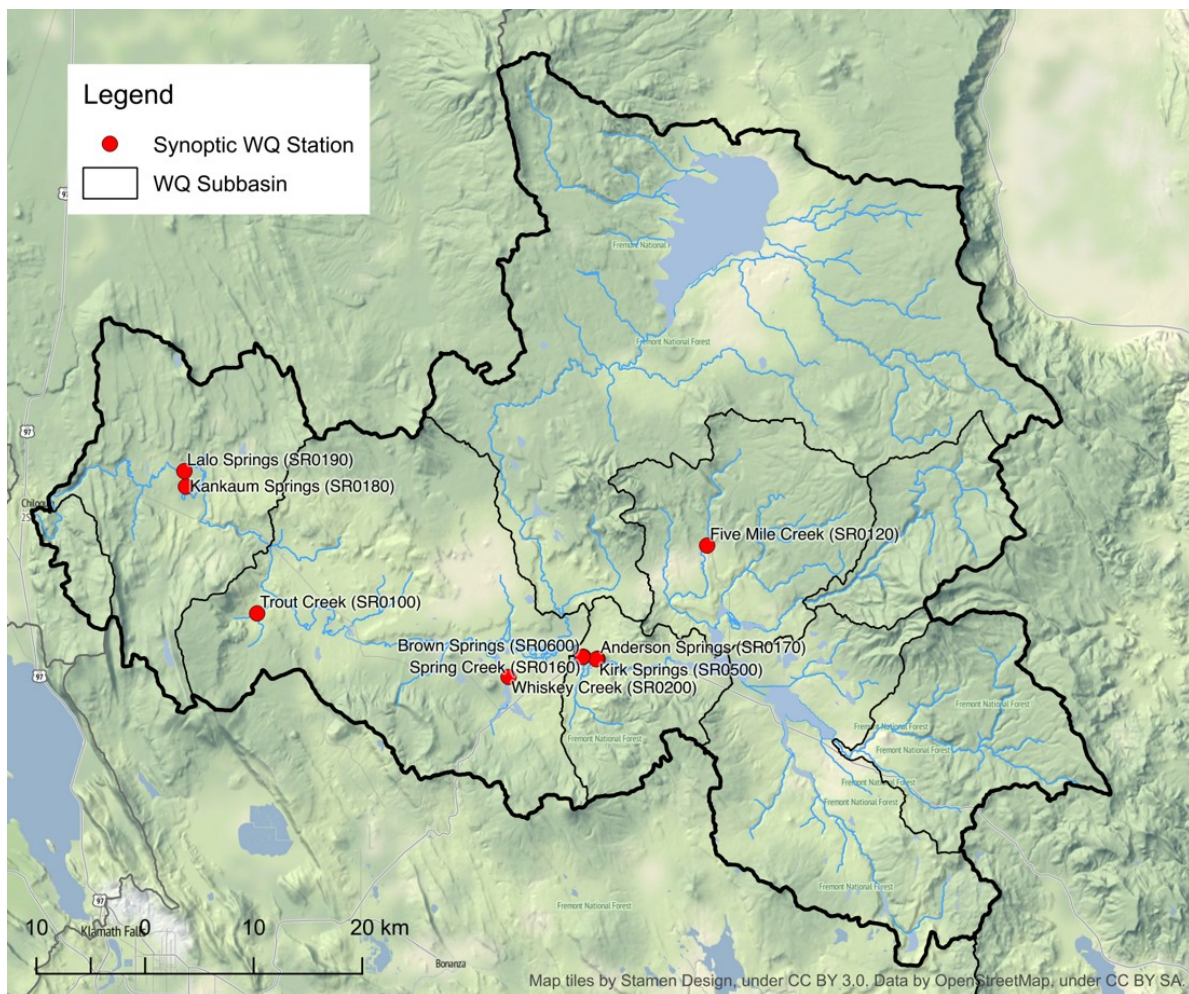


Figure 54: Map of synoptic water quality stations.

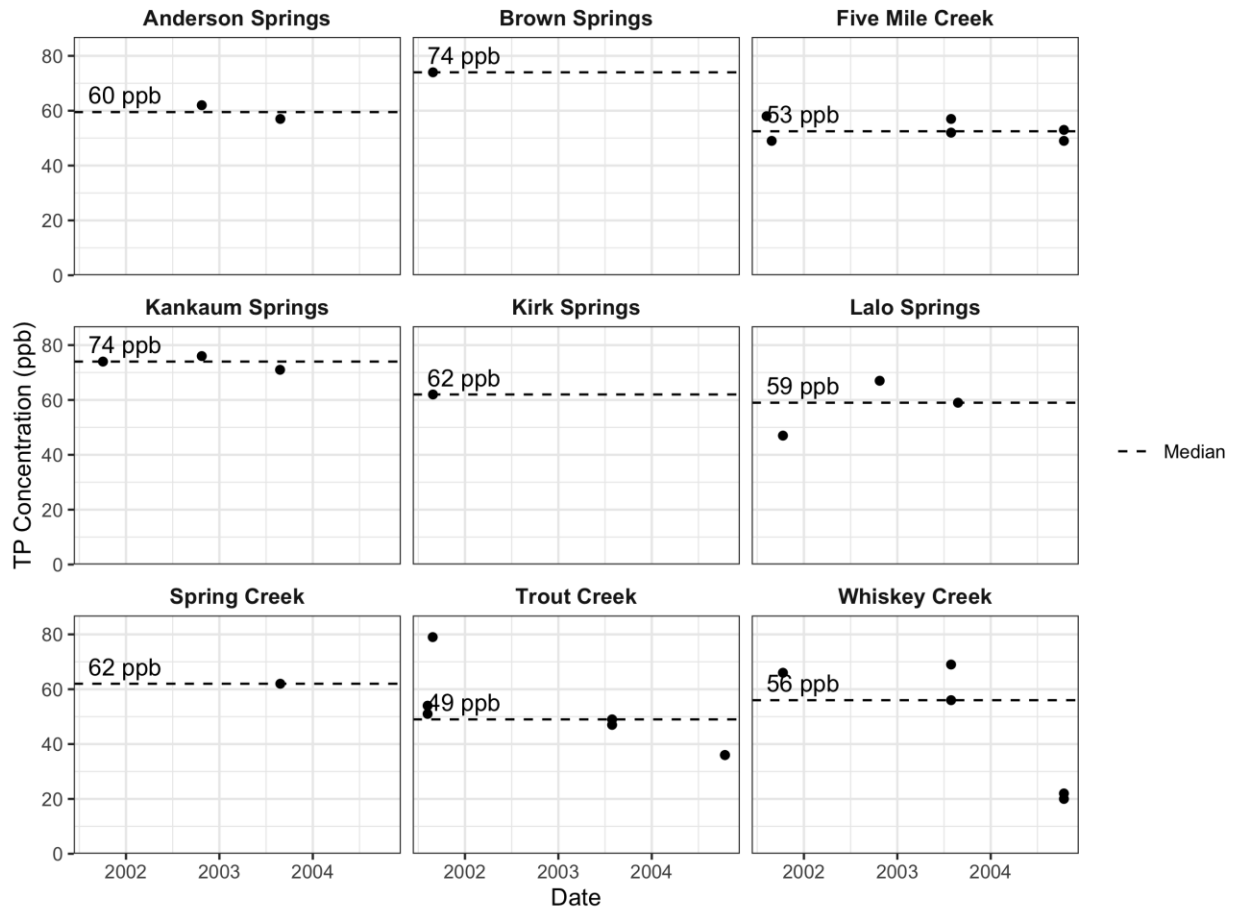


Figure 55: TP concentrations of synoptic springs and creeks.

The median TP concentration and number of samples for each station are listed in Table 10. At three of the stations, only one sample was collected, which was assumed to be representative of the median value for that location. Some sites, notably Trout Creek and Whiskey Creek, exhibit greater temporal variability relative to the other sites. The overall median TP concentration across the stations was 60 ppb, which is 5 ppb less than the background concentration of 65 ppb used in Walker et al. (2012) and Walker and Kann (2022). A concentration of 60 ppb was therefore used as the background concentration associated with groundwater discharge.

Table 10: Median TP concentrations of synoptic spring and creek samples.

Station ID	Description	Median TP (ppb)	Number of Samples
SR0100	Trout Creek	49	7
SR0120	Five Mile Creek	53	6
SR0160	Spring Creek	62	1
SR0170	Anderson Springs	60	2
SR0180	Kankaum Springs	74	3
SR0190	Lalo Springs	59	3
SR0200	Whiskey Creek	56	5
SR0500	Kirk Springs	62	1
SR0600	Brown Springs	74	1
Overall Median:		60	

Although NRCS (2009) reported considerably higher TP concentrations (>200 ppb) in shallow ground water based on direct measurements using shallow piezometers and direct sampling of seeps in the lower Sprague River, these extremely high concentrations are unlikely to accurately reflect background concentrations for groundwater discharge, and are more likely to reflect the effect of agricultural activities, such as manure from cattle grazing and irrigation seepage. Furthermore, shallow groundwater is unlikely to be transported directly to receiving waters in large volumes. If water with sufficient volume and such high concentration were reaching the Sprague River, this would be reflected in large increases in TP concentrations and loads, which are not evident in the results of this study. The shallow ground water measurements referenced by NRCS (2009) were taken in the lower Sprague River reaches and these reaches showed almost no increase in concentration (e.g., see Figure 35). Therefore, high TP groundwater sources with sufficient flow reaching the river channel are not reflected by the data, and thus a background concentration associated with groundwater discharge of 60 ppb is assumed to be more accurate based on the direct measurements from relatively high-volume springs as determined from the Klamath Tribes' synoptic sampling program.

4.8.2 BACKGROUND CONCENTRATION FOR RUNOFF

Using the background TP concentration of 60 ppb and the estimates of groundwater discharge from Gannett et al. (2007), the concentration associated with runoff and other non-groundwater sources that are unaffected by land use alterations or other human activities was estimated from the observed mean annual FWM concentrations for the relatively un-impacted NF and SF stations in the upper North and South Fork sub-basins. For each of these stations, the runoff concentration was computed by the equation:

$$C_{Runoff} = \frac{L_{Runoff}}{Q_{Runoff}} = \frac{L_{Total} - Q_{GW}C_{GW}}{Q_{Total} - Q_{GW}}$$

Table 11 lists each of these terms for the NF and SF sub-basins. The total flows and loads are based on the annual means computed over the 11-year period WY 2010 – 2020, which were listed in Table 8 above.

Table 11: Background TP concentration associated with groundwater and runoff in un-impacted sub-basins.

Station	Total			Groundwater			Runoff		
	Flow (hm ³ /yr)	Load (mt/yr)	Conc (ppb)	Flow (hm ³ /yr)	Load (mt/yr)	Conc (ppb)	Flow (hm ³ /yr)	Load (mt/yr)	Conc (ppb)
SF	45.7	2.02	44.2	21.4	1.29	60.0	24.3	0.73	30.2
NF	77.0	3.72	48.3	52.7	3.16	60.0	24.2	0.56	22.9

Note: calculations were performed prior to rounding and are thus slightly different from results computed using table values.

The estimated TP concentrations associated with runoff for SF and NF were thus 30.2 and 22.9 ppb, respectively. Based on the flow-weighted mean of these two concentrations, the background concentration for runoff across the entire Sprague River Basin was set to 26.5 ppb. This estimated background runoff concentration is likely conservative as it assumes that there is no anthropogenic activity upstream of the SF and NF stations. In reality, there is likely some degree of anthropogenic impacts on water quality due to forestry activities and road-related erosion as well as some potential agricultural activities as suggested by the presence of a few water withdrawal PODs and POUs within these basins (see Figure 11 in Section 2.4.5). However, the extent of these anthropogenic impacts is likely small relative to the other sub-basins within the Sprague River basin.

4.8.3 ANTHROPOGENIC AND BACKGROUND TP LOADS AND CONCENTRATIONS

Using background TP concentrations of 60 and 26.5 ppb for groundwater and runoff, respectively, the total background and remaining anthropogenic loads were computed for each station based on the total mean annual flows and loads over WY 2010 – 2020. Table 12 lists the flow, load, and FWM concentration for each component and water quality station. The background concentration for NF was limited to 22.9 ppb (see Table 11) since it was less than the assumed background concentration of 26.5 ppb used in the other stations.

In order to determine the portions of the total *loads* and *concentrations* associated with background and anthropogenic sources, the flows for the total background and anthropogenic components were set to the total flow at each station. As noted above, the concentration associated with anthropogenic loading represents the *increase* in concentration above the total background level due to anthropogenic activities. Table 13 lists the percent of the total TP load associated with each component. The TP loads associated with each component are shown in Figure 56 for each station.

Table 12: Background and anthropogenic TP loads and concentrations, WY 2010 – 2020.

Station	Total			Background as GW			Background as Runoff			Total Background			Anthropogenic		
	Q	L	C	Q	L	C	Q	L	C	Q	L	C	Q	L	C
Power	404.7	30.4	75.2	301.1	18.1	60.0	103.6	2.8	26.5	404.7	20.8	51.4	404.7	9.6	23.7
Lone_Pine	394.1	28.0	71.0	235.9	14.2	60.0	158.2	4.2	26.5	394.1	18.4	46.6	394.1	9.6	24.5
Godowa	267.5	16.4	61.2	199.3	12.0	60.0	68.3	1.8	26.5	267.5	13.8	51.5	267.5	2.6	9.8
Sycan	91.3	4.6	49.9	18.8	1.1	60.0	72.6	1.9	26.5	91.3	3.1	33.4	91.3	1.5	16.5
SF_Ivory	75.8	5.0	66.6	33.1	2.0	60.0	42.7	1.1	26.5	75.8	3.1	41.1	75.8	1.9	25.5
SF	45.7	2.0	44.2	21.4	1.3	60.0	24.3	0.6	26.5	45.7	1.9	42.2	45.7	0.1	1.9
NF_Ivory	103.7	6.2	60.2	82.2	4.9	60.0	21.5	0.6	26.5	103.7	5.5	53.1	103.7	0.7	7.1
NF	77.0	3.7	48.3	52.7	3.2	60.0	24.2	0.6	22.9	77.0	3.7	48.3	77.0	0.0	0.0

Q = Flow (hm³/yr), L = TP Load (mt/yr), C = FWM TP Concentration (ppb)

Note: calculations were performed prior to rounding and are thus slightly different from results computed using table values.

Table 13: Percent of total TP load as background and anthropogenic, WY 2010 – 2020.

Station	% Total TP Load			Anthropogenic
	Groundwater	Runoff	Total	
Power	59%	9%	68%	32%
Lone_Pine	51%	15%	66%	34%
Godowa	73%	11%	84%	16%
Sycan	25%	42%	67%	33%
SF_Ivory	39%	22%	62%	38%
SF	64%	32%	96%	4%
NF_Ivory	79%	9%	88%	12%
NF	85%	15%	100%	0%

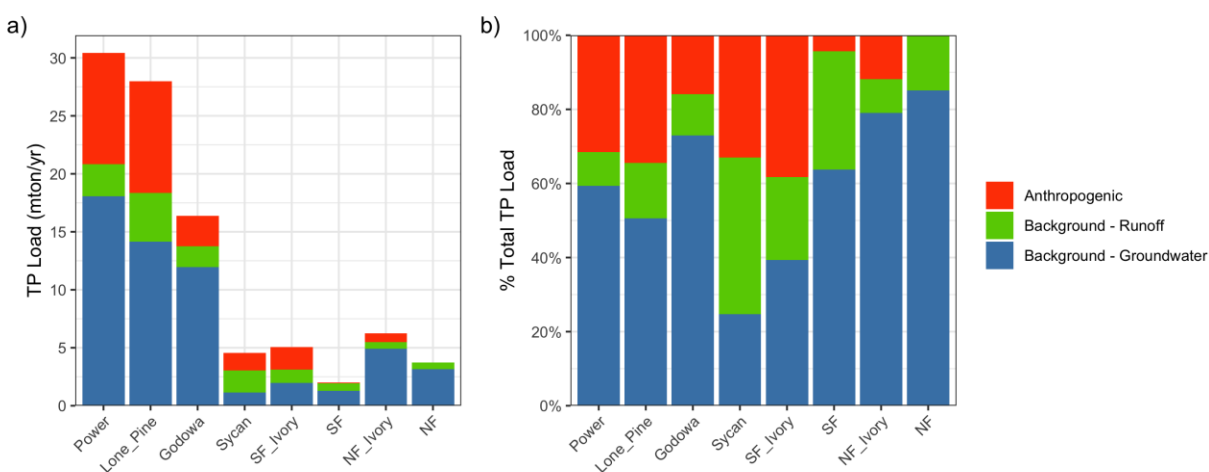


Figure 56: Mean annual background and anthropogenic TP loads by station, WY 2010 – 2020.

Panels: a) total load (mton/yr), b) fraction of total TP load from each source.

As shown in Table 12, total background concentrations ranged from 33 ppb in the Sycan River to a maximum of 53 ppb at the NF_Ivory station in the lower North Fork. The differences in total background concentrations reflect the relative fractions of total flow associated with groundwater versus runoff. At stations where groundwater comprises a greater fraction of total flow, the total background concentrations are greater due to the higher background concentration in groundwater relative to runoff. The increase in TP concentration associated with anthropogenic activities among the impacted

stations³⁹ ranged from 7 ppb at NF_Ivory to 25 ppb at SF_Ivory. At the Power station near the outlet of the Sprague River, the total background concentration was 51 ppb, which is increased by 24 ppb due to anthropogenic activity to yield an overall concentration of 75 ppb. Table 13 and Figure 56b show that the fraction of the total TP load as anthropogenic ranges from a minimum of 12% at NF_Ivory to a maximum of 38% at SF_Ivory among the impacted stations²⁷. At the Power station near the Sprague River outlet, anthropogenic loads account for 32% of the total TP load.

For comparison, Walker and Kann (2022) previously reported that for the total TP loading from all basins and sources to UKL⁴⁰, anthropogenic loads accounted for 32% over the period WY 2010 – 2018, and 35% over the entire period used in that study, WY 1992 – 2018 (see Table E2 in Appendix E and Table 2 of that report). Although basin-specific estimates of anthropogenic loading were not provided in Walker and Kann (2022), applying the background TP concentration of 65 ppb and same methodology as that report to the overall observed concentration at the Power station of 75 ppb (see Table 12), anthropogenic loading would account for only 15% of the total Sprague River discharge. Therefore, the revised methodology used in this study, which accounts for both groundwater and runoff background sources, resulted in lower total background concentrations (51 ppb at Power) and thus higher relative fractions of anthropogenic loading (32% at Power). The lower background concentrations used in this study are also more reflective of the observed FWM concentrations in the relatively un-impacted headwater sub-basins in the upper North and South Forks (48 and 44 ppb, respectively, see Table 12).

One limitation of this approach is that the observed loads at each station incorporate both sources and sinks of nutrients due to in-stream processes such as settling, biological uptake, and flood deposition as well as human activities such as irrigation withdrawals that remove flow (and thus load) from the river. Therefore, a portion of the direct loads to the river are likely not included in the measured loads since some nutrients are lost due to these in-stream processes as water moves downstream. This would result in an under-estimation of the total as well as the anthropogenic loads. In order to more accurately determine the total loads due to both natural sources and human activities, a detailed nutrient budget accounting for all sources and sinks within specific reaches is needed. Such an effort would require a study designed specifically for this purpose, which was beyond the scope of the current effort to provide an initial analysis of the Klamath Tribes long-term Sprague River water quality dataset.

4.9 IMPACTS OF WATER RIGHTS CALLS

During last eight years of the period of record (WY 2013 – 2020), surface water withdrawals in the Sprague River basin were limited due to the Klamath Tribes' exercising their senior water rights (see Section 1.3). To evaluate the impacts of these water use restrictions on instream flows and water quality, the estimated flows, loads, and concentrations at each station during the years before regulation (i.e., pre-regulation period from WY 2002 – 2012) were compared to those during regulation (WY 2013 – 2020).

³⁹ Excluding the un-impacted upper SF and NF stations, which were used as the basis to estimate background concentrations and thus had no anthropogenic loading.

⁴⁰ This estimate includes discharge from the Williamson River and Wood River Basins, other ungauged basins, as well as discharge pumped directly from agricultural areas along the edge of UKL.

4.9.1 SEASONAL VARIATIONS IN FLOW AND WATER QUALITY

The impacts of the Klamath Tribes' water rights calls were first evaluated by comparing the seasonal patterns in flows and nutrient concentrations at each station between the pre-regulation (WY 2002 – 2012) and regulation (WY 2013 – 2020) periods. These comparisons are based on the biweekly measured flows and sampled concentrations, and use LOESS smooth lines to represent the average seasonal patterns of the raw data during each period.

At each of the three mainstem stations (Power, Lone_Pine, and Godowa), flows were generally lower in spring (Apr-Jun) and higher in summer (Jul-Sep) during the regulation period relative to earlier years (Figure 57). The lower spring flows were likely due to reduced snowpack in later years (see Section 4.1.2), while the higher summer flows likely reflect reduced irrigation withdrawals as a result of the water use restrictions. In contrast, flows at the Sycan, SF_Ivory, SF, and NF stations were consistently lower during both the spring *and* summer suggesting the water use restrictions may have had less of an impact on summer low flows⁴¹. Lastly, the largest relative change in flows occurred at the NF_Ivory station where flows were substantially lower in spring and higher in summer. However, note that this comparison (as well as that for SF_Ivory) only includes 3 years of data during the pre-regulation period (WY 2010 – 2012) whereas the other stations include 11 years (WY 2002 – 2020).

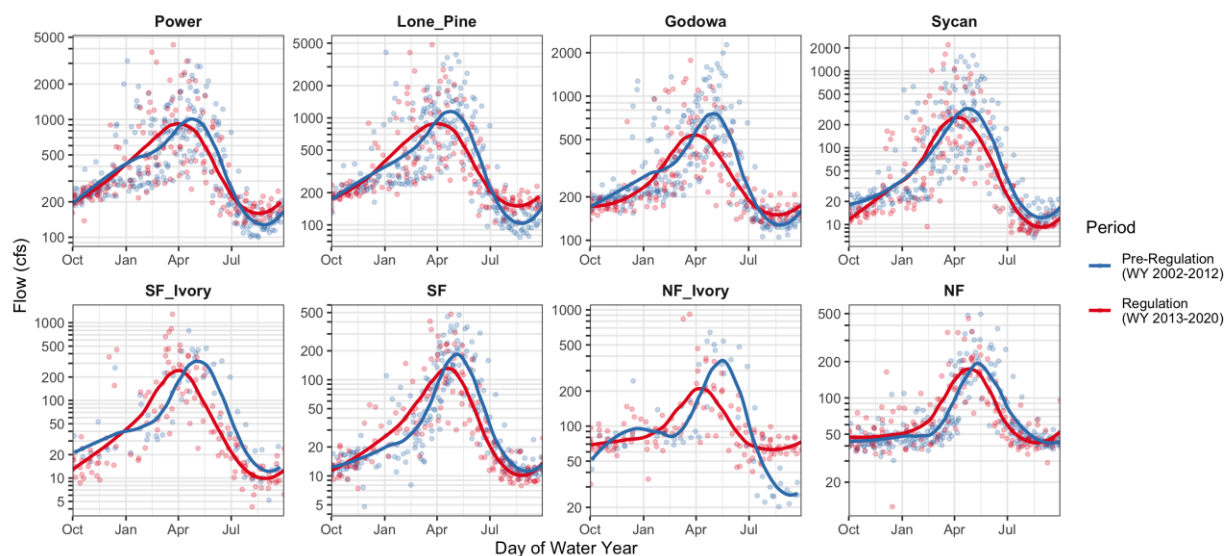


Figure 57: Seasonal variations in flow during the pre-regulation and regulation periods.

Lines show LOESS smooth of data points for each period. SF_Ivory and NF_Ivory only include data during WY 2010-2012 in Pre-Regulation period.

Comparison of the TP concentrations at each station showed relatively little difference between the pre-regulation and regulation periods (Figure 58). Overall, the average seasonal variations as indicated by the LOESS lines were similar at each station. However, there is some indication that spring and summer TP concentrations were slightly lower during the regulation period at the three mainstem stations (Power, Lone_Pine, Godowa). These differences in TP were primarily driven by reductions in dissolved P (PO₄) during summer at Power and Lone_Pine (Figure 59), which may reflect less return flow from

⁴¹ The actual impacts of the water use restrictions cannot be determined from this comparison alone as the summer flows during the regulation period may have been even lower than what actually occurred had water use restrictions not been in place.

agricultural areas during the regulation period. At the upper SF and NF stations, TP concentrations were also slightly lower in early spring (Mar-May) and then higher in summer (Jun-Sep) during the regulation period (Figure 58). Similar figures are provided for other water quality parameters can be found in Figure G1 (Appendix G).

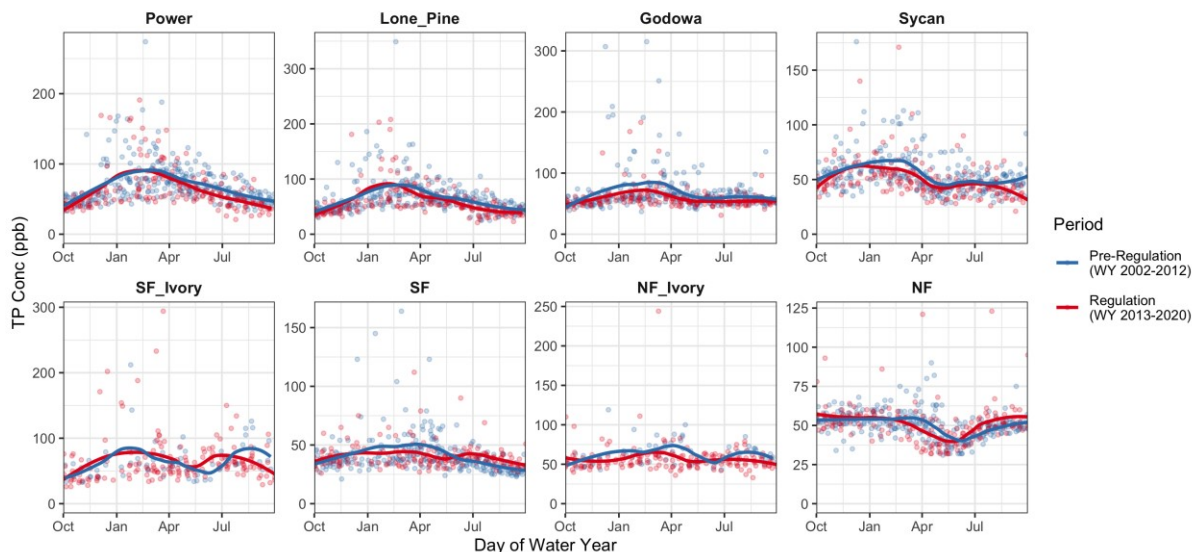


Figure 58: Seasonal variations in TP concentrations during the pre-regulation and regulation periods.

Lines show LOESS smooth of data points for each period. SF_Ivory and NF_Ivory only include data during WY 2010-2012 in Pre-Regulation period

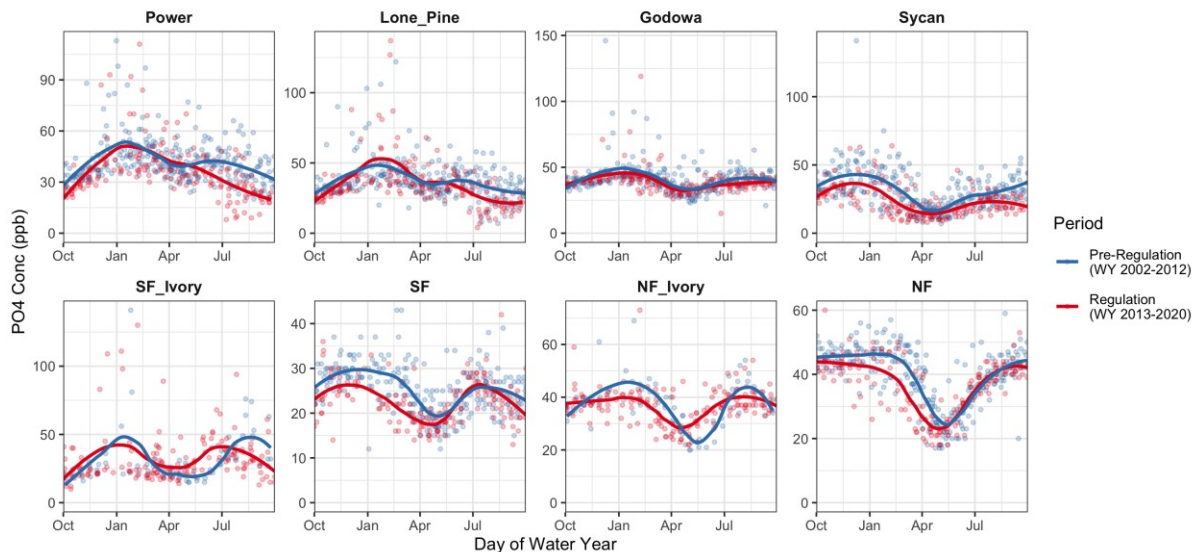


Figure 59: Seasonal variations in PO4 concentrations during the pre-regulation and regulation periods.

Lines show LOESS smooth of data points for each period. SF_Ivory and NF_Ivory only include data during WY 2010-2012 in Pre-Regulation period

4.9.2 FLOW COMPARISON RELATIVE TO CHEWAUCAN RIVER

In addition to comparing the seasonal variations in flow at each station before and during the water use restriction period, continuous daily flows measured in the Sprague River were also compared against flows measured in a neighboring basin (Chewaucan River) where the Klamath Tribes' water rights

restrictions were not in effect. Because the Chewaucan River basin is relatively similar in terms of its geographic and topographic characteristics, it was used as a reference basin to determine whether differences in flows before and during regulation could be attributed to other factors such as climate. Flows at three long-term streamflow gauges within the Sprague River basin, including Sprague at Power (USGS station 11501000) and at Beatty (OWRD station 11497500) as well as at the outlet of the Sycan River (OWRD station 11499100) were compared to those from the Chewaucan River station near Paisley⁴² (OWRD station 10384000) (Figure 60).

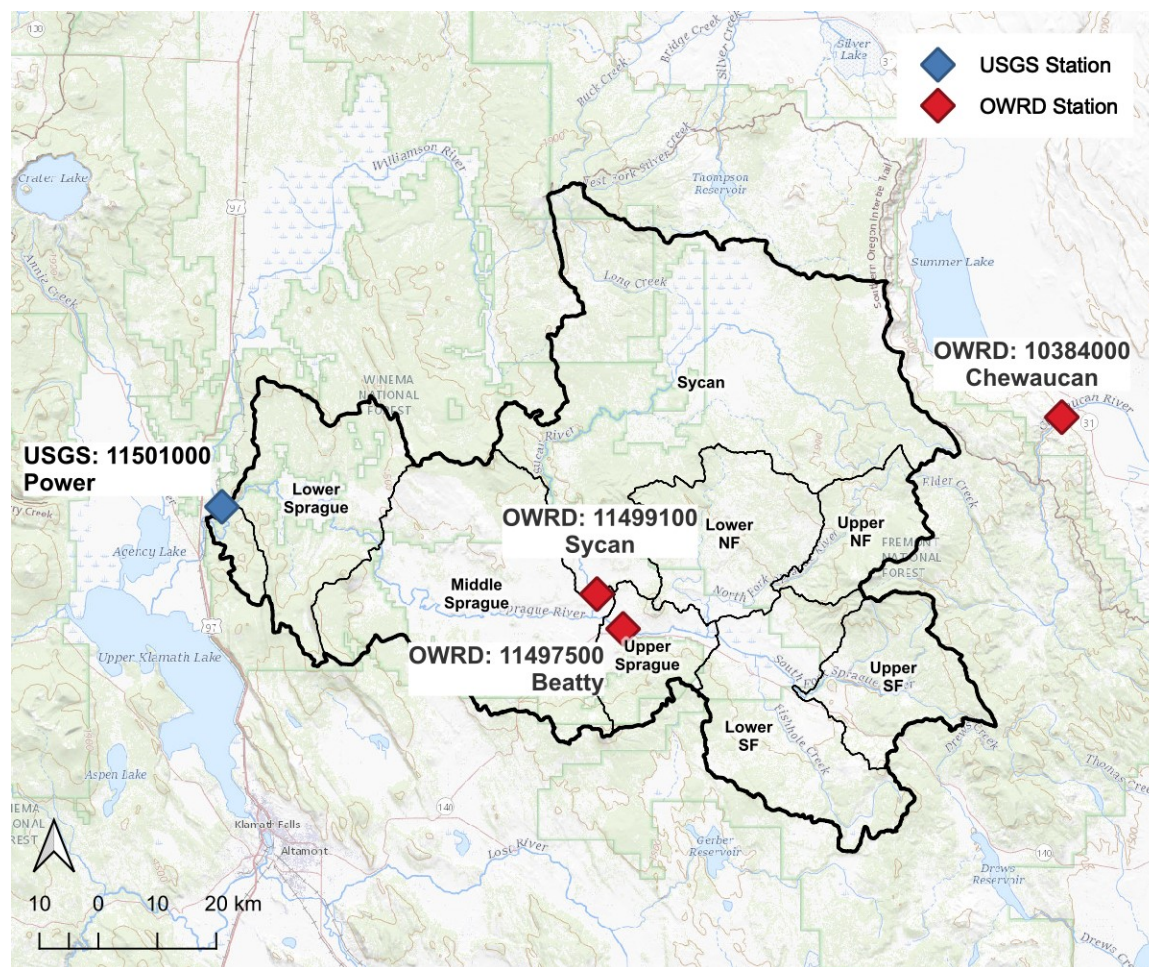


Figure 60: Map of continuous streamflow gauges used for pre-regulation and regulation flow comparison.

Seasonal variations in the daily flows at each of these stations showed that summer (Jul-Sep) flows during the regulation period (WY 2013 – 2020) were generally higher at the Power and Beatty stations on Sprague River compared to the pre-regulation period (WY 2002 – 2012) (Figure 61). At the Sycan and Chewaucan stations, however, summer flows during that period were relatively consistent with those of prior years. In other words, these results indicate that the higher Sprague River summer flows during the regulation compared to pre-regulation period are not likely due to background climatic/hydrologic conditions. If that were the case, the Chewaucan River flows should have also been higher during the

⁴² Because this station is located upstream from irrigated areas, inter-annual variation in discharge is due primarily to climate (e.g., snowpack and precipitation) and not water withdrawal.

regulation period. These results are consistent with those found in the previous Section 4.9.1 (see Figure 57), which showed higher summer flows along the Sprague River mainstem. Furthermore, spring (Apr-Jun) flows at the Power and Beatty stations (and to a lesser extent at Sycan), were somewhat lower during the regulation period, but there was relatively little difference at Chewaucan.

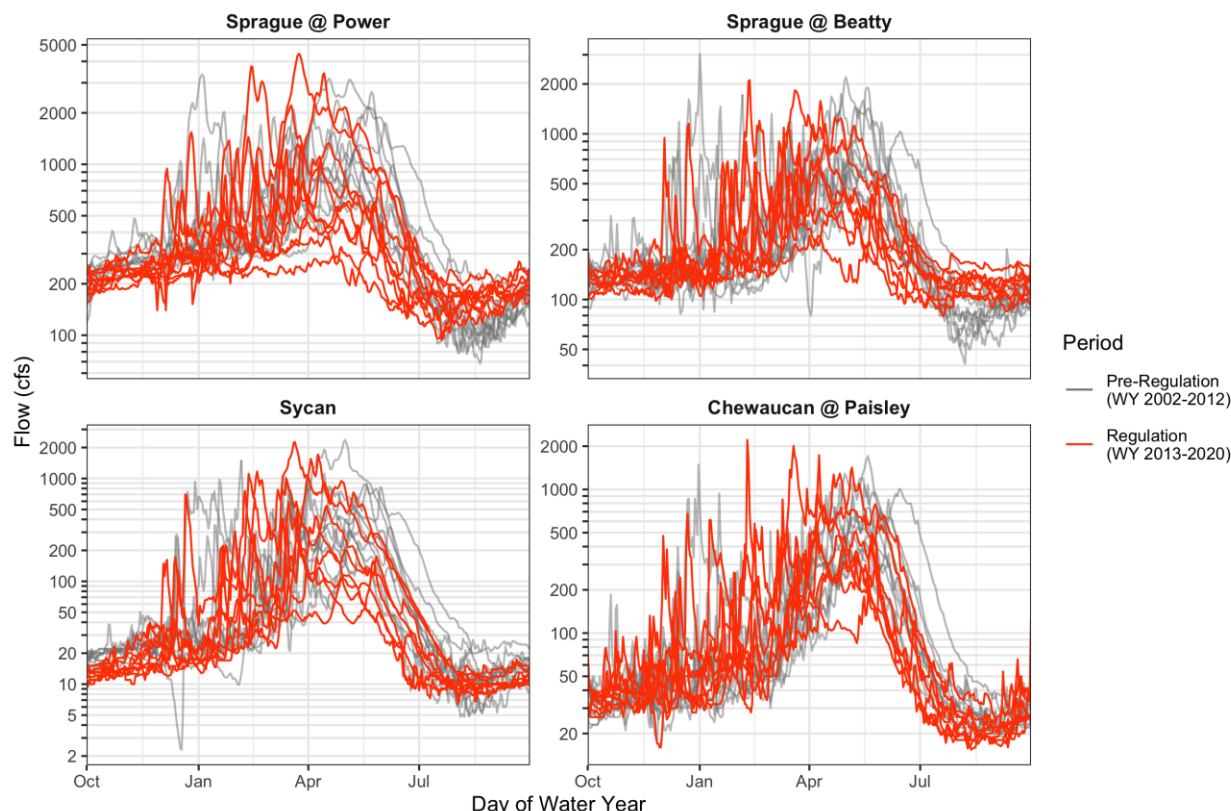


Figure 61: Seasonal variations in daily flow before and during the water rights regulation period, WY 2002 – 2020.

In addition to comparing the seasonal variations of daily flows at each station, mean monthly flows at the Sprague and Sycan River stations were compared against those for the Chewaucan River for each month of the year in order to quantify the change in flow during the regulation period (Figure 62 – Figure 64). Based on the difference between the pre-regulation and regulation linear regression lines, these comparisons show that mean August flows at Power and Beatty stations on the Sprague River were as much as 50 cfs higher for a given Chewaucan River flow during the regulation period as compared to prior years (Figure 62 and Figure 63). Mean monthly flows were also higher at these stations by approx. 25 – 30 cfs in September and approx. 10-20 cfs in July. In addition to the increase in summer flows, these comparisons also show that monthly flows were lower relative to the Chewaucan in spring (Apr-May) and fall (Oct-Nov). For the Sycan River, monthly flows relative to the Chewaucan were relatively unchanged during the summer and lower during the spring (Mar-May) and fall (Sep-Nov) compared during the regulation period compared to earlier years (Figure 64).

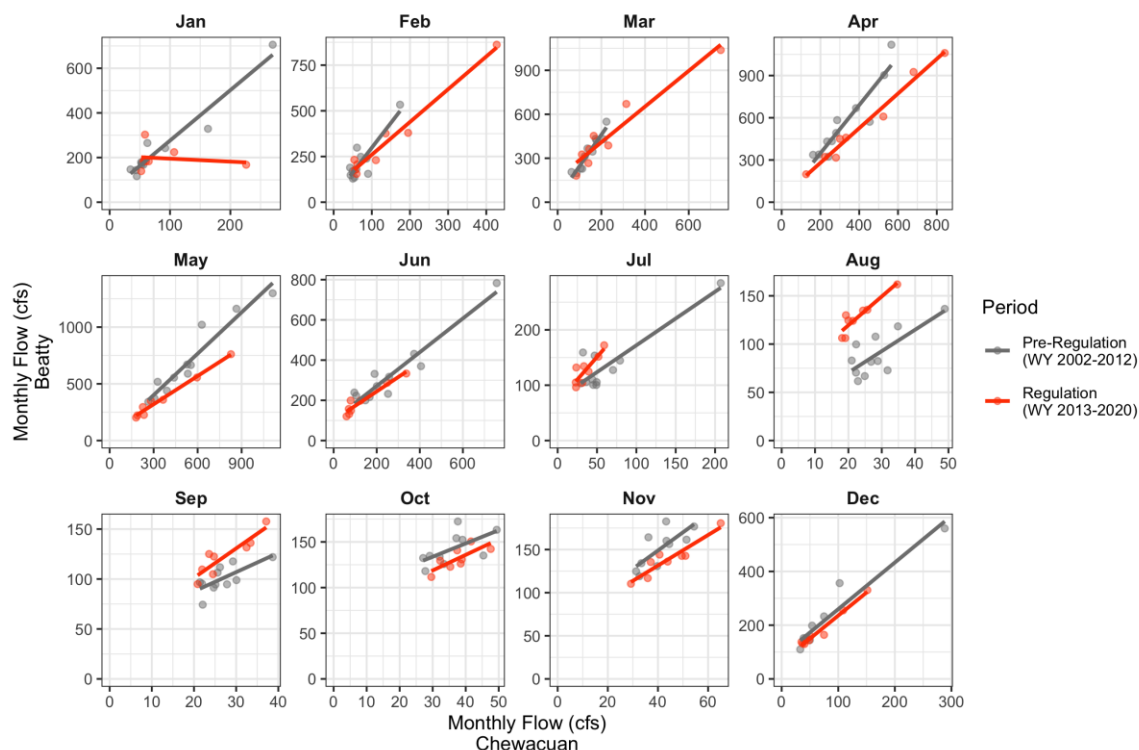


Figure 62: Comparison of monthly flows between Sprague River @ Beatty and Chewacuan River before and during regulation period, WY 2002 – 2020.

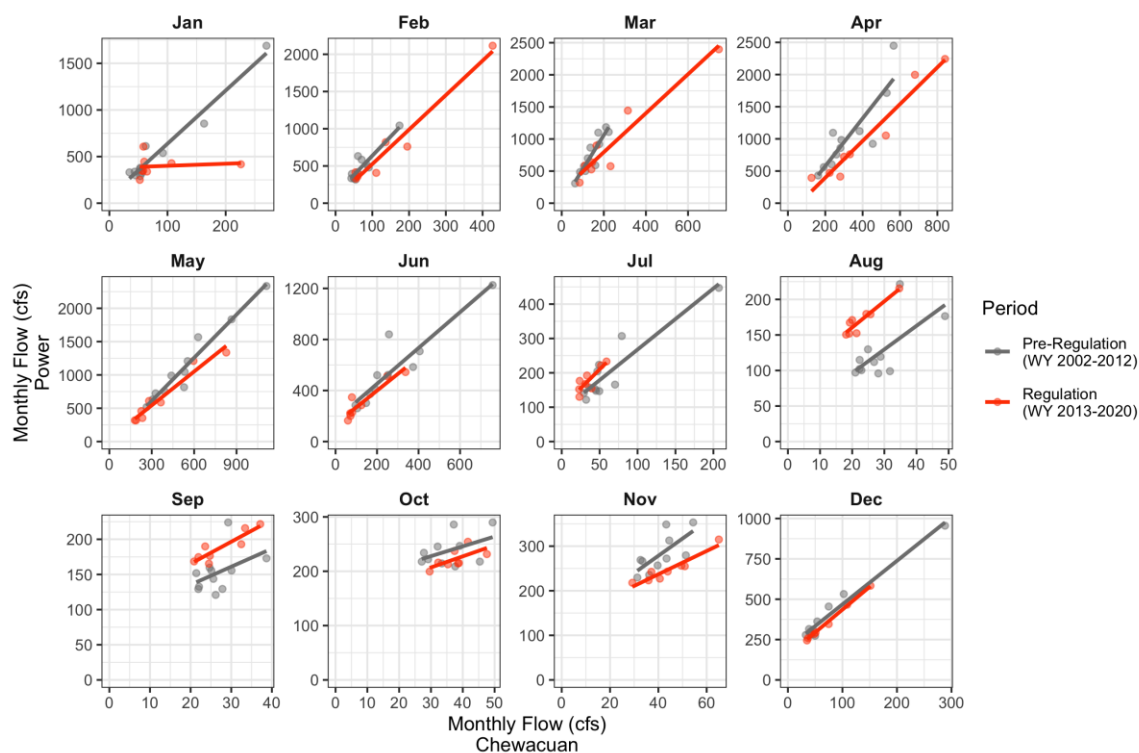


Figure 63: Comparison of monthly flows between Sprague River @ Power and Chewacuan River before and during regulation period, WY 2002 – 2020.

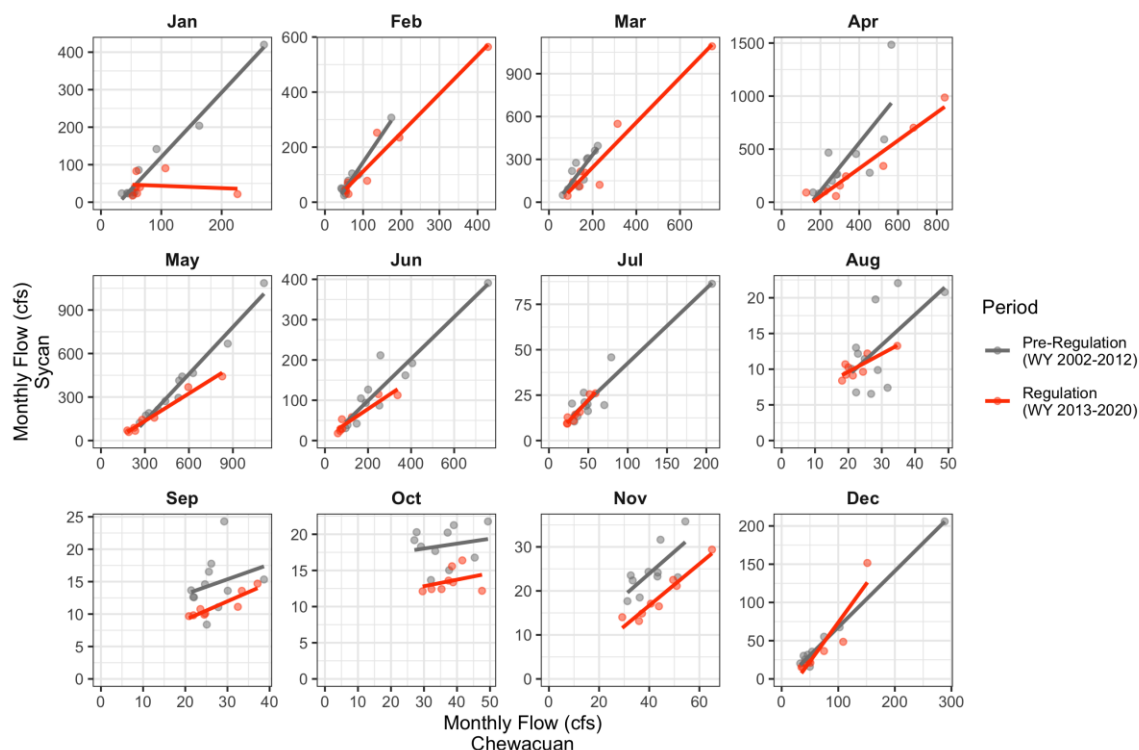


Figure 64: Comparison of monthly flows between Sycan River and Chewacuan River before and during regulation period, WY 2002 – 2020.

4.9.3 ANNUAL AND SEASONAL NET CHANGES IN FLOW AND CONCENTRATION

The final analysis of the hydrologic and water quality impacts of water rights calls in the Sprague River basin focused on evaluating the differences in the *net change* in flow and nutrient concentrations within each incremental sub-basin⁴³. Although the previous two analyses in this section showed that summer flows were higher along the mainstem of the Sprague River during the regulation period relative to prior years, those analyses did not show whether those differences were the result of changes within the mainstem sub-basins (i.e., drainage area along the mainstem), or if they were the result of changes in the upstream sub-basins that then persisted downstream.

Timeseries of annual and seasonal net changes in flow and nutrient concentrations were thus generated for each incremental sub-basin to identify where the differences in flow and concentrations between the pre-regulation and regulation periods originated. Results for the incremental sub-basin between Godowa and the SF_Ivory and NF_Ivory stations (i.e., the “Upper Sprague” sub-basin) were generated as well as for the sub-basin between Godowa and the upper SF and NF stations (i.e., the “Upper Sprague + Lower SF/NF” sub-basin) as the former had a limited period of record (WY 2010 – 2020) due to the late addition of the Ivory Rd stations. For the three headwater sub-basins (Sycan, Upper SF, Upper NF), net changes in concentrations are shown relative to zero since there are no upstream sub-basins from which to compute a net change. Therefore, the net change in concentrations shown for these sub-basins simply reflect the concentrations discharged from sub-basin outlets and are thus substantially higher

⁴³ See Sections 2.4.2, 3.2.4, and 4.5.2.2 for the definition, methodology, and results of the incremental sub-basins and their computed net changes in flows and concentrations

than the net concentration changes for the other downstream sub-basins that were computed by difference.

The net changes in flows show that the only major difference in the regulation period compared to previous years occurred during summer in the Lower NF (between NF_Ivory to NF) where the net change in flow increased by approx. 50 cfs from -25 to 25 cfs at the start of the regulation period in WY 2013 (Figure 65). The net change in flow in the Lower Sprague sub-basin showed some long-term changes such as increases during spring as well as for annual flows, in addition to a small but steady decline in summer. However, because these other changes were more gradual over the entire period, this suggests that they may have been driven not by the water use restrictions, but by other changes such as watershed restoration or climate. There was also an increase in the net flow in the middle Sprague basin during summer, which may or may not reflect impacts of water use restrictions. Although these net changes were negative in all but two years indicating a consistent net loss of water between Lone_Pine and the Godowa and Sycan stations, the fact that these negative values were lower in magnitude in later years (by approx. 25 cfs) may still indicate a reduction in water withdrawals.

These comparisons thus suggest that increases in summer flows along the mainstem of the Sprague River during the regulation period (as identified in the previous sections) were likely driven by changes within the lower NF sub-basin. Furthermore, this substantial increase in the summer net flows within the Lower NF sub-basin (between NF_Ivory and NF) may reflect changes in operation of the North Fork Ditch diversion structure (Figure 68), which is located below the NF station and transports water to agricultural areas in the lower South Fork basin. If this structure was closed (or at least had flows substantially reduced) due to the water rights restrictions then more flow would continue down the North Fork instead of being diverted for irrigation in the South Fork basin, and thus result in greater net flows within the lower NF sub-basin.

The net changes in TP and PO4 concentrations did not show any major changes in any sub-basin between the pre-regulation and regulation periods (Figure 66 and Figure 67, respectively). However, similar to the net change in flow, there were some long-term trends, which more likely reflect watershed restoration activities than impacts of water use restrictions. Similar figures are provided for the other water quality parameters as well as for loads in Figure G2 (Appendix G).

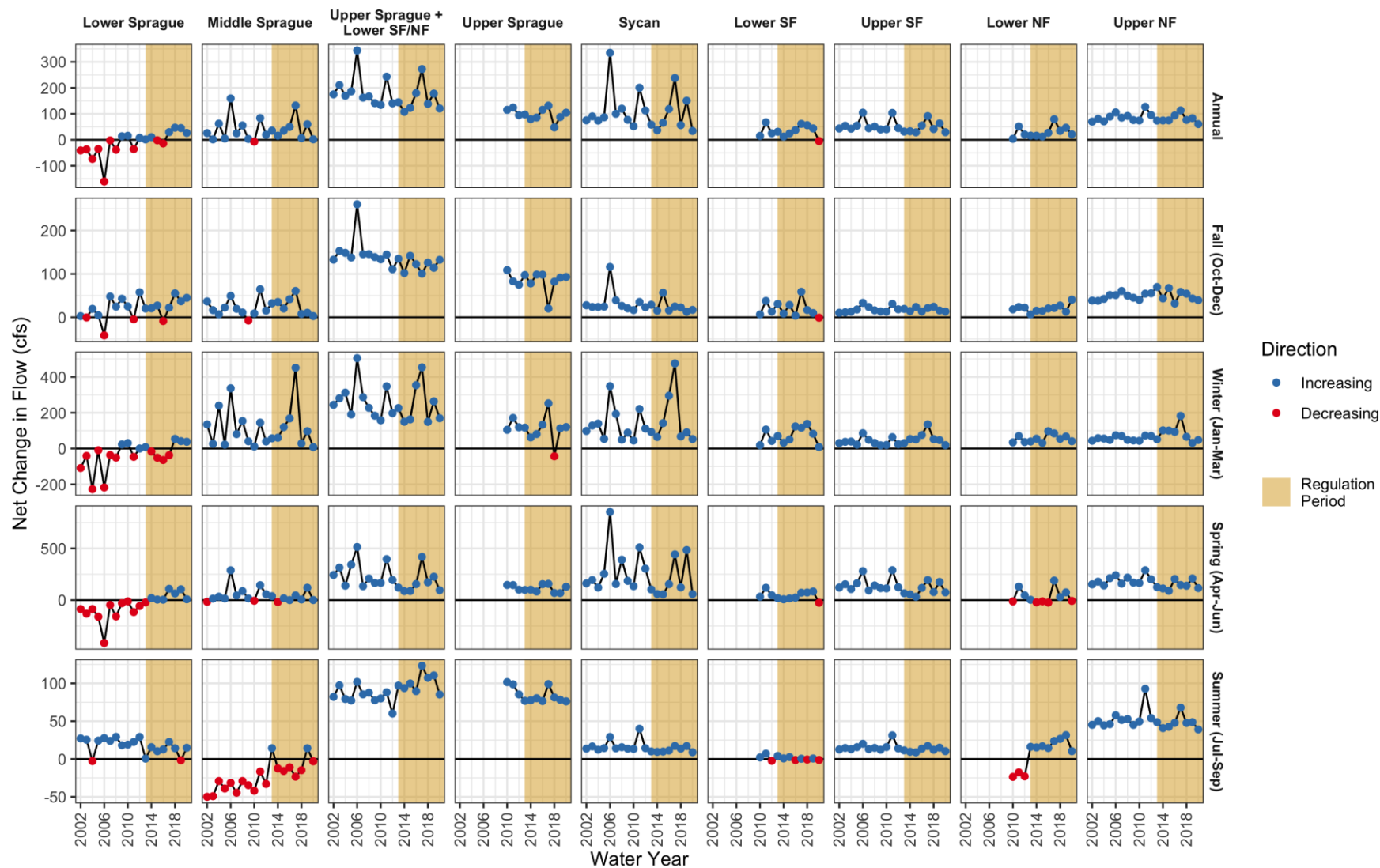


Figure 65: Annual timeseries of net changes in annual and seasonal flows by incremental sub-basin, WY 2002 – 2020.

Upper Sprague + Lower SF/NF includes drainage areas between Godowa and upper NF and SF stations, while Upper Sprague includes are between Godowa and lower NF_Ivory and SF_Ivory, which have a shorter period of record (WY 2010 – 2020).

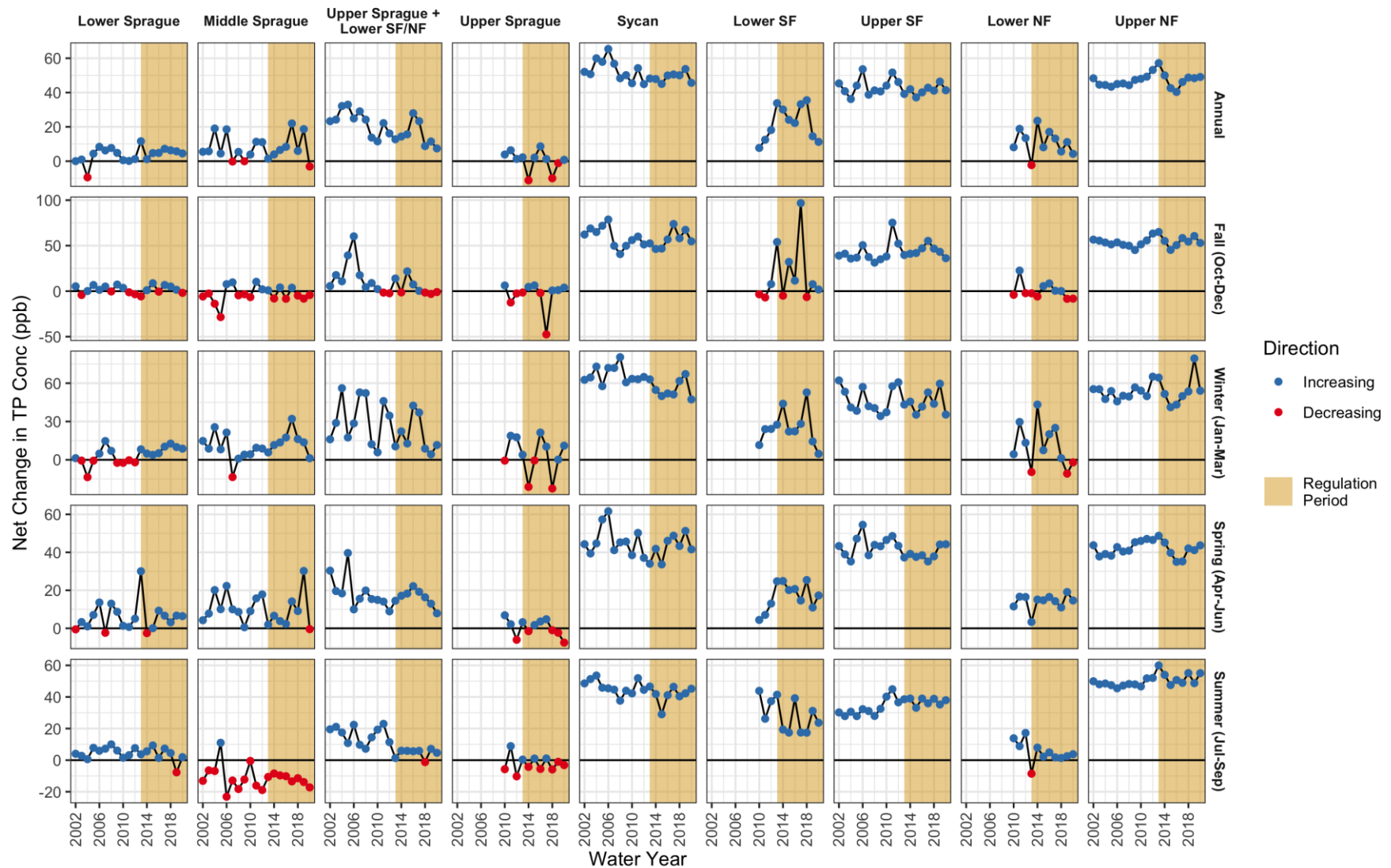


Figure 66: Annual timeseries of net changes in annual and seasonal TP concentration by incremental sub-basin, WY 2002 – 2020.

Upper Sprague + Lower SF/NF includes drainage areas between Godowa and upper NF and SF stations, while Upper Sprague includes are between Godowa and lower NF_Ivory and SF_Ivory, which have a shorter period of record (WY 2010 – 2020). Sycan, Upper SF, and Upper NF show actual concentration since there are no upstream stations to compute a difference from.

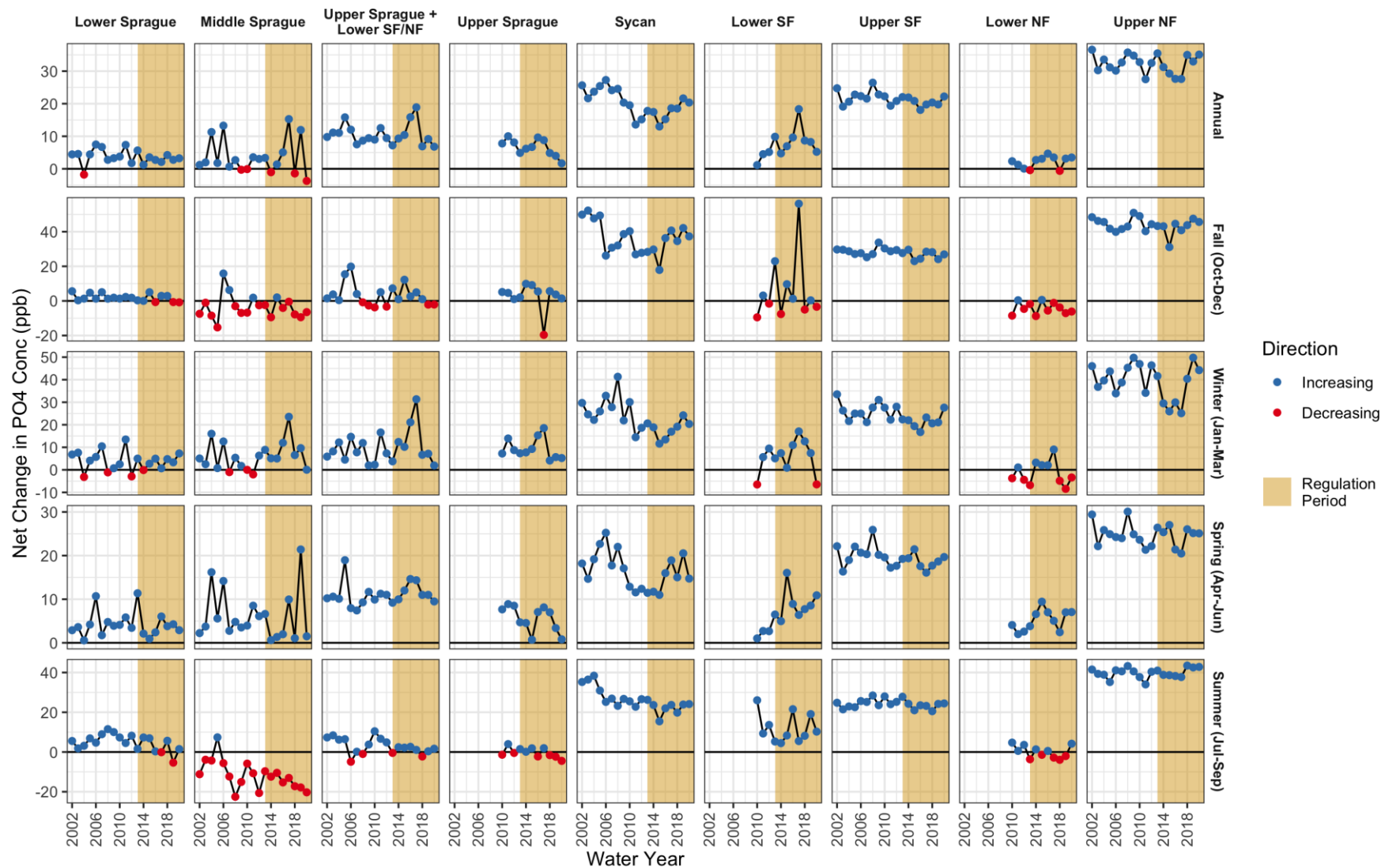




Figure 68: North Fork Ditch irrigation diversion structure located directly below NF station.

4.9.4 SUMMARY

The analyses in this section indicated that summer (Jul-Sep) flows were higher (by as much as 50 cfs in August) along the Sprague River mainstem during the regulation period (WY 2013 – 2020) as compared to prior years (WY 2002 – 2010). Although this difference was reflected at each of the three mainstem stations, the net changes in flow within the incremental sub-basins suggest that this difference originated in the lower North Fork (between the NF_Ivory and NF stations), possibly due to changes to the operation of the North Fork Ditch irrigation diversion, which normally transfers water to agricultural areas in the lower South Fork sub-basin. Therefore, despite the observed differences in flow between the Godowa and Power stations along the mainstem, there did not appear to be any significant changes within the drainage areas between these stations to explain those differences. Instead, the higher summer flows appear to be attributed to changes further upstream in the lower NF sub-basin. These results thus may indicate that groundwater withdrawals and/or illegal surface withdrawals within the sub-basins along the mainstem may have offset any increases in flow due to regulations and restrictions on surface water withdrawals.

In terms of water quality, the only major observed changes were reductions in dissolved phosphorus (PO₄) of approx. 10 ppb at the Power and Lone_Pine stations during summer. The lower PO₄ concentrations in turn caused a small reduction in summer TP concentrations (particulate P remained relatively unchanged). However, these changes may have resulted from long-term changes in the watershed (e.g., restoration) as opposed to water rights regulations.

It is important to note that attributing any of these changes specifically to the water rights regulations requires further research as other factors such as climate change or watershed restoration could have also impacted the basin hydrology and water quality over this period. For example, winter snowpacks tended to be lower during the regulation period than in prior years, leading to lower spring snowmelt and thus runoff. Therefore, a full accounting of the hydrologic and water quality mass balances that accounts for all major sources and sinks within each sub-basin would be needed to determine what specific changes may have been caused by the water rights regulations as compared to other changes in

the watershed. These factors notwithstanding, the comparison to Chewuacan River flows provides confidence that the higher summer Sprague River flows observed during regulation are unlikely to be due to climatic differences, and are more likely to be due to water regulation.

4.10 TREND ANALYSES

Trend analyses were performed to evaluate long-term changes in the flow and water quality at each monitoring station over the period of record (WY 2002 – 2020)⁴⁴. These analyses were performed on monthly flows, loads, and FWM concentrations computed from the continuous daily timeseries. Additional figures and tabulated results of the trend analyses are provided in Appendix H.

4.10.1 DIAGNOSTICS DATA DISPLAYS

Figure H6 (Appendix H) provides diagnostic displays of the trend tests for each station and parameter. These displays include the following elements:

- Timeseries of monthly values with overall trend based on the seasonal Kendall test (top left).
- Timeseries of annual values and trend lines based on the Mann Kendall test and linear regression (top right).
- Timeseries of monthly values grouped by month of the year to show trend in individual months (middle row).
- Bar chart showing the slope and significance of trends in each month, season, and overall annual trends based on the Seasonal Kendall, Mann Kendall and linear regression tests (bottom left).
- Slope and p-value of the primary trend results for the Seasonal Kendall test using all months (Oct – Sep) and for the Mann Kendall test using annual values (bottom right).

An example of these diagnostics is shown below for trends in the FWM concentration of TP at the Power water quality station (Figure 69). These results show that there was a significant ($p < 0.05$) decreasing trend of -1.06 %/yr over the entire period (WY 2002 – 2020) based on the seasonal Kendall test. Results for the individual months and seasons show that this decreasing trend was primarily due to decreases during the summer and early fall (Jun-Sep). However, the tests on annual FWM TP concentrations using both the Mann Kendall and linear regression did not show a significant result ($p > 0.1$). Therefore, these results indicate that although there was a significant decreasing trend in the monthly FWM concentration of TP at the Power station, this trend only occurred in summer and early fall. The lack of significance in the annual FWM concentrations was likely caused by the annual values being more heavily weighted by concentrations in winter and spring (due to higher flows) when no trends in concentration were detected.

These results highlight the benefit of the seasonal Kendall test, which has greater power for indicating significant trends when they occur in specific seasons as opposed to over the entire year as represented by annual values, which can be more heavily influenced by the winter and spring when flows are generally higher.

⁴⁴ Trends for the SF and NF Ivory Rd stations (SF_Ivory and NF_Ivory) were only evaluated over WY 2010 – 2020, and for TSS over WY 2011 – 2020 due to their later addition to the sampling program.

Power | TP Conc

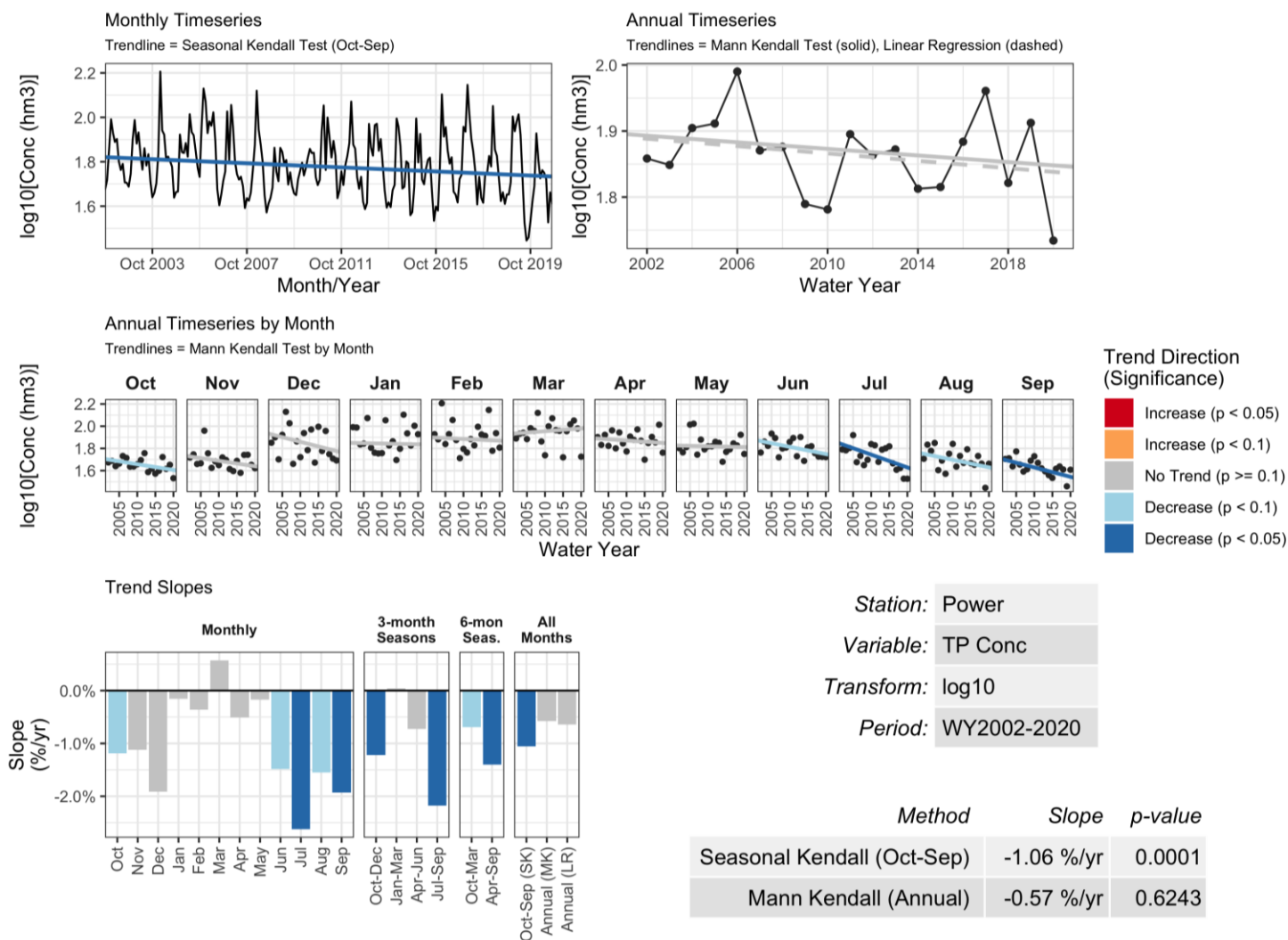


Figure 69: Example of trend analysis diagnostics for TP concentration at Power station.

Colors in bottom left chart denote whether trend is increasing (red), decreasing (blue), or not significant (gray). Shading of colors denotes significance with darker colors for high significance ($p < 0.05$) and lighter colors for moderate significance ($0.05 < p < 0.10$).

4.10.2 TREND SLOPES AND SIGNIFICANCE

Figure 70 summarizes the trend analysis results for annual and seasonal precipitation, flow, TP and TN load, and FWM TP and TN concentration at each station based on the seasonal Kendall test using all months (Oct-Sep) over the full period of record, WY 2002 – 2020. The lower SF and NF stations (SF_Ivory and NF_Ivory) are not shown as these stations were not sampled until WY 2010. The shading and colors of the trend slopes indicate the significance level and direction (positive or negative) of each trend. The slopes are reported in terms of %/yr. Similar figures for the other water quality parameters are provided in Figures H1 and H3 (Appendix H).

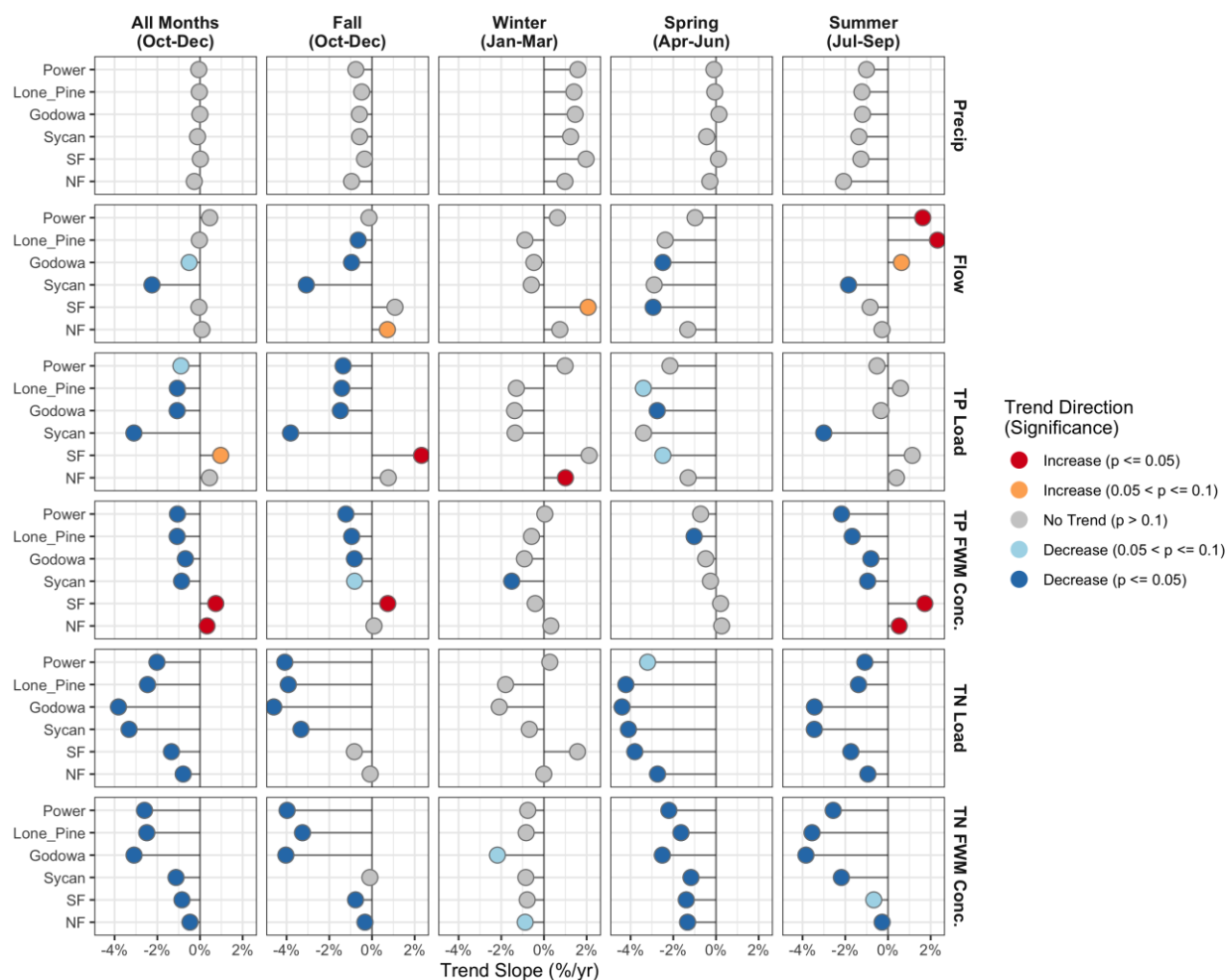


Figure 70: Annual and seasonal trend results of precipitation, flow, TP and TN load and FWM concentration, WY 2002 – 2020.

Colors denote whether trend is increasing (red), decreasing (blue), or not significant (gray). Shading of colors denotes significance with darker colors for high significance ($p < 0.05$) and lighter colors for moderate significance ($0.05 < p < 0.10$). Excludes SF_Ivory and NF_Ivory stations, which had shorter periods of records.

The primary seasonal Kendall test results show that although there was a decrease in precipitation primarily in summer (Jul-Sep) and fall (Oct-Dec) as well as an increase in winter (Jan-Mar), the overall trends were not significant ($p > 0.10$) (Figure 70). Walker and Kann (2022) similarly reported a lack of significance for trends in precipitation, which was based on a observations at a ground-based station (Klamath Falls International Airport) and also included a longer period of record (WY 1992 – 2018).

However, Mayer and Naman (2011) reported a decline in the net inflow to UKL between 1961 and 2007 indicating that precipitation has declined over a longer period than can be detected during the WY 2002 – 2020 period evaluated in this study.

Despite the lack of trends in precipitation, there were a few notable trends detected in the monthly flows at some stations. Large and significant ($p < 0.05$) decreasing trends occurred at Sycan in all months (-2.3 %/yr) as well as in fall (-3.1 %/yr) and summer (-1.9 %/yr). Flows at Sycan also decreased in winter and spring but the trends for those seasons were not significant. There were also large decreasing trends in flow at Godowa and SF during spring (-2.5 and -3.0 %/yr, respectively), and small, but significant decreasing trends at Lone_Pine and Godowa in fall (-0.7 and -1.0 %/yr). Lastly, there were significant *increasing* trends in flows during summer at both Power (1.6 %/yr) and Lone_Pine (2.3 %/yr).

For TP, there were small (-0.7 to -1.1 %/yr) but significant decreasing trends in concentration at the lower mainstem stations (Power, Lone_Pine, and Godowa) as well as at Sycan based on all months, which were primarily driven by changes in fall and summer. These concentration decreases drove similar decreasing trends in TP loads across all months and during fall, but not during summer at the mainstem stations due to the increasing flows. There were also small increasing trends in TP concentrations detected at SF over all months (0.7 %/yr) primarily due to increases in the fall (0.7 %/yr) and summer (1.1 %/yr). Lastly, there were very small, but significant increasing TP concentrations also at NF over all months (0.3 %/yr), which was primarily driven by increases in summer (0.5 %/yr).

For TN, there were large and significant decreasing trends in both loads and concentrations for all stations based on all months as well as in most seasons except winter (Figure 63). The decreasing trends in TN concentrations at the mainstem stations (Godowa, Lone_Pine, Power) ranged from -2.5 to -3.1 %/yr and were much higher than those at the upper stations (Sycan, NF, SF), which ranged from -0.5 to -1.1 %/yr.

In addition to the full period of record, the trend tests were also applied to the last 11 years of data (WY 2010 – 2020) in order to include the SF_Ivory and NF_Ivory stations, which were added to the sampling program in WY 2010 (Figure 71). Compared to the longer period of record (WY 2002 – 2020, Figure 70), there were generally fewer significant trends over this shorter period with a few exceptions. The decreasing trends in TP concentrations at the mainstem stations (Power, Lone_Pine, Godowa) continued to be significant over the shorter period (WY 2010 – 2020) over all months and in summer but were no longer significant in fall. The increasing trend in summer flows at Power was no longer significant ($p < 0.05$) and at Lone_Pine was less significant ($0.05 < p \leq 0.10$) over the shorter period. This suggests the increasing trends over the full period of record (Figure 70) were primarily driven by changes before WY 2010. Lastly, the decreasing trends in TN concentrations during all months as well as all individual seasons except winter remained significant over the shorter period.

At SF_Ivory, there were significant decreasing trends in flow (-3.8 %/yr), TP load (-4.8 %/yr), and TN load (-5.8 %/yr) over all months as well as in fall and summer (decreasing TP loads in fall were not significant). However, there were no significant trends in TP concentrations except in summer (-2.7 %/yr). In contrast, there was a small *increasing* trend in flow at NF_Ivory over all months (2.3 %/yr), which was

primarily driven by large increasing trend in summer (6.6 %/yr). There were also small, but significant decreasing trends in TP concentration at NF_Ivory over all months (-1.1 %/yr) and in summer (-1.6 %/yr).

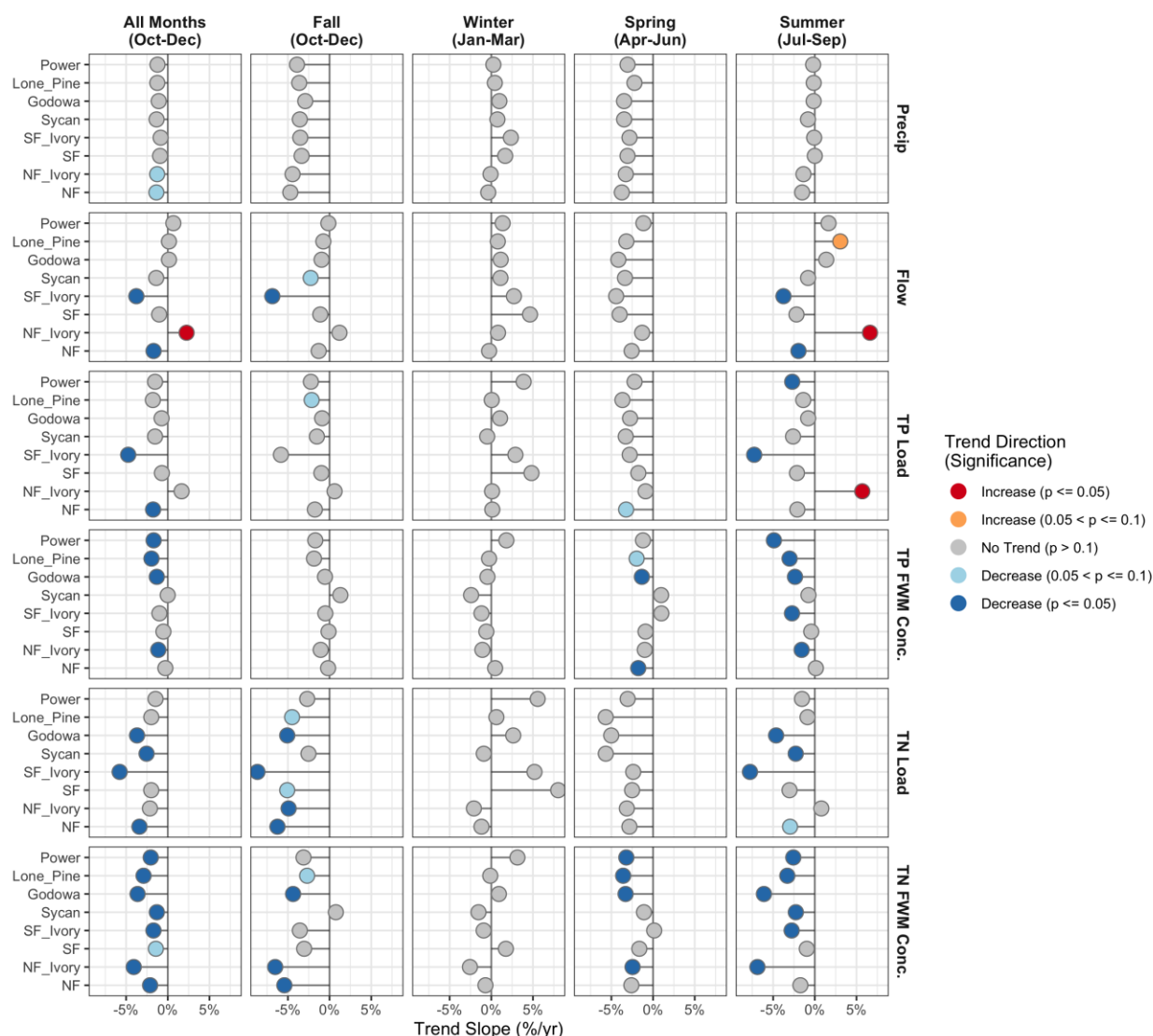


Figure 71: Annual and seasonal trend results of precipitation, flow, TP and TN load and FWM concentration, WY 2010 – 2020.

Colors denote whether trend is increasing (red), decreasing (blue), or not significant (gray). Shading of colors denotes significance with darker colors for high significance ($p < 0.05$) and lighter colors for moderate significance ($0.05 < p < 0.10$). Note that trends shown here were computed over WY 2010 – 2020 at all stations for consistency.

To evaluate which species of P and N were the primary drivers of changes in total P and N, the trend slopes and significance of the monthly FWM concentrations for each parameter are shown in Figure 72 based on the season Kendall test over the full period of record, WY 2002 – 2020. Results for SF_Ivory and NF_Ivory as well as TSS concentrations are not shown due to their shorter record. These results indicate that the decreasing trends in TP concentration at Power, Lone_Pine, Godowa, and Sycan were primarily due to decreases in PO₄ (although there was also decreasing trend in PP at Godowa). In contrast, the increasing trends in TP at NF and SF were due to increasing PP, primarily during the

summer as well as fall at SF and winter at NF. Among the nitrogen species, there were decreasing trends in NH₄ at the three mainstem stations (Power, Lone_Pine, Godowa) in all months, which were mainly driven by decreasing trends in spring. For NO₂₃, there were small decreasing trends at NF and SF across all months and all seasons (except SF in fall and summer) and small decreasing trends at all stations except Sycan in spring.

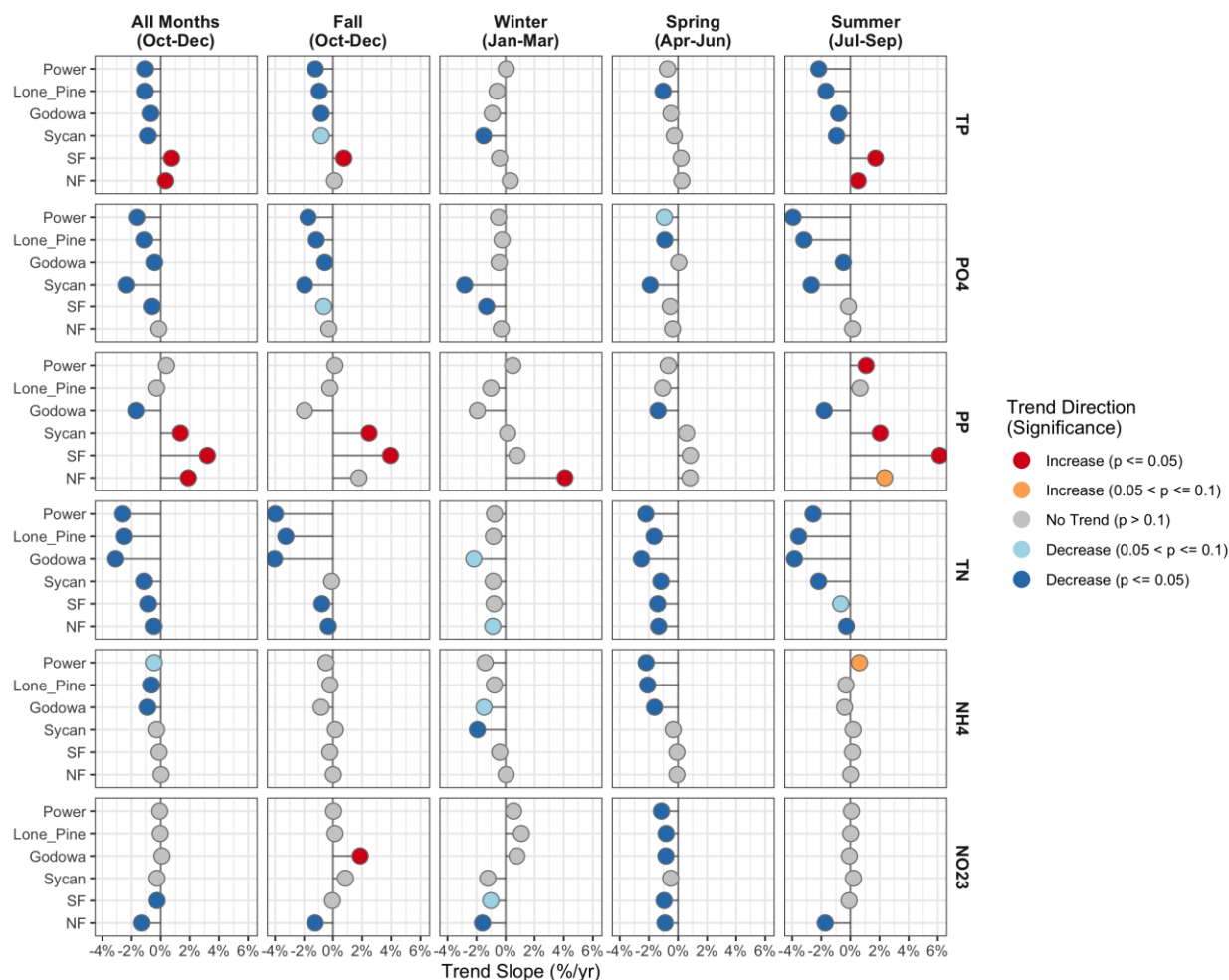


Figure 72: Annual and seasonal trend results of FWM concentrations for each water quality parameter, WY 2002 – 2020.

Colors denote whether trend is increasing (red), decreasing (blue), or not significant (white). Shading of colors denotes significance with darker colors for high significance ($p < 0.05$) and lighter colors for moderate significance ($0.05 < p < 0.10$). Excludes SF_Ivory and NF_Ivory stations and TSS due to their shorter periods of record.

To evaluate trends in nutrient species at the SF_Ivory and NF_Ivory stations as well as those for TSS concentrations, Figure 73 shows the primary trend results for each water quality parameter computed over the shorter period of record (WY 2010 – 2020). Note that the TSS results are based on WY 2011 – 2020 since TSS measurements did not begin until WY 2011.

Over this shorter period, TP concentrations continued to show decreasing trends at the mainstem stations (Power, Lone_Pine, Godowa), primary due to decreases in summer. However, there were large and significant decreases in PP at NF and NF_Ivory in all months as well as spring and summer, which are

opposite the increasing trends observed over the full period. There were also decreasing trends in PP concentrations at Lone_Pine, Godowa, and SF_Ivory, primarily in spring and summer. Lastly, there were relatively few significant trends in PO4 except for large increases at Sycan and SF_Ivory in spring and a large decreasing trend at Power in summer.

TN concentrations continued to show decreasing trends at all stations and over all months, primarily due to decreases in spring, summer, and fall. There were relatively few significant trends in NH4 concentrations, except for increasing trends at Power and Lone_Pine over all months and in winter. There were also few significant trends in NO23.

There were decreasing trends in TSS concentrations at all stations except SF. Most of these decreases occurred in spring, when flows tend to be highest, as well as in summer and fall at some stations (Power, Godowa, SF_Ivory, NF_Ivory). The trends were generally less significant and lower in magnitude at the SF and NF stations, which are less impacted by human activities (except for NF in spring, which had a relatively large decreasing trendf).

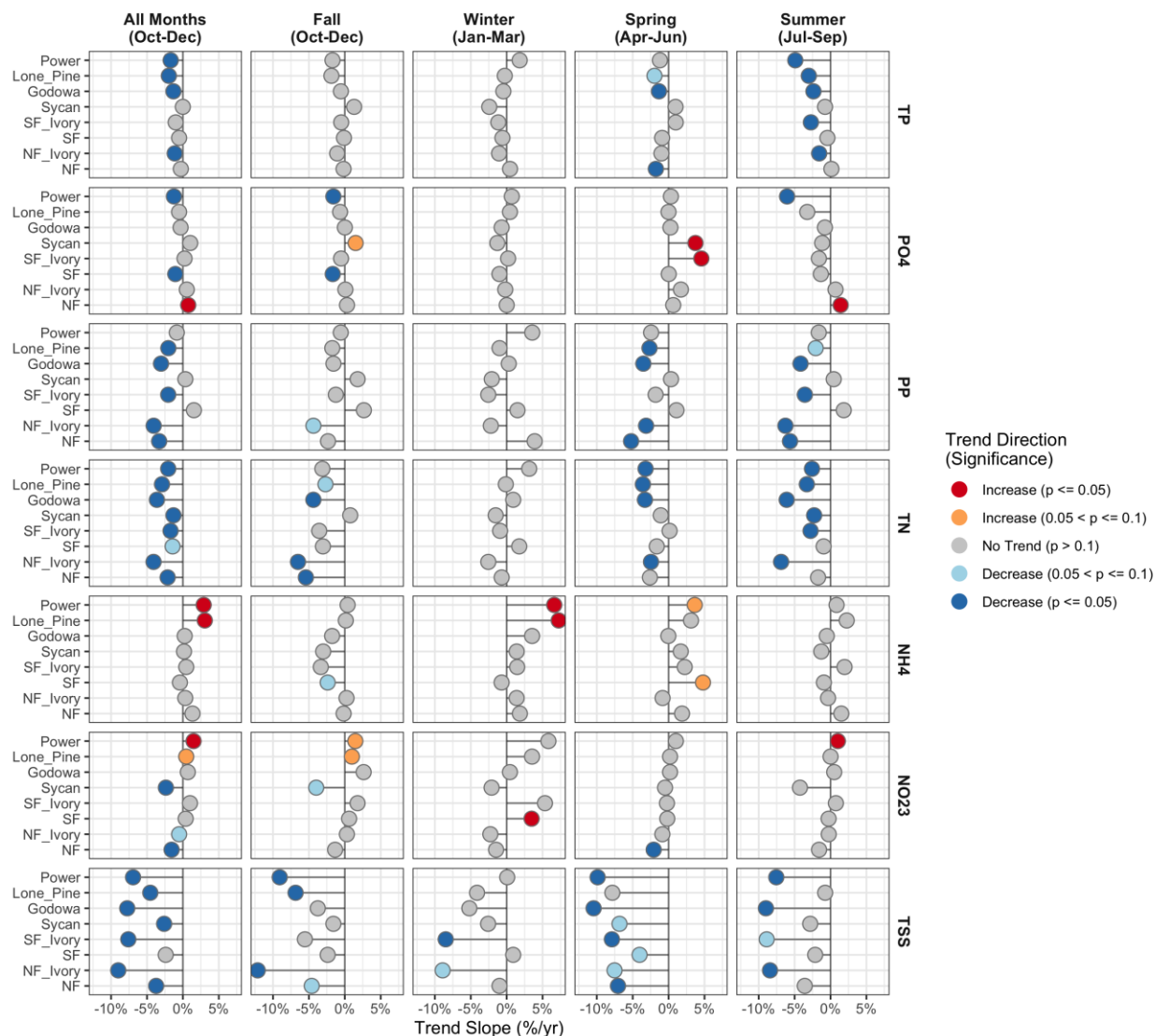


Figure 73: Annual and seasonal trend results of FWM concentrations for all water quality variables, WY 2010 – 2020.

Colors denote whether trend is increasing (red), decreasing (blue), or not significant (white). Shading of colors denotes significance with darker colors for high significance ($p < 0.05$) and lighter colors for moderate significance ($0.05 < p < 0.10$).

4.10.3 SENSITIVITY ANALYSIS TO TREND PERIOD

Long-term trend analyses can sometimes be sensitive to the starting years over which the trends are computed. For many parameters and stations, the primary trend results differed between the full period of record (WY 2002 – 2020) and the shorter period (WY 2010 – 2020) as shown in the previous section (i.e., Figure 70 vs. Figure 71 and Figure 72 vs. Figure 73). To better understand the sensitivity of the trend test results to varying period, the primary trend test (seasonal Kendall test using all months) was recomputed for each station and parameter by varying the starting year from WY 2002⁴⁵ to WY 2016 and leaving the ending year fixed at WY 2020 resulting in periods ranging from 19 to 5 years in duration (Figure 74).

⁴⁵ Rolling periods started in WY 2010 for SF_Ivory and NF_Ivory, and WY 2011 for TSS.

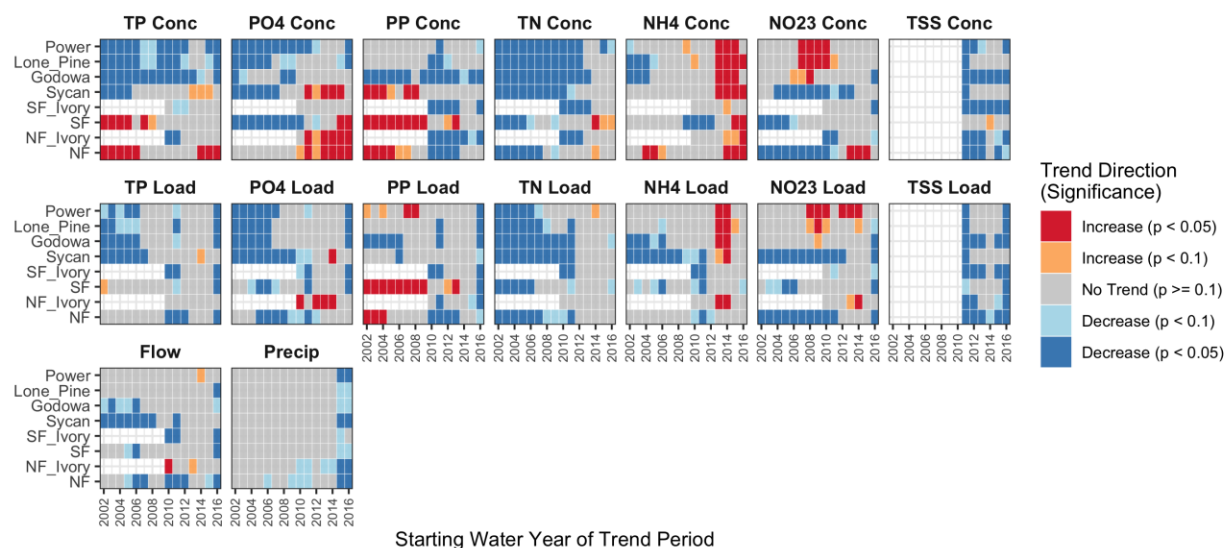


Figure 74: Rolling trend analysis results for precipitation, flow, nutrient/sediment loads and FWM concentrations with periods varying in start years from WY 2002 to 2016 and ending in WY 2020.

Each tile shows the trend direction and significance for a given station and parameter over a period from the starting water year (x-axis value) through WY 2020. Trend tests using seasonal Kendall test on all months (see Figure H5 in Appendix H for individual seasons and Mann Kendall test results on annual values).

The rolling trend analysis results led to the following observations:

- The lack of precipitation trends was consistent over all rolling periods until the last 5 or 6 year periods (beginning WYs 2015 and 2016) when decreasing trends were detected at most stations. There were also decreasing trends in flow over the last 5 years (WY 2015 – 2020) at 5 of the stations.
- The long-term decreasing flow trend at Sycan was consistent over periods starting between WYs 2002 and 2008 indicating that the majority of change in Sycan flows occurred in the earlier years. Similarly, the long-term decreasing trends in TP, PO4, and TN concentrations as well as the increasing trend in PP concentration at Sycan were not detected in the shorter periods (approx. 10-years or less). However, there was an increasing trend in PO4 concentration at Sycan for recent periods with starting years ranging from WYs 2011 to 2015.
- The increasing trend in annual flow at NF_Ivory from WY 2010 – 2020 was no longer significant ($p < 0.05$) when the first year (WY 2010) was excluded but was mildly significant again starting in 2013 ($p < 0.1$). The increasing flow trend starting in WY 2010 was primarily driven by an increase in summer flows, which was significant over periods starting from WY 2010 – 2012⁴⁶ before water rights regulations began (see Figure H5, Appendix H). In other words, increasing flow trends in summer were detected for periods that started a few years prior to regulation but that extended through the regulation period. This is consistent with the observed net change in flow in the lower NF sub-basin, in which there was a large step-change of approx. 50 cfs in WY 2013 (see Figure 65 above), and given the declining trend in annual and summer precipitation during the last 8 years (WY 2013 – 2020), the increased flow trend is likely due to the water use restrictions. Furthermore, there were significant increasing trends in summer flows at Power,

⁴⁶ Meaning that there were increasing trends detected from 2010 to 2020, 2011 to 2020, and 2012 to 2020.

Lone_Pine, and Godowa for most periods starting in WY 2002 – 2009, which is consistent with the changes in seasonal patterns observed between the pre-regulation and regulation periods as shown in the previous section (see Figure 57 above showing increased summer flows during regulation compared to pre-regulation).

- Decreasing trends in TP concentrations among the mainstem stations (Power, Lone_Pine, Godowa) were significant for nearly all periods, and were driven primarily by decreasing trends in PO4 concentrations at Power and Lone_Pine, and by decreasing PP at Godowa. The increasing TP concentration trends at SF (primarily driven by increasing trends in PP) and NF were only significant over the longest periods, although there were later increasing trends at NF over the 3 shortest periods as well.
- Increasing trends in PO4 concentrations were significant over more recent periods starting between WY 2011 and 2016 at Sycan, NF_Ivory, and NF as well as SF in the last two periods.
- In contrast to PO4, the concentrations of PP showed increasing trends over the longer periods starting between WY 2002 and 2008 at Sycan, SF, and NF. The decreasing trend in PP concentrations at Godowa was found for all but one period. Decreasing trends at SF_Ivory, NF_Ivory, and NF were also significant over periods starting between WY 2010 and 2013.
- Decreasing trends in TN concentrations at all stations were consistent over all but the most recent periods (starting WY 2013 to 2016).
- Significant increasing trends in NH4 concentrations were detected over the 3 or 4 most recent periods at most stations (except SF_Ivory).
- The decreasing trends in TSS concentrations were consistent only at Godowa, SF_Ivory, NF_Ivory, and NF (and to some extent at Power). The trends over the full TSS period (WY 2011 – 2020) at Lone_Pine and Sycan were no longer significant when the first year of data was excluded.

Figures similar to Figure 74 above showing rolling trend test results are provided for the four primary seasons using the seasonal Kendall test, as well as for annual values using the Mann Kendall test in Figure H5 (Appendix H).

4.10.4 SUMMARY

The trend analyses led to the following major observations:

- No significant long-term changes in precipitation except for a decreasing trend over the most recent 5- and 6-year periods (for NF_Ivory over the most recent 5- to 8-year periods).
- Large decreasing trends in flow at Sycan over the full period and at Godowa and SF, but only during spring.
- Increasing trends in summer flows at Power, Lone_Pine, and Godowa over the full period, as well as at NF_Ivory over periods that included pre-regulation years (WY 2010 – 2012). These trends appear to be related to the increase at NF_Ivory which led to increasing summer flows along the mainstem of the Sprague River during the regulation period (WY 2013 – 2020).
- Decreasing trends in TP concentrations at the three mainstem stations, which were primarily driven by decreasing trends in PO4 at Power and Lone_Pine and by PP at Godowa. In contrast, there were increasing trends in TP at the relatively un-impacted SF and NF stations driven

primarily by increasing PP, but only based on the longest periods with starting years between approx. WYs 2002 – 2006. There was also an increasing trend in TP concentration at NF in more recent periods (starting in WYs 2014 – 2016).

- There were significant decreasing trends in PO₄ at Power, Lone_Pine, Sycan, and SF over longer periods (starting years over WYs 2002 – 2007). These decreases may reflect restoration activities that reduce the phosphorus content of irrigation return flows or other sources and/or they indicate a reduction in groundwater discharge with high dissolved phosphorus content. Increased groundwater pumping as well as relatively dry conditions with smaller snowpacks during the latter few years in the study period may have caused lower groundwater levels across the basin leading to less discharge. However, there were also increasing trends in PO₄ concentrations at Sycan, NF_Ivory, and NF over more recent periods with starting years ranging from WYs 2011 – 2015.
- PP concentrations showed a significant decreasing trend at Godowa over all periods, and increasing trends at Sycan, SF, and NF over longer periods (starting WYs 2002 – 2007). In more recent periods (starting WY 2010 – 2013), PP concentrations decreased at SF_Ivory, NF_Ivory, and NF.
- Significant decreasing trends in TN concentrations occurred at most stations and for most periods, except more recent periods with starting years from WYs 2013 to 2015. This may reflect the effects of restoration activities targeting runoff or return flows from agricultural areas, which have higher nitrogen content than natural background sources (nitrogen is generally below detection in groundwater sources).
- There were significant decreasing trends in TSS at Godowa, SF_Ivory, NF_Ivory, and NF over nearly all periods starting in WY 2011 to 2015. Decreasing trends in TSS at Power, Lone_Pine, and Sycan were only significant over the full period (WY 2011 – 2020).
- The results for TSS and PP concentrations were generally consistent along the stations due to the close correlation between the two parameters (see Figure 45 above).

5 CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the streamflow and nutrient dynamics of the Sprague River basin over the period WY 2002 – 2020 using biweekly flow and nutrient measurements collected by Klamath Tribes at eight sampling stations across the basin. Continuous daily timeseries of flows, loads, and concentrations were computed using similar methodologies as the previous nutrient budget study for the entire Klamath Basin (Walker et al., 2012; Walker and Kann, 2022). These daily timeseries were used as a basis to investigate the spatial and temporal dynamics of nutrient concentrations and loads, estimate relative amounts of background and anthropogenic loading, assess the potential impacts of the Klamath Tribes' water rights calls on instream flow and water quality in recent years, and evaluate long-term trends at each sampling station.

The results of this study led to the following conclusions and recommendations:

1. Over the 19-year study period (WY 2002 – 2020), annual precipitation was generally lower than the long-term (WY 1982 – 2020) mean in all but five years (WYs 2006, 2011, 2016, 2017, 2019).

Snowpack has also declined over the study period both in terms of magnitude (i.e., maximum depth) and the timing of snowmelt, which has shifted to occur earlier in the spring. The reduced precipitation and snowpack conditions led to regulation of water withdrawals in accordance with water rights beginning in WY 2013 and continuing through WY 2020. These trends in climate conditions are generally consistent with other regional climate and streamflow trends.

2. Based on the annual mean streamflow at each station, the greatest accumulation of flows in the upper parts of the watershed including the upper reach of the Sprague River above Godowa, the headwater sub-basins in the North and South Forks, and the Sycan River. In the lower reaches of the Sprague River (below the confluence with the Sycan River near Godowa), there was relatively little accumulation of flow as compared to the upper reaches. These results were confirmed using separate data sources and suggest that during winter and spring, the floodplains, wetlands, and other depressions along the river corridor in the lower Sprague may be acting as temporary storage basins that trap portions of overbank flows, which are then infiltrated to groundwater or lost by evaporation.
3. During summer, mean annual flows also did not change appreciably between Godowa and Power despite substantial estimates of groundwater seepage from Gannett et al. (2007). Comparisons between mean summer flows and estimates of groundwater discharge by Gannett et al. (2007) showed close agreement for the headwater sub-basins of the upper North and South Forks, the Sycan River, and in the upper section of the Sprague River mainstem above Godowa. However, in the middle and lower sections of the Sprague River, groundwater discharge estimates were substantially higher than the net flow changes along these reaches. These differences suggest significant flow losses likely due to evaporation and irrigation withdrawals.
4. Mean annual FWM concentrations for TP ranged from 44 ppb in the upper South Fork to 75 ppb near the outlet of the Sprague River at Power over WY 2010 – 2020. The majority of this increase occurred in the lower reaches of the South and North Forks as well as in the middle Sprague (Lone_Pine to Godowa and Sycan) primarily due to increases in particulate P. The increases in particulate P suggest that sediment input/transport is a major concern in these reaches and are further reflected by a similar large increase in TSS. On a seasonal basis, the largest increases in both TP and PP occurred in winter and spring when flow conditions are high, further suggesting significant inputs of particulate phosphorus may be due to erosion of stream banks, upland slopes, streambed sediments, floodplains, and/or other areas. During summer, both TP and PO₄ concentrations decreased from the confluence of the North and South Forks to the downstream-most station at Power likely due to biological uptake of dissolved PO₄, which also decreased along the river whereas particulate P concentrations remained steady.
5. Consistent with high groundwater inflow (which includes adjacent springs), the largest increases in flows and TP load per unit area, but the smallest change in FWM TP concentration, occurred in the upper Sprague River basin between Godowa and the SF_Ivory + NF_Ivory confluence. In contrast, the largest increase in FWM TP concentration occurred in the lower South Fork between the SF_Ivory and SF stations. In addition, PP concentrations rose dramatically and consistently in both the lower North and South Forks, while in most years PP concentrations remained relatively steady from Godowa to Power, declining slightly in some years, and increasing slightly in others.

6. Although in some cases misclassification appears to be an issue with the NLCD land use data, rendering analyses less useful than they might otherwise be, comparisons between nutrient concentrations and land use composition of the associated sub-basins for each station showed strong positive correlations between both TP and PP and land uses for planted/cultivated and herbaceous (higher planted/cultivated or herbaceous cover → higher TP and PP concentration). Both TP and PP concentrations were also strongly negatively correlated with forest cover (higher forest cover → lower TP and PP concentrations). For PO₄, there was also a significant correlation with planted/cultivated, but not for any other land use type. This suggests that human activities cause an increase in both dissolved and particulate P.
7. Significant positive correlations were also found between annual mean TP concentrations and the fraction of the lower valley associated with Place of Use (POU) areas for irrigation surface water rights, which were used to represent agricultural areas. On a seasonal basis, the mean TP concentrations had significant positive correlations with fraction POU area in all seasons except spring. Similarly, particulate P was positively correlated with fraction POU area not only annually, but in all seasons except fall. The positive correlation of TSS with fraction POU in all seasons further indicates the effect of human activities associated with agriculture on erosion and sediment flux to the Sprague River. However, dissolved PO₄ showed no significant correlations either annually or in any season, which again suggests that human activities have a larger impact on particulate phosphorus than on dissolved PO₄.
8. The North and South Fork stations all showed positive linear relationships between fraction TP as particulate (% PP) and flow, while the remaining downstream stations showed more non-linear relationships with the % PP higher under lowest flows, decreasing during intermediate flows, and then increasing with increasing flow before tending to level off and decline at highest flows. These non-linear relationships may be the result of bio-uptake of dissolved phosphorus (PO₄) under low flows during summer and increased particulate phosphorus loading through irrigation or other agricultural practices such as cattle access to degraded riparian areas. Relatively high fraction particulate TP under low flows at SF_Ivory compared to the other stations also suggests that even under low flows there is a major source of particulate phosphorus loading to the lower South Fork reach between SF and SF_Ivory. Both TP concentrations and the fraction particulate TP showed positive relationships with TSS further confirming that sediment input/transport is a major source of TP in the Sprague system and that similar to the land use and POU relationships, PP is the major anthropogenic contributor to loading.
9. In light of recent research showing that sediment phosphorus release during summer in Upper Klamath Lake, which is a major driver of algal blooms and subsequent poor water quality, is closely tied to external watershed P loading occurring during the previous winter (Walker and Kann 2022), the results of this study highlight the need for continued watershed restoration to further reduce sources of particulate P and TSS in order to reduce water quality impairments in UKL. Specifically, the need for further watershed restoration is based on analyses showing 1) positive relationships between TP, PP, and TSS with both fraction agricultural land use and fraction POU, and 2) increasing particulate P and TSS occurring during higher flow winter and spring periods.

10. Similar to FWM TP, the mean annual and seasonal FWM TN concentrations showed large increases between the relatively un-impacted SF station and the SF_Ivory station (particularly in summer), but a similar trend was not seen for the NF stations. Despite higher TN concentrations for the Sycan during all seasons, TN only increased slightly for the Sprague stations downstream of the Sycan confluence. Spring and summer NH₄ and NO₃ concentrations were low across all stations likely reflecting uptake by aquatic macrophytes and algae. Unlike other reaches, NO₃ increased sharply between SF_Ivory + NF_Ivory and the Godowa station during fall and winter as flows increased. Sycan NO₃ values were relatively high (compared to other stations) in the summer and fall and decreased in the winter and spring as organic N was exported from the Sycan Marsh upstream.
11. TN concentration was non-linearly related to flow at most stations, with relatively high values occurring during the summer low-flow period, declining values in the fall, and increasing values as flow increased in the winter and spring. As with the phosphorus parameters, TN values tended to be higher in the winter than the spring during higher flows, and similar to PP, TN values tended to level off or decline at the very highest flows.
12. Sycan NO₃ was negatively related to flow, and the pattern at Godowa was unique in that NO₃ values increased with flow in the summer through early winter and then leveled off and declined in late winter and spring as flows increased further, although the cause of these dynamics is not clear. TN and organic-N concentrations generally remained constant over a range of TSS concentrations during summer and fall low-flow periods before increasing linearly with TSS during winter and spring at most stations.
13. Comparisons of flows at each station showed that summer flows were as much as 50 cfs higher along the mainstem of the Sprague River during years when Klamath Tribes exercised their senior water rights (WY 2013 – 2020). This change appears to be driven by a large increase in the net flow accumulation within the lower North Fork sub-basin (between NF_Ivory and NF stations) and may reflect a change in the operations of the North Fork Ditch diversion, which is a large hydraulic structure that normally transfers water from the North Fork to the South Fork for irrigation uses. Aside from some decreases in flows during spring (likely due to reduced snowpack in later years), there did not appear to be any major impacts of the water rights calls on flows in seasons other than summer. The lack of a clear increase in net flow for incremental sub-basins other than the lower North Fork sub-basin, especially during summer, suggests that groundwater and/or illegal surface water withdrawals prevented the continued accrual of instream flows during the regulation period. However, an accurate assessment of the water rights impacts requires a more detailed accounting of the hydrologic budget within each sub-basin as other changes such as climate change or watershed restoration may be confounding those impacts.
14. Comparisons of flow between stations within the Sprague River basin and a streamflow gauge in the neighboring Chewaucan River basin, which was not subject to the Klamath Tribes' water rights restrictions, showed summer (Jul-Sep) flows during the regulation period (WY 2013 – 2020) were generally higher than expected at the Power and Beatty stations on Sprague River compared to the pre-regulation period (WY 2002 – 2012). In addition, mean August flows at Power and Beatty stations on the Sprague River were as much as 50 cfs higher for a given Chewaucan flow during the regulation period as compared to prior years, which was consistent

with the analysis of changes in net flows indicating that summer flows increased by approx. 50 cfs in the lower North Fork (between the NF_Ivory and NF stations) during regulation.

15. Comparisons of nutrient concentrations before and during the regulation period did not show any major effects of the water rights calls on water quality at any station.
16. The relative contributions of background versus anthropogenic TP loads were estimated using a revised methodology compared to that used for the entire UKL basin (Walker and Kann, 2022). Background loads were divided into two separate components, one for groundwater and one for runoff. A background TP concentration of 60 ppb was derived for the groundwater discharge component based on synoptic measurements collected by Klamath Tribes in springs and creeks throughout the basin. For the runoff component, a background TP concentration of 26.5 ppb was computed from the total observed concentrations in the relatively un-impacted headwater sub-basins in the upper North and South Forks after accounting for the loads due to groundwater discharge. These background concentrations were then applied to the groundwater and runoff flow components at each water quality station. After combining the groundwater and runoff background loads, the total background TP concentrations ranged from 33 to 53 ppb. These concentrations are lower than the 65 ppb background concentration estimated by Walker et al. (2012), but better reflect the annual mean concentrations observed in the relatively un-impacted sub-basins of the Sprague River.
17. After estimating background TP loads and concentrations at each station, the anthropogenic loads and concentrations were computed and ranged from 12% to 38% of the total load over the period WY 2010 – 2020 among the stations (excluding the un-impacted NF and SF, both of which had no or minimal anthropogenic loading). The largest fraction of anthropogenic loads occurred in the lower South Fork at SF_Ivory. Near the outlet of the Sprague River at Power, anthropogenic loads accounted for 32% of the total load due to an increase in TP concentration of 24 ppb above a background level of 51 ppb yielding a total observed mean annual FWM concentration of 75 ppb over WY 2010 – 2020.
18. Long-term trend analyses over the entire study period (WY 2002 – 2020) showed a large and significant decreasing trend in flow at the Sycan River. Significant increasing trends in flow during only the summer were detected at Power and Lone_Pine, which is consistent with the analysis of changes in flow before and during the water rights regulations period. There was also an increasing trend in summer flow at NF_Ivory based on its shorter period of record (WY 2010 – 2020), which again likely reflects the change in flow accumulation during the regulation period, potentially due to changes at the North Fork Ditch diversion structure.
19. TP concentration showed small, but significant increasing trends in the upper North and South Forks over the full period (WY 2002 – 2020), despite minimal agricultural impacts in these sub-basins (although there are other human impacts such as forest roads and some grazing). These increasing trends were primarily driven by increases in particulate P (as opposed to dissolved P) suggesting there has been greater erosion in these upper basins.
20. At the other four long-term stations (Power, Lone_Pine, Godowa, Sycan), there were significant decreasing trends in TP concentrations over the full period primarily due to decreasing trends in dissolved PO₄ in fall and summer (except Godowa which also had a decreasing trend in particulate P). There were also small decreasing trends in TP concentrations at SF_Ivory and

NF_Ivory in summer over their shorter period of record (WY 2010 – 2020), which were primarily driven by decreases in PP.

21. All long-term stations showed significant decreasing trends in TN with the magnitudes of these trends being higher in the downstream stations (Power, Lone_Pine, Godowa).

In addition to these key findings, the following recommendations are provided:

1. Continue monitoring for TSS (added in 2010) and continue sampling the more recently added NF_Ivory and SF_Ivory monitoring stations (added in 2009). These important areas showed the greatest increases in phosphorus concentration. Continued monitoring will be useful for future analyses of trends and loading.
2. Perform intensive sampling at select reaches to quantify all sources and sinks and construct a detailed nutrient budget to better understand the magnitudes of the various in-stream and external fluxes of nutrients along the river.
3. Evaluate the efficacy of techniques such as use of stable isotopes to trace pathways of nutrient movement and recycling.
4. Increase synoptic sampling of nutrient concentrations in springs, irrigation return flows, and the lower Sycan (for Sycan determine source of high summer NO₃).
5. Add DOC, DRP, and TOC to the routine monitoring program to further delineate organic fractions of TSS and particulate P.
6. Install continuous water quality probes at existing sampling locations, particularly for the collection of hourly dissolved oxygen, pH, and turbidity data. Compute ecosystem metabolism (gross primary productivity and net ecosystem productivity) for use in understanding ecosystem processes affecting algal and macrophyte related nutrient dynamics.
7. Take action to restore extensive riparian areas and stream channel function in the lower South Fork and lower North Fork reaches where the data show the largest increases in TSS, TP and particulate P concentrations. Riparian plant community restoration is a ubiquitous need that will be the most effective means of reducing erosion-related increases in PP concentration above the NF/SF confluence, and will increase roughness of floodplain surfaces and increase deposition of PP.
8. Reconfigure channelized stream reaches. The lower reach of the South Fork is a good example of a straightened channel that is diked along much of its length. The resulting increased slope, confinement of flow, and minimal lateral connectivity with floodplain surfaces increase erosion, scouring, and transport of fine sediments and the associated PP. Reconstruction of such reaches with appropriate channel morphology to provide lateral connectivity with the floodplain is essential.
9. Consider measures to accelerate aggradation of incised stream reaches, which are prevalent in the NF Sprague and in Meryl Creek. Encouraging beaver activity may be a useful approach (e.g. <http://beaver.joewheaton.org/>)
10. Restore or increase lateral connectivity of the Sprague River with its floodplain by removing or breaching constraining dikes. Focusing such efforts upstream of Godowa would help reduce the PP concentration at Godowa, which is typically the inflection point in PP and TP load plots; slope of these plots decreases moving downstream from Godowa. Similar restoration efforts

downstream of Godowa would reduce PP as well. If done at sufficient scales, this may reduce the magnitude of loading in wetter years like 2006 and 2011.

11. Eliminate direct irrigation returns, which likely have high nutrient content, to rivers and streams.

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